Present and future requirements for the protection of Photovoltaic systems

Nigel P.M. Nurse

Cooper Bussmann, Burton on the Wolds, Leicestershire, UK, nigel.nurse@cooperindustries.com

Abstract

Although the production of electricity using Photovoltaic (PV) cells has been possible for many decades, it is only recently, with increased costs of carbon based electricity production and CO2 reduction initiatives, together with improvements in inverter technologies, that large scale systems have become commercially viable. The paper describes how the protection requirements of both small and large PV systems have developed and the challenges that have been faced by fuse-link manufacturers to provide the end user with over-current protection. The paper will also cover the background to the introduction of international standards for fuse-links to protect PV systems and some of the developments in system components that will influence the next generation of protection.

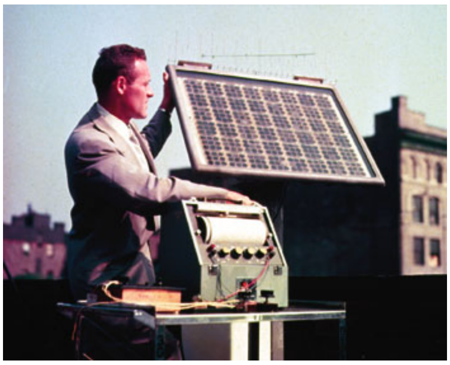
Keywords: electric fuse, PV photovoltaic cells, current limitation, overvoltage.

1. Background

The effects of sunlight on chemicals has been observed for many millennia. The most important effect for our planet is, of course, photosynthesis where sunlight converts carbon dioxide into organic compounds, often sugars. Another notable effect is that observed in photographic and photolithographic processes where light can trigger changes in colour or durability of chemicals.

A photovoltaic (PV) effect (voltage created by light) was observed by the French physicist A.E Becquerel in 1839 and the effect was first demonstrated practically by Charles Fritt in 1883. The effect was explained by Einstein, for which he received the Nobel Prize in 1921. In modern semiconductors the effect was patented[1] in 1946 during work that preceded the invention of the transistor.

Whilst the concept became well known – if light is shined onto a p-n junction a voltage will be created and current will be available to flow through attached components - the assembly techniques were difficult and expensive, with the available power per unit area being very limited. The first PV cells made from silicon were produced during the mid 1950's and limited to just a few milli-watts per cell, with a cost 100 times greater than other methods of generating electric power.



Illus. 1: First solar panel

As each PV cell generates small power levels, to produce a useful amount of energy it is usually necessary to combine the cells in series and parallel combinations.

Most development was in cells made from crystalline silicon, with the area of these cells being limited to the diameter of the silicon ingot it was cut from. The diameter of ingots gradually increased but until the processes to allow larger diameter crystals of silicon to be produced were developed, the current levels were very small for each individual cell. Even now the most popular cells (150mm square) provide less than 9 amperes at only 0.5 volts.

Photovoltaic energy is only usable in direct current (dc) systems and without cost effective and efficient conversion equipment to convert the dc to alternating current, PV systems could only used for standalone situations where limited and predictable energy consumption of direct current was required, and cost was not a major factor. The highest profile example of such an application was to power satellites.

Although the most popular and established method of PV cell manufacture was based on the silicon crystals, there was always research into other possible technologies such as thin films of amorphous silicon or cadmium-telluride. Such methods are not as common place as crystalline silicon but are gaining popularity.

More recently panels (or modules) of serial, and sometimes, parallel silicon crystalline PV cells have begun to be developed in standard sizes which has reduced the cost of a system. Individual cells are made from standard silicon ingot sizes, and doped to be p-n junctions. They are assembled in series within a frame and protected by glass, the whole being placed in an aluminium frame. Typical modules (crystalline cells) are made with 72 cells in series, giving an output capability of up to 9A at 30V and are typically 1.4m x 1m in size.

For modules using thin film technology, where the PV materials and connections are deposited on a glass substrate the outputs would typically be 1.5A at 90V, with the module being typically 1.4m x 1.1m.

The benefits and drawbacks of the various systems are not within the scope of this paper.

