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A Review of Overcurrent Protection Methods for Solar Photovoltaic DC Circuits

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Abstract This paper investigates the current methodology for overcurrent protection in grid-connected solar photovoltaic (PV) systems. Overcurrent testing procedures for PV modules are examined. The report highlights several shortcomings in the current methodology for overcurrent protection, which may be causing premature module degradation and permanent reduction of generating capacity in PV arrays. A series of recommendations are made for improvements to the relevant guidelines and standards.

Introduction

The rapid growth in demand for solar PV systems, demands a similarly rapid development of design and installation standards to ensure that system owners get the performance they are promised and the industry is not tarnished by poorly performing or unsafe systems [1]. Since the first installation of Solar Photovoltaic (PV) systems there has been a tendency to use components and design processes from other electrical technologies, particularly 'low voltage' AC equipment. However the specific characteristics of PV DC circuits show that approach to be unsuitable, including:

- Relatively low short circuit current.
- DC circuit always live during daylight.
- Higher risk of arcing.
- High muscle contraction risk from DC shocks.

Most electrical components in the DC circuits of PV systems are now PV specific, likewise new design processes and standards have evolved to satisfy the specific requirements of PV systems. However, these processes and standards are still evolving and there are key issues where they require further development.



Figure 1: Charred remains of a DC junction box where a fault combined with incorrect fuse installation has caused a fire.

Overcurrent protection is one such issue, which must be provided to mitigate the impact of various risks including:

- Incorrect wiring (wrong polarity / number of modules)
- 2 simultaneous earth faults
- String reverse current due to shading / module fault
- Short circuit between 2 components
- Arcing due to loose connections

Module Characteristics

In power electrical circuits fed by batteries or utility supplies, the short circuit current supplied from the supply in the event of a short circuit fault can be thousands of amps. With a fuse or circuit breakers (MCBs) rated at 20A for example, the short circuit current is ~100 times higher than the fuse rating. However, in a circuit supplied from PV modules, the short circuit is typically only 10% higher than the normal operating current (The exact percentage varies from ~8% to ~40% depending on technology and fill factor).

This low short circuit current is a particular challenge in designing overcurrent protection, if there might be scenarios where the fault current is not enough to disconnect any fuse under fault conditions.

The maximum current passing through a string under normal conditions may be expected to be anywhere up to I_{sc} on the IV curve. Since the datasheet I_{sc} value is tested at $1000\text{W}/\text{m}^2$, a de-rating factor of 1.25 is applied in the UK to DC PV components to allow for irradiance up to $1250\text{W}/\text{m}^2$ [2]. Recent research suggests short term irradiance during variable cloud may be even higher than this [3].

The rating of a string fuse must be greater than the maximum current which might normally flow in that string ($1.25 \times I_{sc}$), but less than the maximum current the PV modules and other DC conductors are designed to withstand. In the US, the National Electrical Code requires that the string fuse rating is at least $1.56 \times I_{sc}$. This historically created a problem for the designer due to the very restricted 'headroom'

between the maximum operating current ($1.25 \times I_{sc}$) and the overcurrent rating of the PV module (which was often not published). Most module manufacturers now specify the maximum string fuse rating to be used with any given module (Figure 2). However it is unclear how this figure is calculated and whether it is set low enough to prevent module degradation in all fault scenarios and to prevent serious overheating.

Brand	Model	Short Circuit Current	Max Series Fuse	Ratio I_{SF} / I_{sc}
		I_{sc} (A)	$I_{SF} \text{ max}$ (A)	
First Solar	Fs-375	1.82	3.5	1.9
Kaneka	G-EA060	1.19	*	
Q-Cells	Q.SMART 75	1.66	4.8**	2.9
REC	SCM210	8.2	10	1.2
Sanyo hit	hit 205	3.84	15	3.9
Sharp	NA-901WP	2.2	4	1.8
SIT	SI 554 T2	5.1	8	1.6
Solyndra	SL-001-150	2.72 A	23	8.5
Sun Power	SPR225BLK	5.87	20	3.4
Suntech	STP20518	8.23	20	2.4
UniSolar	SHR-17	2.35	4	1.7
Würth	WSG36E075	2.4	5.3***	2.2
Yingli	YL210	7.8	15	1.9

Figure 2: PV Module data relevant to fuse selection for 13 different PV Modules.

*Recommended Series Fuse rating not given by Manufacturer, I_{sc} shown here to illustrate range of values.

** Calculated as $I_R (6.5A) / 1.35$

** Calculated as $I_R (3 \times I_{sc}) / 1.35$

IEC 61730-2[4] specifies that PV modules are required to be reverse current (I_r) tested to their specified maximum series string fuse rating multiplied by 1.35 for 2 hours under an irradiance of $50W/m^2$ (any built in blocking diode is short circuited). However most PV fuses would not disconnect at $1.3I_n$ (I_n is the fuses nominal rated current) until after approximately 3 hours, so the requirement to test for 2 hours at 1.35 does not replicate real fault conditions. Some authors imply this reverse current value I_r as the maximum overcurrent rating of the module [5]. The 61730-2 I_r test requires simply that the module doesn't cause charring of an adjacent material, the subsequent visual inspection does not check for any visual damage to the cells (hot spots). Whilst the 61730.2 test may be adequate to maintain the safety of the module under fault conditions it does not consider degradation of the module.

