A Highly Efficient, Redundant Low-Voltage Photovoltaic Solar Topology

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Introduction

In conventional photovoltaic (PV) solar arrays, serially interconnected solar modules are strung together to increase the voltage from module-to-module, limited to 600VDC in North America and 1000VDC in Europe (480 VDC and 800 VDC with required safety margin). Large numbers of these module strings are often connected in parallel to a large central inverter. Imbalances in individual cells or panels where bypass diodes are triggered cause large changes in the peak power point for each string, requiring the need for stringent cell matching in the factory and requiring very uniform illumination, temperature, and other conditions when deployed[1].

Scaled down inverters termed “micro-inverters” have been introduced for smaller systems where the inverter is attached to each module, but retain many of the topological features of the large central inverters[2]. DC optimizers have also been introduced for attachment at the module, for allowing an improvement in string balancing between panels to reduce the inherent mismatch losses between panels[3,4].

There are a number of issues existing in both of these electrical topologies as well as with conventional string topology: one of the most notable is being the single-point-of-failure nature of these entire systems. Failure of any component in a string, including cells, cell connectors, module wiring, combiner boxes, inverters, etc., results in an immediate failure and requires a field service event to repair and restart the lost portion or in many cases the entire array. While micro-inverters and DC optimizers help to minimize the interdependencies of the string components, they introduce a host of additional electrical components with their own single-point-of-failure dependencies and field service requirements.

An alternate topology and resulting efficiency and performance is described here, where there are no single-point-of-failure dependencies within the entire solar array. This highly fault-tolerant topology is much more consistent with other highly distributed technologies, such as in information storage, telecommunications, and the power distribution grid, where failures are tolerated without significant performance impacts, and where repairs are managed on extended and planned maintenance schedules.

Redundant Topology

A redundant topology is illustrated in Fig. 1. Modules used in this topology do not have cells wired individually, but rather use a combination of serial and parallel connections within the module and a proprietary interconnection method (RAIS® Modules: Redundant Array of Integrating Solar). Integrated into each RAIS® module are a set of redundant DC converters where the number of available DC converters exceeds that required to produce full power from the module. Due to the deep electronics integration level and the cell wiring method, any failure in a cell, interconnection, or electronic component does not result in a decrease in the power production capability of the module as current can flow from any cell to any DC converter (the DC converters are not dedicated to specific groups of cells). In addition, the illumination between cells can vary without creating a cell-to-cell constraint as is created in a serial string of serial modules. No bypass diodes are required anywhere in the system.

Between the modules and reversible fuel cell inverters of Fig. 1, the interconnections used are utility grade bus interconnections, where the bus is uninterrupted from module-to-module, eliminating any dependency of any connection upon another. The DC bus is maintained by the reversible fuel cell inverters at a fixed, low voltage. If the power conversion capability of the reversible fuel cell inverter is exceeded, the system voltage rises, and some portion of the modules drop into a constant voltage mode to maintain a constant power operation at the sum of the peak output of the reversible fuel cell inverters.

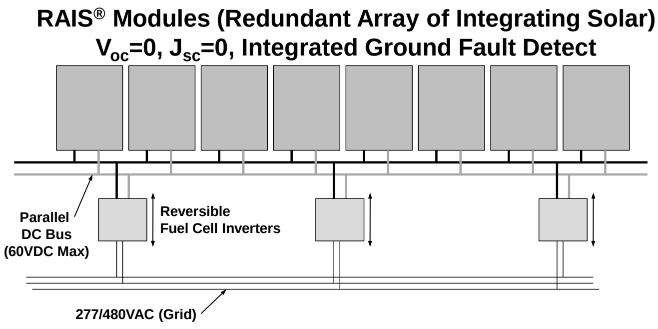

Figure 1. Grid tied redundant array of integrating solar modules interconnected on a parallel bus using reversible fuel cell inverters.

