<u>Technical White Paper</u>

<u>SolarEdge System Design and the National Electrical Code</u>

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Introduction

The SolarEdge Distributed Energy Harvesting System is a state-of-the-art system designed to harvest the maximum possible energy from photovoltaic (PV) modules in utility-interactive (grid-tied) PV systems. A SolarEdge PV system, shown in Figure 1 below, consists of three main elements: PV modules, power optimizers (DC to DC converters) located at each module, and a separate DC to AC grid interactive inverter which can be located at the array or at a remote location, e.g. near the main service entrance. Balance of system equipment such as grounding, overcurrent protection, and disconnects are not shown in this diagram.

UL 1741 Listing

All of the SolarEdge products available in North America have been evaluated by Intertek (ETL), a Nationally Recognized Testing Laboratory (NRTL), and are listed to the UL1741 Standard. The NRTL program is, in turn, regulated by the Occupational Health and Safety Administration (OSHA).

The inverters are listed as utility interactive and are designed for use with ungrounded PV arrays. They comply with the requirements for Ground Fault Detection found in Section 690.35 of the National Electrical Code (NEC). All of the SolarEdge products carry the cETLus Mark indicating that they have been evaluated and approved for use in both the US and

Figure 1 – Basic SolarEdge System Topology

Canada. To be listed, a product must undergo extensive "type testing" in accordance with the requirements of the ANSI/UL1741 Standard. This includes basic safety testing and extensive power quality and anti-islanding tests to ensure compliance with the requirements of IEEE 1547. IEEE 1547 replaced the older IEEE 519 and 929 Standards and is the present source document for all of the utility interactive requirements. Once the product has passed this battery of tests the manufacturer is given authorization to apply the NRTL's Listing Mark to the product. In addition to the initial type testing, 100% of all products are required to undergo a limited number of end-of-production-line tests to verify the performance of protective functions and to guarantee insulation systems. Ongoing compliance with the Standard is provided by random quarterly factory inspections to help ensure that the product being shipped is the same as the product originally tested during the Listing process.
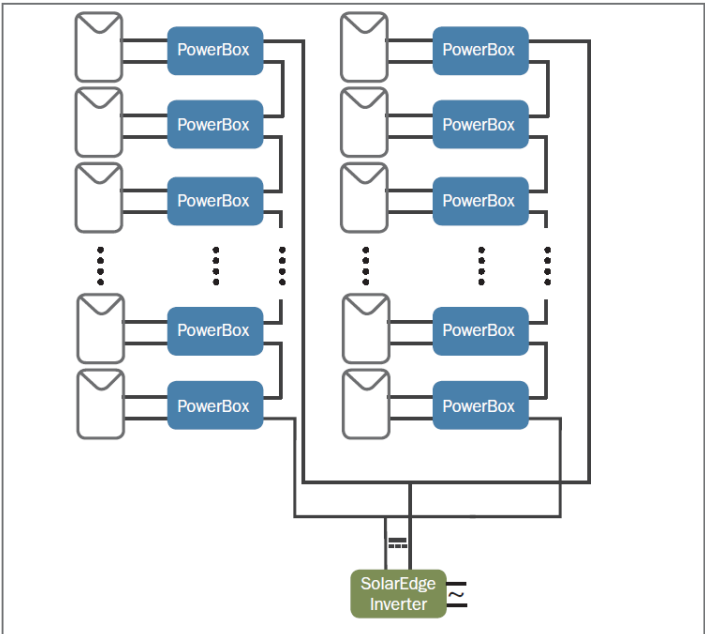
One frequently asked question concerns ongoing verification of product Listing. In all cases, the Listing Mark on the product is the primary reference indicating continuous compliance with the relevant Standards. Intertek (ETL) and other NRTLs also maintain online data bases where the Listing information can be obtained. The ETL Listing database can be found at:

http://etlwhidirectory.etlsemko.com/WebClients/ITS/DLP/products.nsf/$$Search?OpenForm

Although these databases are a secondary reference to the Listing Mark on the product, the listing status can be verified online by searching for the manufacturer's name, i.e. SolarEdge, or Solar Edge.

