TECHNICAL BRIEF

Verifying inverter protective functions and loss of phase condition for IQ8 Commercial PV systems

Applicable regions: North America

Contents

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FCC compliance

This equipment has been tested and found to comply with the limits for a Class B digital device, pursuant to part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference in a residential installation. This equipment generates, uses, and can radiate radio frequency energy and, if not installed and used in accordance with the instructions, may cause harmful interference to radio communications. However, there is no guarantee that interference will not occur in a particular installation. If this equipment does cause harmful interference to radio or television reception, which can be determined by turning the equipment off and on, you are encouraged to try to correct the interference by one or more of the following measures:

- Reorient or relocate the receiving antenna.
- Increase the separation between the equipment and the receiver.
- Connect the equipment to an outlet on a circuit different from that to which the receiver is connected.
- Consult the dealer or an experienced radio/TV technician for help.

Changes or modifications not expressly approved by the party responsible for compliance may void the user's authority to operate the equipment.

Other information

Product information is subject to change without notice. All trademarks are recognized as the property of their respective owners.

User documentation is updated frequently; check the Enphase website for the latest information. https://enphase.com/installers/resources/documentation.

To ensure optimal reliability and to meet warranty requirements, the Enphase microinverter must be installed according to the instructions in this manual. For warranty text, refer to enphase.com/installers/resources/warranty.

For Enphase patent information, refer to https://enphase.com/patents.

1. Introduction

Solar photovoltaic (PV) systems are rapidly evolving, and microinverters, which were traditionally used in residential projects, are now making their way into larger systems such as commercial and industrial (C&I) solar installations.

This technical brief summarizes a few of the operational and protective functions for Enphase microinverters. Enphase microinverters are tested and certified to the standards of IEEE 1547–2018, which further define the requirements for any utility-interactive distributed energy resource (DER), including PV inverters.

IEEE 1547 also details operational response to abnormal conditions, power quality, islanding (separation from the utility grid), commissioning provisions, and other tests universally needed for the interconnection of any DER. The utility company may also define operational requirements at the point of common coupling (PCC) within a utility interconnection agreement. Examples of utility requirements may be the addition of a visible disconnect so electrical workers can ensure the PV array is separated during utility maintenance functions.

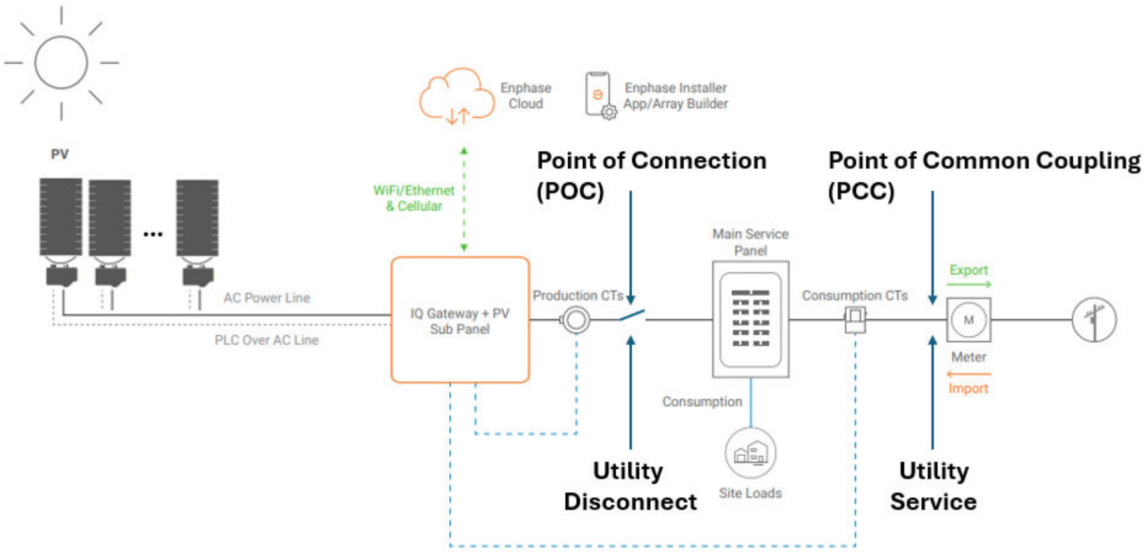

Figure 1: Example site configuration and the difference between POC and PCC

2. Modes of operation

A microinverter converts direct current (DC) from a single solar panel into alternating current (AC) suitable for the grid. Unlike traditional string inverters, which handle the output of multiple panels, microinverters operate independently for each panel. This enables maximum power point tracking (MPPT) on a panel-by-panel basis, enhancing overall system efficiency and reliability.

