

Low Voltage Products

Switches Applications in photovoltaic systems

Switch-disconnectors in photovoltaic applications

1. Introduction

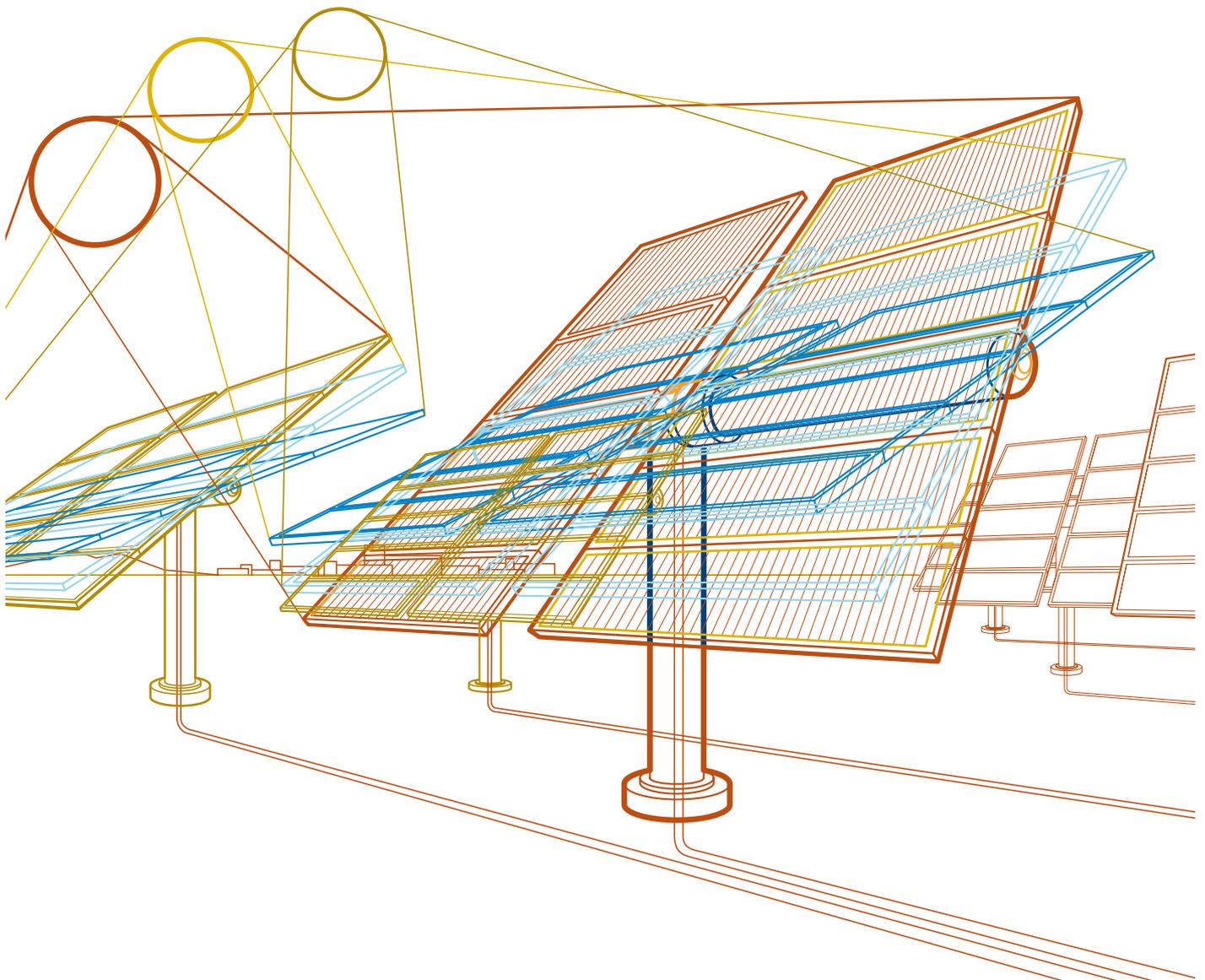
Renewable energies offer humankind infinite sources of power with minimum environmental impact. ABB, as a leading manufacturer in the energy industry, has developed several products for these applications in concordance with its policy of providing its customers with tools to harness the energy in the most effective and sustainable way.

