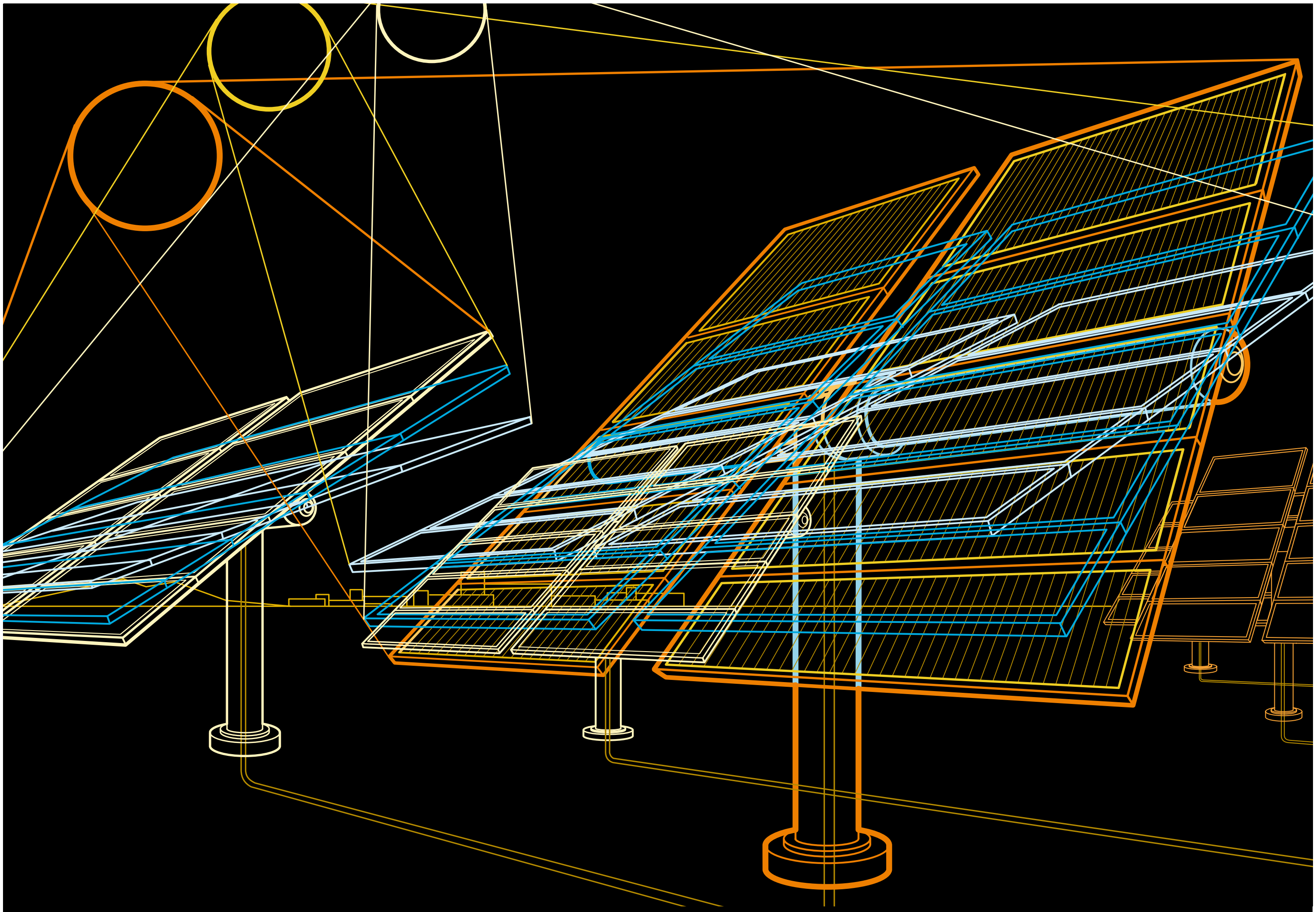


Disconnect switches
Applications in photovoltaic systems

Power and productivity
for a better world™

Disconnect switches in photovoltaic applications

1. Introduction

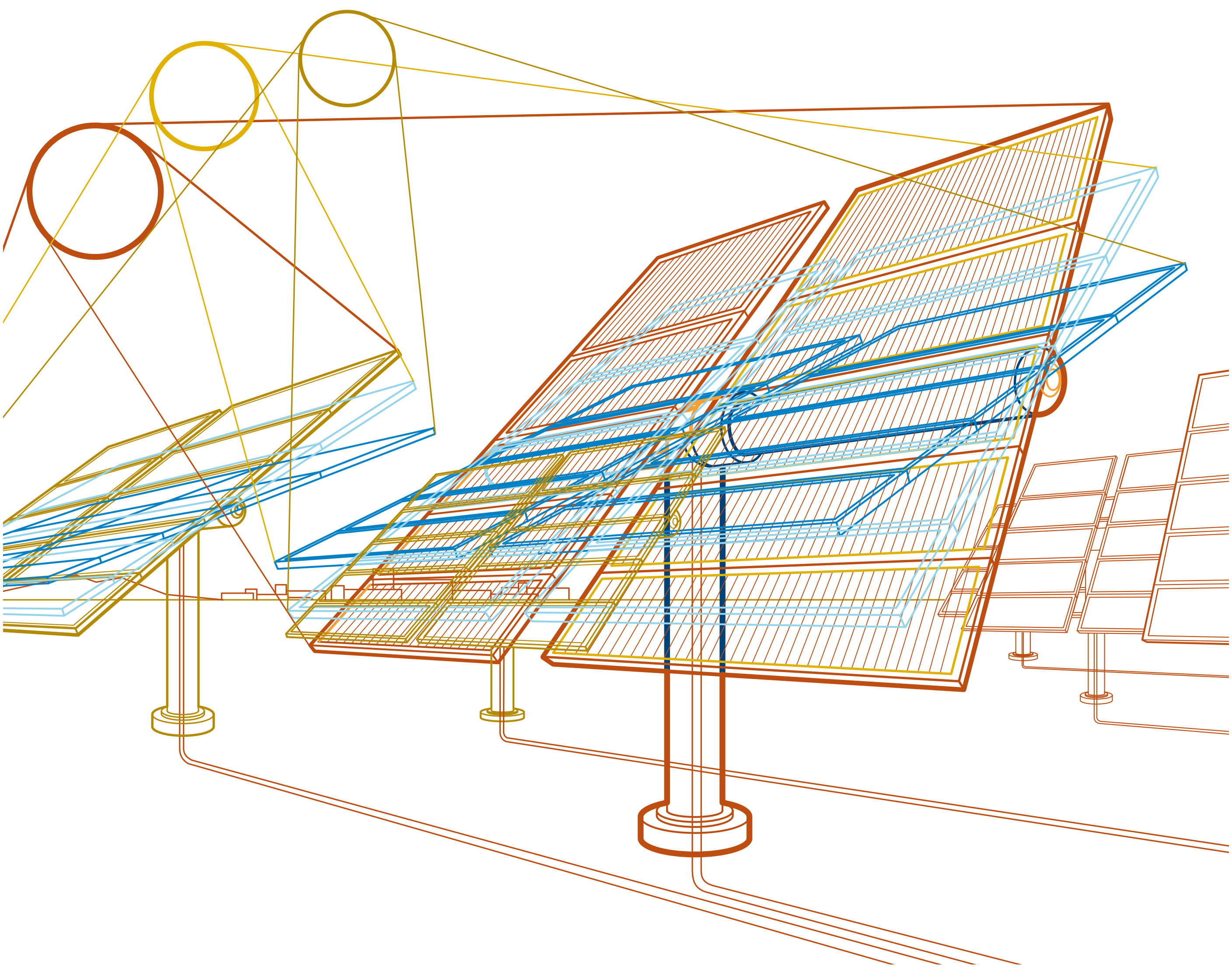
Renewable energies offer us infinite sources of power with minimum environmental impact. ABB, as a leading manufacturer in the energy industry, has developed several products for these applications in concordance with its policy of providing its customers with tools to harness the energy in the most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

