# gPV fuse: special characteristics for photo voltaic cells protection

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Abstract

During the last 50 years, the application of Photovoltaic cells (PV cells) has increased at a high speed. Also the number of cells forming strings and arrays raises, for which the terminal rated voltage, is reaching today values of the order of the thousand volts and the faults currents are slowly increasing its magnitude. PV cells have special characteristics that require protective devices specifically designed for this application, among which the fuse presents optimum features. The main PV cells characteristics are: dc power generation, low short-circuit current magnitudes and X/R ratios (< 25 ms), behavior highly influenced by temperature, etc. Besides the use in the system of storage batteries and reversible inverters, could generate inverse currents due to cells shade, unbalances, and faults. The most used gPV fuse specification is the new IEC 60269-6, that gives some rough guidelines such as: g breaking range, 10 kAdc as minimum breaking capacity, cyclic condition to determine rated current, not applicability of “gates”, fuse selection steps, etc. In order to meet the PF cells characteristics and IEC specifications, several brands of fuses have appeared in the market, showing the actual trend for that application. Also fuse manufacturers give “application rules” that have some inconsistencies and difficult the fuse selection. A summary of the market available fuses and their characteristics is presented, also discussing the advantages and disadvantages of their parameters and characteristics, criticizing some shortcomings and over-dimensioning. The need for more coordinated work between PV cells and fuses manufacturers is stressed, indicating the areas where this work is required.

Keywords: photovoltaic cells, dc fuses, low current interruption, inverse currents, application rules.

## 1. Introduction

During the last fifty years, the application of the photovoltaic cells (PV cells) for the electric power production has increased at a high speed, besides the exploitation of solar energy that initially represented a rarity or sophistication, has become today a sustainable, and mature technology which adapts to the present necessities [1].

The energy content of the solar radiation is on the average of the order of the 1.000 W for square meter, varying thoroughly according to the hour of the day, the time of the year and the geographical location, being for instance, our country Argentina extremely favored for its location [2].

The photovoltaic cell makes the direct conversion of solar radiation into electricity, having the advantage of being formed by modules, simply growing to constitute big generations associating cells, with a useful life of around 25 year. The typical conversion efficiency of the solar generation by using PV cells is ranging from 10% to 15%, acceptable value due to the solar energy has no cost.

This technology advances with the speed with which the photovoltaic cells increase its efficiency, as lower its cost and also as improve its aesthetic appearance. With it, the electricity generation from solar energy is becoming an alternative source to the conventional ones, attractive for being a clean source (free of environmental contamination) and day by day with better economy. The power and energy production from solar radiation increases at world level, whose tendency follows and exponential curve [2].

The biggest energy demand coming from this source bears to the necessity of grouping every day bigger quantity of photovoltaic cells, forming longer strings of cells in series, and parallel arrays of high number of cells. Figure 1 shows a scheme of this type of PV structure. Due to this arrangements the terminal rated voltage, is reaching today values of the order of the thousand volts and the faults currents are slowly increasing its magnitude.

Besides, PV cells have special characteristics that require protective devices specifically designed for this application, among which the fuse presents optimum features.

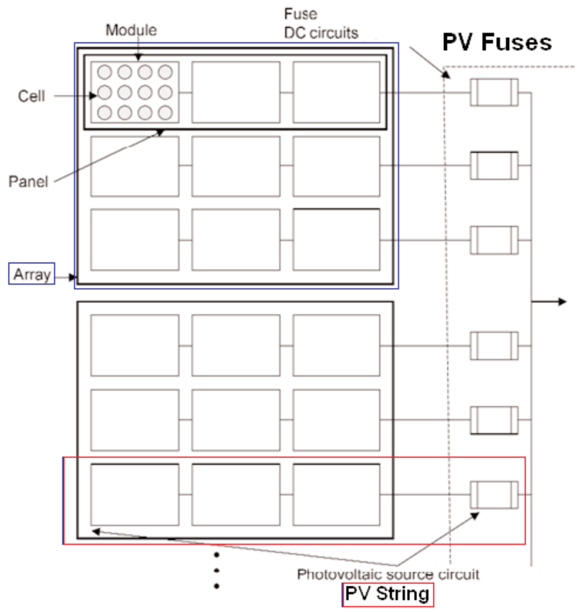


**Fig. 1:** Photovoltaic cells typical structure.

## 2. Photovoltaic cells main characteristics

As it is well known, PV cells possess particular characteristics, as for instance they generate electric power of the direct current (dc) type, its per cell voltage is very low, of the order of 0.3 V for the germanium cell and of 0.7 V for the silicon cell, what allows to assemble modules of 17 V and 35 V, having 36 and 72 series cells respectively, what makes them appropriate to charge batteries of 12 V and 24 V.