The module DC bus interconnects the modules in parallel across the system - and fed into groups of parallel, reversible fuel cell inverters to convert the DC bus voltage into three-phase AC voltage. The amount of energy delivered to each phase may be tailored since any module can feed any reversible fuel cell inverter.

The basic topology of the reversible fuel cell inverter used in Fig. 1 is illustrated in Fig. 2. Because the modules manage peak power at a much more granular level within the module, the capacitance of the system is placed in parallel with the DC input to the reversible fuel cell inverter. A battery can be substituted for the capacitance as well if storage is to be included with the system (integrated PV/storage). Next, the DC input is converted into low-voltage AC using low-voltage, automotive grade components for greatly enhanced reliability. Low-voltage AC power is then stepped into the primary windings of a transformer using a proprietary pulsed control process, where the secondary windings of the transformer are at grid voltage (e.g., 277/480 VAC). The output of the reversible fuel cell inverters within the array is then collected in a conventional AC breaker panel and either connected into an existing building main or a sub-panel, or to the grid through a utility grade mid-voltage transformer (discussed in upcoming System Design section).

System Reliability

Electronic device leakage is a common failure mode[5] in power electronics, where low-level defects or contamination sites result in an initial low-current leakage path through a device or package, and the leaking rate increases over time and eventually results in failure of the device. The power leakage has a V^2/R dependence on voltage; thus a 50VDC device is 400 times less sensitive to leakage and environmental contamination than a device operating at 1000VDC. All active electronics used in both the RAIS® modules and reversible fuel cell inverters are low-voltage, and thereby are not subject to the challenges presented by high voltage active devices used in extended service life field applications such as photovoltaic systems. A very large and diverse supply of high quality electronic power systems has been developed in the automotive and other industries, based on similar application needs of extreme environmental exposures and 25 year service life requirements.

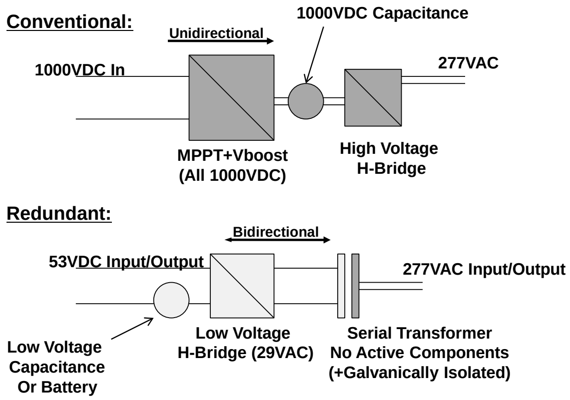

Figure 2. Comparison of a conventional solar inverter and a reversible fuel cell inverter used in the redundant array of Fig. 1. All active components are low-voltage, the only device in the reversible fuel cell inverter exposed to grid voltage are the secondary windings of the transformer.

In addition to better environmental robustness, the reversible fuel cell inverters are also redundant, such that in the event of a reversible fuel cell inverter failure, the power from a group of modules that would normally be lost with a conventional inverter can flow to adjacent reversible fuel cell inverter in the redundant system of Fig. 1. Some peak shaving may occur in the remaining operational reversible fuel cell inverters; however, because of the solar daily power profile the impact of this shaving on the total annual energy production is minimal, allowing any required repairs on the reversible fuel cell inverters to be on a greatly extended and fixed schedule. In addition, to operate more efficiently, a smaller number of reversible fuel cell inverter units are operated during low power periods allowing them to operate in a higher efficiency power range during more of the day and under diffuse lighting. Also, because the voltage step-up is done in a conventional transformer, the reversible fuel cell inverter is highly modular, allowing for a simple module field replacement of the active devices in the event of a failure.

Table 1 is a summary of the four topologies proposed for the solar industry: the first is conventional serial strings, the second is a DC optimizer placed on each panel, the third is a micro-inverter on each panel, and the fourth is the redundant module topology described here. The levels of redundancy are noted in each column, where the terminology used for the RAIS® system is six converters within a module, and the capability to deliver full power with four working converters is noted as 6:4. This capability is in stark contrast to all the other systems and connections in the first three columns where these entire arrays are composed of single points-of-failure components.