Key Characteristics of PV modules

The following are the key characteristics of PV cells that influence the selection of circuit protection devices (and other components):-

- Insolation / Irradiance: The amount of light energy arriving at the PV modules determines their output current. Module data is shown at Standard Test Conditions (STC), but in practice higher values than this are available in many locations.

- STC: operating value of in-plane irradiance (1000 Wm^{-2}), PV device junction temperature equals the nominal operating PV cell junction temperature (NOCT), and air mass (AM =1,5)
- I_{sc}: electric current at the output terminals of a PV device at a particular temperature and irradiance when the device output voltage is equal to or close to zero
- V_{oc}: open-circuit voltage as measured under standard test conditions, STC
- Temperature Coefficients: Both the voltage and current performance of PV modules are influenced by temperature.
- I_{rev} or $I_{MOD\_MAX\_OCPR}$: The maximum reverse current permitted to flow through the module for one hour without damage to the module, according to IEC61730-2, often termed “maximum series fuse rating”.

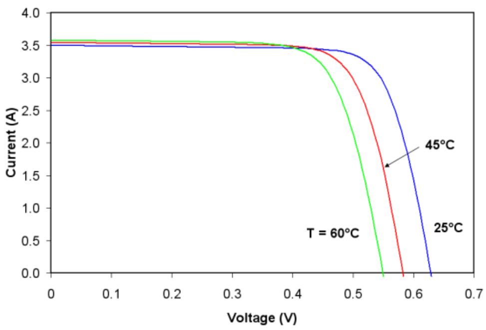


Fig. 1: I-V Characteristic for PV cell

At the same time as larger modules became common place, a new power semiconductor became established; the Insulated Gate Bi-polar Transistor (IGBT). With low drive power requirements and fast switching capabilities, this device allowed high frequency pulse width modulation circuits to be employed to economically and efficiently convert dc to ac. After immediate success in the variable speed drive and uninterruptable power supply (UPS) industries, this device was employed in dc to ac converters for the PV market. Prior to the advent of IGBTs, dc to ac converters employed bi-polar transistors or thyristors. The former suffered from the need for high-power drive circuits and associated poor efficiencies, the latter employed large inductors and capacitors to commutate the thyristors: both these systems were relatively inefficient. However after rapid development during the 1990s, IGBT circuitry became common place and high conversion efficiencies could be achieved. With an efficient inverter system and more cost effective modules, it became possible to create PV systems that could link to ac distribution grids and produce ac power at a cost closer to that from fossil fuels.

Alongside developments in the size of cells, module assembly techniques and inverters, it was observed that the cost of fossil fuels was rising and that burning fossil fuels was potentially the cause of climate change. However, whilst a number of systems were installed by those keen to show that we need not be reliant on fossil fuels for electricity, the cost of installing PV-based generating systems was still not economical. The payback period of PV systems was estimated to be 30 years and as the number of systems would be small, cost reductions from volume manufacture. and would not be achieved. There needed to be one other input to create a situation that would stimulate the market for electricity from PV systems and ensure investors received payback well before the system needed replacement. However with traditional Grid operators being monopolistic and / or bureaucratic, connecting PV systems to the grid was difficult, if not impossible to arrange. This lose – lose situation was only reversed by government interventions that used taxpayers’ money to subsidize the electricity from PV (and often other non fossil fuel) systems. This was to ensure investor returns and there was also government intervention to introduce open markets allowing easier grid connections for smaller suppliers.

In most countries the effect of government intervention has firstly been to remove barriers to grid connections and secondly, and more importantly, to introduce feed in tariffs (FIT) that pay producers an inflated value for the energy produced. The direct effect of these activities is that the production of electricity from PV has risen at around 30% annually since 2000. From a small number of relatively small (<20kW) systems that were perhaps powering isolated users with modules on a house or farm roof, systems have now grown to multi MW systems occupying many hectares, with a prediction of more than 18GW to be installed during 2011.

2. System developments

In a short time, the small PV systems of only a few watts have progressed to a few kW and now, to as large as, 10MW. During this time a number of key changes have happened to the topography and dimensions of the basic components and indeed the types of components themselves.