The more used solar panels in systems with power higher than 20 kW are those of poli-crystalline silicon type, with square shape having side dimensions of 4", 5" and 6", or 10 cm to 15 cm which are able to give a maximum current for panel of 7.5 A. Wide differences exist among the nominal characteristics of the same panel type among different manufacturers, differences that reach to 35%, for what the study of the selection of the protection should be made on the specific characteristics of the panel to install.

For their application in interconnected form with the 110 V or 220 V networks, exploitation completely different from the simple application in isolated places to supply a few appliances demanding a low power amount, numerous cells are required in series. The more accepted dc voltage for this application is between 900 and 1,000 V dc, the first figure is of wide spread in USA and the second is more applied in Europe [1].

As PV cells form groups of modules in series and parallel, similar to the capacitors banks and storage batteries, problems of voltage unequal distribution are presented, causing faults of individual modules and for that circulating currents among modules in parallel, denominated reverse or residual currents, are very frequents. For their constructive characteristics, PV cells have the particularity of only supply low short circuit current values, with low X/R relationships, requiring for its protection of protective device having specific characteristics.

In summary, the main PV cells characteristics are: dc power generation, low short-circuit current magnitudes and low X/R ratios (< 25 ms), and also its behavior is highly influenced by ambient temperature.

In addition, the obtained energy from the solar to electricity conversion should be transformed into alternating current (ac) with 50Hz or 60 Hz, in order to be able to be used locally, injecting the surplus to the distribution network, requiring for it of an inverter dc/ac that also carries out the injection control. In certain cases the equipment includes storage batteries, in order to regularizing the supply, with what important reverse currents can appear in the event of faults, unbalances or cells shadowing.

Cells partial or total shadowing, caused for instance for a branch tree or dust over the cell, is particularly critical due to the generation of high reverse voltage, also some cells operate as load instead of being a source, thus output is dramatically reduced, hot spots are generated, and local damage could be produced. As the fuse can not protect against the effect of shadowing, the solution roots on the utilization of blocking diodes (connected in series with the string fuse as shown in Figure 2). Also, in order to protect individual cells, bypass fuses are used.

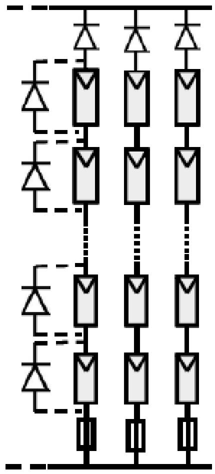


**Fig. 2:** Typical circuit with fuses, bypass and blocking diodes.

The IEC Standard specify the reference conditions, called STC (Standard Test Conditions), for defining rated values and test specifications of solar cells and modules, which are [3]:

- Cell temperature of 25ºC
- Irradiance intensity of 1,000 W/m2
- Light spectrum according an Airmass (AM) of 1.5

Where AM is the optical path length through Earth's atmosphere relative to that at the zenith at sea level.

The Standard Test Conditions were designed in order to ensure comparability among photo voltaic cells from dissimilar origins and different manufacturers.