To illustrate the impact of redundancy within the module, consider the example of 6:4 redundancy. Published estimates of micro-inverter reliability are 330 years MTBF (a very aggressive value for active components at grid voltage), which equates to an annual unit failure rate of approximately 0.5% of all units, and 12.5% of the devices failing over a 25 year life. On a system deploying 10,000 units, this equivalent failure rate predicts the need for replacing 1250 units over the 25 year system life.

For a 6:4 redundant system operating at the same converter annual failure rate of 330 year MTBF (the actual MTBF of a simple DC converter used in a RAIS® module exceeds 1000 years), assuming the converters are independent, an estimate of the annual failure rate for any three converters on any one module containing six converters is $(0.5\%*6)^3 = 0.0027\%$ per year. In 25 years, that would equate to 0.06% of the modules having three failed converters, or on a system deploying 10,000 units, this would be six units that would experience a reduced output below full rated module power as compared to 1250 failed micro-inverter modules.

In conventional solar, cell-interconnect failures, cell cracking, Jbox issues, inverter failures, etc. – all are immediate unscheduled service events to avoid an extended power loss period.

Other factors affecting reliability such as PID[6] (Potential Induced Degradation) and LID[7] (Light Induced Degradation) are also significantly reduced with the RAIS® redundant topology. PID is reduced due to the very low voltage in the module and due to the near-hermetic sealing of the module. LID is reduced due to the ability of the module to produce power from the average of the cells of each module, rather than from the weakest producing cell of a group of interconnected modules. Thus, LID is reduced from being defined by the three-to-five sigma cell variance depending upon the string length, to being defined by the average cell variance in the redundant topology.

	Strings	DC Opt Strings	MicroInv	Redundant Topology
Cell-Cell Connections	Single Failure Point	Single Failure Point	Single Failure Point	6:4 Redundancy
Within Module Connects	Single Failure Point	Single Failure Point	Single Failure Point	6:4 Redundancy
J-Box Connections	Single Failure Point	Single Failure Point	Single Failure Point	8:4 Redundancy
Bypass Diodes	Single Failure Point	Single Failure Point	Single Failure Point	Not Used
Electronics Connections	Not Used	Single Failure Point	Single Failure Point	6:4 Redundancy
Module-Module Connects	Single Failure Point	Single Failure Point	Single Failure Point	Bus
Master Balancing System	Not Used	Single Failure Point	Not Used	Not Used
Module AC Connections	Not Used	Not Used	Single Failure Point	Not Used
Combiner Box Connects	Single Failure Point	Single Failure Point	Single Failure Point	3:2 Redundancy
Arc Fault Circuit Interrupt	Single Failure Point	Not Used	Not Used	Not Used
NEC 690.12 Switch Device	Single Failure Point	Single Failure Point	Not Used	Not Used
Inverter	Single Failure Point	Single Failure Point	Single Failure Point	3:2 Redundancy

Table 1. Illustration of single failure points for three solar topologies vs. the RAIS® redundant topology system.

Safety

The system topology of Figs. 1 and 2 offers several safety advantages, such as low internal module maximum voltage, low system voltage, and other safety features enabled by the module-integrated electronics. Because of the cell interconnection methods employed in RAIS® modules, the maximum internal module voltage is intrinsically limited to less than 16 VDC, which is below the arcing threshold set by UL1703 and others[8]. Below an 18 VDC threshold, PV modules cannot arc internal to the module, eliminating the fire hazard associated with broken connectors between cells and the variety of junction box issues that have been reported.

