



Implementing Arc Detection in Solar Applications: Achieving Compliance with the new UL 1699B Standard

Introduction

With increasing interest and demand for renewable energy sources, the market has seen a surge in the deployment of solar photovoltaic systems that convert sunlight to electricity. While new technological innovations like micro-inverters promise to change the solar landscape, the majority of installations today utilize long runs of high-voltage DC power that have raised concerns over safety issues relating to power arcs. This has led to the drafting of the UL 1699B standard that requires the use of arc detection in high-voltage systems to increase personal safety, protect equipment and prevent catastrophic damage. While this paper focuses on implementing arc detection in solar applications, the technology applies to other electrical applications where high voltages are involved, such as electric and hybrid vehicles.

Safe Arc Detection: UL 1699B

Standards for the solar industry continue to adapt as photovoltaic technology matures and manufacturers expand into new markets. With the ongoing evolution from large “solar farms” consisting of acres of panels to an increasing number of smaller residential and commercial installations, there has arisen a need to impose safety measures to prevent catastrophic events associated with high voltages such as harmful electrical shock or fire.

These events are caused by arcing that can occur over high voltage DC lines where there is any breakdown in wiring or the electrical connectors. These arcs can electrify the installation, causing the mounting system to become electrified, as well and potentially shocking anyone touching the unit. These arcs can also cause fires that damage the electrical equipment or cause extensive property damage. For example, in residential roof-top installations, there is the real possibility of an arc setting the shingles on fire.

To address these important safety issues, the solar industry has developed the UL 1699B photovoltaic arc-fault circuit protection standard. UL 1699B is an addition to the UL 1699 Arc Fault Interruption specification, which is a subset of Article 690 of the National Electrical Code (NEC). It defines requirements for systems with a DC bus voltage equal to or greater than 80 V but less than 1,000 V.

UL 1699B has been under development for quite some time and is expected to be completed by the end of 2012. Europe is anticipated to follow with a similar standard of their own after UL 1699B is in place.

With the adoption of UL 1699B, any company designing equipment for the solar industry that carries more than 80 V on a string of panels will need to comply to the standard and employ arc detection. The standard will impact the design of solar inverters, converters and charge controllers, as well as standalone DC arc-fault interrupters, for residential, commercial and industrial applications.

Part of the UL 1699B standard requires the arc detection system have an annunciator to indicate that the detection system has been tripped by an arc event. This annunciator can take a number of different forms, from a blinking LED to a loud siren. Depending upon the installation, it may be important for the system to support a remote indicator as well. For example, a solar array could notify the utility company or owner of the array that the system has been shut down due to an arc. This could be achieved using a wired or wireless communications link.

Another requirement of UL 1699B is that systems contain a test circuit to verify correct operation of the arc detection unit. This circuit has to be able to simulate an arc event into the unit's input and verify that a failure triggers, much in the same way a person can self-test a GFI outlet in the home. If the self-test fails, the system is required to shut itself down.

The self-test can be triggered from a switch either directly on the unit or via a remote interface. There is also ongoing discussion of making testing automatic given that many people don't tend to actually perform self-testing on a regular and consistent basis.

Solar Topologies

A notable exception to UL 1699B are micro-converters and micro-inverters targeted at residential installations. In a traditional solar array, multiple panels are connected in series on “strings” and connected to a centralized DC to AC inverter (see Figure 1) in a manner referred to as a central or string topology since multiple panels are tied together in series like a long string. Because they are connected to so many photovoltaic panels, each inverter will typically carry 200-600 V in a residential system. Arc detection is required between each inverter and the string of panels to which it is connected.