ABB's complete portfolio for the solar photovoltaic (PV) segment comprises many product lines out of which we can mention switch-disconnectors, contactors, surge-arresters, and circuit-breakers just to name a few. It is the intention of this application note to outline the technical features and importance of one branch of these products: the switch-disconnector and show why they are an optimal choice for use in different applications among PV installations.

2. Application description

Solar photovoltaic systems convert solar radiation into clean electricity using PV-panels. The panels consist of semiconductor cells that absorb the energy from the photons emitted by the sun and produce direct current (DC) to the panel terminals.

Due to the low output of a single panel, a number of PV-panels are usually series-connected for higher voltages and parallel-connected for higher currents. In this manner, several PV-panels form so-called PV-strings. Especially in large systems, a number of these PV-strings are connected in parallel to form a PV-array with a direct-current output equal to the sum of the PV-string outputs. The panel circuitry can be referred to as the PV-generator -regardless of whether it consists of a single panel or hundreds of panels.



The produced energy can be utilized to power a local load (off-grid systems) or it can be fed into the public power-grid (grid-connected systems). As the PV-generator output is DC and most loads and public grids generally accept only AC, PV-inverters are used to perform the necessary DC-AC conversion.

Also, as the current and voltage output of PV-generators are not constant, the inverter must also adjust to the changes at its input circuit, so that the maximum possible power is drawn from the generator.

For example, the amount of light available naturally contributes to the PV-cells' current output, whereas the voltage output is inversely affected by the cell temperature. Between the PV-panels and the AC grid are the so-called

balance-of-system (BOS) components. These include the inverter, the interconnecting cables, wires, over-current and surge protection, earthing equipment and means for switching and disconnecting different parts of the circuit. For example, the International Standard IEC 60364-7-712 requires means for disconnecting the inverter from both sides. Moreover, the standard specifically demands a switch-disconnector to be provided on the DC side of the PV-inverter.

This allows the disconnection and reliable isolation of the inverter from all DC sources.

Additional switch equipment can be used for disconnecting parts of the PV-array, for system earthing or for switching possible energy-storage circuits.

