WHITEPAPER
SAFETY

January 2020

A real point of differentiation with Enphase Energy architecture is safety. Homeowners and Installers alike, worldwide, are interested in safety more than anything else, and Enphase has one of the safest inverter architectures in the industry. To understand more about Enphase's architecture, let us start from the basics.

AC versus DC

Electric current is the flow of electrons in a wire, and this current can be broadly categorized into Direct Current (DC) and Alternating Current (AC). In DC, the electric charge (current) only flows in one direction. In AC, electric charge changes direction periodically.

In Figure1 below, notice that DC requires a constant voltage to move the electrons along (termed as current flow). AC on the other hand, is moved by a voltage that oscillates between maximum and minimum values. Notably, with AC, the voltage crosses the zero point twice, each cycle. This is critical because at that moment when the voltage is at zero, there is no current. With a DC system the current never goes to zero. This is especially problematic when there is a fault or break in a DC insulation system, and safety becomes compromised. We shall come to this point, soon.

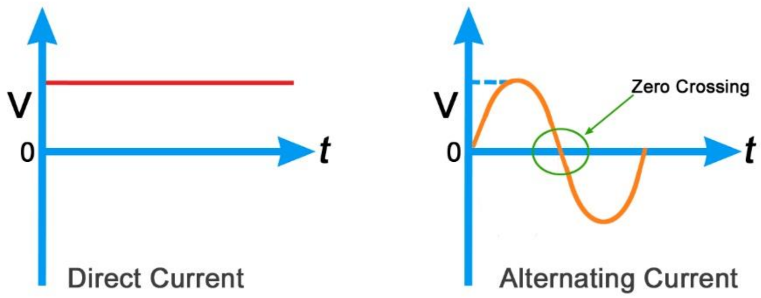

Figure 1: Representation of DC and AC

Many safety concerns for solar are primarily related to the DC voltage and current. At low voltage levels, they are relatively harmless. However, as the DC voltage level increases, so does the risk of harm associated with it, sometimes even leading to dangerous fire disasters.

With old fashioned string inverters, the PV panels (whether they have optimizers underneath them or not) are wired in series configuration (refer to Figure2). Every panel added to the series circuit increases the DC voltage in the circuit. Residential systems can have 600 Volts DC on the roof, and commercial systems can even have up to 1000 Volts DC. Even small systems can have around 350-400 volts DC in the circuit. All this can potentially be very dangerous. Not only is this dangerous for homeowners, but also for the install crews installing and maintaining the systems.

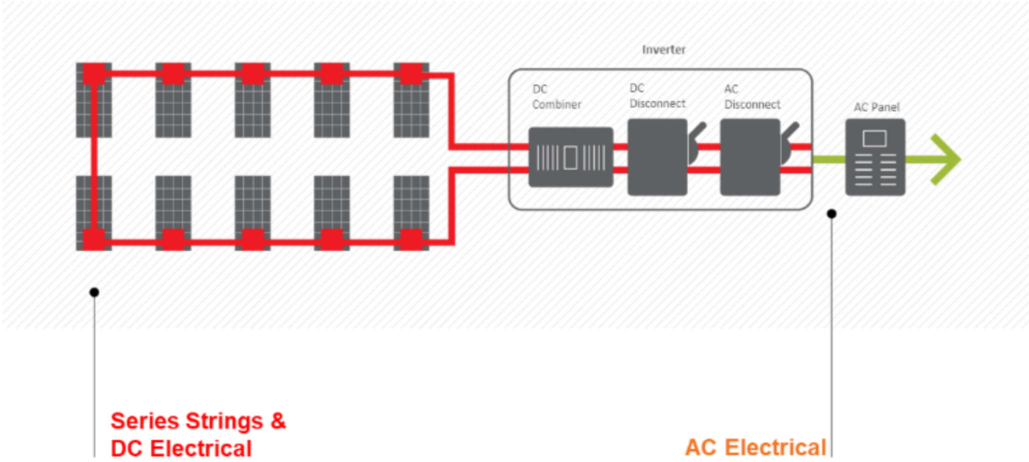

Figure 2: Representation of a typical String Inverter system

By contrast, there is no high-voltage DC in Enphase Systems. Each individual panel has a microinverter underneath it. The DC is converted to AC at the panel level by the microinverter, and therefore the DC voltage remains low. See Figure3. The rest of the system then operates in the AC domain.

