A Highly 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 voltage safety margin of 125%). 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 where the inverter is directly attached to each module and the AC output is wired in parallel, offering the ability to tolerate variation from module-to-module[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 these alternate electrical topologies as well as with conventional string topology, one of the most notable being the single-point-of-failure nature of these entire systems. Failure of any component in a string, including cells and cell illumination, cell connectors, module wiring, combiner boxes, inverters, etc., results in an immediate failure and requires field service to repair and restart the lost array portion or in many cases the entire array. While micro-inverters and DC optimizers help to minimize the interdependencies of the string components, they are often limited in their operating range and introduce a host of additional electrical components with their own single-point-of-failure dependencies and field service requirements.

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

Redundant Topology

A redundant topology is illustrated in Fig. 1. RAIS® (Redundant Array of Integrating Solar) modules used in this topology do not have cells wired serially, but rather use a combination of serial and parallel connections within the module and a proprietary interconnection method to a DC bus. 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. The deep electronics integration level used and the cell wiring method, means 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 in a serial string of serial modules. Bypass diodes are not required anywhere in the system.

Between the modules and inversion of Fig. 1 is a DC bus. The interconnections used to attach the modules to the bus are utility grade interconnections and the bus is uninterrupted from module-to-module thus eliminating any dependency of any one connection upon another. Attached at the other end of the DC bus is a grouped set of inverters for converting power from the controlled low-voltage DC bus to the grid (using either multiple single phase inversion units or three phase units).

The voltage of the DC bus is maintained by the inverters and modules without digital communications (which would introduce another failure point if used). Rather than trying to track MPPT in each inverter, each inverter is set to maintain a fixed voltage value on the bus. If the bus voltage exceeds the set-point of an individual inverter, the inverter will pull energy from the bus and deliver it to the grid (until it reaches its maximum output value). As single inverter units reach their maximum value (assuming sufficient radiation is present), the system voltage rises and another inverter unit begins operating. Since each inverter has a different voltage set-point (voltage ladder of which the set-point values change daily in order to wear level across units), each of the inverters only operates when needed. If an inverter fails, the others continue to operate normally, with the only impact being the lost increment of inversion capacity. All modules can still deliver energy to the grid.