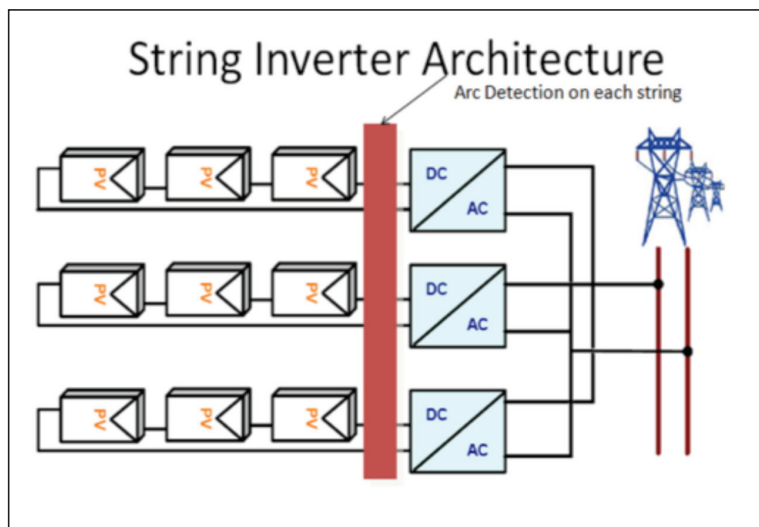


Figure 1: In a central or string topology, photovoltaic arrays are connected in series to a single inverter. Each inverter will typically carry 200-600 V in a residential system. Arc detection is required between each inverter and the string of panels to which it is connected.

Micro-inverters offer an alternative topology where each photovoltaic panel has its own inverter (see Figure 2). Micro-inverters provide greater flexibility than string-based topologies, and their modularity eases installation. They are also easily scalable when installations need to be expanded at a future date. In addition, DC voltage of each micro-inverter is below 80 V with a direct AC voltage output, thus enabling operation at a safe level that does not require arc detection.

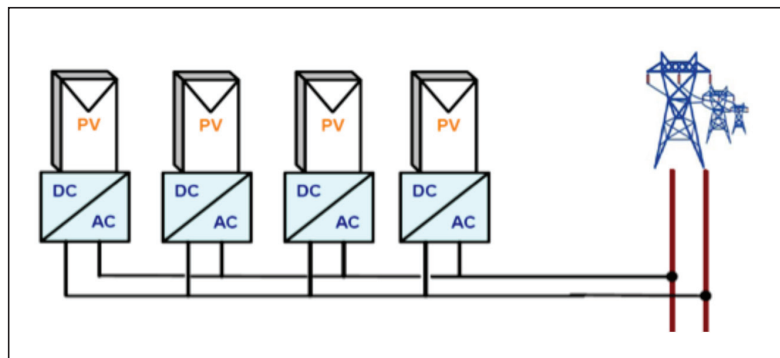


Figure 2: Micro-inverters offer an alternative topology where each photovoltaic panel has its own inverter (see Figure 2). Their modularity and flexibility eases installation compared to string-based topologies. Because the voltage of each micro-inverter is below 80 V, arc detection is not required.

While micro-inverters are gaining in popularity, the reality is that the traditional string approach to solar installations still dominates the market with greater than 99 percent market share. As a new technology, micro-inverters are currently more expensive to deploy. In addition, as individual panels don't yet put out enough power per panel to make single-panel installations beneficial, string-based topologies still offer a superior cost per watt.

Micro-invertors will need to drop significantly lower in price to be on par with string inverters. Given that arc detection adds only a minimal price header to a string-based installation when compared to the total cost of the system, UL1699B does not substantially impact the cost advantage of string-based equipment. For the foreseeable future, the market will continue to be dominated by string inverters. As a consequence, UL 1699B impacts every manufacturer of solar equipment.

The Challenge of Arc Detection

An important element of UL 1699B is that the system must be manually reset when it has been tripped. This makes the cost of a false arc detect a primary design concern, especially for remotely located installations. Specifically, if an entire solar array is shut down from a false arc detect, this represents loss of power until a technician can be sent out to the site to reset the system. This poses a difficult challenge for developers: the cost of failing to detect an arc is potentially high (e.g, physical harm, equipment damage, catastrophic fire) while the cost of falsely detecting an arc is high as well (i.e., unnecessary, yet costly service calls).