Besides the low internal module voltage, the system voltage is kept below 60 VDC, well below the 2014 NEC section 690.12 proposed requirement of a maximum of 80VDC exposure to fire-fighters[9]. Consequently, even an energized array operating at its maximum voltage (less than 60 VDC) is considered safe under this new NEC requirement. Moreover, RAIS® modules are certified with a Jsc=0 and Voc=0 rating since the internal panel voltage is inaccessible to the user -- only the output of the integrated electronics is accessible. Hence, a functional RAIS® module by itself (disconnected from a system) will not have voltage across its output terminals, even when exposed to sunlight.

In addition to providing isolation between individuals and the internal panel voltage, the module-integrated electronics also allow each module to have ground fault detection built within. The electronics are also responsible for disconnecting a RAIS® module from the DC bus if the system DC voltage exceeds 60 VDC.

Therefore, the tenKsolar system is designed to be inherently failure-safe: if the module-integrated electronics fail to operate, the default internal voltage is limited to 16 VDC; and the maximum voltage of an energized or de-energized system is maintained under 60 VDC. For conventional string and DC optimizer architectures, the string voltage is in the range of 600 to 1000 VDC, and any added safety features applied to meet code must be periodically verified as operational to ensure the basic safety of the system remains over time. Conventional architectures and DC optimizer based systems are by default string-based systems with a series of safety switches to make them safe, in contrast to the low-voltage PV system described here that uses electronics to make the system operational and defaults to a safe state.

Large System Design Considerations

The design of large photovoltaic systems have evolved over the past ten years, using long, unprotected runs of DC power, limited only by inverter size and run-length. Because of the inherent variability of solar, several very significant code multipliers are required on voltage and conductor sizing, and are similar in both the NEC and IEC codes. In addition, special double jacketed PV wiring is often required for any DC runs, and is typically two times or more the cost of standard AC wiring.

For the redundant system described above, the design is much more similar to traditional AC power design. Systems vary in size and shape depending on site conditions however an attempt has been made here at a comparable design between the two systems. Fig. 3 illustrates the redundant low-voltage array wiring, with 3(a) illustrating an AC, 3ϕ block that delivers 480VAC output to an AC sub-combiner shown in Fig. 3(b). Fig. 3(b) illustrates the combiners and current requirements for the remaining system out to a 13.8 kV interconnection point.

As a comparison, a typical 600VDC maximum PV system is illustrated as well, using the same basic block size and a DC sub-combiner to route the wiring to the central inverter. An equivalent total amperage total is listed for both sets of runs, considering the base amperage, code multipliers and number of conductors. Comparing the first run to the sub-combiner, the design of Fig. 3 requires 120A of total AC current (sum of all three conductors plus 4/3 multiplier to account for fourth neutral wire) using standard AC wiring, as compared to 171.6A of total DC current (total for two conductors). The second run from the combiners to central inverter requires carrying a total of 1000A (sum of all three conductors plus 4/3 multiplier to account for fourth neutral wire) compared to the DC system requirement of 1373A (total for two conductors).

In the case of a large system placed on a rooftop, an AC interconnection approach for the RAIS® modules very similar to Fig. 4 can be used. For the DC system, rooftop systems in the USA also require the use of arc-fault detection breakers[10] and with ratification of the proposed NEC 2014 code, switches will be required to break each serial connection between panel to limit the DC system when turned off to less than 80VDC[9].

Due to the inaccessibility of the PV system in the RAIS® system (Voc=0), another rooftop interconnection option is available depending on the building layout and accessibility. As illustrated in Fig. 5, rather than a large collection of DC runs over the side of the building to a central inverter which interconnect through a central safety switch, each of the sub-arrays can be dropped into existing sub-panels inside the building, using remote meters to collect the PV generation information. In the event of a fire, shutting off AC power to the building results in a de-energized PV array. For buildings with a back-up generator, the PV array synchronizes with the generator and provides power in the event of a grid failure (since the PV is on the building side of the ATS).

