

OVER-CURRENT PROTECTION IN PV ARRAY INSTALLATIONS

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ABSTRACT

In photovoltaic (PV) arrays with several strings in parallel certain fault conditions may lead to potentially damaging reverse currents for PV modules. The Australian Standard AS/NZ5033 Installation of Photovoltaic (PV) Arrays recommends fuses to protect both cabling and PV modules in case of the occurrence of these fault conditions. The above standard forms the basis of the development of the international IEC draft standard on Installation and Safety Requirements for Photovoltaic (PV) Generators. This international standard development work highlighted the need for improved understanding of the application of fuses in PV array and this paper consequently examines, in detail, requirements for fusing in PV arrays in view of various fault and environmental conditions with respect to protecting both cabling and PV modules.

It reviews and discusses fusing requirements and ratings of the current PV array installation standard. Test results of typical fuse characteristics of fuses used in PV arrays are presented. This testing utilised both a laboratory power supply and a PV array. The paper also examines the relationships between acceptable reverse current levels and exposure durations of reverse currents on PV modules and compares them with trip current of fuses and typical time delays experienced with fuse tripping.

INTRODUCTION

Over-current protection in PV arrays is made difficult by the inherent current limited nature of PV technology. That is, PV module current only increases marginally when going from operating to short circuit condition and hence there may not be sufficient over-current flowing through a fuse or circuit breaker to allow it to operate. Throughout this paper we will refer to this as the *limited fault-current problem*.

However, as the number of parallel interconnected modules or strings of modules increases, potential fault currents and potential reverse module currents do as well. In this paper, we aim to address the question of how many strings in parallel can be connected in a PV array without over current protection and why. Furthermore we discuss the case when we exceed a safe number of PV strings in parallel, what over current protection is required and how do we select the appropriate string protection device.

Our analysis relates to current relevant Australian and international standards (International Electrotechnical Commission 2004; Standards Australia 2005a; Standards Australia 2005b; Standards Australia 2007) and discusses the application of these standards for fault current protection of PV array installations. In addition, some of the rationale to developing the PV Array Installation standard AS/NZS5033 (Standards Australia 2005a) is explained.

In our analysis we only consider fault currents occurring from within the PV array. The reason for this approach is that it represents the worst case scenario from the over-current protection point of view. This scenario is typical of grid connected systems where back-feeding from the grid via the inverter is unlikely. However, the recommendations given are applicable to both grid connected and standalone PV systems. Even though in the case of standalone systems there is a higher possibility of additional fault current from the battery via the charge controller, this in fact aids over-current protection operation as there is no longer a limited fault current problem.

PARALLEL CONNECTION OF PV STRINGS

Critical or undesirable operating conditions of a parallel connection of PV modules can occur when modules are not closely matched in terms of their maximum power point voltages (resulting in mismatch losses), during partial shading of the parallel assembly, or under fault conditions. To overcome the potential mismatch losses, it is recommended to only combine modules of same technology, same manufacturer and with similar specifications in parallel. Partial shading conditions and fault conditions will now be examined with respect to over-current protection requirements.

Partial PV array shading

Partial shading of a parallel assembly is a likely operating condition (particularly in building integrated or rooftop PV applications) and Haeberlin (2007) analyses this in detail. Simulation results of a parallel combination of two typical crystalline PV modules based on Haeberlin's discussions are presented below.

We consider the case where the parallel combination is operating in open circuit. For crystalline silicon PV modules typical single module I-V curves at an irradiance G of 1000W/m^2 and two cell temperatures ($T=25^\circ\text{C}$ and $T=55^\circ\text{C}$) are presented in Figure 1.

The operating point of the fully shaded module is obtained by flipping its I-V curve around the x-axis and determining the intersection point with the relevant I-V curve of the illuminated module(s). In the case of two modules in parallel (one shaded, one illuminated) and for 25°C this is P_2 showing that the reverse current through the fully shaded module would be significantly less than its short circuit current I_{SC} under Standard Test Conditions (STC). In practice, the illuminated module would operate at a higher temperature, e.g. 55°C , resulting in the operating point P_1 and a significantly reduced reverse current through the shaded module compared to P_2 .