IEC 61215 incorporates a Bypass diode test, which tests the bypass diode to $1.25 \times I_{sc}$ at a module

temperature of 75° for 1 hour, it also includes a test where one cell of the module is shaded while the rest of the module is exposed to irradiance whilst being short-circuited, the module must withstand the test without causing 'major visual defects'; $>5\%$ degradation of power, or insulation resistance below $40M\Omega m^2$ (modules $>0.1m^2$). Whilst this test verifies the modules ability to withstand internal faults, it does not consider systemic faults in the context of a module in multi string array protected by fuses.

Therefore, there is a substantial omission in the module tests for overcurrent; none of the tests in 61730.2 or 61215 explicitly verify that a module exposed to the non fusing current of the recommended string fuse, for the time duration of a PV fuse will not suffer permanent reduction in power output.

Thermal fuse characteristics

Traditional thermal fuses do not disconnect instantaneously at their nominal rated current (I_n), but at a greater 'Fusing Current' (I_F). PV fuses are designed with a Fusing current I_F of $1.45 \times I_n$ (Figure 3) however the fuse will only disconnect at $\sim 1.45I_n$ after 10^4 seconds (~ 3 hours) as shown in Figure 4

This delayed disconnect response time is ideal for AC systems since it reduces nuisance tripping from surges due to motors, transformers, etc. But for PV systems (where current is limited by Irradiance), any excessive delay under overcurrent conditions may cause module degradation.

There can be very significant variations in Fusing Current / Pre-arc time from datasheet values for several reasons [5]:

- Manufacturing tolerances.
- Temperature variation in enclosure.
- Heat from adjacent fuses.
- Variation in current.

A new IEC standard for PV fuses IEC 60269-6[6] is now published, with a "gPV" marking for PV fuses. 60269-6 covers fuses to 1500 V DC, allowing for higher voltages in large scale systems (other standards for PV systems to date have been limited to 1000VDC (600V in North America). The US UL Standard 2579 "Fuses for Photovoltaic Systems" is similar to IEC 60269-6 but not identical. IEC 60269-6 specifies fusing & non-fusing currents closer to the nominal rated current of the fuse than for other fuse types, giving higher sensitivity to faults as shown in Figure 3.

Device Protection Type	Symbol*	Current Ratings	
		Non-fusing I_{nf}	Fusing I_f
Semiconductor	gR	$1.1 I_n$	$1.6 I_n$

Semiconductor	gS	1.25 I _n	1.6 I _n
Solar PV	gPV	1.13 I _n	1.45 I _n

Figure 3: Table of fuse sensitivity.* the suffix g denotes fuses which provide both short circuit (fast response) and overcurrent protection (slow response)

Fuses complying with 60269-6 are available from several manufacturers including JeanMueller, Eska; Siba; Schurter; Mersen (formerly Feraz Shawmut). PV fuses are generally only available in ratings 1..6, 8,10,12,15 and 20 Amps.

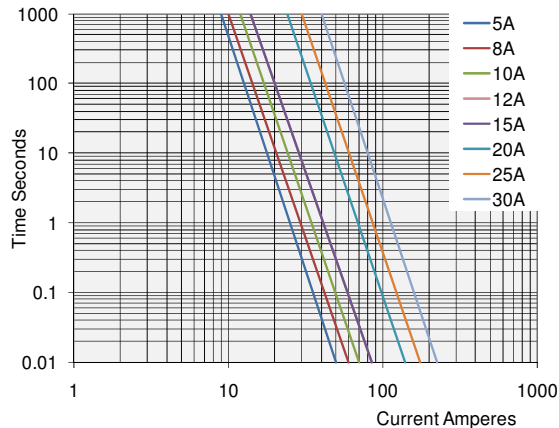


Figure 4: Pre-arc times for typical DC fuses designed for PV systems.

Electric circuits supplied from DC current sources, are more prone to arcing which can occur across Switch contacts; between cables and terminals; between cables and crimped connectors; between connectors after repeated re-insertion; between fuses and holders; within fuses during overcurrent. Arcing occurs if a gap is created in the conduction path whilst current is flowing, this is distinct from AC circuits, where the zero voltage crossing 100 times a second helps to extinguish any arc.

For this reason, the requirement for attention to tightness of terminals and correct crimping of connectors is far greater than many electricians will be used to. Regular thermal imaging surveys of DC wiring, terminals fuses and other site installed live parts in PV DC circuits would be a wise addition to the obligatory testing and inspection of PV systems which would greatly reduce the risk of electrical fires on PV systems. However thermal imaging surveys are not yet mentioned in any installation standards or guidelines as at March 2011.