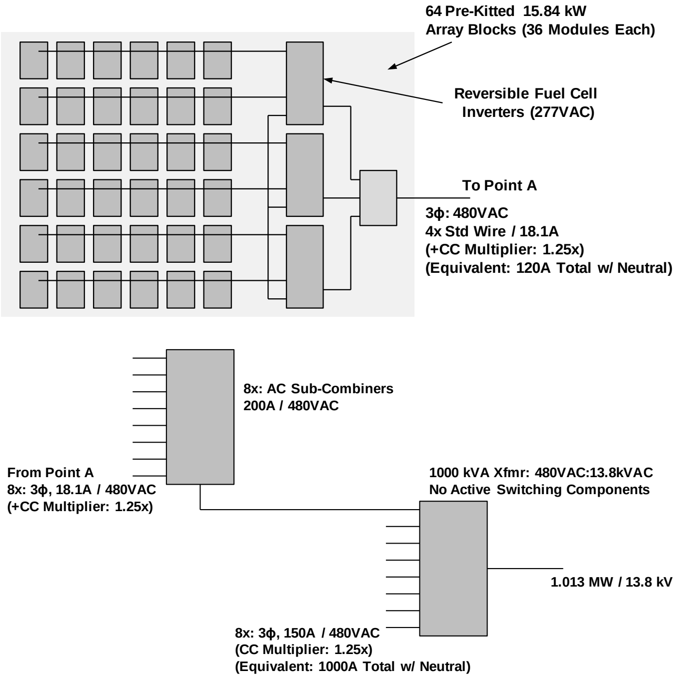

Figure 3. An example layout for a large PV system using redundant, low-voltage base topology, where the region in gray is a pre-kitted block. 64 module blocks are interconnected through eight sub-combiners and connected to a 480VAC:13.8kV transformer. The total amount of current carrying requirements are shown for the main runs to illustrate the design is very competitive in wiring efficiency to current DC PV designs.

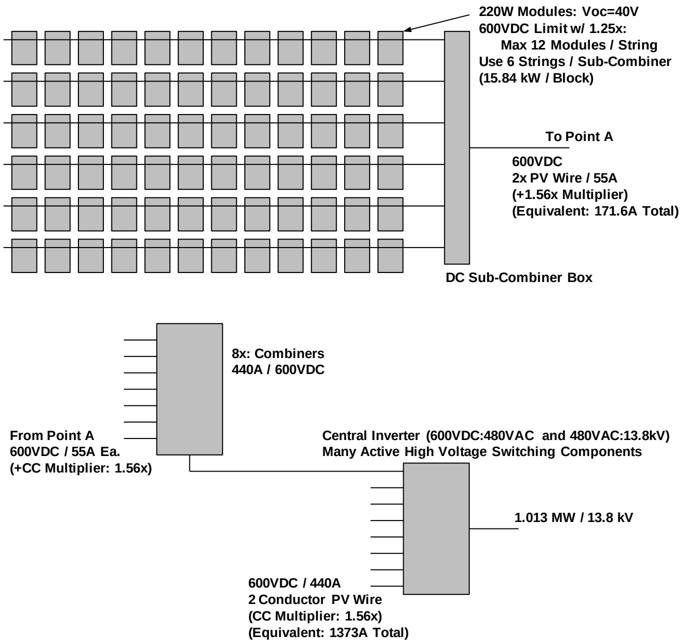

Figure 4. An example layout for a large PV system using a similar PV block size to that of Fig. 3 so wiring runs can be compared. Note with the voltage reduction requirement and the large current multipliers required in 690.8 and the equivalent IEC requirements, the total amount of current carrying wiring is larger than the AC system shown in Fig. 3. Also note this requires the use of double jacketed PV wire throughout the entire system, due to the safety and reliability issues associated with potential back feed of large system currents back into the module wiring.