The rated values or characteristic data of a photo voltaic cell are:

- In = operating current
- Impp = maximum possible working current of a line (MPP = Maximum Power Point)
- Un = operating voltage
- Umpp = maximum possible working voltage of a line (MPP = Maximum Power Point)
- Isc = short circuit current (Isc MOD short circuit current of a module or string, similarly Isc ARRAY) at STC, usually is approximately 1.1 Impp
- IMOD REVERSE = maximum permissible reverse current of a PV module.
- Ipm = maximum power current
- Uoc = no-load or open circuit voltage of a module or array at STC
- Upm = maximum power voltage

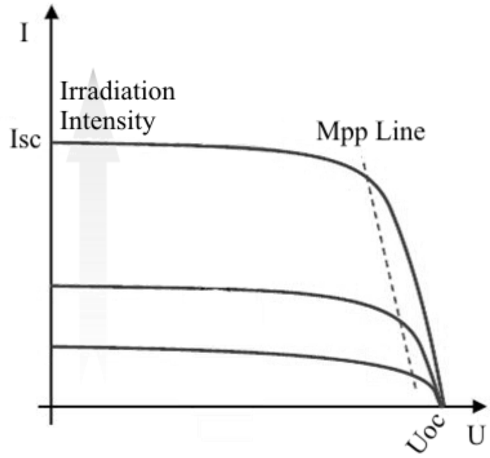


**Fig. 3:** Current – voltage characteristics, showing the meaning of the Maximum Power Point.

As it was already mentioned, the short circuit current Isc that supply each cell is function of the climatic conditions in the installation point, that is to say of the temperature, solar radiation and height over the sea level. If PV cells are located in high zones, low temperatures and solar radiations higher than 1,200 W/m2 can be reached, which requires of correction factors.

The correction factors for maximum solar radiation are as follows, see Table 1 [4].

**Table 1**. Correction factors for maximum solar radiation

| Climatic Zone | Maximum Solar Radiation | Correction Factor |
|---|---|---|
| Normalized | 1,000 $W/m^2$ | 1 |
| Moderate | 1,200 $W/m^2$ | 1.2 |
| Moderate mountainous | 1,400 / 1,600 $W/m^2$ | 1.4 a 1.6 |
| Africa | 1,400 / 1,600 $W/m^2$ | 1.4 a 1.5 |

Equally, the Isc is affected by the ambient temperature, being given the correction factors in % /ºC (for example 0.07 % /ºC).

The voltages of the string of cells are quite variable (no load voltage, Uoc stc, is also determined under standard test conditions), thus due to the possibility that extreme operation conditions are presented (as for example temperatures of - 25 ºC) the corresponding correction factors given in % /ºC should be used (for example 0.4 % /ºC).

### 3. gPV Fuse Characteristics

As the demand of PV cells and the number of installations increase, the necessity of having effective protection against electric transients like as short circuits, overloads, reverse currents and surges is also increasing at a high rate [5].

These new requirements and the present very pressing necessities of electric power, have lead to the design, development and setting in the market of a new series of fuses for PV cells protection whose class is denominated gPV, appropriate for the protection of the manufacturing world leaders' of photovoltaic cells.

At present time it is used in Europe the IEC 60269-6 of recent appearance (year 2010) as design tool, standard that specify the particular characteristics for fuses with this application, similarly it is in study in USA an UL standard with the same purpose, being shortly expected their approval [6].

Optimal protection is reached with fuses located inside the cells string and also in the array output, denominated “string fuse” and “array fuse” respectively [7].

The string fuse functions are [8]:

- Protection in both poles
- Protection required if there are two or more parallel strings
- Always required in systems with batteries or reverse feeding from inverter (high short circuit currents)
- Cable overload protection
- Protection against double earth faults in array and string cabling
- Protection against reverse currents caused by module failures
- Similarly, the array o sub-array fuse functions are:
- Protection in both poles
- Protection against double earth faults in sub-array and array cabling
- Overcurrent protection of sub-array cabling.
- Protection in systems with reverse feeding of inverter.

- Short circuit protection in battery operation if available.

The IEC 60269-6 standard specifies for the fusible gPV the non-fusing (melting) current during one hour as Inf = 1.13 In, where In it is the fuse rated current. Equally it indicates the fusing (melting) current within one hour as If = 1.45 In. The rest of the time – current characteristic can be freely drawn by the fuse manufacturer; several curves have been already proposed by them. The rated current is determined in the classic form of standard IEC 60269-1. Also the mentioned standard indicate the fulfillment of the "Cyclic load" test, which require that 3,000 specific load cycles have to be passed without change of the fuse-link characteristics. Besides it is specified the "Functionality at temperature extremes" that has to be verified with In/If at 50 ºC.