Fuses designed for DC systems incorporate a number of design features to ensure that the fuse is capable of extinguishing a DC arc at up to 1000V: The actual fuse tape is perforated in several places so if it fails and continues to arc it will break in additional places, increasing the arc gap. The fuse is filled with fine sand to fill the gap left when the fuse breaks, thereby also extinguishing any arc.



Figure 5: Cut away photograph of DC fuse for PV systems.

DC Circuit Breakers

Some commentators have suggested the use of Miniature Circuit Breakers (MCBs) for PV DC protection. MCBs offer several advantages over fuses:

- Visual indication of trip condition.
- Reset without spare parts.
- 2 or 4 pole options so + and – conductors of faulty circuit are disconnected simultaneously.
- Options for remote trip or condition monitoring.
- Can also function as load-break disconnect.

Cost is the main limitation of DC MCBs: 2 fuses (10x38mm 1000V DC) and holders would cost ~£30 (~€30), where a 2 pole DC MCB for PV systems with equivalent ratings would cost ~£90.

The extra cost may only be justified for large scale PV systems where the financial impact of outages is likely to be higher.

DC MCBs for PV systems are currently only available in ratings of 10A upwards, so would only be suitable as string fuses for crystalline arrays of >200Wp modules. Alternatively DC MCBs may find use for inverter internal protection.

The sensitivity of DC MCBs is specified to IEC 60947, however this standard is primarily written for electric power circuits supplied from utility supplies or batteries, where the energy source can supply much greater short circuit current, so the fuse / MCB doesn't need to be as sensitive.

Use of blocking diodes

It is unclear whether DC fuses adequately prevent overcurrent and module degradation. There may be many PV arrays with multiple strings inadequately protected by fuses, where use of diodes would reduce the risk of overcurrent or module degradation.

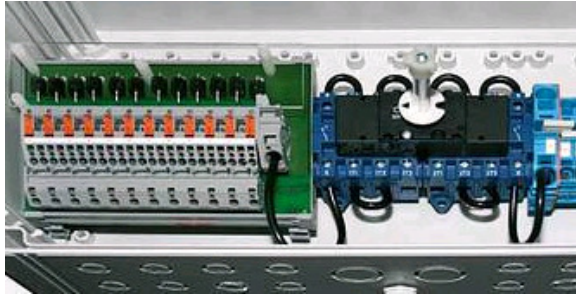


Figure 6: PV Array junction box incorporating diodes, image courtesy of Europartner Solar GmbH.

However, current guidelines imply that fuses offer a superior choice of protection. For PV systems owners in the UK to claim the 'Feed in Tariff' for electricity generated, the system must be installed in accordance with the Microgeneration Certification scheme (MCS) which refers to 2 main guidance documents: BS7671 (17th Edition Wiring Regulations) (based on IEC 60364) and "Photovoltaics in Buildings: Guide to the installation of PV systems (also known as DTI PV guidelines). The DTI PV guidelines state that "*Blocking diodes are not commonly used in a grid-connect system as their function is better served by the installation of a string fuse*"[2]. BS7671 Section 712 does not make any mention of the need to protect PV modules from overcurrent, only the cables.

Electrical designers entering the PV industry will be more familiar with the use of fuses for overcurrent protection. Therefore, there is a problem in the UK and abroad in that the use of blocking diodes may be overlooked by designers.

Diodes introduce a voltage drop of 0.45 or 0.7V (shottky or standard types respectively) into the array, however for grid connected PV systems the system will usually be in the range 300-500V for domestic systems up to 1000V for solar farms. In this context the power loss from the diode will be 0.07-2% depending on diode type, system voltage and current. Note that a few module types have blocking diode encapsulated into the module junction box.

Electronic fuse protection

Several inverter manufacturers now incorporate string current monitoring for each string input which provides alerts via the monitoring system. This system is combined with built-in 10x38mm thermal fuses or electronic fuses. The latter option avoids some of the variability of thermal fuse operation, but requires careful adherence to the inverter specification.

Recommendations & conclusions

Given the long lifetime of PV arrays, and critical link between degradation and financial yield, it is in the

system owners interest that systems are designed to maintain the system performance.

The process for choosing the 'Recommended series string fuse rating (I_{SF}) given on module datasheets needs to be more transparent and based on IEC standards.

IEC standards for module testing should verify that exposure of the module to $I_{SF} \times 1.45$ during fault conditions does not cause any visual deterioration or reduction in power output or insulation resistance.

Datasheets should clearly state how many strings of the module can be connected in series without fuses, and whether blocking diodes are recommended.

Diodes are usually manufactured as circuit board components, so installers must buy ready made diode junction boxes. There is therefore a potential market for diodes in a modular din-rail package which can flexibly be used in any array junction box.

Guidelines for designers and installers need to explain more clearly the need to prevent faults in the DC system, and the process for designing DC PV circuit protection.

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