The challenges for fuse links in the protection of Photovoltaic systems

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Abstract
Production of electricity using Photovoltaic (PV) cells has continued to increase year on year. Whilst growth of PV systems in some countries is predicted to be primarily small off-gird systems, large solar farms continue to be installed in other countries becoming a significant contributor to overall supply, and contributing to reduction in carbon based generation and significant CO_2 reduction. The paper will describe how the protection and system requirements of large PV systems have developed, notably since the last ICEFA conference, and how some new challenges have to be addressed by fuse link manufacturers. The paper will also consider the technical challenges of a global product to protect PV systems that meet the requirements of the differing installation standards world-wide.

Background
As photovoltaic systems have moved from small (<10kW) installations to the multi-megawatt installations (farms) that are becoming common place, so the supporting electrical equipment and components have also changed. Whilst small installations continue to be installed in large numbers on domestic properties and stand-alone applications in India and Africa, the increase in size of grid connected solar farms has required the development of components, and their application, to support the increasing currents and voltages in these large systems.

The method of selecting string protection is based on safe operation of the string fuse-links within the reverse current capability of the modules. Providing the fuse-link current rating (I_n) is lower than reverse current rating of the module and the cables, the only other criteria is that the fuse-link will not operate under normal forward (generating) conditions. To ensure the forward condition is met, this rating is based on the short circuit current of the modules x 1.56. There is an inbuilt safety factor of, maybe, 5% by using the short circuit current of the modules (I_{sc}), rather than the normal output current which will normally be based on the max power point current (I_{mppt}), and includes an allowance for the increase in current due to temperature. Alternatively, the fuse could be chosen by applying factors for increased ambient and irradiance to the output current of the modules and then factors required due to de-rating of the fuse-link for increased ambient temperatures, altitude and any other factor a fuse manufacture may care to add for the cyclic nature of the current due to shading of the modules. These factors also tend towards 1.56; to ensure reliability fuse-link manufacturers are now tending towards suggesting a factor of 1.6 to the I_{sc} of the module, or even more.

If a lower rating fuse-link was to be chosen there would be a risk of nuisance, or premature, operation. The most secure rating would be the highest rating that will protect the cables and the modules against reverse current faults. If lower rated cables are used, this may become a limiting factor and premature operation would be almost inevitable.

As solar farms increased in size, with many strings of modules connected in parallel to form arrays, there became a need for "array fusing".

While the same methods for selecting string fuse-links were initially applied to array fuse-links, systems have grown and become better understood leading this methodology to be questioned. The prime purpose of the array fuse-links will be to protect the cables from over currents due to a short-circuit within the inverter or the array cables within the solar farm, with a fault fed from the converter or utility. A study of the possible fault currents in an array would confirm that the modules would not be protected by any array fuse-link and it would be possible for all the string fuses to operate before an array fuse operated. As the impact on systems are much greater in the event of a premature operation of any part of the array protection than an individual string, the life time and the specific protection requirements are becoming more important to the solar farm operators.

The lifetime duty cycle of PV fuse-links is quite different to the application of general purpose fuse-links; General Purpose (utilisation category gG) fuse-links are usually selected to carry their full rated current for only a short time; diversity factors normally ensure that is so. In most applications good practice would be to not exceed 80% of the fuse rating for long periods of time.

For PV systems the design current should be predicable to some extent. The irradiance and annual variations can be predicted and the sharp shading variations, often seen in individual strings will also be present in arrays. The question then arises as to what factors influence the array currents and how can the correct fuse-link be chosen. The location of the farm will have a large effect on the pattern of current throughout the PV installation. An installation near the equator will see similar daily cycles of irradiance throughout the year, with a predictable daily cycle and limited shading events, but irradiance levels above the standard conditions during several hours each day. An installation in northern Europe will, for example, be active for only eight hours during the winter months and at very low irradiance levels and maybe sixteen hours during the summer, but the irradiance level will be lower than the standard conditions at which the modules' ratings are confirmed. These situations would be different again if the modules are fixed to a solar tracking system, where the higher irradiance level in the location will be maintained for substantially longer each day than a system where the modules are fixed.

With consideration of the above, the following question arises. Will be possible to recommend one ratio to array current for selecting an array fuse link or if the 1.56 suggested in many installation codes and standards is appropriate or will it be possible to suggest a general guidance method to cover all the various systems?

At this point, can it be possible to have a "one size fits all" recommendation without compromising the fuse-link performance or other aspects of the system?

