A Step Change in PV AFCI Technology

Bentek’s new AF2 topology sets the benchmark for AFCIs in modern PV systems with reduced cost, expanded ratings, and enhanced reliability.

Executive Summary. With the widespread adoption of the National Electrical Code 2014, and the ever-increasing nameplate ratings of central inverters, new solutions for PV AFCIs are needed. Bentek Solar has created a new AFCI combiner box line (dubbed AF2), which marks a step-change in the technology for AFCI-compliant PV arrays using central inverters. These AFCIs are more robust, require less power, and take less time to install. They also cost less. Two new flavors include a ground-mount AFCI that draws power directly from the PV/DC bus, while a commercial rooftop model utilizes an undervoltage release feature to ensure rapid shutdown compatibility. This white paper discusses the merits of these new designs, as well as the technology driving the changes in these products.

Overview. Bentek Solar has refreshed its PV AFCI combiner box line, introducing these new models as AF2. Beyond a notable cost reduction, and an expansion in circuit ratings, several distinct configurations have been developed to address unique and emerging market needs. While PV AFCIs have been predominantly built to accommodate commercial rooftop installations that also require rapid shutdown compatibility, a new wave of...
demand for low-cost, ground-mount-specific PV AFCIs has emerged. These ground mount AFCIs are contactor-less, require no additional wiring, and come with large input and output circuit ratings. Bentek’s new AF2 line adds the ground-mount configuration (DC model), but also improves upon all PV system topologies, by offering a model compatible with NEC 2014 Article 690.12 (rapid shutdown) requirements (RS model).

To explore the new feature set, we present a side-by-side comparison of the features of the older Bentek AFCI model, plus the new AF2 DC, AC, and RS models:

<table>
<thead>
<tr>
<th>Bentek AFCI Model</th>
<th>AF (generation 1)</th>
<th>AF2 (generation 2), DC Models</th>
<th>AF2 (generation 2) RS, AC Models</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Application</strong></td>
<td>Commercial rooftop. Smaller Central Inverters, &lt;900 kW,ac</td>
<td>Ground mount only. Any central inverter; compatible with 1-2 MW,ac and beyond</td>
<td>Ground mount or commercial rooftop (RS only). Any central inverter; compatible with 1-2 MW,ac and beyond</td>
</tr>
<tr>
<td><strong>Voltage / Amperage Rating</strong></td>
<td>1kV / 350A (2x 175A / contactor)</td>
<td>1kV / 400A</td>
<td>1kV / 400A</td>
</tr>
<tr>
<td><strong>Representative Model Number</strong></td>
<td>BTK10-AF-G-nnff-Caaa-CS-OV</td>
<td>BTK10-AF2-G-nnff-Taaa-DC-CS-OV</td>
<td>BTK10-AF2-G-nnff-Taaa-RS-CS-OV</td>
</tr>
<tr>
<td><strong>String Configuration</strong></td>
<td>Grounded &amp; ungrounded</td>
<td>Grounded only</td>
<td>Grounded only</td>
</tr>
<tr>
<td><strong># MPPTs / AFCIs</strong></td>
<td>1/2</td>
<td>1/1</td>
<td>1/1</td>
</tr>
<tr>
<td><strong>String Count</strong></td>
<td>12-32</td>
<td>8-32</td>
<td>8-32</td>
</tr>
<tr>
<td><strong>Short Circuit Current Rating (SCCR)</strong></td>
<td>2 kA</td>
<td>10 kA</td>
<td>10 kA</td>
</tr>
<tr>
<td><strong>NEC 690.12 “Rapid Shutdown” Compatibility</strong></td>
<td>Yes</td>
<td>No</td>
<td>Yes (RS only)</td>
</tr>
<tr>
<td><strong>AFD Calibration</strong></td>
<td>Central</td>
<td>Central</td>
<td>Central</td>
</tr>
<tr>
<td><strong>Power Source</strong></td>
<td>ac mains only</td>
<td>DC-DC parasitic supply</td>
<td>ac mains</td>
</tr>
</tbody>
</table>

Table 1. AFCI combiner box feature comparison by target application
Since the electrical conditions of PV installations are so diverse, it is important to configure each product for its target array topology. The target applications and general behavior for each of the AF2 configurations is explained below.