> *Note: NRTL's do not provide letters verifying the validity of product listing. The sheer number of listed products and requests from interested parties simply makes this an impossible task. The Listing Mark on the product is the primary and best way to ensure that a product is listed.*

Power optimizers

The SolarEdge power optimizers utilize a very high efficiency single-stage DC-to-DC converter controlled by custom application specific integrated circuit (ASIC) devices. The power optimizer is typically located immediately adjacent to, or attached directly to, the PV module. In addition to Maximum Power Point Tracking (MPPT) and DC-to-DC conversion the power optimizers provide module level monitoring and a number of safety related functions. MPPT of the module is achieved via a fully independent control loop operating between each module and its power optimizer. The DC-to-DC converter in the power optimizer allows the PV module (input) voltage and current to be completely decoupled from (i.e. unrelated to) the converter output voltage and current. This is a key distinction between a SolarEdge system and traditional PV system designs. The decoupling of input and output voltage and current has a number of Code implications that will be explained in this paper.

 Basic System Operation

The SolarEdge system differs from traditional PV systems in that the SolarEdge inverter operates at a constant DC input voltage regardless of the number of power optimizers wired in series. Since the inverter regulates the inverter input voltage and current any number of power optimizers between 8 and 20-25 (exact number depends on module power) can be connected in a single string, regardless of ambient temperature at the site.
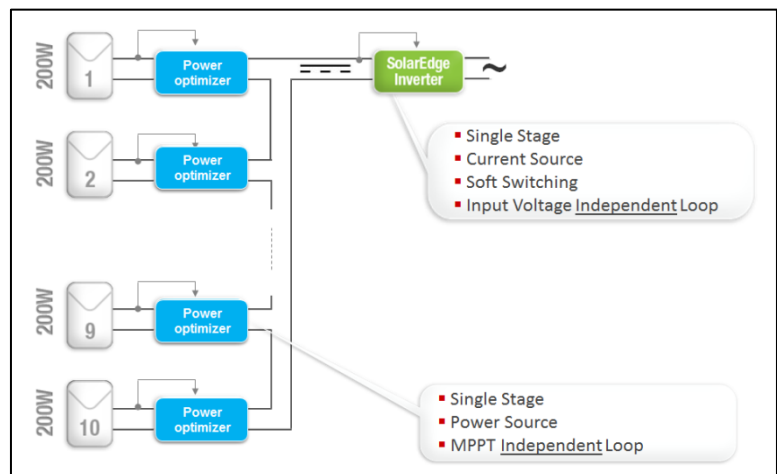

Figure 2 – Basic System operation

For an inverter with a 240Vac output, the DC input to the inverter operates at 350Vdc. A 208Vac output system will maintain the DC input at 305Vdc.

Inverters

The SolarEdge inverters employ a very high efficiency single-stage conversion, transformer-less topology. The SolarEdge inverter includes an independent voltage control loop that regulates the DC voltage at the input of the inverter. When used with power optimizers the inverter operates at a fixed DC input voltage. This is another key difference compared to traditional system designs that include MPPT functions in the inverter. This constant voltage mode of operation results in a number of benefits in terms of system design flexibility while remaining fully NEC complaint. In order to understand the Code impacts of this mode of operation it is essential to examine each element in detail.
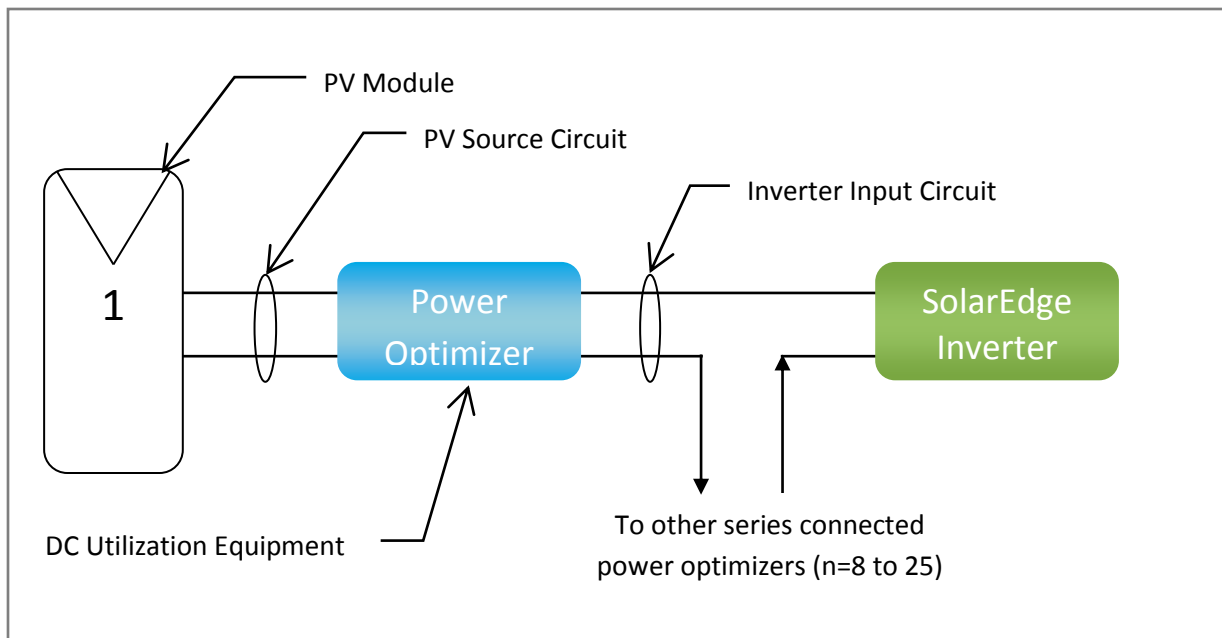