To understand the scope of the overall problem, consider how an arc is detected. The DC voltage is converted into a digital signal and then processed to determine the spectral noise in the nominal power. Figure 3 shows the response of a string inverter during standard operation and when there is an arc. As can be seen, an arcing event changes the nominal power over specific frequencies bands ranging from 40-100 KHz.

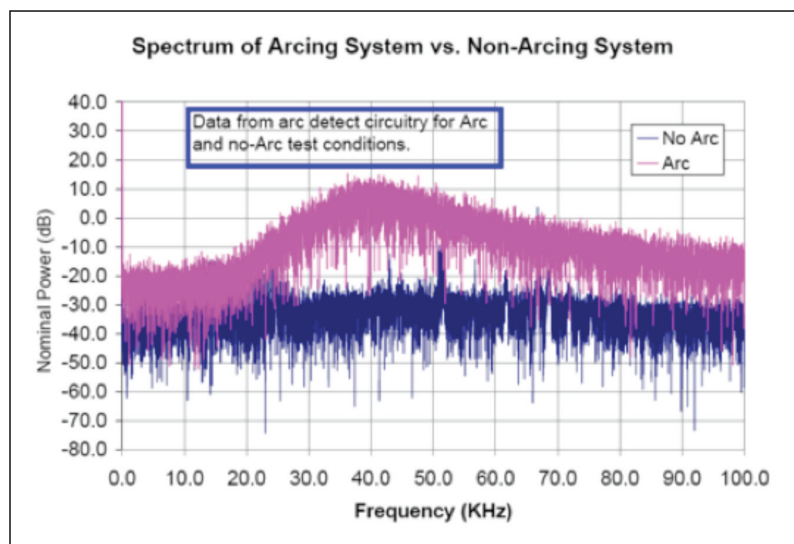


Figure 3. Arcing events cause spectral noise in the nominal power signature of the inverter compared to when the system is not arcing. This noise appears in specific frequency bands ranging from 40-100 KHz.

One approach to detecting an arc is to compare the nominal power to a baseline measurement and note when the noise level increases suddenly. While this would serve to detect an arc, it does so only when the system is already in operation. An arc that occurs during power up when the baseline is being established would pass undetected, thus failing to comply with UL 1699B. The detection system, therefore, requires a detection algorithm that can perform accurately without a baseline measurement.

Further exacerbating this challenge is that the AC inverters generally used in string inverters generate noise that looks very much like an arc event. Figure 4 shows the normal operation of a string inverter compared to when the AC inverter is running and generating noise. As can be seen, the noise peaks higher at points during normal operation than an arc does. In fact, the difference between normal operation and an arc event is very small, making it difficult to distinguish between the two.

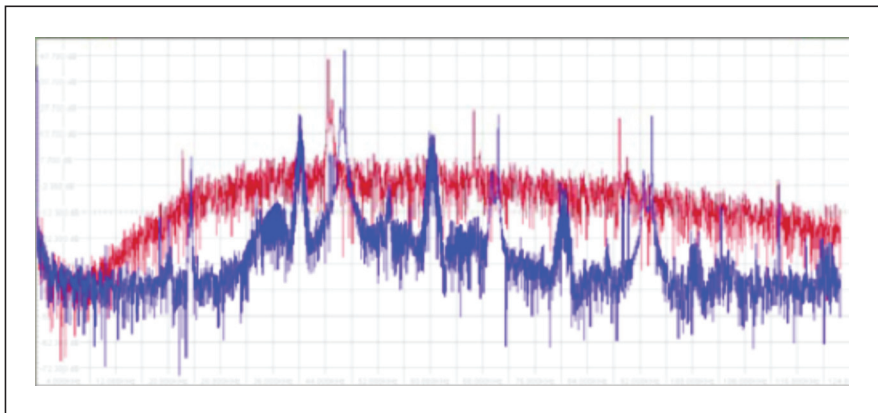


Figure 4: The AC inverters generally used in string inverters generate noise that looks very much like an arc event, making it difficult to distinguish between normal operation and an arcing event.