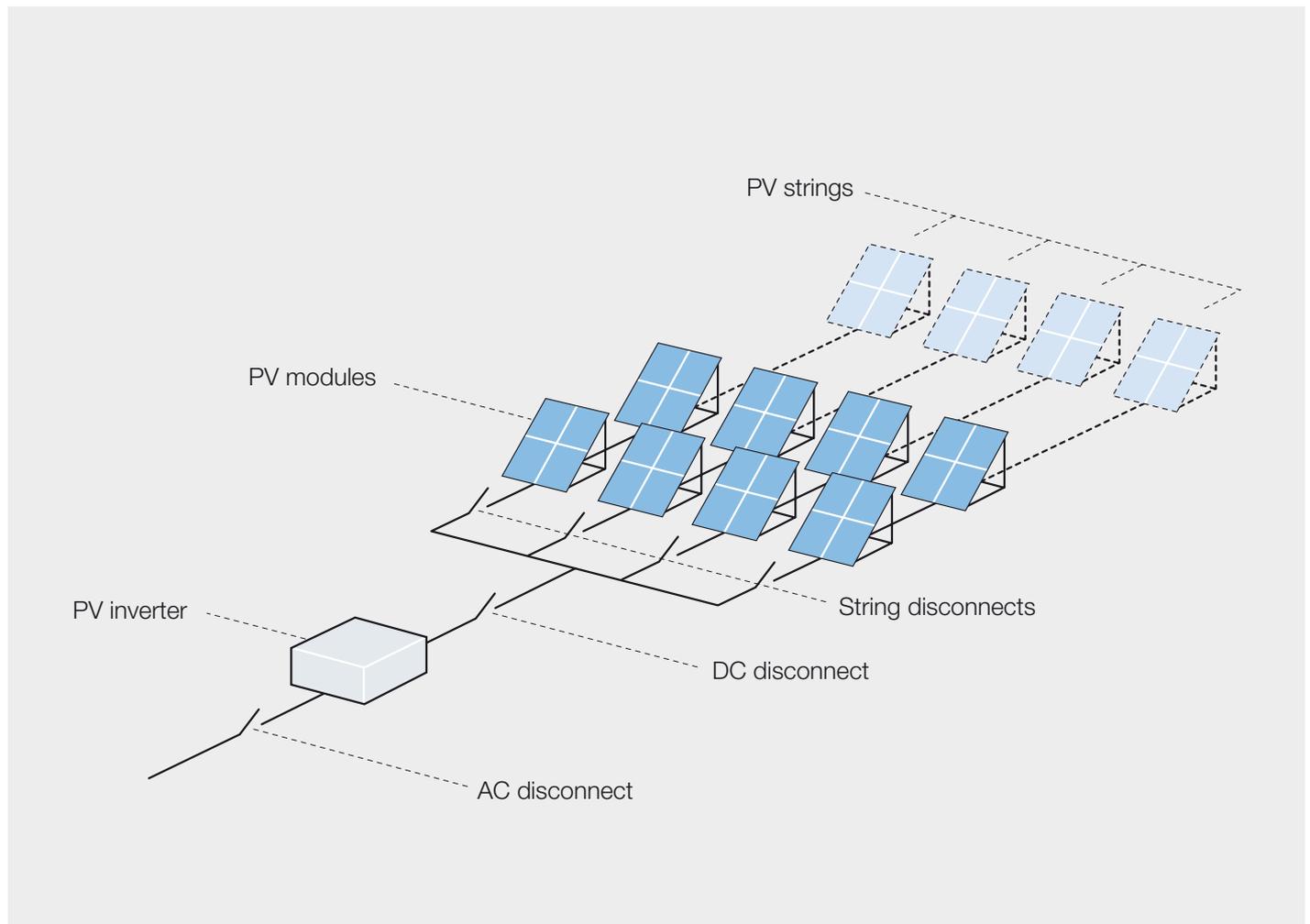


Figure 1. A simplified PV-system layout.

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2.1 System voltages and currents

IEC standardization thus far has not determined any guidelines regarding the DC side voltage levels of PV systems. Therefore the different system voltages used vary greatly, along with the different panel set-ups used in different systems.

Seeking better efficiency through avoiding resistive losses by utilizing higher voltages, in PV-systems the general trend throughout recent years has been that of increasing voltage levels. Many systems today utilize voltages of up to 1000 V DC, and exceeding the 1 kV limit is where the industry is heading. In residential applications lower voltages, such as 500 V or even less than 300 V, are not uncommon. Perhaps the most common voltage level in large systems is in the scale of 800 V DC in IEC countries, whereas for example, the NEC limits voltages in North-America to the maximum of 600 V. Depending on the system design, the voltage at PV-array junctions can be lower than that at the inverter input.

The electrical sizing of the BOS components is based on the properties of the PV-generator-chiefly the sum of short-circuit currents (I_{sc}) of the parallel-connected PV-panels and the sum of open-circuit voltages (V_{oc}) of the series-connected PV-panels. Regarding switches, the PV system voltage should be determined as the maximum obtainable voltage, i.e., the

open-circuit voltage of the series-connected PV sources. However, the “nominal system voltage” is often stated as being lower than the actual open-circuit voltage, as the system is in practice run at a lower voltage level. Inverter systems are typically optimized as to maximize the power output by actively adjusting the load as seen by the PV-source. This can cause a situation in which a switch that is correctly sized according to the V_{oc} and I_{sc} may seem oversized in respect to its normal duty.

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2.2 Breaking direct current

ABB switches are already widely known for their outstanding performance in AC applications, and utilizing them on the AC side of PV systems is straight-forward.

From the switch perspective, however, the DC side is more interesting and should be a subject to somewhat closer attention.

Firstly, DC by nature is generally more difficult to interrupt than AC, as direct current by definition has no natural zero points.

Whereas alternating current by itself passes zero twice per each period, direct current must be artificially forced to zero. Whenever a switch is opened under DC load, the current does not stop immediately, but continues to flow over the open gap between the switch contacts via a light arc. The current flow stops only once the voltage over the arc becomes high enough. Due to the extreme temperature of a burning light arc (up to 20 000 K) it is vital to suppress the arc and break the current as quickly as possible.