Figure 3 - Various elements with the terms defined or referred to in NEC Article 690.2.

Photovoltaic Source Circuit — Circuits between modules and from modules to the common connection point(s) of the dc system.

Photovoltaic Output Circuit — Circuit conductors between the photovoltaic source circuit(s) and the inverter or DC utilization equipment.

Inverter Input Circuit — Conductors between the inverter and the battery in stand-alone systems or the conductors between the inverter and the photovoltaic output circuits for an electrical production and distribution network.

<u>Photovoltaic System Voltage</u> The direct current (DC) voltage of any photovoltaic source or photovoltaic output circuit. For multi-wire installations, the photovoltaic system voltage is the highest voltage between any two DC conductors.

In a SolarEdge system, the power optimizer is the DC Utilization Equipment referenced by the Code. The PV Source Circuits are limited to those conductors between the PV module and the power optimizer. Since every PV module is connected directly to a power optimizer there is no common connection point between adjacent modules.

An example of the PV Source Circuit calculations required by the Code is given below for a typical 245 Watt crystalline PV module and a 250 Watt power optimizer:

PV Module	
Maximum Power	245 Wp
Open Circuit Voltage (Voc)	37.37 Vdc
Max Power Voltage (Vmpp)	30.8 Vdc
Short Circuit Current (Isc)	8.25 Adc
Max Power Current (Imp)	7.96 Adc

Power Optimizer (PB250-AOB)	
Minimum Input Voltage	5 Vdc
Maximum Input Voltage	60 Vdc
Maximum Input Current	10 Adc
Maximum Output Current	15 Adc

Maximum PV System Voltage is calculated in accordance with the requirements of Article 690.7. A typical very low temperature correction factor of 1.25 is required for systems operating at ambient temperatures of -36 to -40 °F (-32 to -40 °C). Using this correction factor the Maximum PV System Voltage equals 1.25*Voc = 1.25*37.37 = 46.71 Vdc. Because this is less than the maximum input voltage of the power optimizer the design is acceptable. Temperature calculations can essentially be eliminated for all modules with a rated open circuit voltage of 48 Vdc or less, i.e. 60Vdc/1.25. Modules with open circuit voltages near 48 Vdc must be evaluated using the temperature correction factors required by NEC Table 690.7 or obtained from the module manufacturer.

Maximum PV Current is calculated in accordance with Article 690.8 and is equal to 1.25*Isc = 1.25*8.25 = 10.31 Adc. The power optimizers include an internal current limiting function as described in Article 690.8 (B)(2) and have been evaluated for continuous operation as permitted in Exception 1 of that Article. The maximum suggested module Isc is therefore 10 Amps.   Use of higher current modules will not damage the power optimizer but could result in reduced energy yield due to current limiting.

