**Selection of a DC Solar PV Arc Fault Detector**

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## 1. Executive Summary

Arc fault current interruption (AFCI) is required on DC conductors of solar PV installations by NEC 2011 (rooftop systems only) and NEC 2014 (rooftop and ground mount systems). To meet these requirements, combiner boxes for central inverters will need to include arc fault detectors (AFDs) as well as other AFCI equipment. UL recognized AFDs greatly ease the process of listing a combiner box, and there are now a handful of UL recognized devices on the market. Beyond UL recognition, which focuses on arc detection but not real world performance, a desirable AFD needs to perform with a minimum of nuisance tripping while offering competitive cost in terms of both capital expenses (CAPEX or initial costs) and operating expenses (OPEX or operating and maintenance costs).

AFDs have been proposed with two architectures. One directly senses arcs on all strings in the combiner ("direct detection") by using sensors which have all the current in the combiner box flowing through them. The other uses one sensor with only a portion of the current in the combiner box flowing through it to detect arcs on all strings in the combiner ("indirect detection"). Indirect detection has the potential for lower CAPEX, but it has a much higher potential for nuisance tripping and does not localize the arc to a subset of strings in the combiner, so it has much higher OPEX and a higher risk of customer dissatisfaction. Direct detection may have somewhat higher CAPEX, but generally offers superior nuisance tripping performance and includes arc localization, so it has much lower OPEX and higher customer satisfaction which quickly offsets the higher CAPEX with savings.

Sensata's PVAF family of DC solar PV arc fault detectors employ direct detection architecture and a proprietary hybrid detection algorithm to offer high performing, cost effective, field tested AFD solutions. Their minimal nuisance tripping and desirable level of detection granularity substantially reduce operating cost and increase customer satisfaction compared to competing solutions. The cost of deployment is further reduced by Sensata's knowledgeable engineering support paired with an easily integrated PVAF detector. This low operating cost, combined with competitive capital cost, shows that Sensata's PVAF is the most cost effective AFD solution on the market.

## 2. Introduction

NEC 2011 includes a requirement for new roof top arrays to include UL1699B listed arc fault current interruption (AFCI). NEC 2014 expands this requirement to include ground mounted arrays as well. The issue driving this requirement – improved safety by avoiding arc generated fires – is important to mitigate lingering PV safety concerns and pave the way for further widespread adoption of PV. However, it requires adding new components to a PV array at a time when cost pressure on PV arrays is greater than ever, and at the same time, the solution must comply with the industry's expectation of minimal maintenance. In light of this cost pressure reality, one must implement the most cost effective UL compliant AFCI with a minimum of expensive disruption to a PV plant's operations and maintenance.

This white paper offers Sensata's perspective on a practical foundation for making an informed decision on selecting an AFD. In this white paper, the considerations required to make prudent AFCI architecture and component decisions are reviewed and discussed. In the final section, Sensata's arc fault detection products are presented in light of these considerations.

AFCI combiner boxes are the focus of this white paper, though many of the concepts apply to AFCI inverters as well.

# 3. UL Requirements

## 3.1. UL Recognition and Listing

A UL 1699B listed AFCI device can be embodied in a number of ways such as an inverter or a combiner box, and is composed of a handful of items including an arc fault detector (AFD) and a disconnection device, such as a contactor, breaker or inverter shutdown. A UL 1699B *recognized* AFD is a portion of the *listed* solution and as such has been tested to the standard's tests that are relevant to the AFD, though not to all the tests required for the listing. Therefore, starting with a recognized AFD significantly eases the complexity and risk when integrating a listed solution, even though additional testing to complete the listing is required. The specific testing required for the listing is dependent on the Nationally Recognized Test Lab (NRTL) defining the test plan.

## 3.2. UL Performance Requirements

UL1699B Edition 2 (2013) describes two types of UL 1699B recognition: Type 1 and Type 2. UL 1699B Type 1 recognition requires that the arc fault detector (AFD) detect a class of series faults. It also allows that the AFD may detect a class of parallel faults. UL 1699B Type 2 recognition requires detection of both a class of series and a class of parallel faults. Neither Type 1 nor Type 2 recognized AFDs are required to distinguish between parallel or series faults. UL 1699B only requires that the AFD detect an arc of 300 W or more in conditions defined in the standard. The requirement for NEC 2011 and NEC 2014 is UL 1699B Type 1 AFCI.