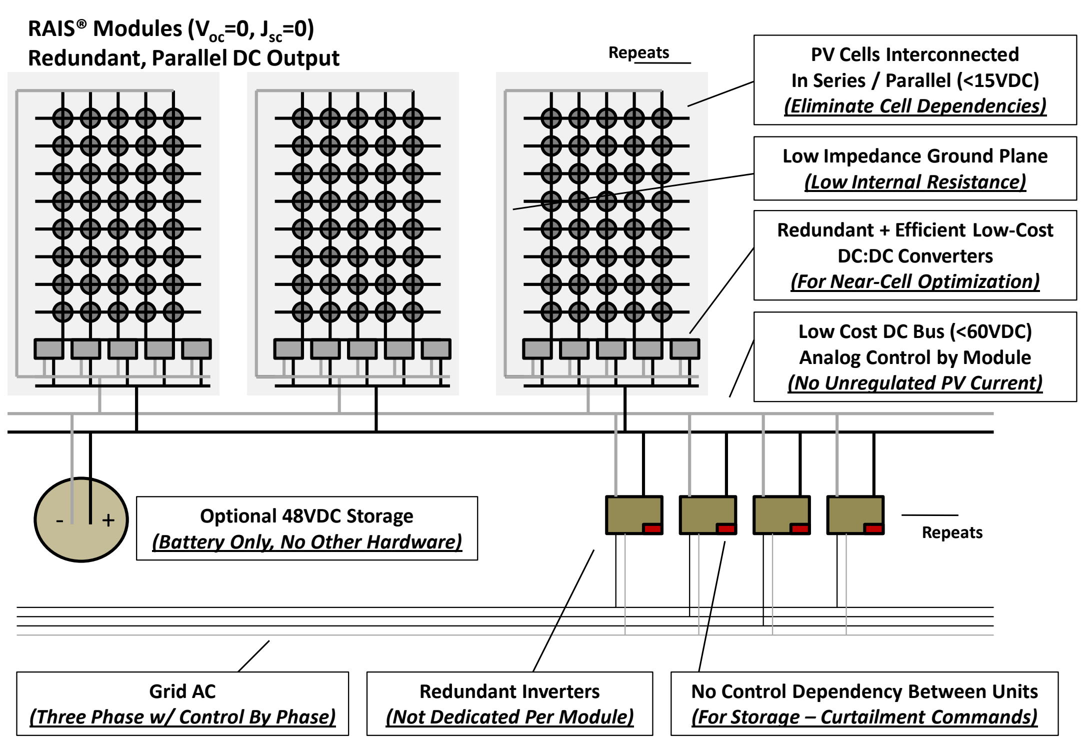

Figure 1. Grid tied redundant array of integrating solar modules interconnected on a parallel DC bus and using redundantly configured inverters for the DC:AC conversion.

If the power conversion capability of the entire set of available inverters is exceeded, the DC bus voltage rises, and some portion of the modules will then drop into a constant voltage mode to self-limit the system voltage and maintain a constant power operation at the sum of the peak output of the inverters. As noted previously, there are no communication requirements across components to manage operation of the system.

It should also be noted the modules are fully intelligent and monitor the system operation as well. If they are not connected to a live electrical circuit through the inverters, the voltage and current values are zero. The modules also communicate their operating and production status digitally through a front-side LED and also through power line.

As noted in Fig. 1, a optional battery can also be included if storage is to be installed with or later upgraded to the system (truly integrated PV/storage). Observe the battery can be connected directly to the DC bus, as the modules limit the maximum voltage allowed in the system. To control the system, the inverter units use either a pre-programmed proprietary voltage ladder, or an external command to define how much energy is allowed to flow from the system at any point in time. Any energy generated by the PV system that does not flow to the grid is stored in the battery, causing the battery voltage to rise. Once it reaches its maximum voltage level, the PV production of the system stops within the modules (i.e., no diversion controller required).

System Reliability

The inversion units used in Fig. 1 are solid-state, fully enclosed and potted elements (for superior environmental isolation, similar to automotive and other industries) that are sufficiently cooled by convection (no moving parts, no filters, no conditioning units, etc.), and are galvanically isolated from the grid for added safety and reliability. Due to the relatively small size of the power unit being converted, they are fabricated with conventional low-cost, high-speed surface mount components and using high-reliability packaging, process and assembly methods developed in other high-volume technology industries.

The conundrum currently facing the PV industry is: to continue using large, central inverters where there is a single, large unit installed often supporting an entire array (more typical in North America), or to use a more granular approach using string or micro-inverters to minimize the impact of failures (use of string inverters has become more typical in Europe). The use of more granular inversion increments is winning the battle world-wide. This granularity is expected to extend down to micro-inverters, as generally micro-inverters have shown to have a lower unit failure rate in the field. However due to the much larger number of micro-inverter units required in a system and the requirement that they be repaired upon failure, the maintenance expense of micro-inverters is generally found to be significantly higher, even when comparing to the limited life expectancies of string and central inverters.

The topology of Fig. 1 enhances the robustness of the inversion process over central inversion three ways:

1) It uses micro-inverters operating to a fixed voltage set-point, with a much improved per unit reliability and no-maintenance requirement,
2) It wear levels across the inverter units, requiring only certain units to operate and only when needed, reducing the duty cycle of each unit (see next section),
3) It greatly minimizes the impact of failure by breaking the direct panel-inverter relationship, such that energy can continue to flow from any panel even if an inverter unit fails.

Wear Leveling

Fig. 2 is an example plot of wear leveling over the period of one year. The dark line is the AC hourly power values sorted from maximum to minimum over the course of one year in Minneapolis, MN. Observe that the time of which peak power exceeds eighty percent is less than 500 hours of the year. Overlaid on the chart is a stair-step line illustrating the number of inversion units operating, in each case just sufficient to support the available power (using a total of six units). By randomly spreading the set-points across the units, the duty cycle shown on each unit is 23.7%. In the conventional case of units dedicated to each module, each unit would be required to operate over all available hours, resulting in a duty cycle of 51.6%.

