This article outlines the technical features and importance of switch disconnectors, and shows why they are an optimal choice for use in different applications in PV installations.

The role of DC switch disconnectors in solar PV systems

Although solar photovoltaic (PV) systems comprise a wide selection of components, we concentrate on switch-disconnectors for the purposes of this article. There are a number of components that work hand-in-hand with these, including contactors, surge-arresters and circuit-breakers (see Fig. 1).

Application description

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

Due to the low output of a single panel, a number of PV panels are usually connected in series for higher voltages and in parallel to generate higher currents. By following this pattern, several PV panels form so-called PV strings.

In large systems, a number of these PV strings are connected in parallel to form a PV array with a DC 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.

Switch disconnectors in PV applications

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). As the PV generator output is direct DC and most loads and public grids generally accept only AC, PV inverters are used to perform the necessary DC-AC conversion.

As the current and voltage output of a PV generator 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.

By way of an 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 a means for switching and disconnecting different parts of the circuit. For example, the international standard IEC 60364-7-712 requires a means for disconnecting the inverter from both sides. Moreover, the standard specifically demands a switch disconnecter 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.

System voltage and current

IEC standardisation has so far 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 configurations used in different systems.

The quest for greater efficiency has resulted in a tendency to use higher voltages to minimise resistive loses in PV systems. Many systems today use voltages of up to 1000 V DC, and breaking the 1 kV barrier is the next step. In residential applications, lower
voltages, such as 500 V or even less than 300 V are not uncommon. Perhaps the most common voltage level used in large systems is 800 V DC for countries conforming to IEC standards, while the NEC limits voltages in North America to a 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.

With respect to 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 run at a lower voltage level in practice. Inverter systems are typically optimised to maximise 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 voltage and current may seem oversized with respect to its OCSC normal performance.

**Breaking direct current**

Manufacturers such as ABB offer switches for AC applications, and using them on the PV systems’ AC side is straightforward. From the switch perspective, however, the DC side is more interesting and should be subject to scrutiny.

DC by nature is generally more difficult to interrupt than AC, as direct current by definition has no natural zero points. Whereas the AC wave passes zero twice per each period, DC 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 soon 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.

To break the current, the opening operation of a switch must quickly build 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, limiting the current and cooling down the arc. This is why switches in DC often have more than one pole connected in series – to expand the arc length rapidly.

Cooling of the arc further increases arc resistance, thus contributing to arc suppression. As the resistance over the switch increases sufficiently in relation to voltage, the diminished current cannot maintain the arc, the arc breaks and the current flow stops.

**Temperature**

PV systems are usually exposed to the maximum possible amount 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 average over 24 hours) by IEC 60947. For the PV system parts exposed to direct sunlight, the required ambient temperature ratings of 50 – 60°C are not unusual. On the other hand, low temperatures cannot be overlooked either as the voltage output of the PV cells increases as the ambient temperature drops, e.g. during night time or in winter.

**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 current breaking. Firstly, most PV inverters incorporate a diode bridge connected in anti-parallel with
the solid state switches of the inverter (see Fig. 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 to bring the solid state switches to a blocking state whenever the switch disconnector is being opened.

**Rated values of switch equipment**

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

- Rated insulation voltage ($U_i$).
- Rated operational voltage ($U_e$).
- Rated operational current ($I_e$).

Inaccurate measurement of any of these parameters could cause a device to malfunction resulting in damage to the installation or associated safety risks to the end-user. Therefore, these ratings will be examined in detail.

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 ($V_{oc}$). In addition, the rated operational voltage ($U_e$) of the switch must be sufficient to cover the voltage level at which the $I_e$, current breaking takes place.

Therefore, the application requirements for the rated insulation voltage ($U_i$) and the rated operational voltage ($U_e$) are 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.

**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 the internal conducting parts of the switch (clearance and creepage distances), different insulation materials from which the device is made (comparative tracking index of the material or CTI), and the atmospheric environment in which the device is installed (pollution degree or 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 characteristic 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 differing degrees of pollution (PD) describe the environmental conditions for which the switch is intended. 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. causing changes in the insulating materials and the impact on the contacts’ operation or current carrying capacity.