The Inf e If values specified by IEC 60269 change depending on the fuse class, being 1.25 and 1.6 respectively for class gG (≥16A); 1.1 and 1.6 for gR; 1.25 and 1.6 for class gS; and finally gPV 1.13 – 1.45 for the under study class gPV; where the times varies from 1 h to 4 h as fuse rated current function.

Correction factors should be applied on the fuse rated current for work conditions different to the standard one, as shown in Table 2:

**Table 2.** Effect of heating of neighboring fuses, specified in EN 60469-1.

| Number of circuits | Derate Factor |
|---|---|
| 2 – 3 | 0.9 |
| 5 – 6 | 0.8 |
| 6 – 9 | 0.7 |
| 10 or more | 0.6 |

As the average load of the fuses usually does not overcome to 70% or 80% of their rated value, only an additional load derating is required when six or more circuits are nearby, when high losses fuses are used, overcoming each of them the 3.4 W limit value (for the case of high rated currents, normally higher than 32 A) [4].

The fuse rated current is determined for 25 ºC, the cells are normalized to same value, but they can operate at higher temperatures, for what the fuses should be derated to such temperatures by means of correction factors, such as shown in Figure 4 (shown as an example of information of one of the well known fuse manufacturers).

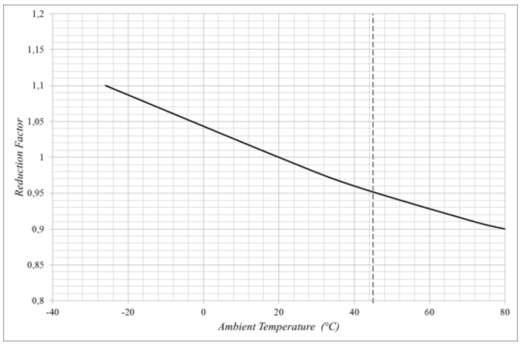


**Fig. 4:** Fuse rated current correction factor as temperature function.

In what concerns to the maximum breaking capacity, a minimum value of 10 kA is specified that seems to be too low in comparison with that of other classes of fuses (minim breaking current for gG class of 50 kA), but to interrupt the short circuit current of the photovoltaic systems it is more than enough.

It should be kept in mind that the time constant (relationship L/R) of the solar cells fault current, for which this breaking capacity is guaranteed, is very low with values from 1 ms up to 25 ms, that makes a great difference with the traditional applications in direct current like the case of railroad and underground short circuit currents that demand values of the order of the 80 ms. Being the minimum L/R of 1 to 3 ms following IEC 60269-6. Most of the manufacturers indicate breaking capacities between 30 and 40 kA, in spite that IEC 60269-6 only specify ≥ 10 kA.

The fuse test voltage should be 20% higher than the unloaded cell voltage under the worst atmospheric conditions. In general, the fuse test voltage is of the order of 1.1 of the rated voltage value (for example 1,000 Vdc and 900 Vdc respectively). It is normal in several fuse types that the test voltage for this class of fuses is the same one that that of operation (normal work condition), for what is common that rated characteristics are given for two work voltages, for example 900 V and 1,000 V (or 1,100 V).

In what concerns to dimensions, for low rated currents, there is enough available space in the standard NH 0 size for such currents, tensions and rated breaking capacities. For very low current values, 1/10 A to 30 A and 1,000 Vdc, it is wide applied the size 10 x 38 mm (adopted by the following manufacturers; Bussmann, Jean Muller, Littelfuse, OEZ, Schurter, Siemens, Socomec, ETI, SIBA, MERSEN, etc.). On the other hand, for higher rated currents, it is widely used the NH 0 and 1c standard size (must be remembered the extension of the series allowed by IEC 60269), from 32 A up to 160 A and 1,000 Vdc whose dimensions of body and total length are for the NH0 66.5 and 125 mm, and for the NH1 71 and 135 mm respectively. For rated currents higher than 160 A the following NH sizes are used but now with longer bodies. The NH1 size covers up to 160 A, the NH2 up to 250 A and the NH3 up to 400 A, all them for 1,000 Vdc, with body and total lengths of 129 and 194 mm, 129 and 209 mm, and 129 and 209 mm for sizes NH1 to NH3 respectively (for 500 V the dimensions for NH2 and NH3 are also similar among them, that is to say 72 mm and 149 mm).