The most notable factors that make the breaking of DC currents a challenge are arc temperature, arc conductance, load inductance (circuit time constant) and the voltage over the switch.

Whereas the typical time constants in the PV systems' DC circuits are not high, the voltage levels on the DC side tend to be significantly higher than the voltage on the AC side. In order to break the current, the opening operation of a switch must quickly build a sufficient clearance between the contacts so that the light arc is stretched as long as possible. The length of the arc adds to total arc resistance that limits the current and also cools down the arc.

This is why switches in DC use often have more than one pole connected in series – to quickly build up the arc length. The cooling of the arc further increases the arc resistance, thus

contributing to the suppressing of the arc. As the resistance over the switch increases sufficiently in regards to the voltage, the diminished current cannot maintain the arc and the arc breaks and the current flow stops.



OT25 with multiple poles for increased contact clearance.

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2.3 Temperature

As is natural, PV systems are often placed in conditions that are exposed to maximum possible exposure of sunlight. In many cases, this means that the conditions regarding the ambient temperatures tend to be above what is usually considered as normal for switch devices. “Normal conditions” are defined as up to 40 °C (35 °C 24 h average) by IEC 60947. For the PV system parts located under direct sunlight the required ambient-temperature ratings of 50–60 °C are not uncommon.

On the other hand, cold temperatures cannot be overlooked either, because the voltage output of the PV-cells increases as the ambient temperature drops, e.g. during night or winter time.

2.4 The PV-inverter as a load

Many factors contribute to the load inductivity and time constant seen by the switch-disconnector. Perhaps the most interesting aspect is the PV-inverter, the construction of which

can actually help the DC switch in the current breaking.

Firstly, most PV-inverters incorporate a diode bridge connected in anti-parallel with the solid-state switches of the inverter, as shown in figure 2.

In the event of opening the DC switch-disconnector under load, depending on whether the inverter continues to modulate or not, this anti-parallel diode-bridge can either lift the voltage-level on the inverter side or let the current circulate in a free-wheel circuit inside the inverter. Therefore, regardless of the type of load the inverter output is connected to, the effective time-constant seen by the DC side switch-disconnector remains very low. Secondly, the switch-disconnector can be equipped with early-break auxiliary-contacts. These can be used for signalling the inverter's logic, to stop the modulation and bring the solid-state switches to a blocking state, whenever the switch-disconnector is being opened.

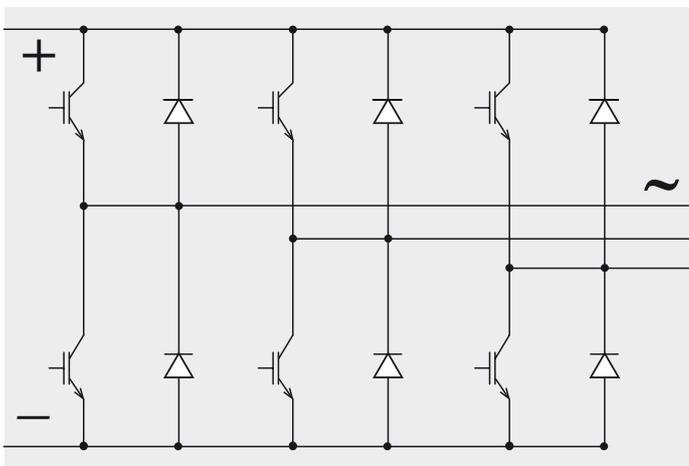


Figure 2: Six-pulse IGBT-bridge with anti-parallel diodes.

3. ABB switch-disconnectors

3.1 Rated values of switch equipment

Three fundamental parameters of switch-disconnectors should be taken in to account when choosing switch-disconnectors for PV-applications:

- The rated insulation voltage (U_i),
- The rated operational voltage (U_e),
- The rated operational current (I_e)

Inaccurate dimensioning on any of these parameters could cause a device to malfunction and thus impose safety risks on the end-user or the installation itself. Therefore these ratings will be discussed in depth in the following chapters.