Considering now the impact of an infinite number of parallel modules connected to the shaded module, the intersection point moves to P_3 . Haeberlin (2007) shows that for a mismatched case where the shaded module has a reduced open circuit voltage in comparison to the other modules the reverse current is higher, but still significantly

below its I_{SC} . However, as mismatch increases, the operating point may move beyond I_{SC} . On the other hand, connecting a load reduces the reverse current through the shaded module. In conclusion, the operation of a parallel connection of PV modules under partial shading is uncritical in terms of over-current conditions, if modules of the same type are used.

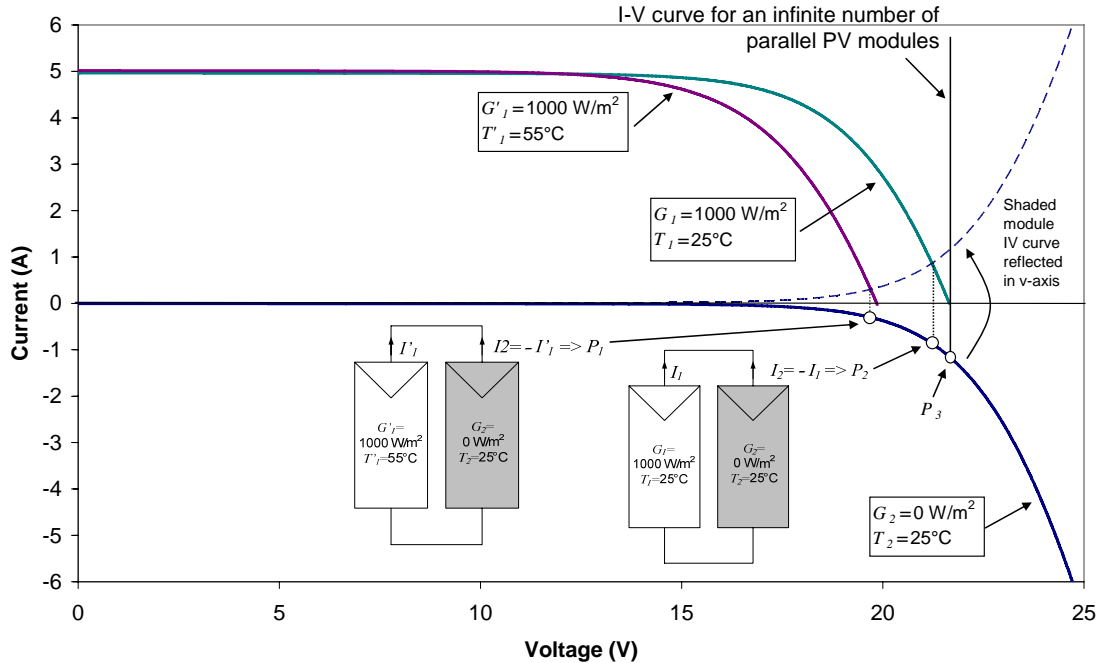


Fig. 1: Simulated I-V curves of typical crystalline PV modules (one-diode model) showing the operating points of a fully shaded PV module in a parallel combination of two or an infinite number of PV modules. The graph shows the impact of the illuminated module's cell temperatures ($T=25^\circ\text{C}$ and $T=55^\circ\text{C}$) on the reverse current through the fully shaded module (based on (Haeberlin 2007)).

Fault currents in PV arrays with several string in parallel

Figure 2 shows an example fault condition in a two string PV array resulting in a reverse current through a PV module. Note that the example uses an earthed PV array where a single earth fault will produce an earth fault current to flow in the PV array. Unearthed PV arrays would require a double earth fault to enable earth currents to flow within the array (a more detailed discussion on possible earth faults is presented in Appendix C of AS/NZS5033 (Standards Australia 2005a)).