ABB's complete portfolio for the solar photovoltaic (PV) segment comprises many product lines including disconnect switches, contactors, surge arresters, and circuit breakers. It is the intention of this document to outline the technical features and importance of disconnect switches and show why they are an optimal choice for use 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 PV-strings. For 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 used to power a local load (off-grid systems) or it can be fed into the public power-grid (grid-connected systems). Since 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, the current and voltage output of PV-generators are not constant; therefore, the inverter must also adjust to the voltage and current actuations at its input circuit in order to draw power 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 balance-of-system (BOS) components. These include the inverter, the interconnecting cables, wires, over-current protection, surge protection, grounding equipment and means for switching and disconnecting different parts of the circuit. The National Electrical Code (NEC) requires a disconnect switch to be provided on the DC side of the PV-inverter.

Additional disconnect switches can be used to isolate parts of the PV-array, for system grounding or for switching possible energy-storage circuits.

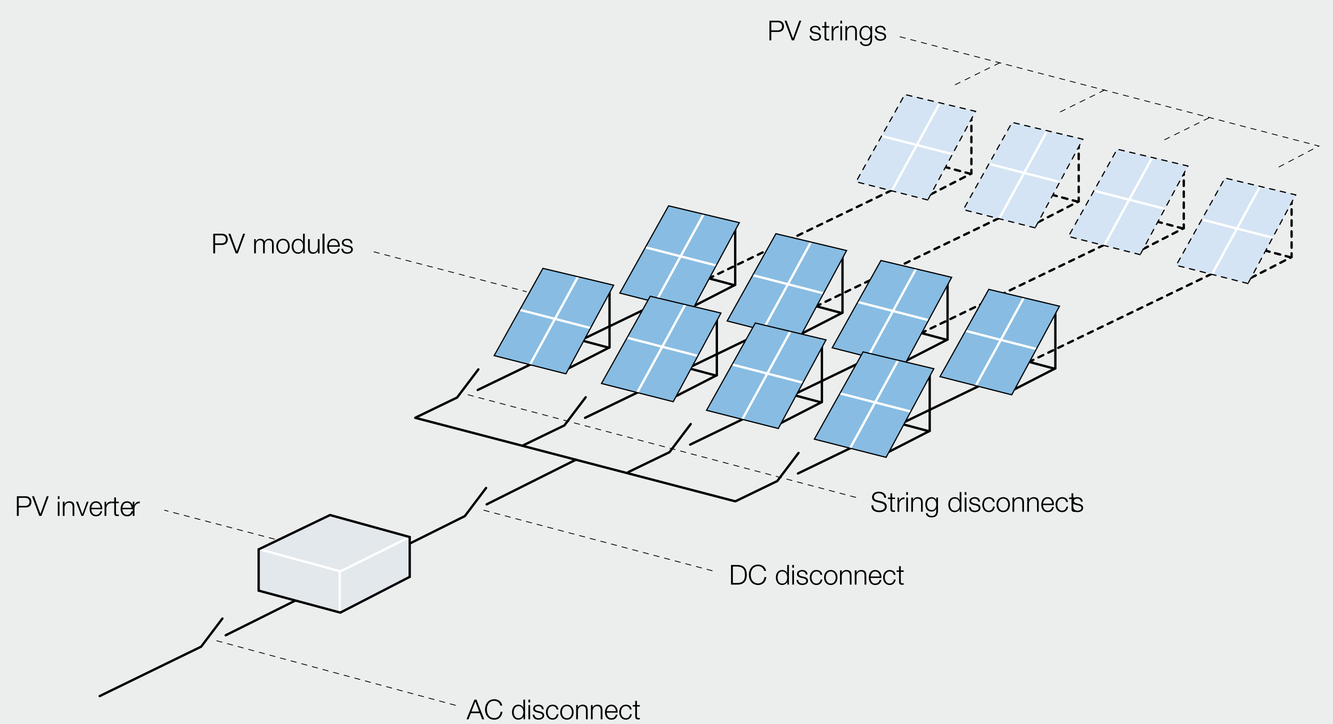


Figure 1. A simplified PV-system layout.