This is not a trivial problem. The algorithms to detect these differences are quite complex and involve the evaluation of multiple filters simultaneously to avoid false detects. In addition, these algorithms have to be performed as quickly as possible to allow sufficient time to break the circuit before the arc can damage the system or start a fire.

Designing an Arc Detection Circuit

Figure 5 shows an arc detection circuit for a solar inverter. It comprises an analog front end, ADC and digital signal processor (DSP). The analog front end is a current transformer that measures the current in the string of panels. It acts as a bandpass filter across the range of frequencies to be observed and adds gain to the signal before it is sampled by the ADC and passed to the DSP for further processing.

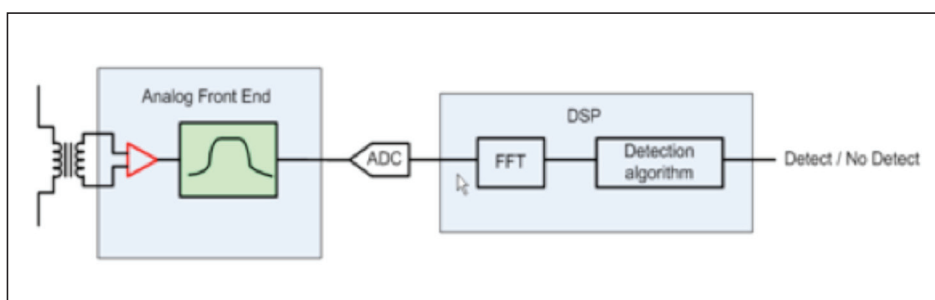


Figure 5: A simple arc detection circuit for a solar inverter consists of an analog front end SM73307/73308), ADC (SM73201) and microcontroller with an integrated CPU or digital signal processor (Piccolo F2803x microcontroller).

To accurately and reliably detect an arc requires a fast, high-resolution ADC. Without enough resolution,

the detection circuit may not be able to distinguish between an arc and non-arc event. Speed is also essential in this process: the UL 1699B standard allows for two seconds to open a switch and shut the system down after an arc event. Ideally, developers want to allocate as much of these two seconds to opening the switch, which is mechanical in nature. A 16-bit ADC sampling at 250 Ksamples, for example, will provide the necessary resolution and speed.

Once the voltage is converted to a digital signal, it needs to be processed in the frequency domain. Further filtering isolates the spectral noise on the DC bus and then the signal is bifurcated into bands and an FFT applied.

As processing is done in the frequency domain using complex algorithms, arc detection requires a DSP with real-time capabilities. A 32-bit architecture enables the fastest and most efficient processing of the incoming signal from the ADC.

Multiple FFT-based filters detect changes in amplitude (peaking) of high frequency noise on the DC bus and then the unit evaluates whether an arc event is occurring.

When an arc event is detected, the unit needs to shut the inverter down. Analog outputs driven by a PWM can be utilized to open front end relays to disconnect the string of panels and trigger the annunciator (i.e., audible or/and visual alarm). Digital outputs can be utilized as a communications interface to send a message to a remote controller. This communications interface can also be used to initiate self-testing remotely.

Implementing Arc Detection

Given that UL 1699B affects nearly all solar equipment in use today and to be deployed in the near term, it is important to understand how it impacts design and the solar industry as a whole. Specifically, there are two primary markets for arc detection: new installations and retrofit units. The retrofit market is going to be extremely important given that existing solar installations with DC lines running over 80 V (i.e., nearly all of them) will need to add arc detection capabilities.

Retrofit units will be standalone devices that sit between a string of panels and their inverter. Retrofit units can be fairly simple, implementing just the arc detection subsystem and circuit breaker. A low-cost device with a high-performance processor like the Piccolo™ F2803x and F2806x microcontrollers. TI's C2000™ microcontroller platform is ideal for this type of application.