As shown in Figure 2 the maximum reverse current through the top right module of the faulty second string is equal to its maximum operating current and it is impossible to size fault current protection to trip in this situation.

Additional PV module strings connected to the array increase the potential reverse module current by the potential current that can be sourced from the extra strings. For n strings in parallel, the potential reverse module current is $(n-1)I_{SC}$. As the potential

reverse current has now increased above the maximum operating current, it is then possible to protect for this occurrence.

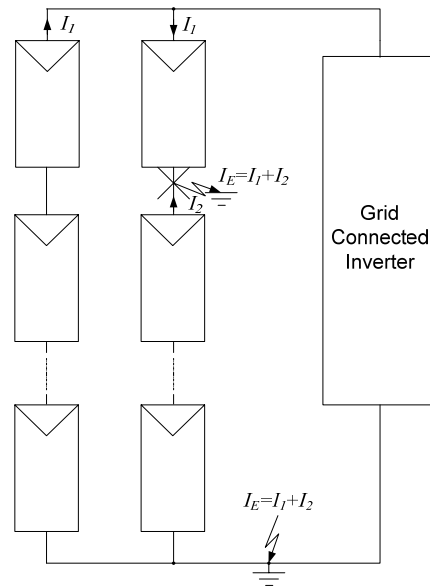


Fig. 2: Earthed PV array with two strings in parallel with earth fault. Due to the fault and a limited DC voltage operating range of the inverter it may not continue to convert power from the array and the top right module is then exposed to a reverse current.

It should be noted that the fault case described above investigates reverse currents in a PV array with n strings in parallel. In large PV arrays with several sub-arrays in parallel the analysis of fault currents and its fault current protection increases in complexity, which is addressed by Haeberlin (2007). In this paper we limit our discussion to a PV array with n strings in parallel.

Maximum reverse module currents

Tests performed by the Fraunhofer Institute (Laukamp, Buecher et al. 1999) for Solar Energy Systems and the Photovoltaic Laboratory of the Bern University of Applied Sciences in Burgdorf (Haeberlin 2007) investigated the effects of reverse currents on PV cells and/or modules.

The tests performed at the Photovoltaic Laboratory in Burgdorf exposed cells and/or modules to increasing reverse currents under laboratory conditions while observing any permanent changes in their I-V characteristics. Generally the tests showed that no permanent I-V curve changes or damages were observed for reverse currents of three times the short circuit current under STC (test were performed for modules employing mono and poly crystalline, as well as CIS technology). The tests further indicated that a reverse current of three times the short circuit current would keep the temperature increase due to the reverse current within tolerable limits, keeping cell operating temperatures below 100°C.

The conclusions of the tests performed by the Fraunhofer Institute report higher permissible reverse currents of generally 6-7 times the short circuit current. However,

the operating temperature may then reach up to 150°C, a value where extended operation is considered undesirable.

Ideally for individual modules the PV module manufacturer should know the permissible reverse current. However, this information may not be provided directly. IEC 61730.2 (International Electrotechnical Commission 2004) has a module reverse current test which is related to the size of the manufacturer's recommended series fuse size. This test passes 135% of the series fuse rating in reverse through the module. The amount of module reverse current that can be safely carried (for hopefully limited time) without long term module damage is then specified by the module manufacturer through the specification of a maximum series fuse rating.

The Australian Standard AS/NZS5033 (Standards Australia 2005a) relates the number of parallel strings without over-current protection to the module reverse current rating ($I_{reverse}$) and the module short circuit current (I_{SC}): For example, if $2 \cdot I_{SC} \leq I_{reverse} < 3 \cdot I_{SC}$ then the number of strings without over-current protection would be 3. For panels not tested to IEC 61730.2 or where no manufacturer's series fuse rating is given, AS5033 requires over-current string protection in every string.

STRING FAULT CURRENT PROTECTION

String fault current protection options include the use of string fuses or circuit breakers. Both need to be rated for DC, the maximum array voltage and the level of fault current protection required. However, further discussion of DC circuit breakers is beyond the scope of this paper and we limit our discussion to fuses.