**DC Model: BTK10-AF2-G-nnff-Taaa-DC-CS-OV**

The DC model of Bentek’s AF2 is meant to be a true “plug and play” AFCI. Since the machine derives its power from the high voltage DC bus, there is no additional wiring required to add AFCI functionality to the PV array. The combiner box utilizes a UL 98B listed, trippable disconnect and behaves the same as any other disconnect combiner. When tripped, however, the disconnect handle rotates 45 degrees, indicating a faulted condition. The DC model provides combiner box level indication of a fault, and must be manually reset. With the DC disconnect serving as both the interrupting device and fault annunciator, the DC model is a simple, lightweight solution for meeting the requirements of 690.11 for PV source circuits.

**AC Model: BTK10-AF2-G-nnff-Taaa-AC-CS-OV**

The AC model of the AF2 provides the same functionality as the DC model, but with the additional benefit of providing four-string “block” indication. Since the AC model is hardwired to a dedicated AC source, the machine is able to keep the information regarding the location of faults at a resolution of up to four strings, unlike the DC model (since this information is lost at night when the DC model powers off).

**RS Model: BTK10-AF2-G-nnff-Taaa-RS-CS-OV**

The RS model has the same features as the AC model, except that it is also equipped with an undervoltage release as the trip mechanism, in order to be compatible with the requirements of NEC Article 690.12. In the event of a fire, the first and simplest method for any first-responder to secure the building is to open the building’s main AC disconnect. Removal of the AC mains power will cause the RS combiner box to trip its disconnect, and remove voltage from controlled conductors. This is a simple, low-cost method for achieving 690.12 compatibility, without the use of additional control wiring or conduits. To prevent unwanted tripping, the supply to RS models may be backed up using an uninterruptible power supply (UPS), that is controlled by a dedicated AC disconnect serving as the rapid shutdown initiating device.

**Analysis: Step-Changes in PV AFCI Technology.**

**Cost Reduction.** PV AFCIs have been known to add 50% to 100%, or more, to the cost of similar, non-AFCI balance of systems equipment. Bentek’s new AF2 line pared down non-essential items while maintaining the critical feature set: all that is required to comply with 690.11 and 690.12 (as applicable). Most notably, we eliminated the ungrounded combiner box design, reduced the enclosure size, and increased our maximum AFCI size to 1000V/400A. Our new design enables users to take two strings and parallel them into a single 30A input, thereby reducing the per-string AFCI cost by half. Finally, the PV/DC based supply (DC model) eliminates the need to install AC branch circuits throughout the PV array, and avoids significant expense. In all, we have reduced material cost, increased power density,
and simplified installation. All of this converts into dramatic savings for customers where AFCI functionality is required.

**1500V Extensibility.** 1500V, DC rated PV installations are becoming commonplace, but products safety standards have been slow to catch up. UL Outline 1699B is still limited to 1000V, which means there are no listed PV AFCIs rated for 1500V. Many people presume that Article 692 of the 2017 National Electrical Code will help users avoid the arc fault requirements of Article 690.11, and with it avoid the need for 1500V rated AFCIs. It is currently possible to design a 1500V PV installation, then request an exemption from 690.11, on the grounds that no 1500V listed PV AFCIs exist. Since the arcing power of electrical faults increases with the square of voltage, it is a crude, but reasonable assumption that the danger posed by arc faults is at least as high in 1500V systems as it is in 1000V, and 600V systems. There is a cost to add AFCI to any PV system, yet there is also a cost per watt benefit to using 1500V over 1000V. For this reason, an unintentional market incentive has been created to build unprotected 1500V PV arrays. To help close this gap in coverage, Bentek Solar has submitted a proposal to expand the scope of UL 1699B to include 1500V rated PV AFCI devices. In addition to writing the proposal, all of our AFCI designs are extensible to 1500V, which will enable use of 1500V equipment in jurisdictions where 690.11 is enforced, when the 1699B standard becomes ready.