- Sleep mode: When there is insufficient solar irradiation (for example, at night), microinverters enter a low-power state to conserve energy.
- Standby mode: During standby, the microinverter is ready to produce power but waits for sufficient DC voltage or grid synchronization. It consumes a small amount of power for monitoring and communication.

- Production mode: Once conditions are met, the microinverter actively converts DC power to AC and injects it into the electrical collection system at the Point of Connection (POC), typically an electrical panel, which further connects site load and ultimately connection to the utility grid (PCC). It is important to understand the distinction between POC and PCC as operational requirements can be performed at either location.

The Enphase microinverters appear as a small passive reactive (capacitive) load when in sleep and standby mode. In large systems, the cumulative standby load of hundreds or thousands of microinverters may appear significant, creating the need for a deeper understanding of their operation and grid interactions.

3. Utility protective functions

To receive the utility-interactive designation, PV inverters must pass rigorous safety testing.

Enphase inverters are tested and certified to stop producing power automatically when the electrical grid to which they are connected goes outside of predetermined operational limits. This is tested as part of the IEEE 1547 testing and certification as a rapid shutdown device. In North America, the following default limits for voltage and frequency apply:

- Voltage: Must remain within 88% and 110% of nominal voltage as measured from line-to-neutral, if a neutral is supplied, and line-to-line.
- Frequency: Must remain between 58.5 Hz and 61.2 Hz.

Utility protective functions and specific requirements, such as the enter service delay, soft-start, and ramp rate differ between IEEE 1547-2018, CPUC Rule 21, and any other applicable standard. Local utility companies may have additional requirements or variations from the IEEE 1547 standards to address local grid conditions and regulatory mandates. These standards ensure that inverters operate safely and effectively within the electrical grid.

4. Reactive currents in Enphase microinverters

Reactive current flows in an AC circuit due to the presence of inductive or capacitive loads, resulting in power that oscillates between the source and the load without being consumed. This is represented by the reactive power component (measured in VAR) and does not contribute to real power (kW) delivery.

The following examples assume a typical three-phase utility service in North America, specifically for the Enphase microinverter system. Details vary, but the same principles apply to any inverter system.

A small (reactive) current can be measured on the phase(s) of the electrical circuits servicing the Enphase microinverters when not producing power (in sleep mode or standby mode). The following table lists the capacitive current (mA) in an Enphase microinverter when measured on a phase when no power is being produced, and the serving grid voltage is at or near nominal.

Table 1: Nominal VAR considerations for 60 Hz three-phase microinverters

<table>
<tr><th>Model</th><th>$V_{L\text{-}L}$ (Vrms)</th><th>$V_{L\text{-}N}$ (Vrms)</th><th>Current (mArms) per inverter</th><th>Var</th></tr>
<tr><td>IQ6 Series, IQ7 Series (other than IQ7PD)</td><td rowspan="3">208</td><td rowspan="3">120</td><td>136</td><td>16</td></tr>
<tr><td>IQ7PD</td><td>122</td><td>15</td></tr>
<tr><td>IQ8H-3P, IQ8P-3P</td><td>417</td><td>50</td></tr>
<tr><td>IQ7AM</td><td rowspan="2">220</td><td rowspan="2">127</td><td>144</td><td>18</td></tr>
<tr><td>IQ8H-3P, IQ8P-3P</td><td>441</td><td>56</td></tr>
</table>

NOTE: The variation of the PV system and site configurations may alter these observed readings +/−10%.

NOTE: For three-phase systems, it is assumed the inverters are balanced across the phases so that the reactive current/power can be expressed per inverter per phase, with the current and reactive power being measured at 120 $V_{L\text{-}N}$ or 127 $V_{L\text{-}N}$.

5. Field verification of enter service delay

Verifying the entry service delay time is an important step in gaining confidence in the protective functions of a utility-interactive inverter system. You can use one of several methods to verify proper operation. The method chosen depends on the tester's initial confidence in the system equipment, availability of test equipment, and availability of natural sunlight.

The protective functions of utility-interactive inverters are tested as a routine part of factory production. In addition, many utilities perform field verification of each utility-interactive inverter enter service/reconnection delay timer before allowing the PV system to export power to the electrical grid.

5.1 Verification methods

There are multiple ways to verify the enter service delay protective function in an Enphase microinverter: clamp on the ammeter, look at the meter, and power measurement.