In this section a number of systems will be detailed and it will be seen that the rapid development of systems has brought a number of unforeseen difficulties and problems. Whilst a small system on a boat or recreational vehicle (RV) may use a single module and a charge controller to charge a battery, the system to produce many MW is somewhat more complex.

As suggested earlier, the current and voltages are limited in PV systems; it is this aspect that influences many of the components and their use. As the power is limited it is important to also limit losses in the system. For example, large systems would not have been developed if the efficiencies of the inverters had not been as high as present IGBT-based inverters.

2.1 Protection requirements

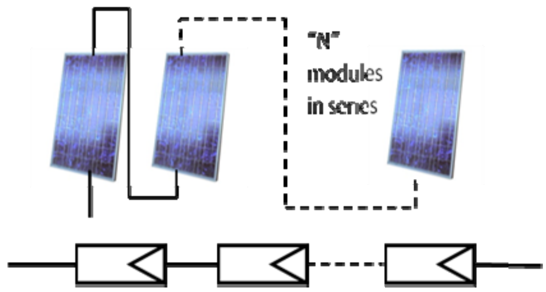
The authors are unaware of any cost effective circuit breakers that might provide protection to circuit elements in PV systems and so this paper will concentrate on over-current protection by fuse-links.

It is clear that cables should not be overloaded and should be selected to be capable of carrying more current than the PV systems can provide, remembering, of course, that in fault conditions current may be available from system elements other than the PV modules.

Until the introduction of FITs, most PV systems were relatively small and the special requirements for protection were unlikely to have been considered in depth. Most of these earlier systems would use only a few modules in series or parallel. If offered at all, any protection would have most likely been provided by general-purpose circuit breakers or fuse-links as the designers felt appropriate. By their nature, PV cells create no voltage when short-circuited, so they can be considered to self protect under these conditions.

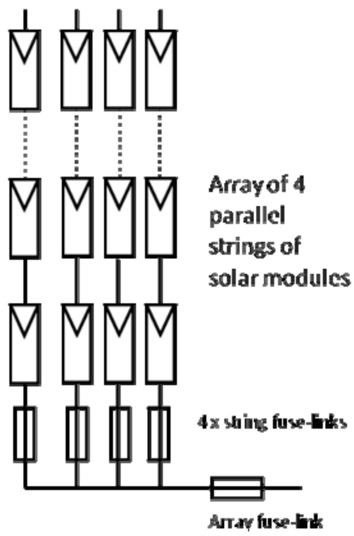
In the event of a reverse current situation the current may be stopped by a 'blocking diode' or the reverse current may not be harmful, as the reverse capability of the cells is often around 3 times the forward capability and the cells should withstand this value for over an hour. In these systems it may be simply that all the components concerned are sufficiently robust and if one item fails, the remainder will not be damaged, or that in these cases, in practice rather than by design, a general purpose fuse-link included as cable protection would provide sufficient protection to the other components.

Only when systems began to be developed with many modules in series, referred to as strings, did the voltages become high enough to expose the limitations of traditional protection. Notably, the requirement for protective devices to open very low overload currents was highlighted, especially at high dc voltages.



Illus. 2: String arrangement

As systems developed further by adding strings in parallel, the arrangement shown in Illustration 3. (showing four strings in parallel) is achieved.



Illus. 3: Basic array

The addition of many strings in parallel to form large arrays of modules and then the further paralleling of a number of arrays gives rise to a number of new faults and failure modes within the PV system which are not seen in smaller systems. As this paper will describe, these systems require circuit protection devices that operate at low levels of over current which have not generally been available, especially at the higher voltages being used in larger systems.

2.3 Requirements for fuse-links

The key requirements for fuse-links in PV systems are :-

- The ability to open safely in dc circuits.
- Be capable of operating at 1.35 times their rated current within one hour.
- Be capable of carrying 1.13 times their rated.
- Ability to operate in ambient temperatures up to 80°C (with allowable current re-rating).
- Have the ability to not deteriorate when subjected to cyclic loading and cyclic temperatures.
- Have the ability to interrupt high fault currents
- Have small physical sizes
- Have low power losses

These requirements are embedded in the international standards (section 3).