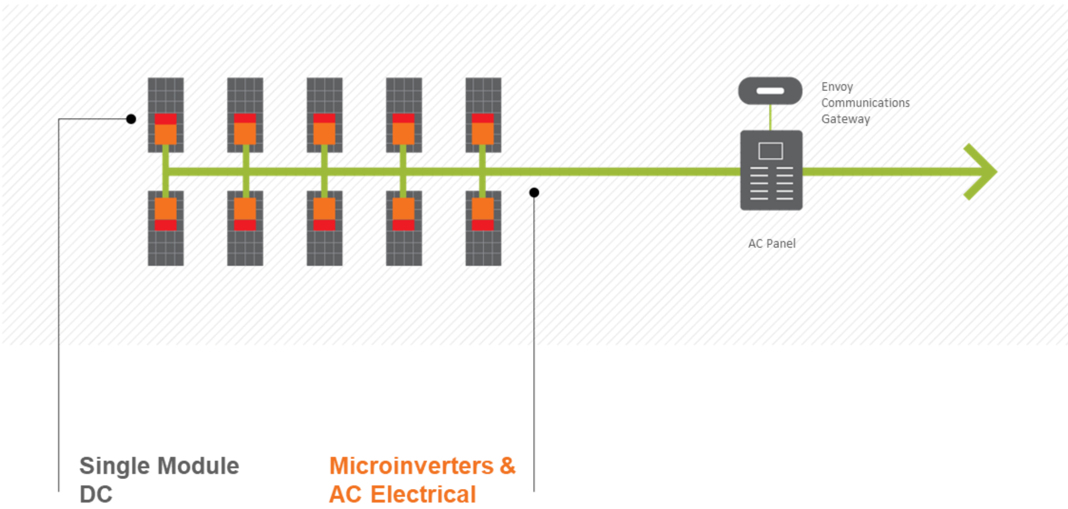

Figure 3: Representation of Enphase Microinverter system

DC arc fault

An arc fault is the flow of electrical energy through an air gap by way of ionized gas molecules. Air is normally regarded as a non-conducting medium, but a high potential difference (voltage) between two conductors (Ex: fault in the wire due to loose wire connections) in close proximity can cause the air molecules to break down into their ionized constituents (called a 'plasma'), which can then carry a charge from one conductor to the other. This flow of charge (electrons) when sustained, results in a bright arc that generates heat, breaking down the wire's insulation and triggering an electrical fire.

Different arc fault possibilities in a string inverter based solar system are highlighted in Figure4. The most important and common fault is D (Series fault in-line with conductor).