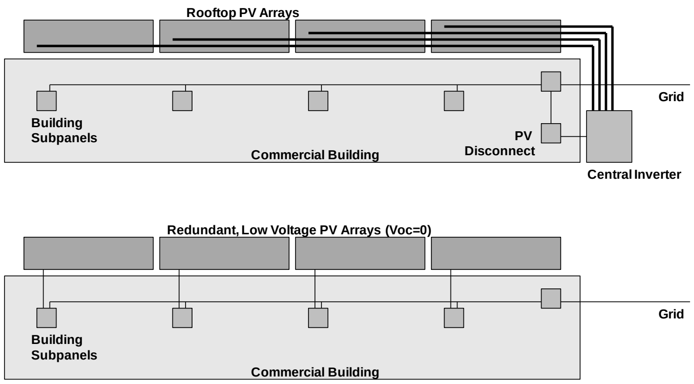

Figure 5. Top image - a commercial rooftop illustration where a series of long DC runs are used to reach a pad-mounted central inverter. The AC side of the PV inverter is connected to the building meter through a central disconnect. When the PV disconnect is turned off, all leads from the PV array on the roof remain energized. Bottom image – a commercial rooftop illustration where the PV arrays are dropped into existing building sub-panels. In the event the AC is turned off to the building, the entire system is de-energized.

System Efficiency

Internal to the RAIS® module, the proprietary interconnection method allows the modules to operate very efficiently by greatly reducing the parasitic-resistance power losses within the module, as well as virtually eliminating the cell-to-cell mismatching losses within the module. In addition, the RAIS® integrated electronics are highly efficient, and when including the parasitic and cell-to-cell mismatch losses of a typical conventional module (typically 2% - 4% loss), a RAIS® module produces more DC power per watt of input cell power than a conventional module.

In addition to the module being more efficient internally, the DC:AC system losses typically observed with conventional string panels are also reduced. The RAIS® module DC rating includes the module integrated converters, therefore the only DC:AC system losses remaining are the thermal, DC resistive losses, and losses in the reversible fuel cell inverters (which operate at a 96% - 97% average efficiency at the fixed voltage value used in the RAIS® system). The system DC resistive losses are minimized by using a continuous interconnection bus and proprietary utility-grade style connectors, resulting in complete isolation of each module. The soiling, shading, and other non-uniform current related losses often included as part of the system losses are also reduced by uncoupling the cells within the module[11] (soiling affects only the cells near the soiling, rather than the entire module being impacted).

To further improve the system efficiencies, the RAIS® modules are most typically installed in the RAIS®-WAVE racking system, which uses a spectroscopic reflector integrated into the racking. Light that would normally fall between the gaps of the solar array is reflected onto the adjacent module, increasing the output of the module by as much as 50%. The ability to use reflected light is made possible by the internal design of the module where non-uniform illumination is acceptable. On a conventional panel with or without a DC optimizer or micro-inverter, the mismatch from the static reflector would only add heat and cause the bypass diodes to trigger due to the optical imbalance between cells[12].

As an example of system performance, Fig. 6 is a daytime trace on May 4, 2012 for a RAIS®-WAVE system installed and monitored by NREL in Golden, CO[13]. The reflected modules in the system peak at nearly 110% of their nameplate value, whereas the corresponding conventional array peaked at approximately 82% of nameplate, due to the reflected gain of the RAIS®-WAVE system. Therefore the efficiency of the RAIS® -WAVE system while operating in this highly redundant, low-voltage mode of operation is actually much higher than that of a conventional serial string array.

Levelized Cost of Energy (LCOE)

From an LCOE perspective, the RAIS® modules sell for the price of a quality conventional solar panel depending on model type and quantity; and the RAIS®-WAVE racking, which includes the spectroscopic reflectors is of similar cost to zero or low-ballast conventional racking systems. Thus, with the added energy production, the resulting LCOE for the system is much less than for a conventional system, and much less than for other systems that use panel-level electronics, such as micro-inverters and DC optimizers, which offer a few percentage points of energy harvest gain for a much more significant increase in system cost.