Fuse-links are renowned for their ability to interrupt high fault currents especially in ac circuits. However, they are known to have difficulties in operating at low over-currents especially in dc circuits and where they are exposed to high ambient temperatures and where the currents are cyclic in nature.

For fuse manufacturers, these requirements represent a challenge. The design techniques required to satisfy some of the above criteria can adversely affect other criteria.

In general, to achieve a higher voltage capability (especially in dc circuits) additional series weak spots and additional length are added to fuse elements. Whilst additional length and weak spots will ensure the higher voltage is safely interrupted, both these items both add resistance to the fuse-link, which increases power losses during normal conditions.

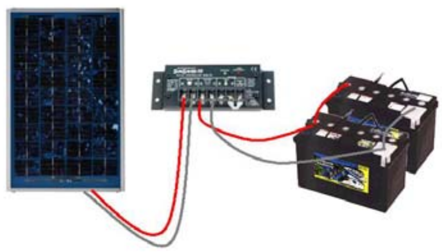
According to standards, fuse-links must carry a current above their rating for a set time without operating (the non-fusing current). Fuse-links will also be required to operate within a set time at a value above their rated current (the fusing current). For fuse-links to protect strings in PV systems, the difference between these two defined currents is smaller than in any other fuse system previously developed, and means the tolerance window for designers is tighter than previous systems.

These challenges have been overcome and fuse-links that meet, or exceed, the requirements of the standards (section 3) are now available. This ensures that installers can have the high quality protection and reliability they expect from fuse-links.

2.3 Battery systems

For systems involving batteries, care must be taken to ensure that, in the event of a failure of the series diode (if fitted), the current from the battery cannot damage the PV module. Whilst in daylight the module will supply small currents to the battery, at night the battery can discharge through the module unless it is limited by some other means. The module has a reverse current withstand rating established during its approval process. This rating should not be exceeded by more than 1.35 times for more than one hour. Therefore, any module or series of modules supplying battery systems should include series fuse-links that will open within one hour when carrying the reverse current rating for the module. Fuse-links to class gPV (see section 3.) provide this protection.

To protect the cables and other circuit components it is also necessary to use fuse-links in any cables supplying loads (inverters for instance). The fuse-links should be selected to provide protection to cables and/or downstream devices and should be rated to be capable of opening in dc circuits at a voltage greater than the battery voltage. Fuse-links in these two positions will also protect the battery from damage in the event of short circuits in cables from the modules or to the output equipment.



Illus. 4: Layout of battery-based system

2.4 Multi-string, single array systems

The largest numbers of PV installations are those that would be termed 'small systems'. They would typically be under 10kW, and are either isolated or connected to the grid. They would use a number of strings of modules and a single inverter. Such systems are not only the highest number of installed systems but they also represent 80% of the generated capacity presently installed. It is expected that the installation capacity in the near future will also be at this rate, with only 20% being in the large solar farms (see later).

As indicated previously, when three or fewer strings are in parallel, it is not necessary to use fuse-links to protect modules against reverse currents from strings in parallel that are feeding current into a string that has a faulted module, as the healthy modules in that string will usually survive twice the forward current in the reverse direction for many hours. However, fuse-links should still be included in the strings to ensure protection of modules and cables in the event of fault current originating from failed inverter components. These fault currents may be of a high value if capacitors can discharge into the modules. Of course, if the string cables were insufficient in size to carry the maximum current from two strings then string fuses rated to protect the cable would be required. (see Illustration. 3.)

2.4.1 Selection of string fuse-links.

The string fuse current rating must be selected to allow for the maximum output currents from the modules (correcting the datasheet values for irradiance and operating temperatures) and allowing for fuse-link re-rating due to local ambient temperature and altitude. The string fuse-link voltage rating must be selected to be higher than the maximum voltage from the string (number of modules in the string multiplied by the datasheet maximum output voltage for the module), corrected to include any variation due to ambient temperature of the modules.