It is important to note that UL 1699B is written to verify that the AFCI detects and mitigates a class of arcs, however it has only very limited testing to show that the AFCI or AFD avoids nuisance tripping. With this in mind, merely obtaining a UL listing or recognition is not sufficient to show that an AFCI or AFD is capable of satisfactory performance under real world conditions in the field.

# 4. System Performance Considerations

## 4.1. Operation Concept - Differentiation Between True and False Positives

Electrical arcs occur when current jumps an air gap between two conductors, producing dangerous levels of heat. On solar PV systems, this can occur when conductors are damaged, or connectors make inadequate connections. Arcs can be in series, such as current flowing through a single damaged wire, or parallel, such as when current flows from one damaged conductor to another conductor that is intended to be at a different voltage level.

Arcs produce electrical noise which has distinct characteristics, such as the frequencies generated, which allow it to be detected. A critical aspect of successfully detecting arcs is differentiating between arcs and other electrical noise in the system, such as inverter noise, switches, contactors, local radiated EMI sources, etc.

To detect the arc accurately and ignore other electrical noise, an AFD operates best when the signal-to-noise ratio is high. This requires that the arc signal power is strong enough compared to the background noise for it to be accurately detected. This is the same effect a person experiences when carrying on a conversation in a quiet house compared to a noisy restaurant – the same volume of speech that is easy to hear in a quiet house is barely audible in a noisy restaurant due to the difference in background noise. This aspect limits the ampacity of AFDs which can accurately distinguish between arcs and other electrical noise.

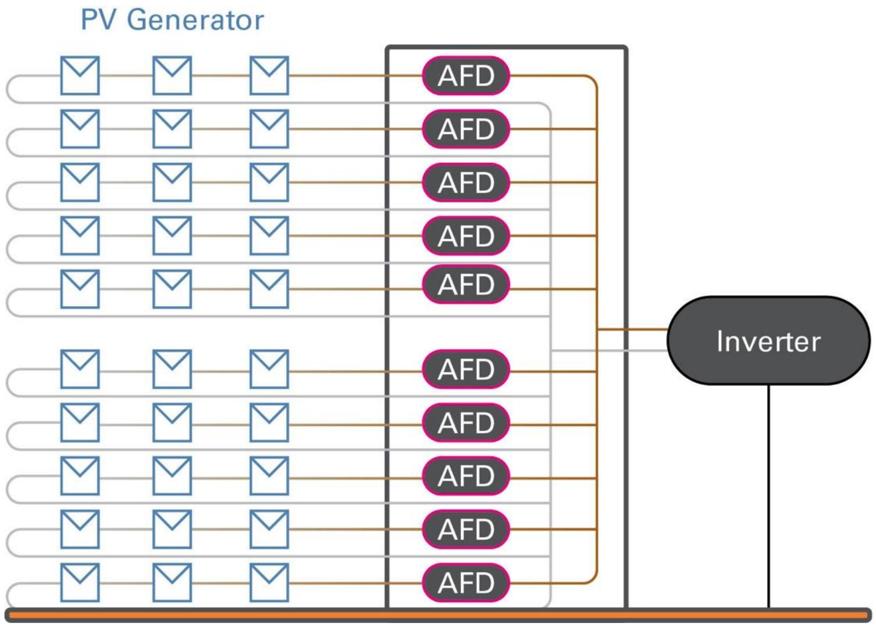
## 4.2. Performance Capability Based on Architecture

Differentiation between true and false positives is key to offering UL listed protection while avoiding nuisance tripping. In order for an AFD to perform acceptably in the field, it must fulfill its core purpose of detecting “true positive” arcs as described by UL 1699B and rejecting potential false positives generated by all other system events or noise. Nuisance tripping due to false positives increases the amount of time the PV array is shut down due to detected arc faults – decreasing energy generated, increasing service calls, and decreasing customer satisfaction.