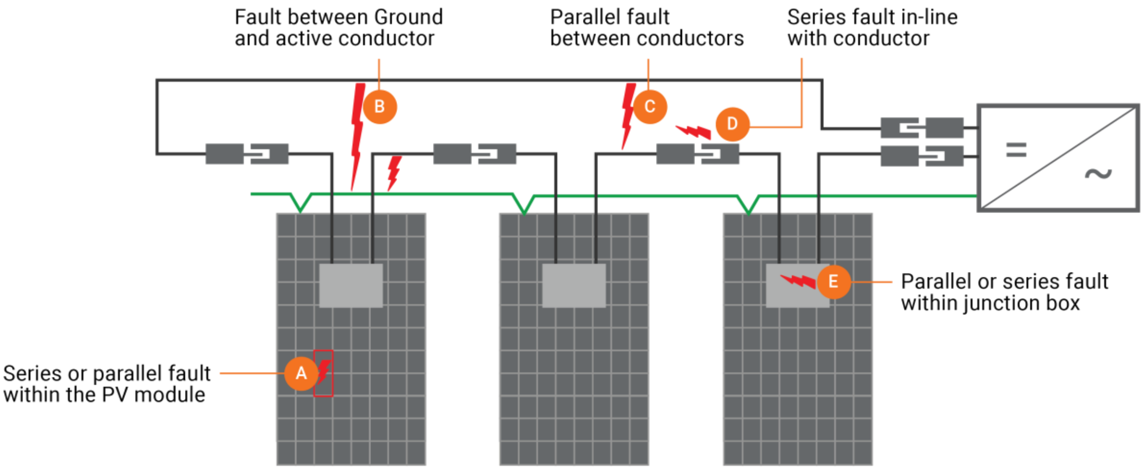

Figure 4: Different Arc Fault possibilities in a typical String Inverter system

Watch the demonstration of an arc fault in the video here. The gap between the two conducting wires in the first instance is about ½ to ¾ an inch, at around 280 V_{DC}. The arc at this point is hot enough to melt tungsten! Essentially, you are welding. This demonstrates how dangerous it can be to have a high voltage DC system on your roof.

In the second instance of the video, the demonstration of the arc fault is around 35 V_{DC} and over a much, MUCH smaller gap. The faint arc fails to sustain itself. Let us understand the two behaviours in detail.

When connected to microinverters, the PV system is inherently much safer than a string inverter based system with high DC voltages. Should a series arc occur in the DC wiring, the inherent characteristics of PV panel, the microinverter's dc input capacitance and the behavior of the MPPT algorithm, all play a big role in mitigating the arc. These three elements interact automatically and nearly instantly causing a series arc to essentially self-extinguish as it forms. Let's look at each element and how they interact.

I-V curve of the PV panel

The electrical operating envelope of all PV panel are defined by their characteristic I-V curve. Refer Figure5. For a given irradiance level and operating temperature, the panel's voltage and current will always be on this I-V curve. The end points of the I-V curve define the maximum current (I_{sc}) and maximum voltage (V_{oc}) the PV panel can produce. Ohm's law defines Power as Voltage multiplied by Current (P = I x V). Since the PV panel output follows an I-V curve, there is an optimum voltage (V_{mp}) and optimum current (I_{mp}) on the I-V curve where the panel output power is maximum.

MPPT

When the microinverter is operating, it continually measures the PV panel voltage and current, and adjusts the microinverter output power to maintain the panel at its maximum power point operating point. This function is known as maximum power point tracking or MPPT. In practice, this means the PV panel is at its maximum power point whenever the microinverter is operating. Because the microinverter input capacitance is in parallel with the PV panel, this capacitance is also at the maximum power point voltage (V_{mp}).

Microinverter input capacitance

All Enphase microinverters have relatively large input capacitances which act to stabilize the PV panel voltage at the maximum power point. When a series arc forms, it creates an instantaneous voltage of 20 to 40 Volts, that is in series with the voltage on the input capacitance. Because the input capacitance is much larger than the capacitance of the panel, the DC input voltage of the microinverter essentially remains constant as the arc forms. The formation of the arc therefore requires a 20 to 40 Volt increase of the panel voltage in order to sustain the arc. This combined capacitor voltage plus arc voltage lies above the panel's open circuit voltage (V_{oc}). So, it is not possible for the panel to produce current at this voltage. As a result, the arc self-extinguishes as it forms, reducing the chances of fire to a great extent.