**Short Circuit Current Rating (SCCR).** The most important factor to consider when selecting any electrical equipment—including AFCI combiner boxes—is the short circuit current rating. Electrical equipment that is connected to a source with an available fault current that is higher than its SCCR is subject to catastrophic failure, and may cause damage to property, personal injury, or death. Currently UL 1741 does not require short circuit ratings of DC equipment, but UL 1699B does.

Differences in UL 1699B listed AFCIs usually come from the making and withstand capacity of the interrupting device. The interrupting device has been traditionally a UL 508 DC contactor, due to its low cost, but there are other types that could be used: UL 489B molded case switches or breakers, and now UL 98B trippable disconnects.

DC contactors are limited in their ability to handle high fault currents because their contacts may weld, or even be forced apart by the magnetic forces caused during a fault. While ruggedized DC contactors may emerge in the future, at present, care should be taken when introducing DC contactors into PV arrays in order to limit the fault current that they may be exposed to. Shunt-trip PV molded case switches and breakers similarly have problems achieving high SCCRs, with their nameplate interrupt ratings typically at or below 5kA. There does not appear to be a good path forward for the technology at 1500V, either, with interrupt ratings a mere 3kA for 200-400A rated switches.

Alternately, a new technology has emerged that combines a PV disconnect with a trip
feature. This product enables manual operation of the disconnect, while also providing an electronic means of interruption, which is the ideal solution for AFCI combiner boxes providing Type 1 (series) arc fault protection.

Bentek has designed both types of combiner boxes; using DC contactors (AF generation 1 products) as well as the new trippable disconnects (AF2). The applications are different, primarily due to differences in short circuit current ratings of the finished AFCI combiner boxes. The major benefit of our new AF2 combiner is its 10kA SCCR (highest available on the market). To demonstrate this fact, we plotted the maximum inverter size and corresponding DC:AC ratio; effectively the maximum size array an AFCI combiner box should be connected to, based on its SCCR:

**Figure 1. Maximum DC:AC ratio versus inverter size for AFCI combiner boxes**

Observe that at the lower SCCR of 2kA, the user is restricted in the DC:AC ratios that they could use on inverters above about 600 kW, and should not use the equipment above 900 kW. Conversely, using the trippable disconnect with a 10kA rating, it can be connected to any size 1kV inverter on the market without posing a risk to the equipment (as of this writing). Consequently, we recommend...
any contactor-based AFCI to be installed with smaller central inverters. Note that all Bentek AF2 models have the 10kA rating, and are therefore suitable for central inverters of all sizes.

*Parasitic DC-DC converter versus AC power supply.* Bentek’s AF2 DC model derives its power parasitically from the PV array. This modification to the AFCI’s power source has several benefits:

i. The AFCI is isolated from the AC mains voltage, and not susceptible to grid related surges.

ii. There are fewer components per box, improving the reliability.

iii. The customer does not need to route low voltage (110-240 Vac) branch wiring throughout the PV array, resulting in substantial labor and materials savings.

*Note: the AF2 is available with an AC-derived power supply, in which case the following does not apply.*

Several operational differences result from having a power supply that turns off every day, and those are described below:

i. The AFCI loses power each day. With it, the arc fault detector (AFD) PCBs will reset. As a result, the LED indicator on the DC model is merely for verification of the AFD’s integrity during a SELF TEST sequence, and shall not be used to verify that an arc fault event has or has not occurred.

ii. While the AFD will reset each day, the trippable disconnect cannot reclose, and indeed must be reset manually. So in the event of an arc fault, the trippable disconnect will open, and will also provide the visual indication that a fault has occurred. In UL 1699B jargon, the trippable disconnect’s handle position becomes the *annunciator.* The handle rotates 20-45 degrees when it has tripped, and the fault can be confirmed by observing that the external, Type 4X (red) LED indicator is illuminated. This indicator is linked to the auxiliary contact of the trippable disconnect, and reports the “true” status of the AFCI’s contact position. Presence of an arc fault detection event can also be seen using “zone” monitoring with your PV system—a feature available on all Bentek Solar recombiners.

iii. Because the combiner box resets each night, the trippable disconnect provides the arc fault indication at a combiner box level. The LED indicators on each AFD board that detect on groups of 4 strings reset each day and therefore cannot be relied on to provide location information regarding a potential arc fault.