> ***Note:*** *In areas where irradiance levels are frequently above 1000 W/m^2 we recommend limiting the maximum Isc to 10A/1.25 = 8 A to ensure that current limiting, and the resultant power loss, does not occur.*

PV Conductor Sizing The power optimizers are typically located in close proximity to the PV modules, and the PV circuit conductors are normally limited to those supplied as part of the listed PV module. In this case no additional ampacity calculations are required. In the unlikely event that additional wiring is needed between the PV module and the power optimizer these conductors should be sized in accordance with Article 690.8 (B) (1). The minimum *recommended* temperature de-rated ampacity for these conductors is 10*1.25A = 12.5 A.

Exposed Conductor Types Because the SolarEdge system operates the modules in an ungrounded state, all exposed conductors including any conductors attached to the modules or added by the installer must be listed to UL Standard 4703 and be labeled PV Cable, PV Wire, Photovoltaic Cable, or Photovoltaic Wire as required by NEC 690.35(D).

Over Current Devices The SolarEdge power optimizers include automatic reverse current protection which prevents current from flowing from the inverter input circuit back into the PV module. Since there are no other parallel connected sources of fault current between the module and the optimizers, no overcurrent devices are required in accordance with 690.9 (A) exception a.
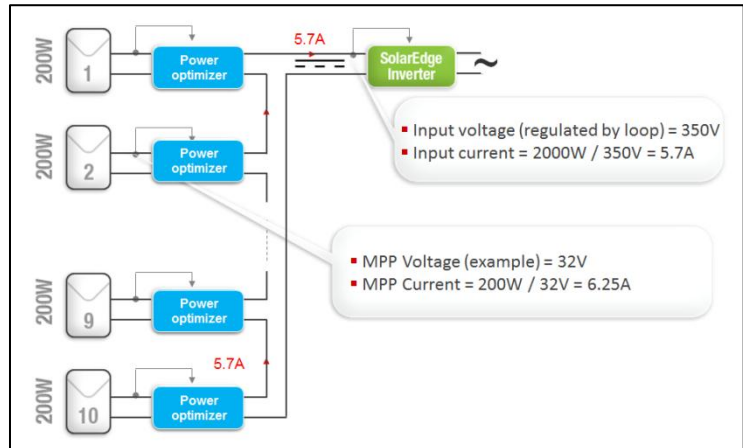
Inverter Input Circuit

Calculation of the voltage and current in the inverter input circuit requires an understanding of the operation of the SolarEdge system. Traditional PV inverters have MPPT functions built into the inverter. This means the inverter adjusts its DC input voltage to match that of the PV array connected to it. In this type of system, the modules are wired in series and the maximum system voltage is calculated in accordance with NEC Article 690.7, using the number of modules in series, the open circuit voltage of each module and the lowest expected ambient temperature at the system location.

In contrast, the SolarEdge inverters operate with a fixed DC input voltage that is regulated by the inverter. For a system connected to a 240 Vac grid, the inverter regulates the DC voltage at approximately 350 Vdc. For systems connected to a 208 Vac grid the DC voltage is regulated at approximately 305 Vdc. *The constant input voltage design of the inverter means that the inverter input circuit current is proportional to the total array power in accordance with Ohm's law I=P/V where I is the inverter input current, P is the total power of that string and V is the dc input voltage set by the inverter.* The relationship between inverter input current and total array power is central to the operation of the SolarEdge system.

The following example illustrates the operation of the system for the two most common utility voltages in the United States; 208Vac and 240Vac. The example system consists of (10) 200-Watt modules with power optimizers connected in a single string that is connected to a SolarEdge constant voltage inverter. For the 240Vac system, the DC voltage at the inverter input circuit will be 350Vdc. The 208Vac system will result in a DC voltage at the inverter input circuit of 305Vdc. To simplify the calculations the power optimizer efficiency is assumed to be 100%.
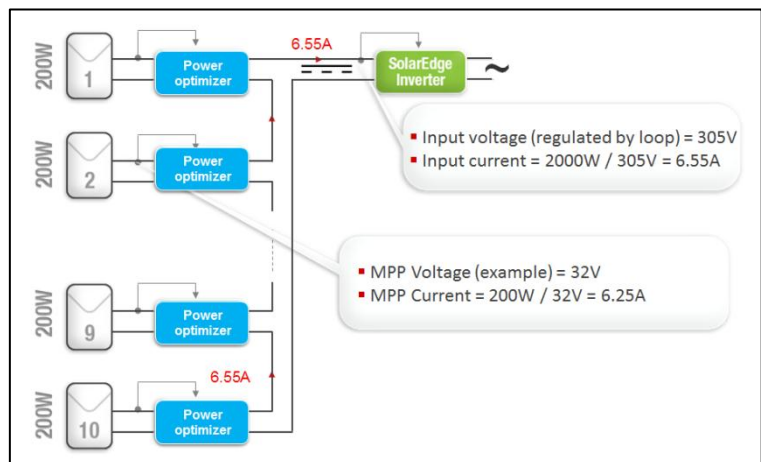
240Vac Operation (STC)