In new installations, arc detection can be integrated directly into the string inverter. As a consequence, system cost can be contained by combining arc detection with other inverter functionality on the same processor. For these types of applications, TI's Piccolo F2803x and F2806x microcontrollers are ideal, because these high-performance devices have undergone additional reliability tests and are well suited for solar inverters and converters. The high level of integration of these Piccolo devices, with full-featured peripheral sets are ideal for solar applications and enable developers to minimize the number of external components in the arc detection and breakaway circuitry. Developers can also select from TI's broad portfolio of C2000 microcontrollers for a device offering the optimal balance of performance, peripherals and memory for their high-voltage applications.

The use of a high-performance processor can maximize system efficiency in several ways by providing sufficient headroom to perform additional tasks. For example, a single arc detection unit with enough processing capacity can simultaneously analyze multiple incoming strings to minimize component count and equipment cost (see Figure 6). This approach also simplifies installation and reduces the number of points of failure in the system.

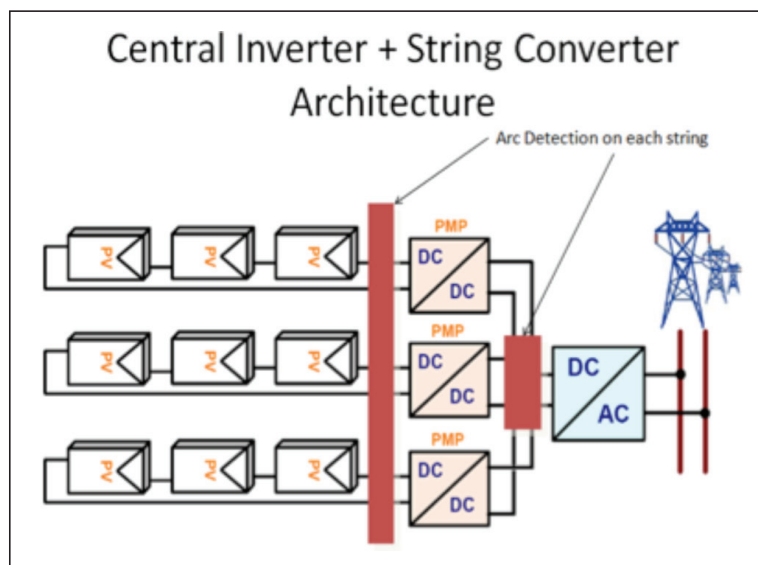


Figure 6: The use of a high-performance processor enables a single arc detection unit to simultaneously analyze multiple incoming strings, thus minimizing component count, lowering system cost and reducing the number of points of failure in the system.

The availability of processors with multiple cores provides further system cost savings by enabling a single processor to manage both arc detection and other processing tasks required by solar applications. For example, the Control Law Accelerator (CLA) on TI's C2000 Piccolo microcontroller platform gives developers a second core for handling Maximum Power Point Tracking (MPPT).

MPPT is a technology that increases the efficiency of photovoltaic panels by dynamically adjusting panels to maximize their exposure to the sun. Because the CLA has direct access to the C2000 Piccolo microcontroller ADC and PWM peripherals, it can operate independently of the DSP core handling arc detection. In addition, the two cores are collocated on the same chip and connected via internal registers, enabling the MPPT power stage to be immediately pulled offline when an arc is detected.

MPPT brings a high value to solar applications, as does the ability to consolidate MPPT with arc detection onto a single processor. In addition to reducing system complexity, the extra processing capacity of a dual-core device enables developers to increase both system efficiency and reliability for the lowest cost.

Arc Generation

Developing a reliable arc detection subsystem requires the ability to generate an arc under controlled circumstances. However, arc generation equipment is not a commonly available type of lab equipment, so developers will likely need to build their own generator.

Figure 7 shows the basic architecture of a circuit that will generate an appropriate arc. The arc detection system requires a DC power supply that represents the string of solar panels the unit is monitoring. A resistive ballast is used in the system to simulate any resistive load that an actual system may have and to dissipate the energy of the generated arcing event. A knife switch enables developers to trigger the arc when desired.