2.1 System voltages and currents

NEC limits one and two family dwellings, with certain limitations, to 600V. Other than this limitation, there is no defined maximum voltage for solar/photovoltaic applications, according to NEC. However, for voltages greater than 600V, special attention must be given to NEC Article 690.

PV Systems are migrating to higher voltages in order to improve efficiencies. Higher voltages reduce resistive losses. Many systems are reaching voltages up to 1000 VDC with the trend to exceed even this in the future. In residential applications, lower voltages, such as 500 V or even less than 300 V, are not uncommon. The most common voltage level for large systems in the U.S. is 600V. Depending on the system design, the voltage at PV-array junctions can be lower than the inverter input.

Sizing of the BOS electrical 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, in practice, runs at a lower voltage level. Inverter systems are typically optimized to maximize the power output by actively adjusting the load 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 with respect to its normal duty.

2.2 Breaking direct current

ABB switches are already widely known for their outstanding performance in AC applications. Utilizing ABB disconnect switches on the AC side of PV systems is straight forward. From the switch perspective, however, the DC side is more challenging.

DC by nature is generally more difficult to interrupt than AC because direct current has no natural zero crossings. Alternating current contains two zero crossings per cycle. 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 low energy arc. The current flow stops only when the voltage over the arc becomes high enough. Due to the extreme temperature of this 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.

Time constants in PV DC circuits are not very 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 gap between the contacts so that the light arc is stretched as long as possible. The arc length adds to total arc resistance to limit the current and also cool down the arc.

This is why switches in DC applications 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, and therefore contributes to arc suppression. As the resistance over the switch increases sufficiently in regards to the voltage, the reduced current cannot maintain the arc; therefore, the arc breaks and the current flow stops.

OT40 with multiple poles for increased contact clearance.

Disconnect switches in photovoltaic applications

2.3 Temperature
PV systems are often placed in conditions that are exposed to maximum sunlight conditions. In many cases, this means that the conditions regarding the ambient temperatures tend to be above what is usually considered normal for switch devices. “Normal conditions” are considered to be temperatures up to 40° C (104° F). For PV systems located under direct sunlight, ambient-temperature ratings for components between 50–60° C (122-140° F) are not uncommon.

Although high temperature is a main concern, cold temperatures cannot be overlooked. The voltage output of PV-cells increase as the ambient temperature drops, (i.e. during night or winter time). These higher voltages must be considered during the design stage. NEC 690.7 provides voltage correction factors for various ambient temperature conditions.

2.4 The PV-inverter as a load
Many factors contribute to the load inductivity and time constant seen by the disconnect switch. Perhaps the most interesting aspect is the PV-inverter. PV inverter construction can help the DC switch break current. Most PV-inverters incorporate a diode bridge connected anti-parallel with the solid-state inverter switches, as shown in figure 2.

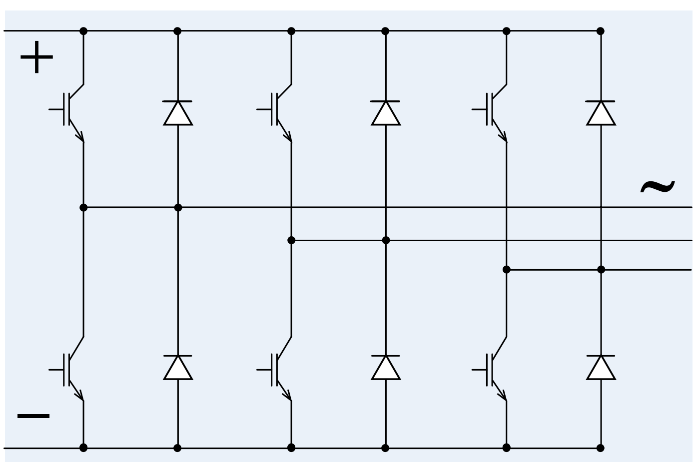


Figure 2: Six-pulse IGBT-bridge with anti-parallel diodes.