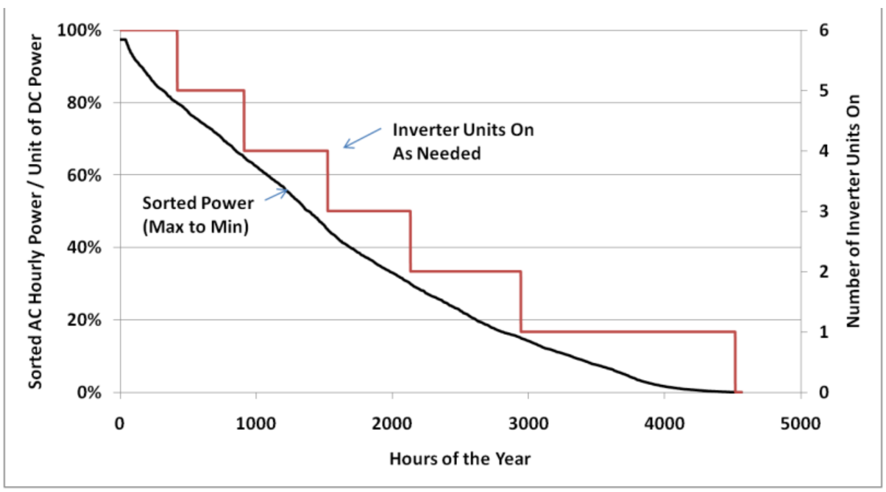

Figure 2. An example of the impact on duty cycle for the redundant inversion system of Fig. 1, using n=6 inversion units. The dark line is the hourly power values after sorting from maximum to minimum in Minneapolis, MN. Also shown in red is the active inverter units required at each of these power levels.

Effect of Redundancy

A compounding statistics model was used to model the resulting performance of the entire system (modules plus inversion) as failures occur over time using a linear failure rate (other profiles can be used). Fig. 3 is an output of the model for illustrative purposes, showing the unit failure rates over time within each group of six redundant inverters. The model assumes a large field with groups of six throughout, so the percentages shown are the distributions for any group of six.

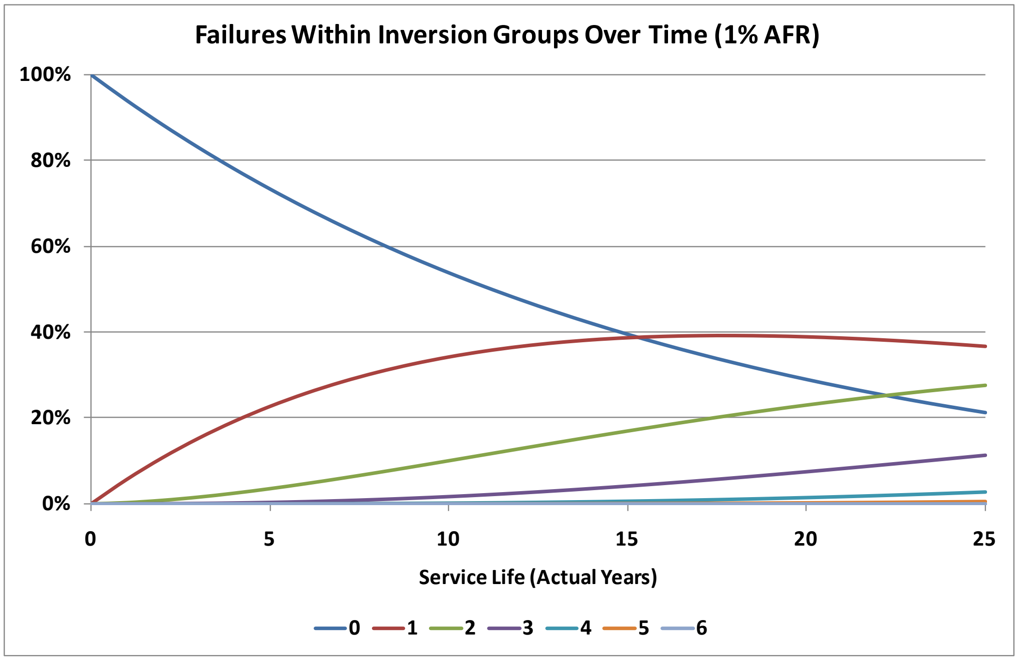

Figure 3. An illustration of the failure rates over actual time of inversion units in a 6x configuration, with a 1% annual failure rate [conservative estimate since actual time used (rather than power-on hour times) and not accounting for the duty-cycle reduction of Figure 2]. Observe at year 25, 80% of the groups of six have at least one failure within, 38% have one failure (red line), 28% have two failures (green line), and 10% have three failures (purple line).