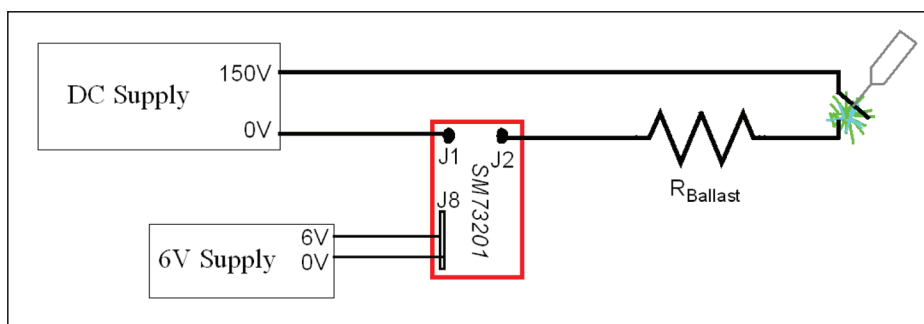


Figure 7: This figure shows the basic architecture of a circuit that will generate an arc to test arc detection capabilities. The DC power supply represents the string of solar panels the unit is monitoring, and the knife switch enables developers to trigger the arc when desired.

Hazardous voltages are required to create an arc, and appropriate protection precautions must be taken to avoid personal injury or damage to development equipment and prototypes:

- Use a knife switch with a long handle. The handle should be wrapped in non-conductive material as well as be flame-resistant.
- Use a polycarbonate enclosure surrounding the knife switch. Polycarbonate provides physical protection from the arc and is available in flame-resistant varieties. It will also block any UV radiation produced by the electrical arc.
- The ballasting resistor must be able to withstand greater than 200 W. Incandescent light bulbs can be used for this load.
- Note that while the voltage is high, the testing current can be low and still create an arc. This further increases safety when generating the arc.

The detection algorithm will need tuning, as well to optimize the system to recognize an arc. Be sure to consider any environmental factors such as temperature and humidity that may impact accuracy and responsiveness. TI's arc detection implementation utilizes multiband dynamic filtering which evaluates specific frequency bands individually and then aggregates the results to create an arc profile. Developers can tune the filter by selecting which bands to process, choosing what thresholds to use, setting the minimum frequency and determining the weight for each filter, among other characteristics.

To assist developers in developing a reliable arc detection subsystem, TI offers the **SM73201-Arc-Eval Photo-voltaic arc detection system** (see Figure 8) with a C2000 Piccolo microcontroller on board. This is a full reference design, complete with hardware and software, including TI's production-ready arc detection algorithm capable of accurately identifying arcs without producing false detects. The detection software is available at no charge to customers.

