The global demand for green energy sources is driving strong market growth for solar power systems. Although a great deal of development work is still focused on making PV (photovoltaic) energy conversion more efficient, there is also an acute need to make the delivery of solar power more efficient, reliable, and cost-effective. This need has been recently highlighted by an announcement from the US DOE (Department of Energy) regarding its “SunShot” initiative, which is aimed at reducing the total costs of utility-scale PV energy systems by about 75 percent, and designed to make them cost competitive with other methods of electrical power generation.

Circuit design at the cutting edge

Responsibility for practical PV electrical system development eventually falls on the shoulders of electrical circuit designers, including those who work for companies that create complete solar energy systems, system integrators who provide turnkey systems to end customers, and designers of various solar energy subsystems. Many of these designers are charged with creating electronics that optimize the performance and cost of PV installations. These engineers are typically involved with the design of electrical circuits for solar arrays, DC combiner boxes, or inverters.

Solar energy systems involve relatively new technology, so PV system designers often have greater experience in working on different types of electrical and electronic systems. For example, a company that is now producing small solar inverters may have previously focused on building power conversion or UPS systems. In their new positions, these new PV system designers may be called on to design solar energy circuits on a scale of 1MW DC for connection to the electrical grid. Designing circuits and specifying components for these high voltage solar energy applications is very different from the same tasks when applied to other DC power systems or even high power AC applications.

Basic circuit protection needs

The selection of circuit protection devices for solar energy circuits is one area where designers can get into trouble. These circuits may be used in systems ranging from residential-scale applications to those intended for large industrial facilities and grid-connected solar farms. On all of these systems, circuit protection devices are needed in many locations (Figure 1). Many application notes are available to provide guidance on selecting circuit protection devices for AC power and digital communication systems used for monitoring and control. Those areas are beyond the scope of this article, which focuses on the DC side of solar energy systems, where circuit designers are more likely to encounter unanticipated problems.
In a typical solar energy electrical system, individual solar panels or modules are connected in series to increase output voltage, which in turn increases efficiency. Multiple strings are connected in parallel to obtain the required output current and resulting power. Depending on the system size and design details, parallel strings can be connected in string-combiner boxes, which can be connected in parallel within array-combiner boxes, then connected to an inverter (Figure 2).

In most cases, multiple strings and arrays are connected using combiner boxes in accessible locations. These common connection points help simplify assembly and maintenance of the system. Wherever they are used, it is necessary to analyze the circuit to determine the available fault current (that is, the short-circuit current) of the system in comparison to the over-current capabilities of the
components and then install appropriate circuit protection devices to prevent damage to PV modules, disconnects, wiring, and wiring devices. **DC vs AC circuit protection**

**DC vs AC circuit protection**

Circuit breakers are often the preferred method of protection on the AC side of a solar energy system, and it may be tempting to try using the same circuit breakers on the DC side. Although the circuit breaker method is convenient, as a general rule, it is not always the best approach. The designer must carefully determine that the circuit protection device being used on the DC side of a solar energy system has been designed, tested and certified to a PV standard by an outside agency such as UL (Underwriters Laboratories) or VDE to be confident that the device will operate properly in the event of a fault. It is much more difficult for a circuit protection device to interrupt DC voltage than the equivalent RMS AC voltage. This is driven by the fundamental principle that AC circuit voltage reaches zero volts twice during each voltage cycle, which is a key factor affecting circuit protection devices’ ability to interrupt the voltage safely and isolate the troubled circuit.

Given that solar PV panels generate DC power, the current and voltage are constant for a given level of irradiance on the PV panels. With high voltage DC current, it is difficult for typical circuit protection devices to interrupt the circuit reliably under the range of operating conditions likely to occur in a solar energy system. In the worst case, a circuit protection device that’s not designed and certified for DC PV systems may fail violently, causing equipment damage, fire and possibly even injury to personnel. However, the most common problem will be that the devices don’t operate quickly enough under typical PV system overcurrent conditions.

For example, in a string, the $I_{SC}$ (short circuit current) may not be much higher than the normal current. A typical solar string might output 4.2A in normal operation, and its forward ISC will be around 4.5A. When combined with other strings in a small 450VDC 10kW system, the short circuit current that the properly sized 10A OCPD (overcurrent protection device) will be called on to interrupt in the event of a string fault will be approximately 20A. These high DC voltage, low overload conditions present a major challenge in designing a cost-effective OCPD that can interrupt a circuit over the appropriate range of voltage, current, and temperature.

For these reasons, the most common first line of defense is OCPDs in the form of fuses (**Figure 3**). Fuses, which are inherently passive devices, can be designed to be less costly than circuit breakers with the same performance characteristics. These PV system fuses and their testing are described in UL Standard 2579, Low-Voltage Fuses for Photovoltaic Systems, and IEC standard 60269-6. These fuse standards have been created in coordination with PV panel standards UL 1703 and IEC60129, as well as inverter standards UL1741 and IEC 61727.
Depending on the application and system design, the DC string voltage will typically be in the range of 300V to 1000V but may have the potential to go as high as 1500VDC in grid-connected systems. Fuses, disconnects, wiring devices, etc. for combiner boxes must be selected accordingly. In addition, UL and IEC standards have specific performance requirements for OCPDs used in these applications.