AS/NZS 3000:2007 (Standards Australia 2007) clause 2.4.3 sets out types of fuses which are suitable. Essentially the selected fuses are required to meet the AS60269 series (Standards Australia 2005b). The AS/NZS60269 series provides the requirements and defines the specification of fuses. The terminology and parameters describing fuses used in this standard series are listed in Table 1.

To choose a suitable fuse to provide over-current fault protection, let us review what needs to be protected and the potential fault conditions. Essentially, all the faults relate to situations where a string becomes a "load" to the rest of the array. The easiest situation to understand is the ground fault in an earthed array (see Fig. 2). Other possibilities would include a short circuit in a PV string wiring or a double earth fault in an unearthed array.

Typically, in an electrical installation, over-current protection is provided to prevent damage to the installation cabling and associated equipment (i.e. switches, switchboards etc). The over-current protection is coordinated in such a way that the lowest level trips first (commonly described as discrimination). Other equipment and appliances connected to the installation are then designed either to protect the equipment or fail in a safe way (i.e. present no danger of fire or electrical hazard to people). For a PV array, the over-current protection is provided to protect cabling and the PV modules.

Tab.1: AS/NZS60269 fuse terminology and parameters

Characteristic	Common symbol	Description
Rated nominal current	I_n	A value of current that the fuse link can carry continuously without deterioration under specified conditions (note: in AS/NZS5033 I_{trip} is used and this is equivalent to I_n .)
Conventional fusing current	I_f	A value of current specified as that which causes operation of the fuse link within a specified time (conventional time).
Conventional non-fusing current	I_{nf}	A value of current specified as that which the fuse link is capable of carrying for a specified time (conventional time) without melting.
Conventional Time		The conventional time relates to the thermal time constant of the fuse link and varies between 1 and 4 hours depending on the current rating.
Breaking Capacity		The breaking capacity is the highest value (for a.c. the r.m.s. value of the a.c. component) of prospective current that a fuse link is capable of breaking at a stated voltage under prescribed conditions of use and behaviour.

To determine the level of the string fault current protection we refer to AS/NZS5033 and distinguish two cases:

1. If the relevant manufacturer information is available, we can determine the number of strings without over-current protection, and if this is exceeded use the manufacturer's recommendation on the series fuse rating.
2. For panels not tested to IEC 61730.2 or where no manufacturer's series fuse rating is given, AS5033 requires over-current string protection in every string and the rated nominal current of the fuse is to be determined by $1.25 I_{SC} \leq I_n \leq 2 I_{SC}$.

Example: String fault current protection as per AS/NZS5033

To determine string fault current protection and discuss associated issues we consider an example. Based on the module data in Table 2 below we determine the number of PV strings we can have in an array without string protection (in our case this is $n = n_p = 4$, where n is the number of strings in parallel and n_p is the number of strings in parallel without over-current protection).

We now consider a 5 string PV array (i.e. exceeding the number of parallel strings without protection by one string, $n=5$) and we then require string over-current protection according to AS/NZS5033. We need to choose a fuse so that it will operate in a suitable time in a fault situation. The maximum current available in a fault situation in one string of the array is equal to $(n-1) \cdot I_{SC} = (5-1) \cdot 5.5A = 22A$. In Figure 3 the "4x I_{SC} " line represents this level.