*Note: if 4-string “block” resolution is required, please choose the AF2 combiner with the optional AC-based power supply at the time of your purchase (AC or RS models).*

iv. The AFCI is off until the minimum turn-on voltage of 200V is reached. This is not a problem for series arc fault protection, since this value is above both the minimum turn-on voltage and minimum MPP voltage of a 1kV inverter. In general, if there is no load, then there is no risk of a Type 1 / series arc fault, and the AFCI is allowed to be OFF. A word of caution: 600V applications may not be compatible with the DC model AFCI, since they may operate below 200V. Always confirm with the inverter datasheet or a support
representative that this condition will not occur, to ensure continued protection against series arc fault hazards.

Recap: there are subtle differences in AFCI behavior, depending on the power source used. While there is a loss of resolution using the DC-DC based design, there are notable advantages insofar that the new combiner is a “drop-in replacement” for non-AFCI combiner boxes, without additional wiring required. Since arc fault detection events should be incredibly rare, the loss of resolution should not pose an undue burden on the O&M teams that are sent to respond to an event.

Summary. Bentek Solar has created a new generation of AFCI products (AF2) that take us beyond the less robust, contactor-based, rooftop commercial AFCIs. There are nuances between these new models that make them ideally suited for a particular application. The AC-mains powered/undervoltage release design (RS) is optimally suited for commercial rooftop installations requiring rapid-shutdown compatibility. The DC powered machine (DC) is best suited for the biggest PV inverters on the market today, and for use in exclusively ground-mount settings, or where rapid shutdown compliance is not required. A table showing the major differences is provided one more time:

<table>
<thead>
<tr>
<th>Item</th>
<th>AFCI version 1 (“AF”) (discontinued)</th>
<th>AF2 (DC model)</th>
<th>AF2 (RS, AC model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intended Application</td>
<td>Commercial rooftop</td>
<td>Ground mount PV</td>
<td>Commercial rooftop (RS only) or ground mount</td>
</tr>
<tr>
<td>Intermittent Device Type</td>
<td>Normally-open, UL 508 contactor</td>
<td>UL 98B Trippable Disconnect</td>
<td>UL 98B Trippable Disconnect</td>
</tr>
<tr>
<td>AF Annunciator Type</td>
<td>LED indication</td>
<td>External disconnect handle</td>
<td>External disconnect handle, additional resolution shown by LED indication</td>
</tr>
<tr>
<td>Power Source</td>
<td>AC grid (external 100-240 Vac wiring required)</td>
<td>DC / PV array-powered (self-powered)</td>
<td>ac grid (external 100-240 Vac wiring required)</td>
</tr>
<tr>
<td>NEC 690.11 Compliance</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>NEC 690.12 Compliance</td>
<td>Yes</td>
<td>No</td>
<td>Yes (RS only)</td>
</tr>
<tr>
<td>Max Inverter Size</td>
<td>900 kW,ac</td>
<td>3 MW,ac</td>
<td>3 MW,ac</td>
</tr>
<tr>
<td>DC Short Circuit Current Rating at 1kV (SCCR)</td>
<td>2 kA</td>
<td>10 kA</td>
<td>10 kA</td>
</tr>
</tbody>
</table>

Table 2. High level comparison of Bentek AFCI combiner box models

We hope that this technical note has been informative for the user by showing the different methods of providing AFCI protection, their trade-offs and benefits using the new AF2 solution. Our goal is to ensure that our customers choose the optimal product configuration, and thereby get the best possible value and protection for their PV array.
Please get in touch with us if you would like to learn more about our PV balance of systems solutions. We have applications engineers standing by!

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