When opening the DC disconnect switch under load, depending on whether the inverter continues to modulate or not, the 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 disconnect switch remains very low. The disconnect switch can also be equipped with early-break auxiliary-contacts. These can be used as an input to the inverter in order to stop the modulation and bring the solid-state switches to a blocking state, whenever the disconnect switch is opened.

3. ABB disconnect switches
3.1 Rated values of disconnect switch equipment
Three fundamental parameters of disconnect switches should be taken in to account when choosing disconnect switches for PV-applications:

- The rated insulation voltage (V_i),
- The rated operational voltage (V_e),
- The rated operational current (I_e)

Inaccurate selection of these parameters could cause a device to malfunction and create safety risks to the end-user or the installation itself. Due to the importance of these ratings, they will be discussed in depth in the following chapters.

Disconnect switches 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 (V_i) must never be less than the open-circuit voltage (V_{oc}). Also, the rated operational voltage (V_e) of the switch must be sufficient to cover the voltage level at which the current-breaking takes place. Therefore, it is common in many PV applications for the

rated insulation voltage (V_i) and the rated operational voltage (V_e) to be the same. Likewise, the rated operational current (I_e) 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. NEC also requires additional sizing requirements for disconnect devices used in PV applications. Please refer to NEC 2008, section 690.8, for details.

3.1.1 Rated insulation voltage

The rated insulation voltage (V_i) describes the isolation capabilities of a disconnect switch. The value of the rated insulation voltage V_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 disconnect switch'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, and then applying a variable voltage to a 3 mm-thick sample of the same material. The voltage needed to break the material's insulation provides 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, (i.e., by causing changes in the insulating materials or by affecting the way the contacts operate or carry current).

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

3.1.2 Operational voltage and operational current

The *rated operational voltage* V_e is defined as the value of voltage that together with the rated operational current I_e determines the intended application of the equipment and to which the relevant tests and utilization categories are referred. The difference between V_e and V_i is that the former is the maximum voltage under which the switch may be operated, whereas the latter is a measure of the switch's ability to reliably isolate two electrical circuits. For a disconnect switch, the V_e can never exceed the V_i. In PV-circuits, the disconnect switch's V_e 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 disconnect switch. The rated operational current I_e of a disconnect switch 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 disconnect switch range for PV-systems currently extends up to an I_e of 600 A at a V_e of 1000 V DC – allowing sufficient sizing even for very large PV-systems. The high "*voltage-breaking*" capacity of ABB switches is due to the switch design incorporating two breaking points per pole instead of one. The compact and modular design allows the poles to be series-connected 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

Although utilization categories are not related to U.S. standards, a brief discussion is warranted due to their importance in describing switching capabilities. Utilization categories are used to describe the switch device's intended application. As they take into account the load inductivity seen by the disconnect switch, the utilization category is always a very important aspect from a switch point-of-view; especially so in DC circuits in which the current breaking is more challenging.

Utilization categories for disconnect switches are defined in the standard IEC 60947-3. The most common utilization category for PV systems is DC-21B. DC-21B states 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 disconnect switch 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 Ie of the device. In practice, the time constants of PV-inverters can be a fraction of this due to reasons explained earlier in this text.

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

3.1.4 Temperatures beyond normal conditions

Whenever a current passes through an electrical circuit, a fraction of the energy is dissipated in the internal resistances, thus producing heat. The thermal current ratings of a switch device (such as I_{th} and I_{the}) provide the maximum value of current that can be applied without overheating the device. The temperature-rise limits are defined by relevant standards. UL98 allows a temperature-rise between 30°C (86°F) and 65°C (149°F) at switch terminals depending on the type of installation (i.e. fused, non-fused, etc.)