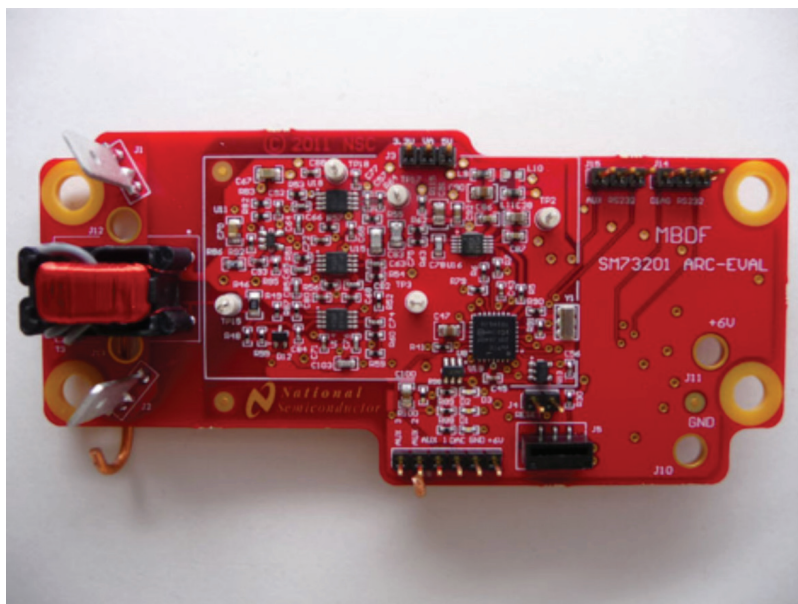


Figure 8: The SM73201-Arc-Eval Photo-voltaic arc detection system contains a C2000 Piccolo microcontroller and offers developers full reference designs, complete with hardware and software, including TI's production-ready arc detection algorithm capable of accurately identifying arcs without producing false detects.

This evaluation board demonstrates reliable detection of electrical arcing events without producing undesirable false positive detections. Developers can evaluate the system using a DC power supply with 200 V/2 A. The board itself can be powered by a 6 V/150 mA power supply or 9V battery.

TI is also the world leader in processors supporting MPPT and associated photovoltaic functions, with nearly 80 percent of the market, and offers a full, open-source library for MPPT with evaluation boards and a production-ready reference design. These tools enable developers to also quickly introduce the efficiency of MPPT to new designs as well as existing systems.

Beyond Solar

DC arc detection has many uses in applications outside solar inverters and converters where high-voltage DC is in use. For example, the increasing acceptance of hybrid and electric cars in the marketplace presents the need for safer technology. These vehicles utilize a 400-500 V battery pack and source a great deal of high-voltage DC throughout the car.

Specifically, the high-voltage DC busses between the primary batteries and inverter stages in these vehicles is known to be a potential cause of catastrophic vehicle fires. With arc detection capabilities built in (see Figure 9), the risks associated with high voltages can be mitigated, leading to safer vehicles and greater acceptance of hybrid cars in the market.

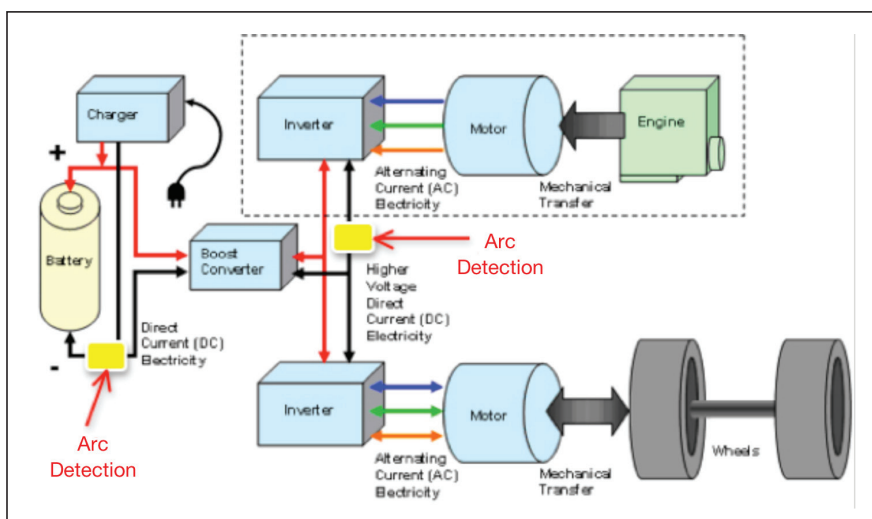


Figure 9: Arc detection can be added into a variety of high-voltage applications to mitigate the risks associated with high voltages. In an electrical vehicle, for example, arc detection can monitor the high-voltage DC busses between the primary batteries and inverter stages that are known to be a common cause of catastrophic vehicle fires.

The UL 1699B specification marks the beginning of a trend across industries to increase safety in high-voltage applications. The availability of low-cost and high-performance silicon combined with innovative detection algorithms enables developers to implement reliable safety mechanisms without false detects. As arc detection technology gains traction in the solar industry, other industries will begin to require it as well.

For more information on TI's solar solutions, please visit: http://www.ti.com/lscs/ti/apps/alternative_energy/solar/overview.page

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