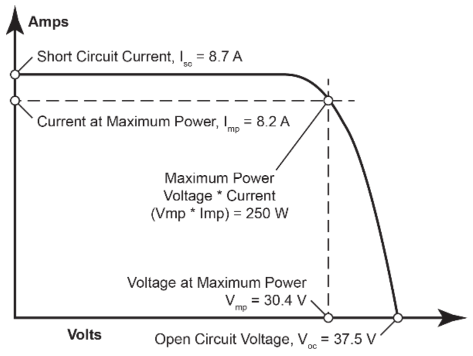

Figure 5: I-V curve of a solar panel

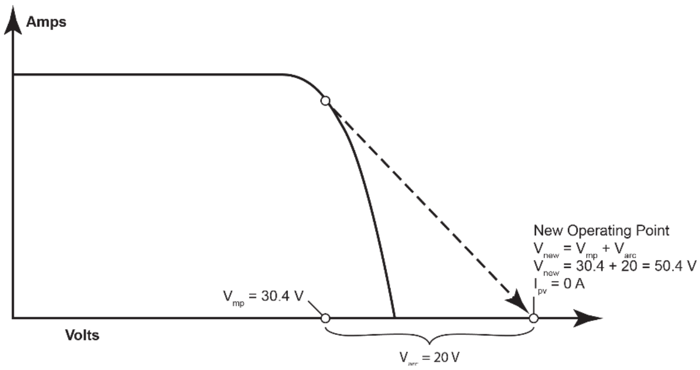

Figure 6: With an arc-fault in series with a working microinverter, the voltage rises to Vmp + Varc. The transfer characteristic of the PV Panel forces the current to zero. With zero current, the microinverter falls off MPPT (Maximum Power Point Tracking) and shuts down.

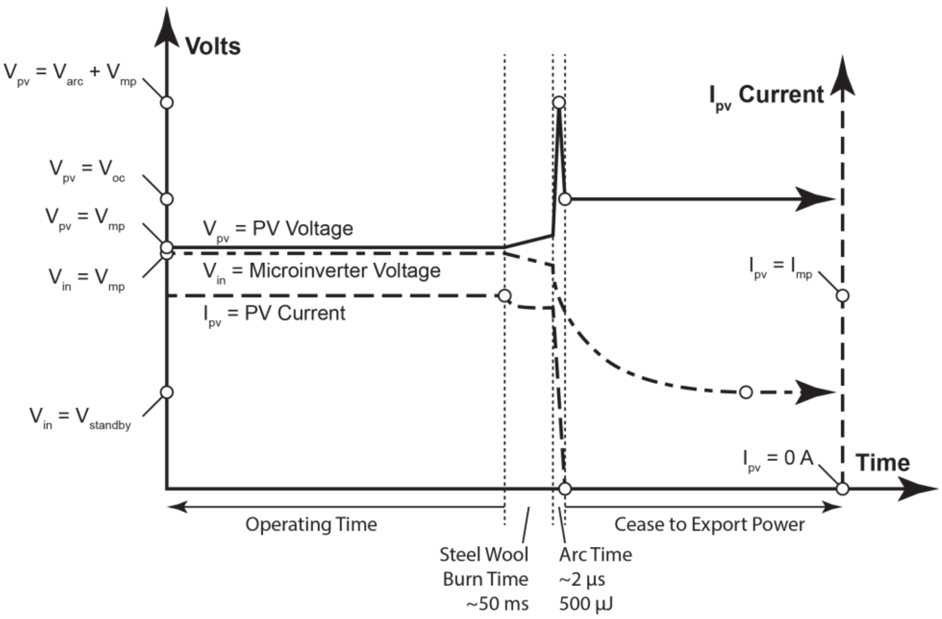

Figure 5: I-V curves explaining the microinverter behaviour during an Arc Fault

For an arc to sustain, this equation must hold true: $V_{oc} > V_{arc} + V_{mp}$. For a single module system, $V_{mp} + V_{arc}$ is greater than V_{oc}. So, the arc cannot exist. For two modules in series, the equation *might* be true depending on the temperature and fill factor of the module, i.e. shape of the I-V curve. For three modules, or more wired in series, $V_{arc} + V_{mp}$ will be less than V_{oc}. So, the string becomes capable of sustaining the arc.

Let us try to understand this phenomena in string inverter systems non-mathematically. Once the arc forms, the strength of the arc is dependent on the current. Because the total DC voltage in a string is high (around 600 to 1000 Volts DC), the arc voltage of 20 to 40 Volts in series does not create a significant change in the string voltage. This means the PVs will continue to supply the current that is essential to sustain the arc. As a result, the arc does not self-extinguish, and other means become necessary to reduce arc fault hazards.