The technical catalog data of low-voltage switches, given in accordance to the relevant standards, are applicable under normal conditions. However, in PV-applications the ambient temperatures can be above normal. The higher the ambient temperature, the lower the remaining allowed temperature-rise.

In case temperature-derating is necessary, the appropriate calculations can be used in order to obtain estimated derating factors. The derating calculations are based on the maximum allowed temperature-rise values given by the switch standard and the fact that resistive losses are related to the current squared. Thus, the derating factor for a disconnect switch in an ambient temperature of T_{amb} (°C) is given by:

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

where the $T_{max\ normal}$ is the maximum allowed average temperature under normal conditions 40°C (104°F) and $\Delta_{max}T$ is the maximum allowed temperature rise 65°C (149°F). Plotting this gives the following curve for derating-factor as function of ambient temperature.

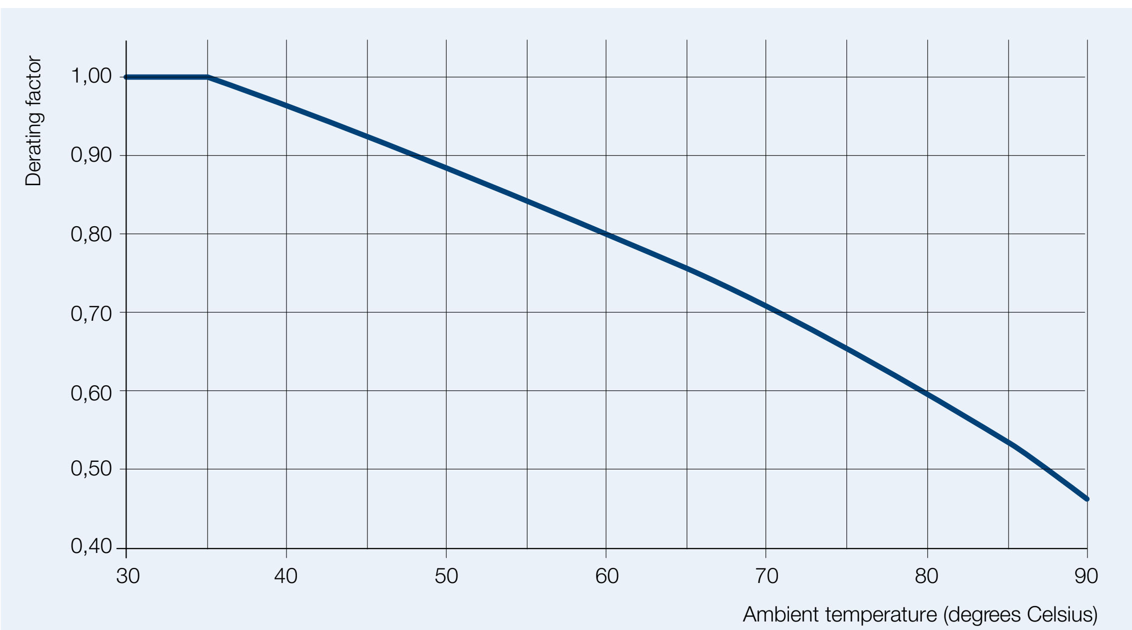


Figure 3. Estimated derating Factor, Function of Temperature (°C).

Disconnect switches in photovoltaic applications

4. Sizing the inverter disconnect – an example

Assume that a disconnect switch 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 VOC of 28.4 V DC and an ISC rating of 7.92 A. The highest inverter power output is obtained at the maximum power point, which occurs with approximately 146 A (Impp) at the inverter input.