Switch-disconnectors must be rated according to the full open-circuit voltage (V_{oc}) of the PV-source. In order to guarantee proper isolation after disconnection the rated insulation voltage (U_i) must never be less than the open-circuit voltage (V_{oc}). Also, the rated operational voltage (U_o) of the switch must be sufficient to cover the voltage level at which the



current-breaking takes place. Therefore it is common that the application requirements for the rated insulation voltage (U_i) and the rated operational voltage (U_o) are the same. Likewise, the rated operational current (I_o) of the switch device should be equal to or greater than the sum of the short-circuit currents of the parallel-connected PV sources, even though the current level is clearly lower at the actual point of maximum power output.

3.1.1 Rated insulation voltage

The rated insulation voltage (U_i) describes the isolation capabilities of a switch-disconnector. The value of the rated insulation voltage U_i is based on several parameters; the dielectric strength, the distances between its internal conducting parts (clearance and creepage distances), different insulation materials of which the device is made of (*Comparative Tracking Index* of the material, CTI), and also on the atmospheric conditions in which the device is utilized (*Pollution Degree*, PD).

The term *clearance distance* is defined as the distance between two conductive parts measured along the shortest possible straight line, whereas *creepage distance* is the shortest distance between two conducting parts measured along the surface of insulating materials. These two distances directly affect the switch-disconnector's insulation capability. Naturally, greater distances permit higher insulation voltages.

The CTI value describes the electrical breakdown properties of an insulating material. The material is tested by exposing it to 50 drops of 0.1% ammonium chloride solution, after which a variable voltage is applied to a 3 mm-thick sample of the same material. The voltage needed to break the material's insulation gives a representative value of the material's insulating performance, and thus, the CTI value.

The different *pollution degrees* (PD) describe the environmental conditions in which the switch is intended to be used. The PD depends on the amount of humidity, gases and dust present in the atmosphere. These factors may affect the performance of the switch, e.g., by causing changes in the insulating materials, affecting the way the contacts operate or carry current.

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By providing switch-disconnectors with strong dielectric capability, maximizing clearances and creepage distances while minimizing overall device size, and using materials with extremely high CTI values, switch-disconnectors are made safe, strong and reliable.

3.1.2 Operational voltage and operational current

The *rated operational voltage* U_o is defined as the value of voltage that together with the rated operational current I_o determines the intended application of the equipment and to which the relevant tests and utilization categories are referred. The difference between U_o and U_i is that the former is the maximum voltage under which the switch may be operated, whereas the latter is a measure of the disconnector's capability to reliably isolate two electrical circuits. For a switch-disconnector, the U_o can never exceed the U_i of the device. In PV-circuits the switch-disconnector's U_o should always be equal to or greater than the voltage level at which current-breaking takes place. As explained earlier, the higher the voltage at which the switch is operated, the more difficult the current-breaking for the switch-disconnector. The rated operational current I_o of a switch-disconnector should be equal to or greater than the current at which the current-breaking takes place, typically the sum of I_{sc} of parallel-connected PV-sources.

The ABB switch-disconnector range for PV-systems currently extends up to an I_o of 600 A at a U_o of 1000 V DC – enabling the sufficient sizing of switch-disconnectors even for very large PV-systems. The high “*voltage-breaking*” capacity of ABB switches is due to the switch design incorporating two breaking points instead of one per pole. The compact and modular design compliments the possibility to series-connect the poles for DC-use, and greatly contributes to the breaking capabilities, while maintaining an effective footprint. Moreover, the modular switch-design allows scalable sizing of the switch to match the different system voltages in different PV-installations.

3.1.3 Utilization categories of switches

Utilization categories are used for describing the switch devices intended application. As they take into account the load inductivity seen by the switch-disconnector, the utilization category is always a very important aspect from a switch point-of-view - especially so in DC circuits in which the breaking is more challenging.

Utilization categories for switch-disconnectors are defined in the standard IEC 60947-3. The most typical of the utilization categories of PV systems is DC-21 B, meaning that PV inverters are considered as non-inductive loads, the possible overloads in PV applications are moderate and that the on-off operations conducted with the switch device are infrequent. The breaking and making capacities of the switch-disconnectors in this category are tested in a circuit with a time constant (L/R) of 1 millisecond, at a test-current of 1.5 times the rated operational current I_o of the device. In practice, the time constants of PV-inverters can be as low as a fraction of this due to the reasons explained earlier in this text.