Consequently, the requirements for fuses suitable to protect PV cells are [8]:

- Fuse rated voltage at least equal to 1.2 $U_{oc}$ (applied up to dc 1,100 V that allows for extreme operating conditions such as temperatures up to - 25 °C),
- Fuse rated currents up to 25 A for string protection fuse and up to 400 A for array or sub-array protection fuses,
- Safe breaking of low fault currents,
- Is mandatory to have characteristic of full-range protection, class gPV (under no circumstances aR fuse should be applied),
- Fast operation,
- Resistant against cyclic loading,
- Low power dissipation, and
- Compact dimensions.

When fuses do not fulfill IEC specifications the following situations can arise and the indicated risks could take place.

- Too high fuse rated current:
    - Module charged with improper currents
    - Reverse current withstand exceeded

There is danger of overheating and fire.

- Too low fuse rated current:
    - Interruption of currents still inside acceptable borders

Service interruptions and loss of earnings

- L/R<1 ms:
    - Insufficient rated breaking capacity for the installation

Fuse explosion, arcing and fire hazard

- Nonconformity gPV-requirements related to cyclic loading:
    - Fuse operation during normal or standard work conditions

Service interruption and loss of earnings

- Requirements functionality at temperature extremes not fulfilled (e.g. exposure of junction box to direct sunlight):
    - Interruption during standard operation

Service interruption and loss of earnings

## 4. gPV Fuse application rules

The fuses suitable for the protection of the PV cells should fulfill the following requirements:

The modules and fuses should support continually the direct direction residual current without excessive temperature rise following IEC or the corresponding standards.

The currents that the fuse can be called to interrupt, are the reverse currents caused by failed modules, currents of double fault to earth and the ones due to connection errors, which the fuse should interrupt in reliable form and at the right time [9].

In what concerns to rated current, in order to avoid the unwanted operation (melting) of the fuse under normal operation conditions and in the event of a fault of another parallel string, the rated current of the fuse should overcome the short circuit current of the module or respective string in at least 40 %, that is $In \geq 1.4\ Isc$.

The reverse residual current supplied by the power system or by the remaining modules in parallel, represents a serious interruption problem. This inverse current Isc is obtained by multiplying the short circuit current of the module (affected by the environmental conditions through the corresponding correction factors, usually between 1.2 and 1.6), for the number of modules in parallel less one (Isc REVERSE = (n-1) * Isc MOD).

In order to protect the photovoltaic modules of an inverse current that could overcomes the supported value, the minimum fuse operation current should be smaller than the one allowed and tested of the module. The photovoltaic modules are usually tested with a reverse current of the 1.35 times their reverse current value during two hours, being the pass condition the lack of evidence of overheating, for what the protective device should be able to interrupt such a current in a shorter time. Same manufacturer recommend I MOD REVERSE = 1.35 Maximum module rated fuse.

It must be remembered that for the fuse it is defined the melting current If (also called big test current) of 1.45 In that operates it in less than one hour.

The use of the fuse can be avoided if the capacity to support inverse current is superior to the residual one, that is I MOD REVERSE > Isc REVERSE.

If In >1.4 Isc, the fuse is melted with 1.82 Isc

In order to assure the coordination of the module capacity of supporting reverse current (I MOD REVERSE) with the fuse disconnection, it is recommended the use of a factor of 0.9 for the fuse rated current, that is In = 0.9 I MOD REVERSE [8].

For these studies, in conservative form the current collaborations from the storage batteries and from the inverter are neglected.

In case the solar module is factory assembled, the protection of the cables is already insured, in contrary case should be verified that the cables support the short circuit current of each module so many times as modules had in parallel, that is n * Isc MOD. This protection is determined based on the Iz conductor current in the traditional form. Being Iz is the conductor permissible current carrying capacity [10].

If several PV cells systems are operating together, the rated current of the group fuse should be at least 1.2 times the total short circuit current of the group.