By providing switch disconnectors with strong dielectric capability, maximised clearances and creepage distances while minimising overall device size, combined with the use of materials with extremely high CTI values, switch disconnectors are made safe, strong and reliable.

**Operational voltage, current**

The rated operational voltage ($U_e$) is defined as the value of voltage which, together with the rated operational current ($I_e$), determines the intended application of the equipment.

The difference between $U_e$ 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 ability to isolate two electrical circuits reliably.

In a switch disconnector, the $U_e$ can never exceed the $U_i$ of the device. In PV circuits, the switch disconnector’s $U_e$ 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 switch disconnector. The $I_e$ of a switch disconnector should be equal to or greater than the current at which the current breaking takes place, typically the sum of $I_e$ of parallel connected PV sources.

The ABB switch disconnector range for PV systems currently extends up to an $I_e$ of 600 A at a $U_e$ of 1000 V DC, providing a range of switch disconnectors that can cater for large PV systems. The high “voltage-breaking” capacity of these switches is due to the switch design; the incorporation of two breaking points instead of the commonly used one per pole.

The compact and modular design enables the circuit designer to series-connect the poles for DC use. This and contributes greatly to the breaking capabilities while maintaining a minimal footprint. Moreover, the modular switch design allows scalable sizing of the switch to match the different system voltages for a range of PV installations.
Utilisation categories of switches

Utilisation categories are used for describing the switch devices’ intended application. As these categories take into account the load inductivity seen by the switch disconnector, the utilisation category is always a very important aspect from a switch perspective, particularly for DC circuits in which the breaking is more challenging.

Utilisation categories for switch disconnectors are defined in the IEC 60947-3 standard. The most typical of the utilisation categories of PV systems is DC-21 B, which categorises PV inverters as non-inductive loads. The possible overloads in PV applications are moderate and 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 ms at a test current of 1,5 times the rated operational current (Ie).

In practice, the time constants of PV inverters can be a fraction of this.

When used as a disconnector i.e. in the utilisation category DC-20, no current breaking takes place and the disconnectors can be used to cater for their full thermal ratings (Ith) and full insulation voltage ratings (Ue). Additionally, two-pole devices can be used instead of multiple poles in series to provide reliable isolation.

Temperatures beyond normal conditions

Whenever an electrical current passes through an electrical circuit, a percentage of the energy is expended to overcome the internal resistances, producing heat. The thermal current ratings of a switch device (such as Ith and Ue) convey the maximum current value that can pass through the device without excessive heat build-up.

The temperature rise limits are defined by relevant standards. IEC allows a maximum temperature rise of 70°C in normal conditions. The implication is that for a period of 24 hours the accumulated heat for an environmental temperature of 35°C adds 70°C, the resultant combined total of 105°C is the maximum allowed temperature of a switch device.

The technical catalogue performance data of low-voltage switches is listed in accordance with the relevant standards, applicable under typical conditions.

However, especially in PV-applications the ambient temperatures can exceed the norm. 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 (see Fig. 3).

In case temperature derating is necessary, the appropriate calculations can be applied to obtain estimated values for derating factors:

\[
\text{Derating factor} = \sqrt{\frac{T_{\text{max}} - T + T_{\text{tamb}}}{T_{\text{tamb}}}}
\]  

Sizing the inverter disconnect: an example

Assume that a switch disconnector must be chosen to provide a 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 with 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 ratings of the switch disconnector: 30 × 28,4 V = 852 V. Selecting a switch disconnector with an Ue and Ue of 1000 V DC would allow a safety margin greater than 15% – more than sufficient.

The sum of ISC of parallel connected strings determines the current capability requirements for the switch. The sum of ISC gives: 20 × 7,92 A = 158,4 A.

If the customer predicts that the ambient temperature at the installation site may rise, say by up to 60°C, a temperature derating factor can be taken into account. For 60°C, the factor is 0,8, calculated as described earlier. Applying the factor by dividing the maximum power point current by the factor indicates the switch disconnector’s rating for normal conditions: 158,4 A / 0,8 = 198 A.

The calculations have now given us an indication of the requirements for the switch-disconnector, and the selection decisions can be made.

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