When utilized as a disconnector, i.e. in the utilization category DC-20, no current-breaking takes place, and the disconnectors can be utilized up to their full thermal ratings (I_{th}), and full insulation voltage ratings (U_i). Also, two-pole devices can be used instead of multiple poles in series, to provide reliable isolation. ABB's basic disconnector models range up to 3150 A, 1000 V DC.

3.1.4 Temperatures beyond normal conditions

Whenever an electrical current passes through an electrical circuit, a fraction of the energy is spent in the internal resistances, thus producing heat. The thermal current ratings of a switch device (such as I_{th} and I_{the}) tell the maximum value of current that can be run through the device without excessive heating up of the device. The temperature-rise limits are de-

finied by relevant standards. IEC allows a maximum temperature-rise of 70 °C from normal conditions that temperature-wise mean a long-term (24h average temperature) maximum of 35 °C, thus totalling at 105 °C which is the maximum allowed temperature of a switch device.

The technical catalogue data of low-voltage switches, given in accordance to the relevant standards, are applicable under normal conditions. However, especially in PV-applications the ambient temperatures can be above normal. The higher the ambient temperature, the lower the remaining allowed temperature-rise, as in higher temperatures a smaller current is able to heat up the switch up to the maximum allowed temperature.

In case temperature-derating is seen necessary, the appropriate calculations can be utilized in order to obtain estimate values for derating factors.

The derating calculations are based on the maximum allowed temperature-rise values given by the switch standard and on the fact that the resistive losses are closely relative to the current squared. Thus, the derating factor for a switch disconnector in the ambient temperature of T_{amb} (°C) is given by:

$$\text{Derating factor} = \sqrt{\frac{T_{\max \text{ normal}} + \Delta_{\max} T - T_{\text{amb}}}{\Delta_{\max} T}}$$

where the $T_{\max \text{ normal}}$ is the maximum allowed average temperature under normal conditions (35 °C) and $\Delta_{\max} T$ is the maximum allowed temperature rise (70 °C). Plotting this gives the following curve for the derating-factor as function of ambient temperature.