All currently available DC AFDs are rated for similar ampacity in the range of one to a few strings of current due to the physical limits of reliable arc detection and false positive rejection based on the system’s signal to noise ratio. However, there are two major AFD integration architectures proposed.

Most solutions require that all the system current must pass through the AFD, which we refer to as “direct detection” architecture. These AFDs are subjected to the full power of an arc on that conductor and as such, set the sensitivity thresholds to trip at the power of one arc. They also localize the detected arc fault to a subset of strings for faster debugging. Higher current AFDs can be wired in line with a few strings and can detect arcs on those few strings simultaneously, but substantially reduce the localization benefits of individual string sensing.

**Direct detection architecture**

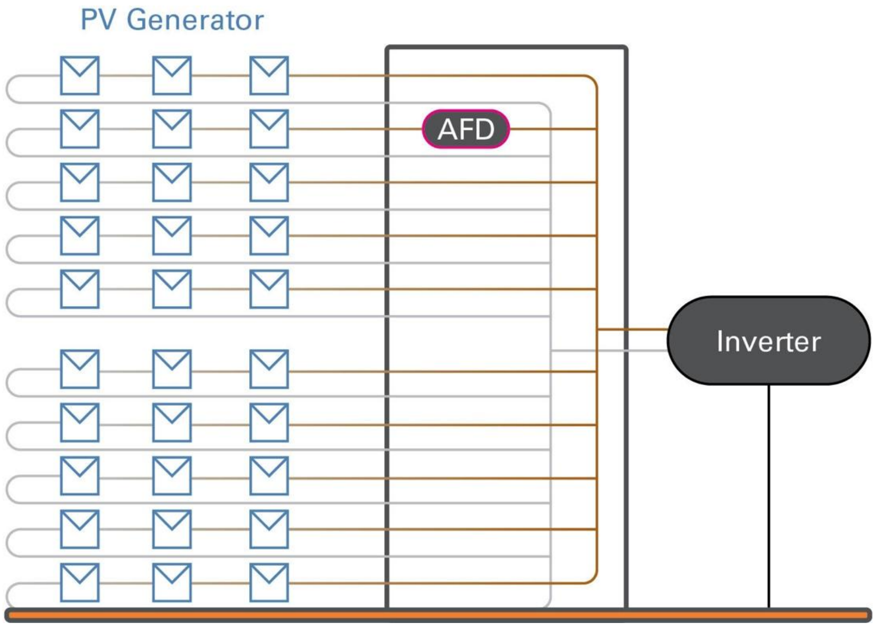


Other AFD solutions recommend that a single AFD is used for an array of string inputs, with only one of the inputs passing through the AFD. We refer to this as “indirect detection” architecture. In this architecture, the arc power is disbursed among many string circuits as it proceeds to the AFD, so only a small fraction of the arc power is sensed by the AFD. Therefore, the AFD trip sensitivity thresholds must be set to very sensitive levels to catch all the required true positive arcs. This high sensitivity setting brings with it a high possibility of nuisance trips.

For instance, in this second architecture, an AFD is recommended to be directly sensing one single string input on a 16 string combiner box while detecting arcs on all strings in that combiner box. In this case, detecting an arc on a string that is not the string the AFD is mounted on would require that the AFD’s trip threshold be set to trip at a power level that is 17 times more sensitive than an AFD that has the arcing string passing through it. This is due to the arc noise disbursing at the combiner’s comb to each of the other 15 strings and the combined line before reaching the AFD. This would lead to a system that is 17 times more susceptible to nuisance tripping than a system that has an AFD with the arcing current directly passing through it.