The North American code, NEC defines the maxim circuit current as 125% of the current of short circuit of the photovoltaic cell, Isc, indicating that the conductors and the overcurrent protective devices shall be designed for 125% of the maxim circuit current, that is to say 156% of the Isc.

Additionally the BS EN7671, Sec 712 for Solar Photovoltaic (PV) Power Supply systems specifies that the conductors load capacity should be equal or bigger to 125% of the Isc.

The Isc is given by the cells manufacturers in its leaf of characteristic data that typically is only of the 110 to 115% of the current of maximum power Ipm of the solar module. The Isc is also determined under the normalized conditions previously described.

These values indicate that the short circuit current is very limited and therefore the fuses should operate indeed with very low overcurrents values. The fuse designer's task is extremely complicated for the requirement for the fuse of interrupting low current values with high direct current voltages.

SUMMARIZING

Requirements:

- Un depending on expected lowest ambient temperature (see Table 3) [8].

**Table 3,** Correction Factor for rated voltage as function of ambient temperature.

| TºC | 20 /24 | 19/15 | 14/10 | 9/5 | 4/0 | -1/-5 | -6/-10 | -11/-15 | -16/-20 | -21/-25 | -26/-30 | -31/-35 | -35/-40 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CF | 1.02 | 1.04 | 1.06 | 1.08 | 1.1 | 1.12 | 1.14 | 1.16 | 1.18 | 1.2 | 1.21 | 1.23 | 1.25 |

- Number of parallel strings higher than two
- Tripping current of protection device:
- 1.4 * Isc MOD ≤ I TRIP ≤ 2,4 * Isc MOD
- 1.25 * Isc ARRAY ≤ I TRIP ≤ 2.4 * Isc ARRAY

Selection of fuses (according IEC60269-6)

- Un = 1.2 * Uoc MOD respectively according IEC62548
- In ≥ 1.4 * Isc (Isc MOD or Isc ARRAY respectively)

Taking into account:

- Ambient temperature of 45°C (reduction factor 0.945)

Differing Values according to chart (rated current as temperature function)

- A higher irradiation of 1,200W/m² (factor 1.2)
- Cyclic loading (fixed reduction factor 0.9)

In ≥ 1/0.945 * 1.2 *1/0.9 * Isc = 1.4 * Isc

- For string fuses: In ≤ 0.9 * M MOD REVERSE.
- If tested maximum reverse current withstand value of the module is specified
- For (sub-) array fuses: In ≤ Iz ARRAY CABLE
- For cable and line protection if other sources (e.g. batteries) can provide over-currents

## 5. Selection Methodology

Depending on the wanted capacity of the photovoltaic system, several cells will be connected in series (string) and several strings in parallel, in order to reach the wanted voltages and currents.

The systems that possess three or more strings in parallel require protecting each string, since the current of the generated fault can cause damages to the conductors or other cells. The values of short circuit currents generated when faulted, are of the order from two to three times the rated current, the standard fuses are not adapted to this protection type and they cannot be used. These weak overcurrent values have needed of the development of fusible able to eliminate this defect type.

The adopted solution is to place a fuse in each string, reducing the damage and minimizing personal risks, protecting this way the conductors and isolating the failed cells. It cannot be placed to earth neither the positive pole neither the negative, for what is required of a fuse in each pole of the string of cells.

The fuses should be of more voltage that the string, being recommended that it overcomes in 15% to the corresponding for no-load conditions, for that that Vn ≥ 1.15 Voc * M with M similar to the number of cells in series of the string.

The fuse rated current should be between 1.5 and 2 times the current Isc (stc) of each line. The cable should withstand a current value superior or similar to the fuse melting current If.

According to RISE the trigger current should be higher than 1.25 Isc and smaller to 2 Isc.

Needed data to determine a satisfactory protection

- M, number of series modules
- N, number of paralleled strings
- $I_{sc}$ (stc), cells string short circuit current
- $U_{oc}$ (stc), cells no-load voltage

## 6. Conclusions

The methodology for the PV cell and gPV fuse coordination is presented in summarized form, indicating the main PV cells special characteristics that require of a purposely designed fuse. The traditional g class fuse is not suitable for this protection, its use pose personal and equipment on risk. The need for more coordinated work between PV cells and fuses manufacturers is stressed, indicating the areas where this work is required.