When the OCPD is a fuse, it must be selected to protect a PV source circuit operating at its short-circuit current rating, and also protect it in case of a fault on that circuit. NEC Article 690.8(A)(1) defines the fault current as 125% of the PV’s $I_{SC}$, plus any reverse or feedback current that could flow in the opposite direction from normal current flow.

Generally, the source of reverse current during a fault would be from back-feed current ($I_{backfeed}$) from the other strings in the affected array. $I_{backfeed}$ can be calculated to be approximately $I_{SC} \times (n-1)$ where $n$ equals the number of strings in the affected array. UL1703 and IEC60129 specifies PV panel testing to insure there is no dangerous overheating of the panel in the case of a back fed current equal to or less than $I_{string \ fuse} \times 135\%$ for two hours. The UL PV fuse standard subsequently defined the PV fuse opening characteristic of not greater than $I_{string \ fuse} \times 135\%$ for one hour. This guarantees proper coordination when using a UL or IEC panel with a UL fuse. 

**More on low-current interruption and the UL and IEC fuse standards**

Most circuit designers naturally equate the labeled rating of a circuit protection device to closely approximate the load current that will cause that device to open. However, in circuit protection devices that are designed to interrupt DC voltage, high AC voltage or to offer extreme levels of short-circuit current limitation, this is often not the case. Because of the extremely challenging nature of interrupting high-energy faults, circuit protection designers often have to sacrifice low overload protection. In most applications that need this type of circuit protection, such as UPS systems or VFD (variable frequency drives), this is a very acceptable trade off, as the UPS or VFD systems use microprocessor or solid-state based controls to detect and interrupt these low-overload currents. Using this type of low-overload protection across tens, hundreds or thousands of junctions in a solar PV system is very cost prohibitive, so designers use individual OCPDs.

This is a perfectly acceptable design option as long as the OCPDs are designed and certified as full-range fuses. A full-range fuse would be defined as any fuse designed to interrupt currents between...
110% of labeled rating for UL and 113% for IEC and the labeled maximum interrupting rating. For UL this would include all Listed fuses and some Recognized fuses. When using a Recognized fuse, care must be taken to insure that it is also a full-range fuse. For IEC this would include all fuses with a characteristic designation that begins with “g” (e.g. gPV and gR). Fuses with a characteristic designation that begins with “a” (e.g. aR and aM), are not acceptable for DC PV circuit protection and should not be used.

Other PV system circuit protection issues

In addition to the critical coordination of string protection devices with panels and the requirement for full-range protection, the UL and IEC standards also address other unique electrical characteristics of solar PV power systems, such as, difficult environmental condition and high levels of current cycling.

Solar energy systems frequently operate in harsh outdoor environments under temperature conditions that can cause thermal shock. Temperature cycle testing, like those mandated in UL 2579 and IEC 60269-6, helps ensure there is no significant temperature drift (aging characteristic or other performance shift) associated with a fuse’s operation. The UL and IEC requirements for temperature cycle testing further restrict the fuses that can be used in solar energy systems.

Solar energy systems use high voltage to transmit power efficiently, which requires designs that are substantially different from those powered by 120 or 240 volts. When designing circuit protection and other elements of a solar energy system, keep in mind the requirements for robust, long-life performance. Although a five-year life might be acceptable for a DC power supply in consumer electronics equipment, it would be completely unacceptable in solar energy systems that are often expected to perform for 25-years. Remember that electronics will be located outdoors, exposed to high and low ambient temperatures, and experience ESD surges caused by nearby lightning strikes. Therefore, it’s crucial to select components that are robust, from board traces to bus bars to mechanical elements. Enclosures should be both sturdy and waterproof. Surge suppression devices should be installed in appropriate circuit locations.

Engineers are always under pressure to come up with cost-effective designs, but taking shortcuts in PV system development can lead to problems. For example, using a circuit breaker in a PV system combiner box to merge disconnect and OCPD functions may sound appealing but using properly approved devices would likely result in a less-than-optimum cost structure and using inexpensive devices would likely result in safety and reliability problems. In most cases, the cost of fuses, fuse holders, and separate disconnects, when needed, will have a lower initial cost, and be less costly to maintain. Many circuit breaker manufacturers require annual exercising and re-calibration of their products to ensure proper operation and to avoid invalidating the manufacturer’s warranty. Circuit breakers must be removed from service, allowed to cool, and re-calibrated according to the manufacturer’s instructions. This annual maintenance requirement adds considerable expense, difficulty and safety hazards.

This article focuses on circuit protection needed on the DC side of a PV system. However, as Figure 1 shows, many other locations require other circuit protection devices. Protection of other components in the system from transient overvoltage, ESD and AC over-currents also must be addressed by the system designer. Thankfully, application of devices, such as MOVs, TVS Diodes and AC fusing that protect from these threats is typical to other systems that have been properly designed and protected for decades. There are generally no differences in PV power systems for these applications and safe diligent design work would be recommended.
Dan Gilman is Global Sales Engineering Director, POWR-GARD Products, at Littelfuse, Inc in Chicago, IL. He can be reached by email at DGilman@littelfuse.com, or by telephone at 773-62-0714. He graduated with honors with a Bachelor of Science in Mechanical Engineering from Bradley University. In June of 2007, Gilman graduated from Northwestern University’s Kellogg School of Management with his Masters in Business Administration. He is currently responsible for sales, marketing, applications support, new product development, and manufacturing support for Littelfuse’s photovoltaic product offering. In this role he and his team are actively engaged with OEMs and System Designers across Europe, Asia and North America.