Considerations of the Life time of fuse links

Operation of fuse-links under low-over current situations which would lead to long operating times, is at the m-effect part of the fuse element. M-effect (after Metcalfe ref 1.) is where a low melting point alloy is added to a fuse element. The alloy will diffuse into the base element material and eventually has the effect of dissolving through the base element causing current interruption when the element temperature is much lower than that which would normally cause the base element material to melt. As with any diffusion process this is a temperature and time dependant process following similar rules to other diffusion processes.

During normal fuse-link operation the temperature of the fuse element will stabilise. For a long life-time, the temperature of the m-effect must be kept to a temperature at which the alloy will not diffuse thought the base element material to the point at which the fuse-link operates.

As previously mentioned, the life time of the fuse-link, as one of the array components, is of great importance to the owner of a solar farm.

Several aspects of a system will influence the lifetime of fuse-links; this will be true in PV systems, as it is in other industrial applications. It is known that the cyclic nature of the current has an impact on the longevity; it is also known that the temperature of the metals within the fuse-link will have a major impact on the life time. The paper will not consider details of the cyclic situations.

If the fuse element material is of copper the temperature of the element must be kept low enough that will keep oxidation to a minimum. If an oxide film was to develop this will be non-conducting, thus reducing the effective element thickness and reducing the effective current carrying capability of the fuse link. Any oxide film formed will then tend to break from the base metal, thus a further surface is exposed and oxide layer subsequently formed. As the element thickness is reduced by this process the element temperature will increase for the same current flowing through the fuse-link. As the oxidation rate is faster at higher temperatures the process of element degradation will start to "run away" even if the changes are initially very slow and the whole process may take many months or years.

In fuse-links with m-effect, the longevity of the fuse will only be ensured if the temperature of the m-effect material is maintained below the temperature at which diffusion of the m-effect is below that which will cause the fuse link to open.

Whilst this process may take many years, it is possible for the fuse-link to operate in only a few hours at rated current due to m-effect operation; under this situation the temperature of the m-effect will be sufficiently high for diffusion to take place in that time.

Work by "Daalder" (ref 2), investigated the temperatures and rates of diffusion of m-effect alloys on fuse element materials. From his work it is possible to extrapolate the information in order to predict the lifetime of fuse-links if the temperature of the m-effect is known under specific conditions.

It may be noted that the rate of diffusion is constant at a given temperature, so if the material is thicker it will take proportionally longer for the fuse element to operate for a given temperature. Furthermore, if the temperature is reduced the diffusion will be slowed down, but it cannot be reversed.

By taking the data from the work of Daalder and selecting the distance that the m-effect material diffuses through the element material at which the fuse link is considered to have deteriorated to a near operating point, it is possible to estimate the life of the fuse link, provided the temperature of the element at the m-effect position is known or can be estimated.

As a first estimation, it was considered that diffusion to 50% of the thickness would be a condition when the fuse may then go into the state where fuse operation was imminent. For a PV fuse link the lifetime (in years) was then based on a 50% loading of the current with the m-effect temperature maintained at a given value.

The graph shows an indication of the situation where the above approximations are extrapolated.

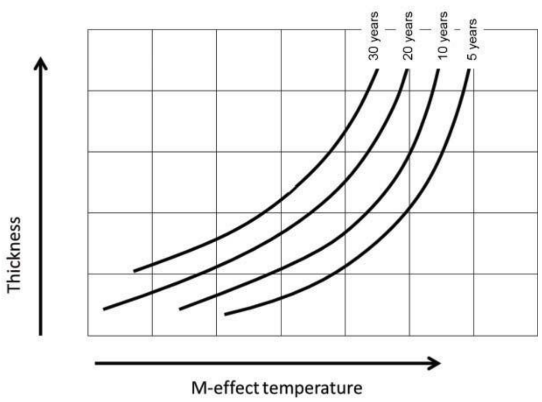

Fig 1. Suggested lifetime for different element thickness at varying m-effect temperatures

Trials on production fuses for PV applications are presently being undertaken to confirm the data in the graph. However, even with 110% loading according to the published fuse rating, fuse-links are taking longer than the graph indicates, which is suggesting that the use of the graph gives pessimistic lifetime expectancies and full results are not available at the time of writing.

This brings us to the question of how to correctly select the rating of array fuses to ensure a maximum lifetime.

The current in any PV array depends on many factors.