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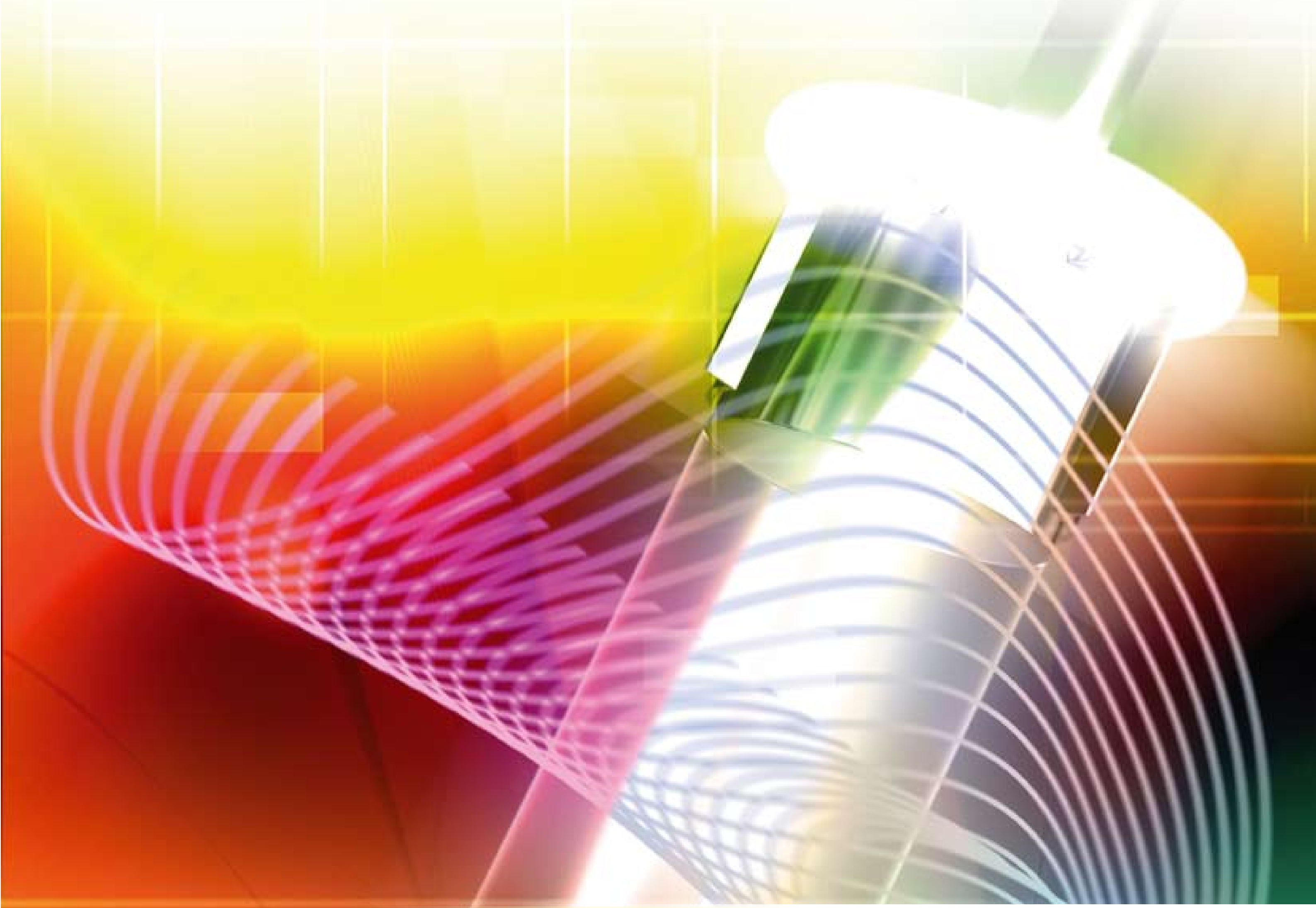

## FAULT CURRENTS AND PROTECTION TECHNIQUES IN PHOTOVOLTAIC SYSTEMS

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