- The VOC determines the minimum voltage rating of the disconnect switch: 30 × 28.4 V = 852 V. Selecting a disconnect switch with a V_i and V_e of 1000 V DC would give a safety margin greater than 15% which is more than sufficient.
- The sum of I_{SC} parallel-connected strings determines the current-capability requirements for the switch. The sum of I_{SC} gives: 20 × 7.92 A = 158.4 A. At a minimum NEC 690.8 requires this value to increase by 125% (or 158.4 x 1.25 = 198A) to address increased currents during solar noon.
- If the customer predicts that the ambient temperature at the installation site may rise, e.g., up to 60 °C, a temperature derating factor must 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 disconnect switch should be rated under normal conditions: 146 A / 0.80 = 182.5 A.

The calculations have now given us a picture of the requirements for the disconnect switch and can be used to properly select a disconnect switch for a given PV application.

NOTE: Refer to NEC Article 690 for additional sizing requirements.

5. Wiring schematics / grounding requirements

According to NEC Article 690, at least one pole of the disconnect should be grounded for safety purposes. For ABB disconnects, the schematics below should be utilized.

NOTE: Connection for installation in a grounded feed per NEC Article 690 connections shown for negative grounding (positive grounding may also be allowed). Switch cannot be applied to energized grounded conductors.

Diagram A (4 pole)

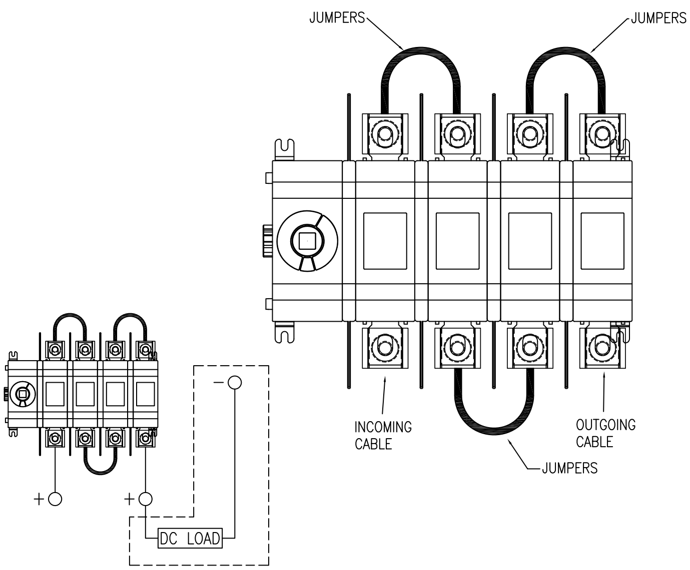
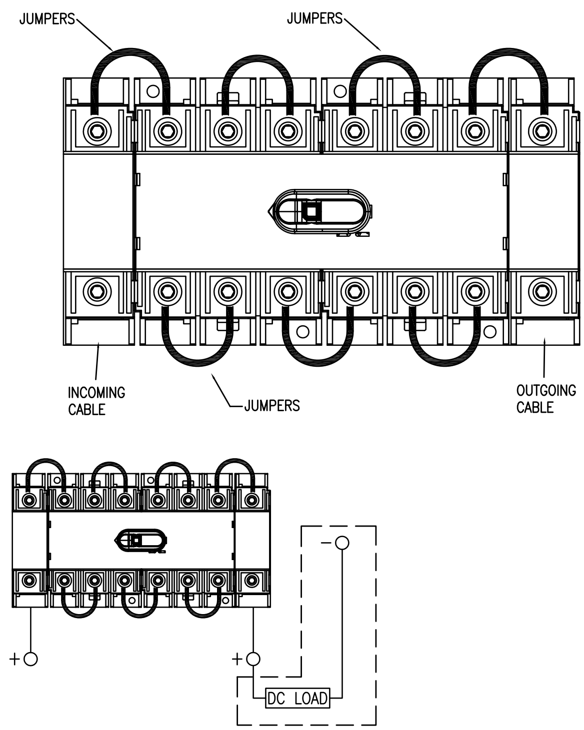


Diagram B (8 pole)



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