5.1.1 Method 1: Using a clamp-on ammeter

Clamp-on current meters come in several varieties. Some measure both AC and DC current, while others measure AC current only. In this brief, the term current probe includes both measurement types. All but the least expensive models provide true RMS measurements.

Clamp-on meters include a display, and most also measure voltage. Clamp-on probes can provide the same functionality and are used in conjunction with a standard digital multimeter. Both types of equipment are manufactured by Fluke, B+K Precision, Ideal, AEMC, Amprobe, and Extech, among others.

Procedure

NOTE: The PV array must be illuminated with direct sunlight. Therefore, this procedure will not work at night, early in the morning, or sometimes late in the afternoon.

1. Disconnect the PV array: Open the PV system switch, disconnect (POC) or circuit breaker, or an individual phase of a three-phase system if testing for loss of phase (LOP)
   a. Note the reading (should be zero for instances where all phases are disconnected simultaneously).
2. Reconnect the PV array: While closing the circuit breaker or switch, note the time or start a stopwatch.
   a. Refer to Table 1 for the microinverter capacitive reactive current value, which can be read during this standby state (not producing power). This is a normal condition.

After the enter service delay period (from the start time noted) the PV inverters within the PV Array are allowed to produce power. The rate of power production, or ramp rate to full power production, may vary by other operational set points. The enter service ramp rate is especially significant where 1547-2018 is applicable because the ramp rate is such that it takes another 5 minutes for the inverters to reach full power (assuming sufficient illumination and not otherwise power limited).

There are shortcomings with this procedure:

- The measurement does not take the power factor into account
- The measurement depends on irradiance

resulting in some ambiguity and the opportunity for error or misinterpretation of results. Specifically, if the irradiance and array size are such that the current during power export approximates the reactive current during non-export, it will be difficult to determine when the system begins exporting power.

There are three remedies:

1. After the enter service delay time (five minutes in most cases, 15 seconds in California) has elapsed, note the current reading, then cover some portion of the array and verify that the change in current is proportional to the obscured portion of the array.
2. Repeat the test when the irradiance is substantially different (either higher or lower).
3. Use other methods described herein.