In this case all ten modules are receiving irradiance of 1000 W/m^2 and are producing full rated power. Temperatures and wind speed are such that the modules are operating at a temperature of 25 degrees Celsius. The total string power is 2000 W (200 W *10 = 2000W). Each module is independently MPP tracked by its power optimizer. The PV source circuit voltage is assumed to be 32 Vdc (rated max power operating voltage at 25°C), and the source circuit current is 6.25 A (200W/32V = 6.25A). The inverter input voltage is regulated at 350 Vdc and so the inverter input current is calculated by Ohm's law (I=P/V) to be 5.7 A (2000W/350V = 5.7A)

- Input voltage (regulated by loop) = 350V
- Input current = 2000W / 350V = 5.7A

- MPP Voltage (example) = 32V
- MPP Current = 200W / 32V = 6.25A

208Vac Operation (STC)

In this case all ten modules are receiving equal irradiance (same as the 240Vac example above) and are producing full rated power. The total string power is 2000 W = 200 W*10. Each module is independently MPP tracked by its power optimizer. The PV source circuit voltage is assumed to be 32 Vdc, resulting in a source circuit current of 6.25 A (200W/32V = 6.25A). The inverter input voltage is regulated at 305 Vdc and so the inverter input current is calculated by Ohm's law (I=P/V) to be 6.55A (2000W/305V = 6.55 A).

- Input voltage (regulated by loop) = 305V
- Input current = 2000W / 305V = 6.55A

- MPP Voltage (example) = 32V
- MPP Current = 200W / 32V = 6.25A

Maximum Inverter Input Circuit Current

The maximum inverter input circuit current is limited by the lower of two factors:

1) The output current of the power optimizers is internally limited to 15 Amps continuous. In systems with multiple parallel strings the maximum continuous inverter input current will be limited to the lesser of:
   a) 15A*n where n = the number of strings in parallel
   b) The total array power divided by the fixed inverter input voltage of 350 Vdc (240 Vac) or 305 Vdc (208 Vac).

2) The maximum recommended inverter input current is proportional to the inverter power rating divided by the fixed input voltage. Recommended input limits for each inverter can be found in the inverter datasheet.

Inverter Input Overcurrent Protection and Disconnecting Means

The SolarEdge system has been designed to allow the inverter to operate at full power with a maximum of two strings of power optimizers. The SolarEdge inverter does not allow reverse current flow from the grid back to the power optimizers during fault conditions. As a result no overcurrent devices are needed between the inverter and the power optimizers if the PV system is configured with one or two strings of power optimizers.

> ***Note:*** *In rare cases where three or more strings of power optimizers are wired in parallel, fusing will be required to protect the wiring between the power optimizers and the inverter. Because the circuit conductors are not grounded, fuses would be required in both the negative and positive conductors. The recommend fuse size of 20 Amps is calculated using the 15 Amp continuous output current limit of the power optimizer multiplied by 1.25 in accordance with NEC Articles 210.19 and 240.4.*

The SolarEdge inverter is supplied with a listed combined DC and AC disconnecting means fulfilling all requirements of NEC Article 690.35 (A) and associated references to 690 Part III. The DC side of the switch disconnects both positive and negative conductors, i.e. all ungrounded conductors. The DC/AC disconnect includes lockout tagout provisions for enhanced safety of installers and service personnel.