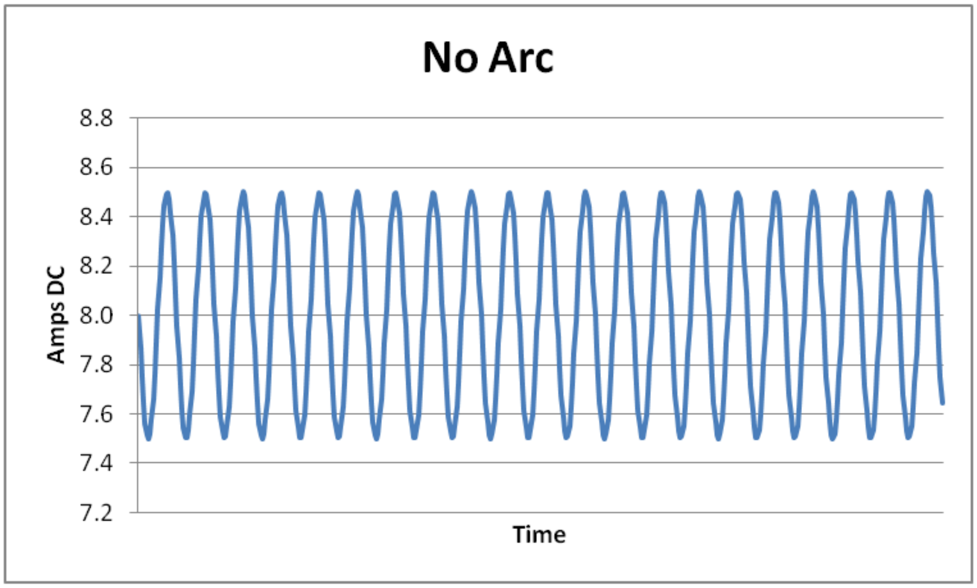
This strategy does not distinguish in which string the detected arc fault exists, so debugging a detected arc will require more time than if a subset of strings were indicated.

**Indirect detection architecture**

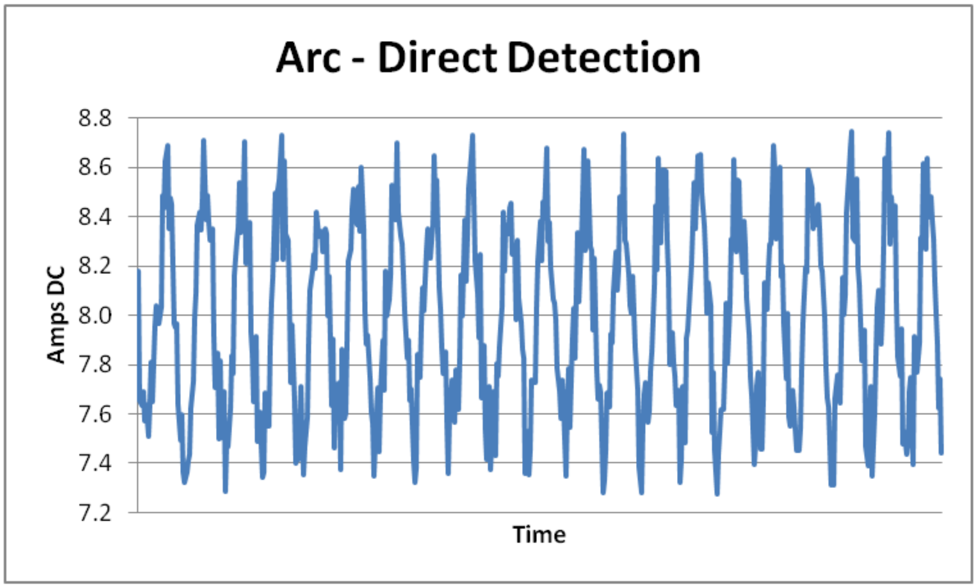


The dramatic difference in arc signal observed by each detector architecture is easily seen in a conceptual plot. This shows that the direct detection method observes a much more pronounced signal when an arc occurs than the indirect method.