Future Extensions of Redundant Low-Voltage Topologies

The reversible fuel cell inverters can also be used to actively phase-balance the grid with or without PV generation, by back-feeding from certain AC phases and back through the DC interconnections as illustrated in Fig. 1. A measurement and active DC voltage set-point control system is the only additional component required.

As the price of energy storage declines (making the economics more attractive), adding storage at the location illustrated in Fig. 2 to the DC side of the system is a straightforward attachment to the existing RAIS® system. This addition of storage does not require replacing existing components as would be required with conventional strings, micro-inverters or DC optimized topologies. An active control system to measure and optimize system performance based on system set-point values is optional, along with a utility controlled load-management system, depending on the degree of control required. With an active control system, an integrated PV/storage system can also be used to store off-peak wind energy, by using the reversible fuel cell inverters to charge storage units on the DC side, and feed this energy back through the reversible fuel cell inverters when desired.

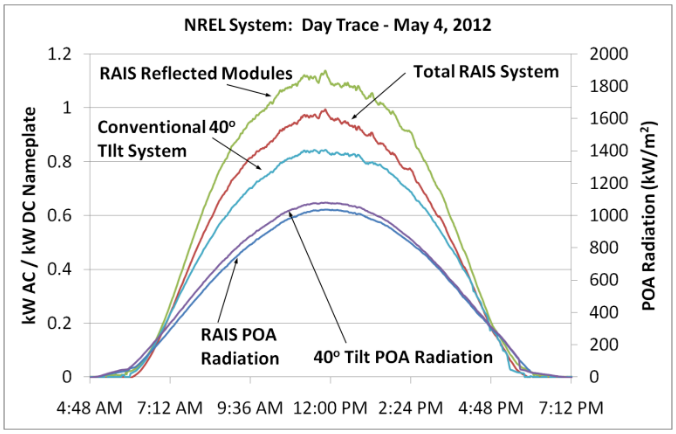

Figure 6. A sample output of an array located at NREL (National Renewable Energy Laboratory) in Golden, CO, using RAIS® modules and the reversible fuel cell inverter topology. The combination of system efficiency and the use of reflected light in the WAVE system delivers a large increase in the kW AC per kW DC of the system.

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References

1. *Handbook of Photovoltaic Science and Engineering*. Edited by A. Luque and S. Hegedus, 2003 John Wiley & Sons, Ltd ISBN: 0-471-49196-9.
2. *Enphase Micro-Inverter Literature*, see website overview, and attached paper: Reliability Analysis of Electrolytic Capacitors, published 2009. *enphaseenergy.com*
3. *Tigo Energy*, String DC Optimization Overview. *tigoenergy.com*
4. *Solar Edge*, String DC Optimization Overview. *solaredge.com*
5. *International Rectifier*, Reliability of FET and IGBT Devices, 2007.
6. *Potential Induced Degradation of Solar Cells and Panels*, Berghold, J., Frank, O., Hoehne, H., Pingel, S., Richardson, B., Winkler, M., Proceedings of the 5th World Conference on Photovoltaic Energy Conversion, Valencia, Spain. 2010.
7. *Light Induced Degradation in Monocrystalline and Polycrystalline Solar Cells*, NREL, 2006.
8. *Underwriters Laboratories*, Photovoltaic Module Specification – UL1703, Figure 40.1.
9. http://www.necplus.org/Features/Pages/ProposedChnagestothe2014NEC%28Part2%29.aspx?sso=0
10. *NEC 2011 Code Publications,* 2011
11. *PVWATTS System Analysis*, NREL, 2012.
12. *Effect of Photovoltaic Module Shading Properties on Project Energy Density*, Meyer, D., Berg, L., Dodd, O., Johnson, T., Weiss, L., *tenksolar.com*, 2012
13. *Energy Production Summary for RAIS® WAVE System installed at NREL*, Meyer, D., Johnson, T., Berg, L., Dodd, O., Murnan, T., *tenksolar.com*, 2012