Tab. 2: PV module example

PV Module Specification		Rating	Source
Module Short circuit current	I_{sc}	5.5 A	Module Specification Sheet
Maximum Series Fuse Rating	I_{series}	15 A	Module Specification Sheet
Module reverse current	$I_{reverse}$	20.25	Calculated from I_{series} $I_{reverse} = I_{series} * 1.35$ as per IEC 61730.2
Number of parallel strings without over-current protection	n_p	4	$3I_{sc} \leq I_{reverse} < 4I_{sc}$ as per AS/NZS5033

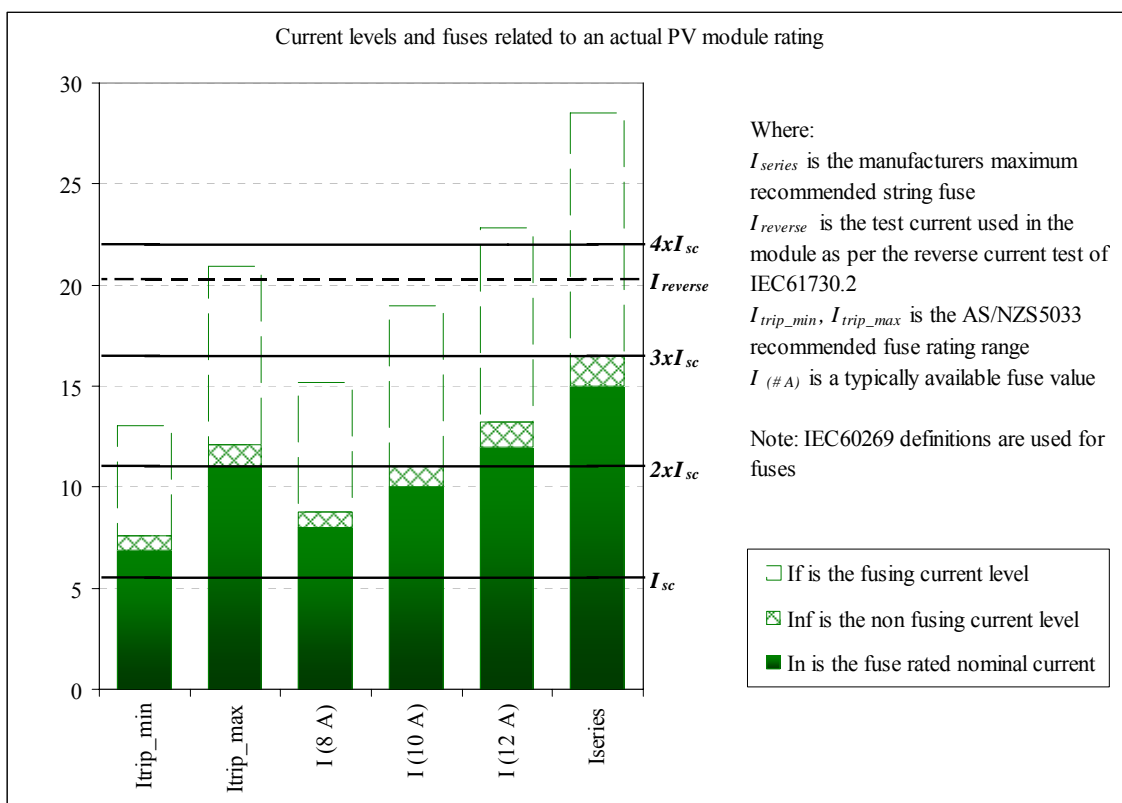


Fig. 3: Over-current fault protection scenario for a 5 string PV array example.
 $(I_{series}=15A)$

The rating for the over-current protection device according to AS/NZS5033 is as per PV module manufacturer, in our case: 15 A (see Tables 2 and 3). However, if a fuse is based on this rating, it may not operate until optimal solar irradiance conditions are present for a significant time. This can be seen in Figure 3 as the $4 \times I_{sc}$ line passes through the I_f band of I_{series} . As defined in Table 1, the I_f band in Figure 3 represents current levels that may take 1 or more hours to operate a fuse. Further to this, PV will only supply this fault current during the middle of the day and a low impedance fault

must exist. As the fusing current I_f in this example will never be exceeded, a fast operation will not occur. Depending on the solar conditions, a fault current greater than 16.5 A is required for at least 1 hour before the fuse may operate. Obviously, if additional strings are connected, the potential fault current increases and the levels required to operate the fuse arise quicker.