Because Enphase microinverter systems always operate at lower levels of DC voltage, it is unnecessary to add an external DC AFCI (Arc Fault Circuit Interrupter) to an Enphase microinverter system installation. The inherent characteristics of the microinverters makes it a much safer inverter technology.

AC arc fault

DC is direct, meaning the conductor is always alive, never goes to zero. AC is alternating, and crosses the zero once every half-cycle, so it inherently has a much lower risk for sustaining arc faults than DC. So, it is not necessary to add an AC AFCI (Arc Fault Circuit Interrupter) to an Enphase microinverter system installation. Also, converting the PV power to AC at the panel level reduces the length of DC cabling and thus the risk of series arc faults.

Electric Shock

The direct nature of DC means that during an actual electrical shock, it tends to hold you and "pull you in", whereas AC tends to push you away, due to its alternating nature. Houses are wired with AC, and not DC for many reasons, and one of the biggest being safety.

Rapid Shutdown

The intent behind Rapid Shutdown requirement is to improve fire fighter safety when responding to fires on buildings with solar systems. The ask is to provide a simple method for fire fighters to de-energize solar system DC conductors easily to ensure a safe condition on the roof of a building during a fire. This is because on a standard string inverter solar system, when the inverter is switched off, the DC wiring from the solar system to the inverter remains live as long as the sun is shining.

As detailed earlier, solar electric PV systems with Enphase microinverters have one utility-interactive inverter directly underneath each solar panel, converting low voltage DC to utility grid-compliant AC. When the utility grid is available and the sun is shining, each microinverter verifies that the utility grid is operating within the grid interconnection requirements (Ex: IEEE 1547). Only then does it export AC power into the electric service for use by loads onsite or export power to the utility grid for others to use. When the utility grid has a failure, or the PV system AC circuits are disconnected from the utility service via an AC breaker, AC disconnecting means, the microinverters stop producing AC power in few AC cycles. Enphase microinverters (IQ7™ series, IQ6™ series, M series, S series, and C series) cannot operate as an AC voltage source. This means that without an AC utility source, Enphase microinverters are not able to energize connected wiring, and no AC voltage or current will be injected into the inverter output circuits or the grid.

String inverters on the other hand require additional equipment to achieve Rapid Shutdown compliance – Specialized Rapid Shutdown electrical boxes installed on the roof within 1 foot of the array. The shutoff switch or rapid shutdown actuator has to be accessible to first responders (fire fighters) on the ground. A provision also has to be made for the wiring to control the roof mounted Rapid Shutdown devices. All this additional hardware and wiring means additional installation time and more cost. Most importantly, each of those pieces needed for Rapid Shutdown are failure points, so you can end up with multiple single points of failure, where each is dependent on the other to keep the system safe. So, are those mechanisms installed correctly every single time? And do those mechanisms ever fail? All it takes is one time.

Some String inverters with optimizers like to call their DC, “Safe DC”. When Rapid Shutdown is initiated (due to wire fault, or inverter shutdown, or inverter breakdown), each optimizer puts out 1 volt DC. However, when an optimizer fails, it can pass the DC voltage, or even worse, if multiple optimizers fail, you could have the DC voltage from multiple PV panels pass their voltages and potentially shock whoever is working on the array – installer or the homeowner, specifically at a point in time when that person thinks the system is powered down.

In some regions, the regulations explicitly ask for initiator devices to turn off the PCUs or Power Conditioning Units (microinverters). In the case of Enphase Microinverters, breakers in the main load center (connecting the PCUs to bus bar), or combiner breakers, act as initiator devices.

The bottom line is, in an Enphase microinverter system, when the AC utility source is removed from the inverter output circuits via any means, such as an AC breaker, AC disconnect or removal of the solar, the microinverter performs the Rapid Shutdown function. With an Enphase Microinverter System this shutdown occurs in few seconds, and because all the inverters are located within the array, there are no other energized conductors extending more than 1 foot in all directions from the array including inside the building. Hence, Enphase microinverter systems inherently meet the rapid shutdown requirement without the need to install any additional electrical equipment.