To compute the impact of failures on the energy production of the system, information regarding the energy lost as a result of an incremental inversion unit lost is required. Fig. 4 is an illustration of the system energy lost as a function of inversion capacity. Observe the curvature to the line which is a result of the daily and weather related variances in solar energy production. Having insufficient inversion capacity near full array capacity has little impact since the amount of time operating at full power is low. As the inversion capacity falls, the impact to annual energy production increases as the amount of impacted time of less inversion capacity increases. Also observe that for a system where the inverters are dedicated to the modules, the impact is much more severe, as shown by the linear line in Fig. 4.

Now combing the effects of Fig. 3 and Fig. 4, one can now compute the energy production of the system over time including the effects of system degradation and failures. Using an annual failure rate (AFR) of 1% / actual year for the inversion units, an AFR of 0.5% / actual year for each of the module electronic units, and a degradation factor of the module at 0.2% / year, the entire system performance over time is shown in Fig. 5 (the use of a degradation rate for the module of 0.2% is related to the reductions in degradation mechanisms associated with the redundant and low-voltage topology within the module, including cell-interconnect failures, cell cracking, Jbox issues, PID, LID and others).

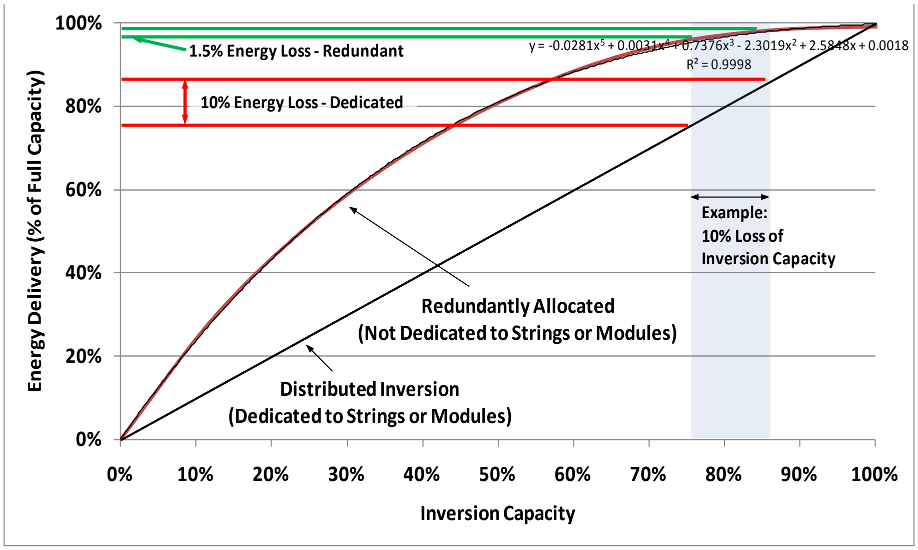

Figure 4. An example of the dependency of energy production on inversion capacity, stated as the percent of module nameplate. The location for this graph is Minneapolis, MN. As is done for considerations of inverter sizing, as most inverter capacities are selected below the system nameplate value, the chart illustrates that due to the energy profile of PV systems, undersized inversion levels initially results in very minimal annual energy losses. For a dedicated inverter per panel, the relationship between inversion capacity and energy production is linear, since a single inverter failure results in energy loss at all points of the day and year.