Tab.3: Fuse examples

Fuse Specification		Max recommended Series fuse (I_{series})	Example Selected Rating	Source
Rated nominal Current	I_n	15 A	10 A	Fuse data sheet
Conventional fusing current	I_f	28.5 A	19 A	Fuse data sheet
Conventional non-fusing current	I_{nf}	16.5 A	11A	Fuse data sheet
Conventional Time			1 hour	
Note: the I_f depends on the type of fuse selected and can be either $(1.6 \times I_n)$ or $(1.9 \times I_n)$ – fuses trialled at RISE have been a type gR (full range breaking capacity/fast acting fuse) and this data is shown above.				

Choosing a fuse below the maximum (e.g. 10 A as in the Table 3) can be necessary, particularly when n_p is exceeded by only one or two strings. In this situation, fault currents exceeding 11 A will be present sooner and the likelihood of the fuse operating is higher. It can be observed in Figure 3 that the I_f band for $I(10\text{ A})$ is entirely below the $4 \times I_{sc}$ line and largely below the $3 \times I_{sc}$ line. This means that on a good solar day, I_f will be exceeded during the middle of the day and will cause the fuse to operate.

FUSE TESTING

The issues described in the example above, the limited fault-current problem and the problem that fault current levels vary and may be reduced during conventional times were demonstrated with testing of three types of fuses at RISE.

In selecting typical fuses, we assumed I_{sc} for a common PV panel to be around 5A. If the manufacturer does not give any recommendation with regards to the rated trip current of the fault current protection device (i.e. I_{series} in Table 2), the maximum size string-fuse allowed by AS/NZS5033 would be 10A (see Case 2 above) and this would present the worst case scenario for the limited fault-current problem. Three readily available DC fuse types were selected to approximate this scenario (see Table 4).

Part A of the fuse testing involved a programmable power supply feeding into a short circuit via the fuse under test. Current was stepped up from 5A to several different currents levels and the length of time taken for the fuse to operate (pre arc time) was measured. It should be highlighted that each data point represents a different fuse and only a single trial was used for each data point. The experimental results are compared with the manufacturers' specification in Figure 4.

Tab. 4 Three fuse types selected for testing

SIBA gR ultra rapid (DII)	10A	500VDC
Bussman DMM (DMM)	11A	1000VDC
SIBA PVFuse (PV)	10A	900VDC