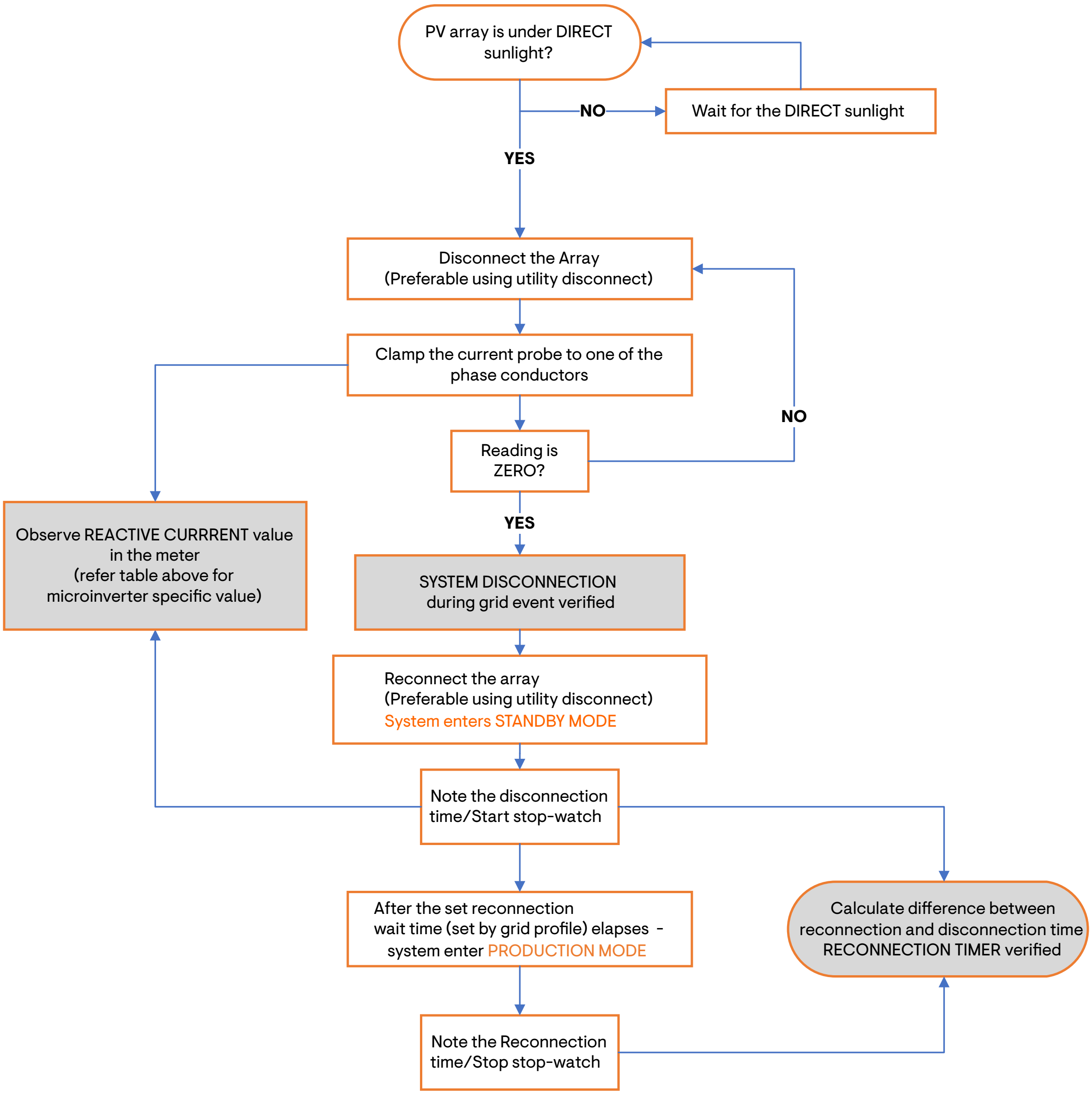

Figure 2: Example sequence of testing

5.1.2 Method 2: Observing the utility meter

This method is extremely simple as it requires no test equipment and is easy to perform. The one drawback is that absolute accuracy requires all other loads on the premises to be disconnected. The procedure also relies on the fact that the socketed meter only measures real power. In cases where a dedicated meter is associated with the PV system, this procedure is extremely reliable.

Procedure

NOTE: The PV array must be illuminated with direct sunlight. Therefore, this procedure will not work at night, early in the morning, or sometimes late in the afternoon.

1. Turn off the switch or circuit breaker to the PV system.
2. Turn off all circuit breakers associated with this meter.
3. Note the meter reading and caterpillar movement (the caterpillar should not be moving).
4. While turning on the breaker or switch, note the time or start a stopwatch.
5. Wait a few seconds and again note the lack of movement of the caterpillar.
6. Watch the caterpillar as they enter service delay time elapses (from the start time noted in step 4). At some point between the end of the enter service delay and another 30 seconds from turning on the breaker or switch, the caterpillar should start showing export of power.

5.1.3 Method 3: Using higher accuracy power measurement equipment

This is the most deterministic method, requiring the largest investment in capital equipment. It is extremely accurate and provides basic verification of system performance.

Procedures will vary depending on the specific piece of test equipment used. Examples of equipment that can perform this test include:

- Fluke 1735
- Fluke 434
- Fluke 41B
- Fluke 43B
- Hioki USA 3169-20

If the equipment is not available, a power quality analyzer can be rented.

This procedure is simpler than the preceding methods.

Procedure

1. Open the PV system circuit breaker or disconnect the switch.
2. Connect the power measurement equipment per the manufacturer's instructions, following all safety precautions.
3. Note the readings for Watts and VAr.
4. While closing the circuit breaker or switch, note the time or start a stopwatch.
5. Note the readings for Watts and VAr. The Watts will show extremely low consumption (milliwatts per inverter) and reactive power (capacitive, that is, leading) per inverter according to the table above.
6. After the enter service delay time has elapsed, the system will show real power export (proportional to system size and irradiance) and near unity power factor.

You can also verify the loss of mains functionality using these methods by opening the circuit breaker or disconnecting the switch when the system is exporting power. It is then a simple matter of confirming that the system returns to the prior conditions (Watts and VAr, or current) to close the circuit breaker or disconnect the switch.

6. Field verification of open phase

The capacitive loading described in Table 1 is common to all solid-state inverters (string, central, or microinverters). The Enphase microinverter hardware includes an integrated output filter to ensure a high-fidelity output and meet regulatory EMI requirements. This filter is the source of the capacitive loading.

According to IEEE 1547-2018, an open phase in a three-phase system occurs when one of the three phases experiences complete loss, typically caused by a faulty connection, blown fuse, or damaged wire, resulting in an unbalanced power supply across the phases.

An open phase fault can arise anywhere between the PCC and the POC, a local condition even if the utility grid is functioning correctly. The Enphase IQ8 Commercial Microinverter (IQ8P-3P, IQ8H-3P) senses all three phases of the system at all times and thus responds safely to either local or utility system faults.