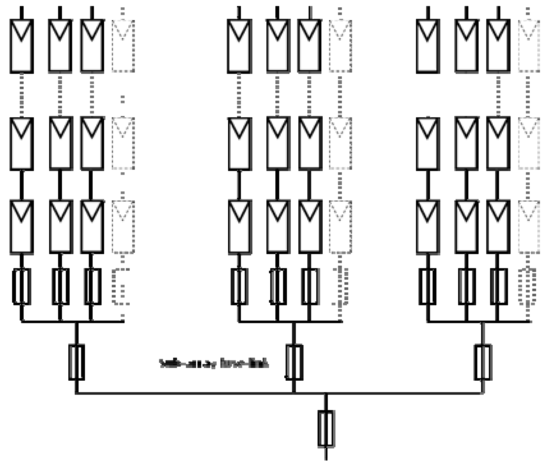
The selection of string fuse-links is detailed in fuse-link manufactures' data sheets and many other sources. However, it has been suggested that to simplify the selection of the fuse-link a current rating of 1.56 x I_{sc} of the module can be chosen.

Under low over-current conditions it is not likely that any two fuse-links in series would operate at the same time so even in systems where there is a fuse-link in both the positive and negative cables they should each be capable of operating alone at the maximum positive system voltage.

2.5 Multi- array systems

For solar farms the typical arrangement is to combine the current from the strings in a combiner box together with string fuse-links and then connect larger cables to the inverter.

In the largest systems this process may combine the arrays in a similar manner before the current reaches the inverter, as shown in Illustration. 5.



Illus. 5. Large multi-array system

As with string fuse-links in an array, any fuse-links in the larger cables should be rated to protect the cables and consideration should be given to the possible fault currents available from parallel faults.

The fuse-links not directly in the strings are referred to as sub-array fuse-links and array fuse-links, if there is a second layer of combinations as shown in Illustration 5.

Guidance on design of arrays will be detailed in the forthcoming IEC 62548 "Design requirements for photovoltaic (PV) arrays". Guidelines are also being prepared within the IEC committees for the specific installations requirements for large solar farms and also for installation on buildings.

Installation practice is also now being regulated with many countries having certification for installers to ensure competence of the installation and safe practice for those installers connecting the electrical elements of the system and the grid connections. The installation practices on solar farms where system voltages of 1500v dc are being proposed will bring new requirements for installations and safe practices, including fencing.

3. Standardisation

Even before the rapid growth of large PV farms was established, the need for codes and regulations had been anticipated by the bodies concerned with Standardization: the need was noted in the 2002 edition of IEC 60364 section 7-712 [2] where the DC part of PV installations is noted as "under consideration". By 2005 the AS/NZS standard 5003[3] was published which gives extremely comprehensive guidance for PV installations and their protection, and the later recent editions of IEC 60364 section 7-712 detail the installation of PV systems and the protection elements required. This section specifies circuit protective devices in strings and for array protection; as well as showing reverse diodes on modules and blocking diodes for strings.

For fuse-links, standardisation of specific devices had been discussed in the USA and Europe during 2008. A first draft of UL 2579[4] was published that year and proposals for the IEC standard being discussed during the early part of 2009. After one of the most rapid introductions of a standard, IEC60269 part 6[5], "Supplementary requirements for fuse-links for the protection of solar photovoltaic energy systems" was published in September 2010. This standard recognises a number of physical sizes for fuse-links, standardises testing and establishes the utilisation category of gPV fuse-links that specifically protect PV systems.

The key feature of this standard is that fuse-links should operate within their conventional time at 1.45 times their current rating under test conditions, which in practice means the fuse-links will operate within one hour at 1.35 times. This ensures that the modules are protected because the standards for modules require that they should withstand 1.35 times their rating for two hours.

The standard also includes temperature cycle and current cycling tests that are designed to reflect real-world situations and which mirror the tests required of the modules.

The full voltage testing is also intended to represent practical situations, recognising the low inductance of PV supply circuits but including faults current of at least 10kA which may occur in the PV circuit in the event of failures within the inverter system.