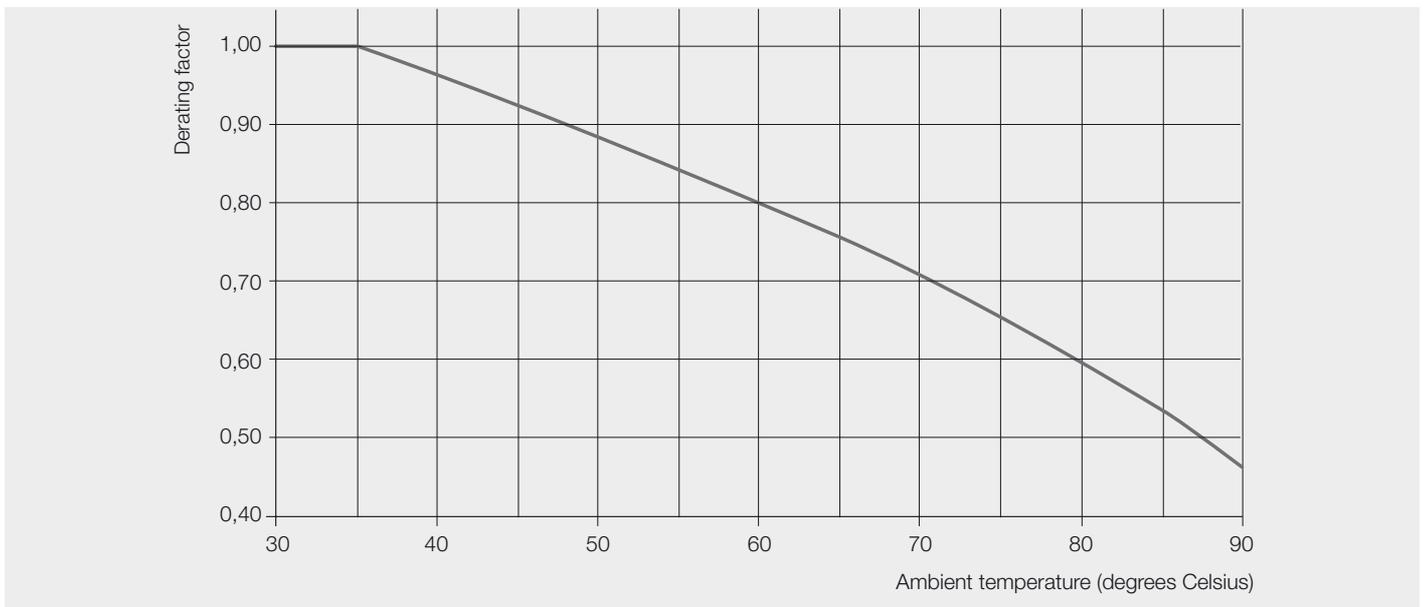


Figure 3. Estimated derating Factor, Function of Temperature (°C).

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4. Sizing the inverter disconnect – an example

Assume that a switch-disconnector must be chosen to provide means for disconnecting a PV-inverter from its source. The supplying PV-array consists of 20 parallel-connected PV-strings. Each string consists of 30 series-connected PV-modules, each of them having a maximum V_{OC} of 28.4 V DC and an I_{SC} rating of 7.92 A.

The highest inverter power output is obtained at the maximum power point, which occurs with approximately 146 A (I_{mp}) at the inverter input.

- The V_{OC} determines the minimum voltage ratings of the switch-disconnector: $30 \times 28.4 \text{ V} = 852 \text{ V}$. Selecting a switch-disconnector with an U_i and U_e of 1000 V DC would give a safety margin greater than 15 % which is more than sufficient.
- The sum of I_{SC} of parallel-connected strings determines the current-capability requirements for the switch. The sum of I_{SC} gives: $20 \times 7.92 \text{ A} = 158.4 \text{ A}$.
- If the customer predicts that the ambient temperature at the installation site may rise, e.g., up to 60 °C, a tempera-

ture derating factor can be taken into account. For 60 °C the factor is 0.80, calculated as described earlier. Applying the factor by dividing the maximum power-point current by the factor tells us how the switch-disconnector should be rated under normal conditions: $146 \text{ A} / 0.80 = 182.5 \text{ A}$.



The calculations have now given us a picture of the requirements for the switch-disconnector, and the decision can be made. For example, the ABB's OT250E33 is rated at a U_g of 1000 V and an I_g of 200 A, DC-21 B, and would thusly be an ideal choice.

IEC vs. UL and NEC

The IEC practices regarding sizing, selecting and even utilizing switches in PV-systems can differ greatly in countries such as those that follow UL standards and the National Electrical Code (NEC). While this paper mostly discusses PV-systems and switches from an IEC standpoint, a few words on the North-American practices are in order.

Perhaps the most notable difference is that whereas NEC sets a distinct limit at 600 V, IEC practically does not limit the voltage of PV-systems. That said, IEC does set the maximum of low voltage DC at 1500 V. Differences in PV-system earthing practices also exist. While IEC systems utilize a separate *protective earth* (PE) –conductor and the minus and plus circuits

are interrupted by the switch-disconnector, American systems use one of the two conductors as a grounded neutral and the interrupting of this wire is by premise forbidden by NEC.

Regarding switches, the differences are in the applications but also in the standardization regarding switches. The UL/CSA standards are adopted as national standards in the United States and in Canada. The switch standards, UL 98 and UL 508 differ fundamentally from the IEC 60947, and therefore switches must be evaluated separately for use in systems that call for UL listed or recognized products.

To mention a few of the notable differences between the standards, a UL listed switch product can have but one general purpose rated current, whereas IEC allows the definition of several, e.g., per each voltage level or utilization category. UL98 standard does not recognise utilization categories similar to those defined in the IEC. Therefore the current and voltage based selection of an inverter disconnect can result in having a physically larger switch-device in an American PV-system when compared to a corresponding PV installation, for example, in Europe.

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