As mentioned previously the insolation will vary in a reasonably predictable manner, but will this will vary greatly depending on the location. Without consideration for the insolation (and thus generated current) varying with latitude, the daily cycle will change dramatically depending on the location. For example, in the UK a PV system will generate for 8 hours in the winter with a current output of 10% of I_{sc} for a short time. Compare this with nearly 18 hours in the summer with 95% of I_{sc} for only 4 or 5 hours.

In some larger systems the outputs are limited to well below output capability during the peak of the day, but guarantee a lower output over a long period to help with consistency of supply to the grid. In other systems, modules are rotated to track the sun and thus maximise output. These aspects add further complication to the rating of system components.

Depending on the location there may be considerable cyclic "loading" due to shading events. Whilst some locations may have reasonably consistent levels of insolation, others will have weather patterns that give rapid fluctuations in the PV currents; this is taken into account in the cyclic tests in the standards for modules and fuse-links but the test conditions are necessarily simplified and it is not known how closely they represents true conditions, shown in the graph below.

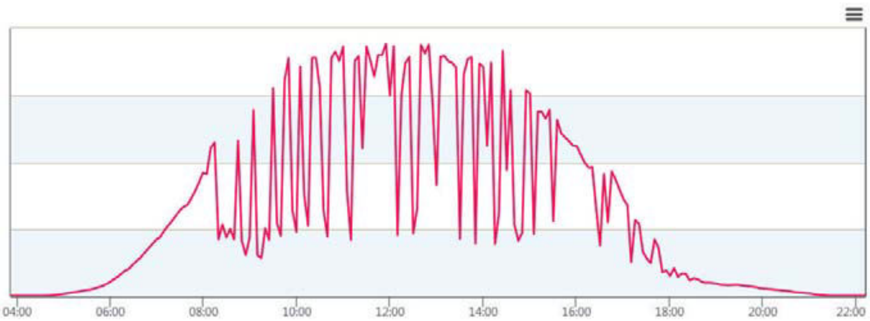

Fig 2. Typical daily profile for string current (UK, May 2015)

If the rating of the fuse link was selected based simply on the $I_{sc\text{-}array}$ as a continuous current then it is possible the fuse may be significantly over or under rated depending on all the situations described.

The array current for protection is usually based on the I_{sc} of the modules (strings) combined, as the true operating current is more likely to be based on the I_{mpp}, which are typically 5% to 7% lower than the I_{sc}, maybe it would be an option to base protection on I_{mppt}.

Only in a few locations will the insolation be the same as that in the standardised tests for the modules. Typically the actual I_{sc} (and I_{mmpt}) will be lower due to insolation but there may be an increase in these currents due to the ambient temperature of the modules. It is important to include insolation and module ambient temperature in the I_{sc} or I_{mmpt} used for cable and protection requirements

When selecting an array fuse-link a further factor in the favour of the fuse-link is the duty cycle. Fuse-links should be able to carry their nameplate rating "continuously". This "continuous" has to be a theoretical term as diffusion takes place at room temperature, so in theory any fuse link with m-effect will operate with no current flow and at room temperature. As indicated previously fuse-link lifetime can be predicted from the temperature of the m-effect with the temperatures being related to the current through the fuse. As previously indicated, the location of the array and any solar tracking will greatly influence how long the higher currents are generated by the array. The fuse-link rating can thus be selected based on the variable currents and times these will be present. A simple 12 hours on / 12 hours off approach may be suitable for installations near the equator, with analysis of real duties this may be refined to 8 hours at high currents, 4 hours at reduced current and 12 hours without. In more temperate areas the higher current may be 10 or more hours a day but over 4 or 5 months each year the higher currents may not be achieved at all.

Fuse-links will require some de-rating if they are installed in locations with a raised ambient condition e.g. an array combiner box.

Summary

Eaton is presently performing tests to confirm the lifetime of fuse-links with specific temperatures at the m-effect in order to validate the proposed lifetime expectance; recommendations based on the data developed by Daalder. However, the results of the work so far are indicating if the fuse links being used in the trials were subjected to 85% of their IEC rating, a lifetime of at least 10 years would be achieved in a PV application, assumming they were selected solely based on the current rating of the fuse-link being the same as the $I_{sc\text{-}array}$.

To date our information suggests that using a factor of 1.25 times of the $I_{sc\text{-}array}$ for fuse-link selection would reduce the normal current (mid day time maximum - $I_{sc\text{-}array}$) to 80% of the fuse-link current rating. At 80% of the fuse-link nameplate rating, the temperature of the fuse m-effect would be reduced to a value that would suggest lifetimes of over 20 years in a PV application.

References

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