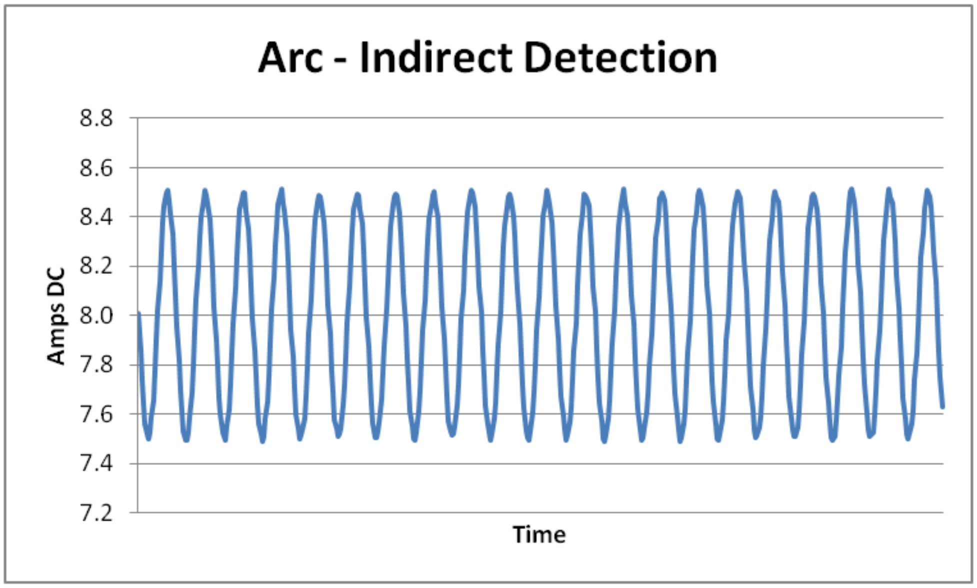
When no arc is present, just the DC current and the system's background noise is present, as shown below.



When an arc exists in a string with direct detection, the signal observed by the AFD would appear as below. One can clearly see the white noise of the arc overlaid on the system's background noise. This signal is dramatically different from the background noise alone and allows the AFD to clearly distinguish between the background noise and the arc noise.



Alternatively, when an arc exists in a string with indirect detection, the signal observed by the AFD in a 16 string combiner box would appear as below. The arc signal is 1/17 of the strength of the signal in the direct detection architecture. This indirect detection signal is only slightly different from the background noise and makes distinguishing the arc from background noise using this signal very difficult and greatly increases the risk of nuisance tripping.



## 5. Cost Effectiveness

A model was developed to estimate the capital expense and operating expense of different categories of AFCI solutions based on their cost and performance parameters. This model was used to run sensitivity tests to identify the parameters which matter most in minimizing system and lifetime cost, and maximizing energy production and customer satisfaction.

### 5.1. Model development and assumptions

The model was developed to capture the major added capital expenses (CAPEX) and operating expenses (OPEX) due to integrating a current generation PV solar AFCI. This was done for a handful of scenarios with varying AFD price, nuisance tripping frequency and detection granularity. The main system assumptions are:

| | |
|---|---|
| Array power | 500kW (one central inverter) |
| Combiner boxes (50kW per box) | 10 boxes, 16 strings each |
| Cost of capital | 6% |

For each AFCI scenario, a handful of components required to implement AFCI were totaled to estimate CAPEX on a per string basis. This is only intended to model the incremental cost of the major added components for AFCI, not the total cost of the complete balance of system. The AFD cost itself was varied during sensitivity analysis to investigate the impact on lifetime cost.

| | |
|---|---|
| AFD | \$9/string baseline, \$4 low, \$15 high |
| Parasitic Power Supply | \$48/each, \$3/string |
| Contactor | \$96/each, \$6/string |

Also, for each AFCI scenario, the AFD performance was assumed as an input to the model calculations. The same frequency of true positive trips was assumed in all systems since they are not dependent on AFD choice. False positive tripping (nuisance tripping or tripping when no dangerous arc was present) was varied during sensitivity analysis to model the differing resistance to nuisance tripping of various solutions. These trip frequencies are assumptions used in an effort to generate a meaningful analysis and are not representative of a specific array or AFCI solution. The unit “Inverter-year” indicates the trips experienced on one inverter running for one year.

| | |
|---|---|
| True Positive Trip Frequency | 0.1/inverter-year |
| False Positive Trip Frequency | 0.4/inverter-year baseline, 0.1 low, 1 high |

Indicating multiple strings as having a fault during a single true positive or false positive arcing event was handled separately from false positive tripping, by separately calculating the value of the added troubleshooting effort and incremental loss of production required to isolate the source of the fault. This was done using a granularity parameter that defines how many strings were indicated in the fault in addition to a constant parameter that indicates how many strings were electrically opened.

| | |
|---|---|
| Strings opened on trip | 16 strings (whole box) |
| Strings indicated on trip | 8 strings baseline, 4 low, 16 high |