6.1 Point in the system where the loss of phase is introduced

If there are loads present in the system between the point of connection (POC) of the PV system and the point where the open phase condition is introduced, the voltage on the open phase (line-to-neutral) may change significantly (higher or lower). Since these other loads can take on a wide variety of different magnitudes (and types) a general statement regarding the voltage to expect on the open phase cannot be established. However, if there is a current in the open phase line servicing the PV system, it likely means there are additional loads on-site between the PV system and the point where the open phase is created.

When performing loss of phase tests on three-phase systems the following points should be kept in mind.

1. All standard field operating and safety precautions should be observed when testing electrical systems.
2. Proper measurement equipment should be used for the applicable test.
   a. The reactive impedance of a single IQ8P-3P is approximately 860 ohms. The total Impedance line-to-line can be calculated by dividing the impedance of a single inverter by the number of inverters attached line-to-line.
      For example, if 30 inverters are installed per phase, the line-to-line reactive impedance is 860/30 which is about 28.5 ohms. This may be too low to be nulled by some stray voltage adaptors when testing an open phase.
   b. A properly sized shunt resistor can be used to verify the elimination of power potential. A shunt is simply attaching something between the open phase on the PV side and the neutral.
   c. Adding a shunt will show the power potential - it does not eliminate a power potential. For instance, in a system with 57 IQ8P-3P Microinverters per phase, a 5-ohm shunt will bring the voltage down to about 31 V at 6.1 A, so will consume about 190 W in the shunt.
      Voltage drop: $V = 6.1\ A \times 5\ \Omega = 31\ V$
      Power dissipated: $P = 31\ V \times 6.1\ A = 189.1$ (approximately 190 W)
3. LOP testing should be measured on the PV array side connections at the location of the PV disconnect device (utility switch) at the point of connection (POC). Testing in other locations, such as the grid side of the serving transformer or the point of common coupling (PCC), may include other loads or site conditions that will alter the test.
4. All other loads on the service should be isolated from the PV array by means of breakers (if at the same sub-panel) or physical separation.

6.2 System reaction to open phase

When performing the test and the tested phase is opened, the PV system (Inverters) will stop producing power. Enphase IQ8 Commercial inverters are equipped to monitor all three phases at all times and respond to abnormalities in any individual phase. They detect voltage or phase imbalances at each microinverter location and stop producing power to prevent unsafe operation, islanding, or damage to the equipment.

7. Normal behavior of voltage divider

When the inverters halt power production as is required in a loss of phase situation, the inverters' output filters (passive components) will continue to load the circuits such that a voltage will be present on the open phase due to the two remaining phases continuing to be energized from the grid. This observed voltage is normal, and not due to the inverters attempting to continue to produce power, rather it is from the passives of the output filter and a voltage divider that is created by the output filter between the two phases that remain energized.

Figure 3 shows the voltages expected in a loss of phase test where there is no other loading in the system and no transformer between the open phase and the PV system.

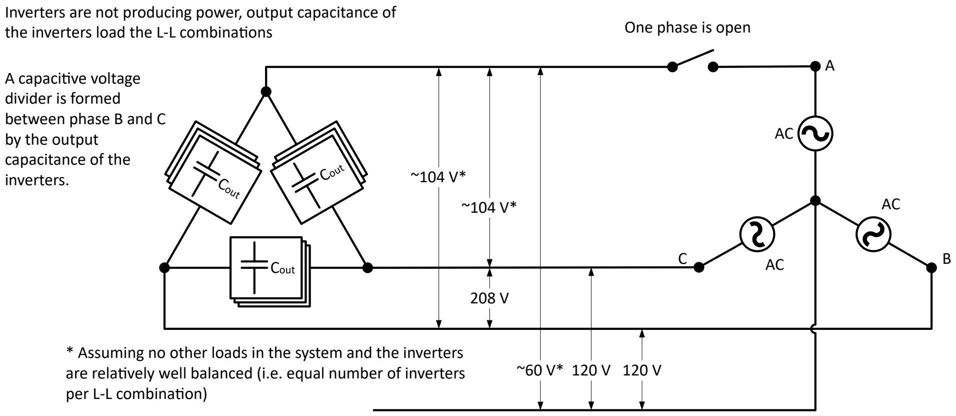

Figure 3: Typical voltage divider diagram

In the open phase condition, there will continue to be reactive current in the phases that remain energized, although this current will be lower than when all phases are energized (and the inverters are not producing power). Refer to Table 1 for contributions by each microinverter.

8. Revision history

Revision	Date	Description
TEB-00249-1.0	March 2025	Initial release.