Safety Features

Ground Fault Protection The SolarEdge system includes ground fault detection as referenced by Article 690.5 and required by 690.35 (C). Because the array circuit conductors are ungrounded, only the requirements of Article 690.35 (C) (1), (2) and (3) apply. Each power optimizer monitors its connected modules and communicates any detected fault to the inverter. The inverter monitors the conductors between the power optimizers and the inverter. In response to a ground fault the inverter will cease to export power, shut down the power optimizers to isolate the faulted circuit, and indicate the ground fault on the inverter's display. The location of the ground fault is also flagged in the web-based monitoring software and, optionally, an email notification of the fault can be generated.

Safety Voltage The SolarEdge system includes a special safety voltage mode that greatly reduces electrocution hazards for installers and emergency response personnel. During installation and commissioning of the system the output voltage of each power optimizer is automatically limited to approximately 1 Vdc. Since the maximum number of power optimizers is limited to 25 or less the maximum safety voltage of the system is limited to approximately 25 Vdc, which is below the UL wet location shock hazard limit of 30 Vdc.

The inverter input circuit voltage (equal to the sum of all power optimizer ouput voltages) only increases to the normal operating voltage when connected to a properly operating inverter. The system automatically reverts to safety voltage mode, i.e. 1 Vdc per power optimizer, should the inverter experience any fault condition, be disconnected from the grid, or if the power optimizers are disconnected from the inverter.

Conductor Routing Single conductor cables in exposed outdoor locations within the PV array are permitted by NEC Article 690.31 (B). Article 690 Section IV, requires all DC conductors to be contained in a metallic raceway once they penetrate a building. In addition, beginning with the 2011 code, these raceways must be run along structural members, must be labeled with "Photovoltaic Power Source" every 10 feet, and on every section that is separated by enclosures, walls, partitions, ceilings or floors. The DC raceway must be at least 10 inches below the roof sheathing where it is not immediately below the PV array. Note that a type MC metal clad cable also meets the raceway requirement.
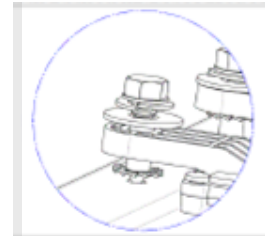
Grounding

The SolarEdge system utilizes ungrounded PV arrays as allowed under NEC Article 690.35. Because the array is ungrounded, the requirements of 690.42 and 690.47 are not applicable and no main system bonding conductors or DC grounding electrode conductors are required. The inverter and power optimizers must each be supplied only with an equipment ground as required by Article 690.43. The equipment grounding conductors should be sized and installed in accordance with the requirements of Articles 690.45(A), 690.46 and 250.122.

Power Optimizers Where the output of the power optimizers is protected by an over current device, the array equipment grounding conductors should be sized based on the size of the overcurrent device. Since no over current protective devices are required in a typical SolarEdge system, the equipment grounding conductors should be sized based on the maximum power optimizer output current of 15 Amps.   NEC 690.45(A) would yield a minimum equipment grounding conductor size of 14 AWG copper, but 120(C) may require a larger size.

Equipment grounding of power optimizers can be accomplished using one of two methods as outlined in the SolarEdge installation manual.

1) Power optimizers are typically bolted directly to a metallic support structure and can be grounded through that support structure using stainless steel star washers between the power optimizer and the support structure. The star washers supplied with the power optimizers have been evaluated and listed as a grounding means in accordance with the requirements of NEC Article 690.43(C).

2) When mounted to metallic structures using sliding nuts, or to non-metallic structures, a separate equipment grounding conductor is required. The power optimizers include separate supplementary grounding hardware for this purpose.
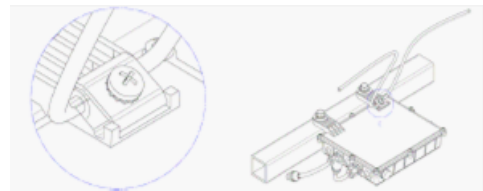
Inverters The AC output equipment grounding conductor for the inverter is required in accordance with Article 690.43(C) and Article 250.122. The size of the equipment grounding conductor is based on the size of the AC overcurrent device protecting the AC output circuit connected to the inverter. The minimum allowable size of the AC overcurrent device should be sized based on the continuous output current of the inverter * 1.25. The maximum size of the AC overcurrent device for each inverter is specified in the inverter documentation.

For additional information concerning the installation of SolarEdge equipment please refer to the installation manuals and white papers supplied with the equipment or on the SolarEdge website www.solaredge.com.