When trips occur, an estimate of the expense to debug the fault and restart the PV system was totaled to address the lost production due to tripping off and the cost of troubleshooting the portion of the array tripped off by the AFCI.

| | |
|---|---|
| Ratio of restart visits vs. full inspections for every false trip | 3:1 |
| Truck roll equipment cost | $250/each |
| Technicians responding | 1 |
| Technician hourly rate | $75/hr fully loaded |
| Hours to get to site and begin work on roof | 3 hours; direct cost included in truck roll, lost kWh cost additional |
| Hours to debug an indicated string | 1 hour/string |
| $/kWh generated | $0.20/kWh |

The model assumes that every time the AFCI trips, a technician is deployed to the site the same day to debug the array. It is assumed that 3 out of 4 times when the tech goes to the site and it is a false trip, the problem is resolved with a restart of the array and no debugging. The other 1 out of 4 times it requires full debugging.

It is assumed that the technicians only work while the sun is up. It is also assumed that in the full inspection case each string that is indicated as possibly having a fault is treated the same and fully inspected for having a fault before restarting the array. As is current industry state-of-the-art, it is assumed that technicians must rely on the localization of the arc done by the AFCI, and cannot further localize it with usual field tools like meggering or current tests.

The model does not take into account the cost of fixing failed components in the array, since the pricing will vary dramatically depending on the fault, and the cost of the repair is not dependent on the arc fault detector.

## 5.2. Results of sensitivity analysis

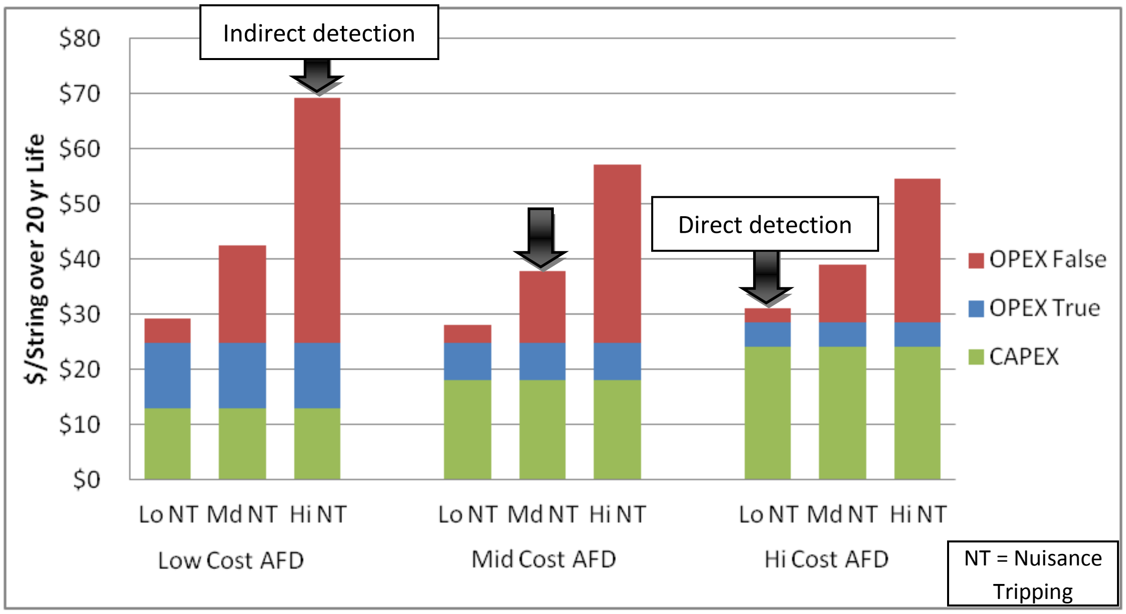
The two primary concerns highlighted by the model are the value of minimized false positive tripping and the value of very granular resolution of which string is faulted.