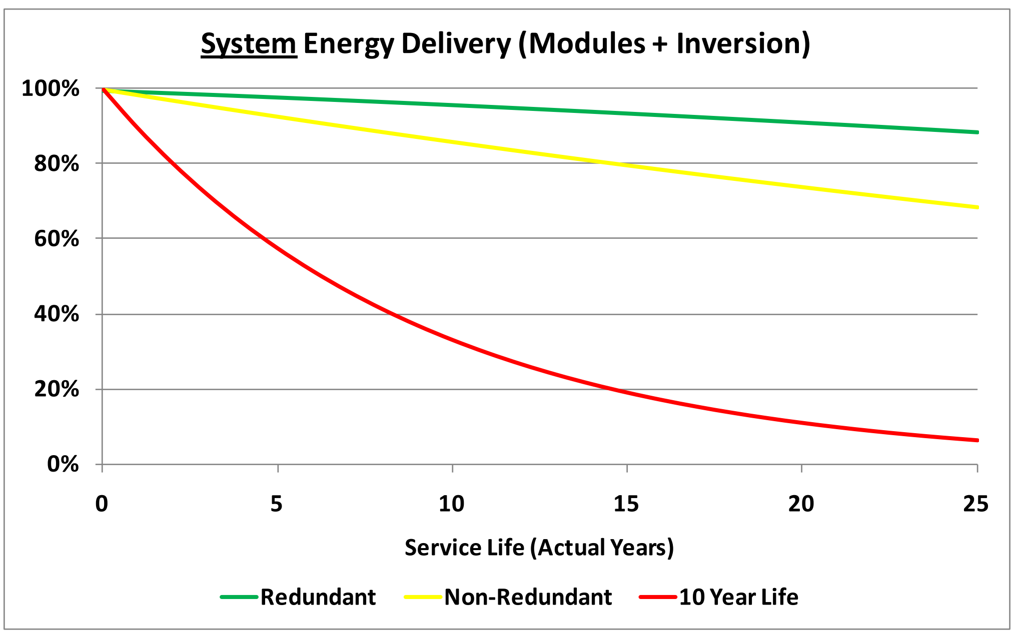

Figure 5. An example of the system energy delivery using the inverter losses of Figure 3, and using a module degradation rate of 0.2%, and a module electronics failure rate of 0.5% / actual year. The redundant system shown in green, without maintenance or repair will produce 88% of nameplate energy at year 25. This is significantly better than the warranties offered on most modules which does NOT include inversion loss. The yellow illustrates the production for dedicated inversion per module, and the red illustrates the energy production for a conventional 10 year expected life inverter without maintenance (it is obvious why maintenance is required on that system).

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 log-normal standard deviation of cell variance, depending upon the conventional string length, to being defined by the average cell variance in the redundant topology.

Table 1 is a summary of four topologies used in 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/inversion 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-point-of-failure components.

	Strings	DC Opt Strings	Individual 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 Connectors	Single Failure Point	Single Failure Point	Single Failure Point	Continuous Bus
Master Balancing System	Not Used	Single Failure Point	Not Used	Not Used
DC Combiner Box Conn.	Single Failure Point	Single Failure Point	Not Used	6:4 Redundancy
Module AC Connections	Not Used	Not Used	Single Failure Point	Loop Redundancy
Arc Fault Circuit Interrupt	Single Failure Point	Single Failure Point	Not Used	Not Used
NEC690.12 Switch Device	Single Failure Point	Single Failure Point	Not Used	Not Used
Inverter	Single Failure Point	Single Failure Point	Single Failure Point	6:4 Redundancy

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

Safety

The system topology of Fig. 1 offers several safety advantages over conventional strings, 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 internally, 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 safe under this new NEC requirement. Moreover, RAIS® modules are certified with a J_{sc}=0 and V_{oc}=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 internal ground fault detection. The electronics are also responsible for disconnecting a RAIS® module from the DC bus if the system DC voltage exceeds 60 VDC, or if the AC is disconnected from the system.

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 over time. Conventional architectures and DC optimizer based systems are by default string-based systems with a series of safety switches added 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.

Figure 6. Left image: an example of a building roof fire with a large conventional solar array. Due to the shock and flash hazards presented to the first responders (i.e., the inability to de-energize the PV system during daylight hours), the roof could not be trenched and the fire stopped. What would have been a roof isolated repair ended up resulting in a total loss (right image). Fortunately no one was injured in this event.