Whilst PV systems and their key protection requirements were addressed by the standard, it was recognised that installers needed a recognised standard in place immediately, rather than delay publication while a more comprehensive document was developed; hence the standard did not include requirements for holders for gPV fuse-links. To ensure that holders were not excluded from the standard for too long and to ensure suitable protection for any new developments in PV systems could be included, the standard was immediately put in to a maintenance cycle.

4. Where are we going from here?

The components for PV systems are under constant change. Whilst there seems to be little expectation of higher current ratings from crystalline cells in the near future, there is progress in organic films which will need protection and developments in cells with PV concentrators where lenses or mirrors increase the insolation. The protection requirements for these developments are still unclear, so fuse-link manufacturers await the challenges ahead.

Inverter topologies and the arrangements of modules with respect to earth are continually changing and adequate protection of alternate arrangements will always need to be considered as each is developed.

In large inverters the use of high speed fuse-links to protect the semiconductor devices is still commonplace and any changes to topologies or devices used will influence the specific requirements of these fuse-links. The more common use of transformerless inverters certainly means that dc and ac fault current may be present and the relative magnitudes may require novel testing systems to be developed.

Only with time, will we see if PV farms will develop with large central inverters using only one or two inverters connected to the grid or if systems will develop with many smaller inverters connected to the grid. Problems can be envisaged with grid stability for either of these systems. For large systems, the effect on the grid in the event of disconnection may be considerable. For smaller systems the reliability of the control systems which must maintain grid frequency at nodes with a large number of inverters may be a problem. In both systems the development of the protection regime will be important and should include fuse-links whether the grid connection is to a low or high voltage network.

In order to improve system efficiencies there are a number of inverter and system installers that are preparing to increase the open circuit voltage of larger PV installation to 1500V. This will be a challenge for fuse-link manufacturers as well as all the other system component manufacturers. Once suitable components become available, then the installation standards and working practices will, in turn, have to be adapted to suit higher system voltages.

The debate as to whether to use fuse-links for protection if reverse diodes are included will surely go on for some time. The higher power loss of diodes relative to fuse-links and the possibility that the diodes fail short-circuit, does suggest that string fuse-links will be included in systems for many years. The use of fuse-links to protect strings is enshrined in installation codes and manufacturers' installation manuals so this doctrine should continue for many years to come; the author has estimated that there are many millions now installed.

In some installation guides there are references to "earth" fuse-links, although the exact purposes and required operational performance is not clear. With the various topologies of inverters and options for grounding modules, there will be discussions for some time to come on the inclusion of fuse-links in the earth connections of installations or not.

The IEC standard will be required to be specific about the 1.35 times condition for the fusing current to align fully with standards for modules. The standards will need to further review the requirements for array fuse-links as to whether a true gPV fuse-link is required or whether only a gG fuse-link is required. Alternatively, it may be necessary to adjust the "conventional times" for fuse-links to be 1 hour for gPV fuse-links so as to prevent damage to modules in arrays.

Selectivity of array fuse-links and string fuse-links will be a further discussion point. From the protection point of view it is important to protect the modules from damage from over currents but operationally it may be undesirable to have both array fuse-links and also string fuse-links operate, a situation that can potentially occur, albeit a remote possibility.

Module and inverter manufactures may be using solar modules for their test programs whilst many approvals test facilities use rectified ac for the dc test source or a static dc source (e.g. a battery). Although a PV module will follow the V-I curve (no voltage when shorted varying to maximum voltage when no current is flowing), a rectified or static dc source will have a voltage – current relationship that is based on the performance of the fuse-link and any series inductance and resistors. It would be useful if independent test houses could use test sources that better simulate the output of PV cells when performing tests on fuse-links.

For the fuse-link designers there are a number of challenges. The ever-present need to reduce package sizes and power loss whilst ensuring a high dc voltage capability at very low over currents will be with them for the foreseeable future.

One thing to be sure of is that the use of PV systems will continue to be a large part of the overall mix of renewable electric power generation and, if cost-effective power storage can developed successfully, it will form an even larger part when we can start to utilise PV generated electricity during the night as well as the day.

References

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