A handful of scenarios with similarities to AFD products currently being marketed were developed. They use the same baseline as earlier described and vary 3 parameters at 3 levels each to present 9 scenarios.

| | Low Cost AFD | | | Mid Cost AFD | | | High Cost AFD | | |
|---|---|---|---|---|---|---|---|---|---|
| | Low NT | Mid NT | Hi NT | Low NT | Mid NT | Hi NT | Low NT | Mid NT | Hi NT |
| AFD Price ($/string) | $4 | $4 | $4 | $9 | $9 | $9 | $15 | $15 | $15 |
| Nuisance Trip Frequency | .1 | .4 | 1 | .1 | .4 | 1 | .1 | .4 | 1 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (Trips/inverter-year) | | | | | | | | | |
| Strings Indicated on Trip (strings) | 16 | 16 | 16 | 8 | 8 | 8 | 4 | 4 | 4 |

It was found that the cost of nuisance tripping is very high over the life of the system and at high nuisance tripping frequency, is even larger than the CAPEX. Additionally, a low cost of the AFD in the mid and high nuisance tripping frequency case does not make up for the high cost of nuisance tripping. In high nuisance tripping cases, customer satisfaction will also be reduced.



The black arrows indicate the likely outcomes with each type of detector. For instance, as discussed in the performance section (section 4.2), the lower cost AFD architectures will tend to have more nuisance tripping than the higher cost ones. Therefore, the high nuisance tripping case is most likely for the low cost version and vice versa for the high cost one, as shown by the black arrows.

Additionally, it can be seen that **frequency of nuisance tripping is the dominant input to the lifetime cost effectiveness of all of the solutions**. The variation based on detection granularity is much less, as can be seen by comparing the sum of the OPEX's in each of the low nuisance tripping scenario bars, and comparing low nuisance tripping scenarios shows that OPEX difference is largely cancelled out by the difference in CAPEX for the systems. However for the high nuisance tripping scenario, it is more significant since the array would need to be debugged much more frequently.

A desirable lifetime-cost-minimized AFCI solution should include a major effort to minimize false positive tripping even if a CAPEX premium is required. Additionally, maximizing string indication granularity in the system is desirable, but since it is a secondary life time cost driver to nuisance tripping, paying for increased granularity without additional nuisance tripping avoidance it only worth a small increase in CAPEX.

# 6. System Installation and Support

## 6.1. System Installation

In addition to performance and cost concerns, it is important that an AFD is easy to install in the field. Beyond just offering a compatible electrical interface, the AFD and AFCI system must result in a simple installation experience, which avoids installation and configuration issues common in other combiner box electronics, such as complex monitoring systems that result in numerous extra installation hours and service calls. Additionally, a desirable solution would work “off the shelf” without tuning or adjustment. In this way, the AFD and AFCI can be utilized without slowing down installation, requiring additional training or creating undue deployment and support risk.

## 6.2. Support

Beyond the immediate “hard” concerns already discussed, many soft considerations also exist. Specifically, support of and confidence in the supplier is important for a system such as an AFD, which is intended to accomplish a complex task over a long period of time.

Some important items to consider when evaluating suppliers include:

- Extent of field testing with AFD and supplier’s knowledge of pre-tested inverters for confident system integration.
- Engineering support for combiner box integration.
- Supplier’s depth of knowledge in arc fault detection and understanding of their algorithm, including ability to adjust it if needed, even in the field.

# 7. Sensata’s Arc Fault Detection Products

Sensata’s PVAF family of solar PV arc fault detection products offers high performing, cost effective, field tested solutions to the solar industry. The Sensata PVAF family is the best choice to use when creating and deploying listed solar DC AFCI products.

- UL Recognition
  - Two major variants UL recognized, designed for different types of combiner boxes and inverters
- Robust Performance
  - Proven nuisance tripping avoidance
  - Lab and Field tested
  - Direct detection - All currents pass through the AFD for maximum true positive and false positive differentiation
  - Proprietary hybrid algorithm
- Cost Effectiveness
  - Minimal nuisance tripping and desirable level of detection granularity dramatically reduce operating cost and increase customer satisfaction

    - Low operating cost with competitive capital cost combine to create most cost effective AFD solution on the market
- Simple Installation and Support
    - Works off the shelf without tuning or adjustment
    - Simple integration
    - Simple installer interface
    - Knowledgeable engineering support available
    - Sensata's large size, stability and 75+ year history in electrical protection