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 mismatch 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 inverter group. The inverter group is more efficient than micro-inverters dedicated to each module, since at low illumination, each dedicated inverter is operating at a relatively low efficiency. In the redundant topology used here, only the units needed are operating, keeping the operating units well into their peak efficiency range over all illumination conditions. The system DC resistive losses are minimized by using a continuous interconnection bus and proprietary utility-grade style connectors, resulting in complete decoupling 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 in the module[11] (soiling affects only the cells near the soiling, rather than the entire module being affected).

To further improve the system efficiencies, the RAIS® modules are most typically installed in the RAIS®-XN and RAIS®-XT racking systems, which use 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 15-30%. The ability to use reflected light is made possible by the internal design of the module where non-uniform illumination between cells within a single module is acceptable. On a conventional panel with or without a DC optimizer or dedicated micro-inverter, the mismatch from the static reflector would only add heat and cause the bypass diodes to trigger due to the photo-generated current imbalance between cells within each module[12].

As an example of system performance, Fig. 7 is a daytime trace on May 4, 2012 for a RAIS®-XN system installed and monitored by NREL (National Renewable Energy Laboratory) 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 (typical), due to the reflected gain of the RAIS®-XN system.

Therefore, the efficiency of the RAIS® systems 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)

The RAIS® modules sell for the price of a quality conventional solar panel depending on model type and quantity; and the RAIS® racking, which includes the spectroscopic reflectors is of similar cost to other low-ballast conventional racking systems. The inversion costs for the grouped inverters is quickly approaching the cost of string inversion, and by eliminating maintenance and the cost of future inverter replacement costs, the cost of ownership for redundant inversion is lower than string inversion. Also, since the inverters are lightweight and pre-packaged, use much shorter wires and are receptacle based for quick field connections, the installation costs are much lower as well. As shown within, the use of aluminum wiring for the AC runs reduces the system costs even further.

Thus, with the added energy production and system costs as noted, 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 panel-dedicated micro-inverters, AC modules, and DC optimizers, all which offer a few percentage points of energy harvest gain for a much more significant increase in system cost.

Future Extension of Redundant, Low Voltage PV Topology

As the price of energy storage declines (making the economics more attractive), adding energy storage as illustrated in Fig. 1 to the DC side of the system is a straightforward upgrade 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.

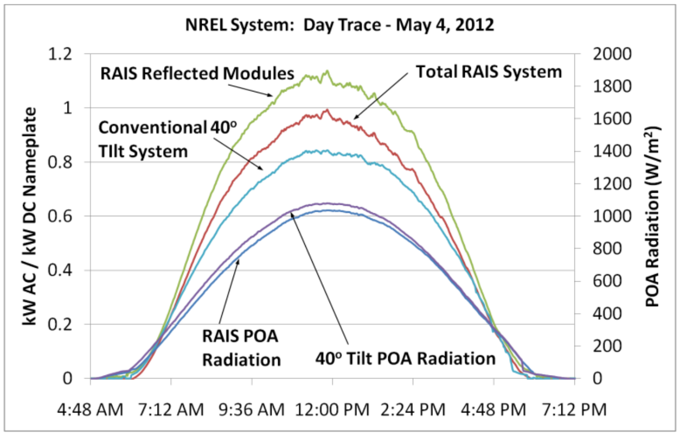

Figure 7. A sample output of an array located at NREL (National Renewable Energy Laboratory) in Golden, CO, using RAIS® modules with and without reflected light. The combination of system efficiency and the use of reflected light in the WAVE system deliver a large increase in the kW AC per kW DC of the system.

Conclusions

The low-voltage, redundant system topology outlined herein while providing advancements in safety and reliability, is also more energy efficient as compared to conventional systems which may include DC optimizers or micro-inverters. The reliability improvement is achieved by uncoupling the individual photovoltaic elements down to the most basic level, and providing alternate current paths through the system (from cell-to-grid). The ability to efficiently generate and deliver AC from the system is also reviewed. Future system upgrades such as energy storage are possible using the same hardware and topology, many of which are considered highly desirable for future grid stability as renewable sources increase as a percentage of the grid. Finally, this topology combined with static, spectroscopic reflectors allows the maximization of both module energy production and the project energy density[12].

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