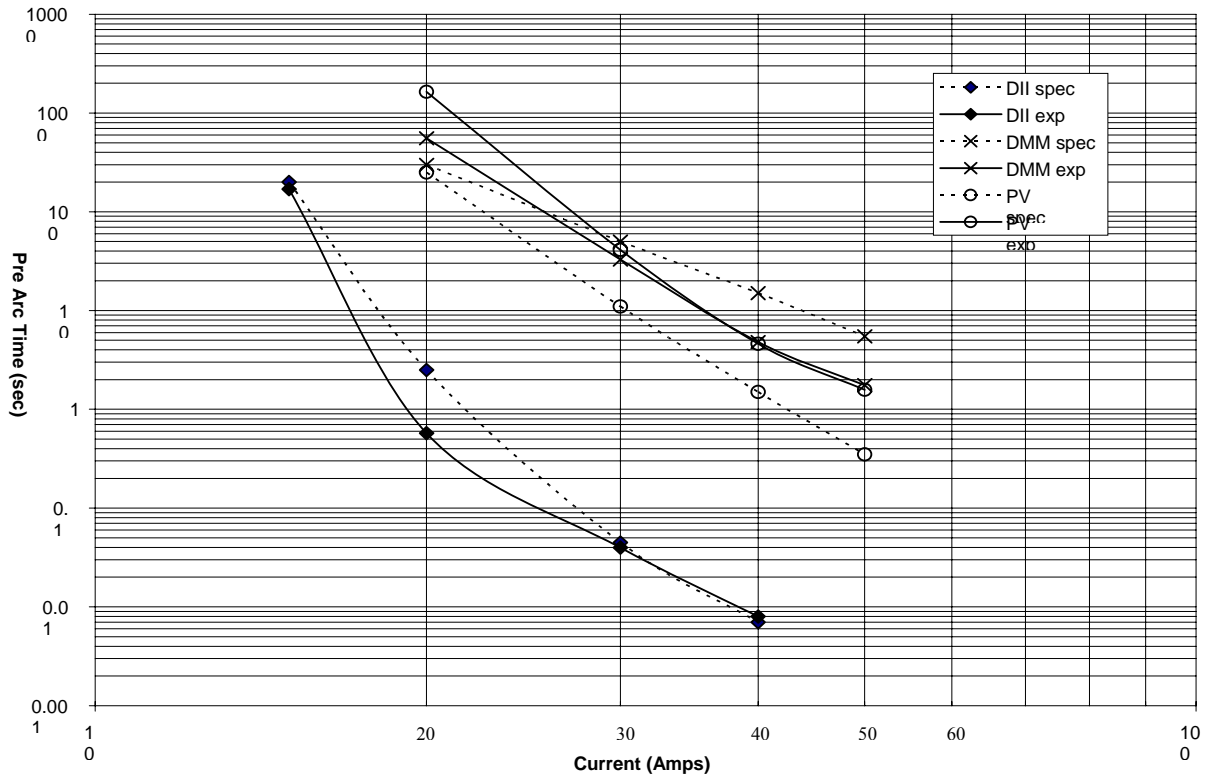


Fig. 4: Fuse testing part A - Pre arcing time for three types of fuses: Experimental results and manufacturers' specification.

It can be seen in Figure 4 that the manufacturers specified pre arc time was consistently exceeded for the PVfuse but the other two fuses generally met specification (with the exception of the DMM fuse at 20 Amps). It should be noted that all three fuses were tested at 15A operation but only the ultra rapid fuse became open circuit at this level (in only a few minutes). Although this complies with the fuse specifications, it highlights the importance of fuse type selection with regard to the limited fault-current problem. That is, 15A is equivalent to three PV strings being short circuited through a failed fourth string in our example. Hence a 4 parallel string array with this fuse sizing is essentially unprotected for 2 out of 3 of these fuse types.

Part B of the fuse testing was undertaken utilising the PV array at RISE on several fine days during March 2008. The array was arranged into 4 parallel strings of 15 BP275 PV modules in series. The same fuse selection was used as in the previous testing. It should be noted that $I_{SC} = 4.75$ A for BP275 modules and hence the selected rated fuse currents were slightly higher than maximum allowed by AS/NZS5033 (i.e., $I_n = I_{TRIP_MAX} = 2 I_{SC} = 9.5$ A). One string was connected through the fuse under test into short circuit. The

three additional strings were then connected in parallel and pre arcing times were measured with results shown in Table 5.

Tab. 5: Fuse testing part B: Fuse pre arcing time when connected to real array.

Case	Fuse type	Transient	Pre arc time
1	SIBA PVFuse (PV)	connected to 4 strings at 2:30pm with $I = 18.9$ A and falling	No break
2	SIBA PVFuse (PV)	connected to 4 strings at 11:30am with $I = 17.4$ A and rising	Break at 12:40pm 19.8A
3	Bussman DMM (DMM)	connected to 4 strings at 20A	Break in 514s
4	SIBA gR ultra rapid (DII)	connected to 4 strings at 20A	Break in 0.7s
5	SIBA gR ultra rapid (DII)	connected to 4 strings at 15A	Break in 15s

This testing highlighted a further difficulty that a real PV array has with respect to the limited fault-current problem. That is, real PV strings are rarely capable of supplying I_{SC} for a sustained period of time and hence there is a further difficulty in getting fuse protection to operate (e.g., consider Case 1 in Table 5). The critical nature of fuse type selection is once again highlighted comparing the ultra rapid fuse to the others.

Several important issues that have not been considered in this testing require investigation. These include the possibility of fuses blowing at lower than expected current because they are in a hot environment or deterioration and the possibility of fuses blowing due to current exceeding I_{SC} because of cloud or snow reflection Haerberlin (2007) recommends that rated fuse currents should generally be between 1.4-2.4 of I_{SC} and 1.6-2.4 of I_{SC} in regions where higher power generation due to snow and associated light reflection can be expected. In addition, it is probable that the type of termination and cabling that connects to a fuse will influence fuse temperature and hence pre arc times.

CONCLUSION AND RECOMMENDATIONS

The following recommendations are valid for PV arrays consisting of typical crystalline silicon modules.

In a three string array – any fault current protection used may never trip due to the characteristics of the fuses, described previously. The cable is then sized appropriately to safely handle the maximum current that could flow which is equal to two times the maximum expected short circuit current (i.e. $(3-1) \times (I_{sc} \times 1.25)$ (as per requirements of AS/NZS5033). The maximum expected short circuit current is considered within the AS/NZS5033 standard to be 1.25 times expected short circuit current which accounts for high incident radiation events greater than 1000 W/m^2 .

In a situation where n_p is not exceeded and there are 4 or more strings then the cable can be sized similarly according to $(n-1) \times I_{sc} \times 1.25$ or string fault current protection can be

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used and cable sized according to that. The string over-current fault protection device should be selected such that its rated nominal current is between $1.25 \times I_{SC}$ and $2 \times I_{SC}$.

In a situation where n_p is exceeded by 1 or 2, a string over-current fault protection device should be selected such that its rated nominal current is between $1.25 \times I_{SC}$ and $2 \times I_{SC}$. This will ensure the fuse will operate in a fault current situation at some point.

As the number of strings increases beyond this, the potential available fault current increases. In these situations, with more strings, it is recommended not to exceed the module manufacturer's recommendation for series fuse rating. In addition, ensure that the maximum fault current is a level that is greater than the conventional fusing (I_f) current for the selected fuse. In such a fault situation it will follow that potentially damaging currents in the PV array string are stopped by the fast operation of the selected fuse.

When selecting fuses, careful consideration should be given to the manufacturer's pre arc time data. Experiments on this have shown that this fuse characteristic can vary considerably between fuse types and this has important ramifications for the limited fault-current problem. It should also be noted that manufacturer data seemed overly optimistic for one type of fuse tested. It is hoped that this is an unusual occurrence.

In selection of fuses other factors (not detailed here) should also be considered to ensure selection of correctly rated devices for the PV array installation:

- Voltage rating (higher voltage rating typically have increased resistance)
- Power loss (lower rated fuses typically have a higher resistance)
- Potential fault current paths (i.e. earthing systems impedance)
- Temperature within fuse enclosure (a warmer fuse breaks at a lower current)

In conclusion, the protection of the cable is provided by ensuring it is capable of carrying maximum current available from all sources in an array. When string protection is present, this will limit the maximum current and the cable size is then determined by the nominal rating of the fuse and the requirements of AS/NZS3000. Correct selection of string fuses will also protect PV modules in the array from potentially damaging currents.

The work presented contributes to the recommendations for PV array installation requirements for the IEC Standard on Installation and Safety Requirements for Photovoltaic Generators, a draft standard which is currently being prepared.

BRIEF BIOGRAPHY OF PRESENTER

After completing her electrical engineering degree at Darmstadt University, Germany, Martina Calais worked as a research engineer on automotive power supplies in the Electrical Drives Department at Daimler Benz Research and Technology in Frankfurt. She then moved to Perth and completed her PhD in Power Electronics at Curtin University. Since 2000 Martina is with Murdoch University where she was principally involved in the development and coordination of the Renewable Energy Engineering Degree. She now lectures in Power and Renewable Energy Engineering and is a research associate with RISE, pursuing her research interest in grid connected PV system technology. During 2007 she worked with Verve Energy and gained experience in sustainable energy business development. She is a member of ANZSES, ISES, IEEE and the Institution of Engineers Australia.

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