Maximizing PV solar project production over system lifetime

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ABSTRACT

Anyone familiar with the PV industry can attest to the remarkably accelerated pace of innovation aimed towards generating solar power more cost effectively relative to conventional means. Many of high-technology's best minds are bringing expertise in materials, manufacturing process, and electronics to tackle the challenge. The resultant gains in cost effective manufacturing, silicon availability and greater irradiance conversion efficiency will make continuous and sustainable impact to cost per kW generated. These advances are akin to the predicable improvements in transistors per mm^2 that have fuelled the semiconductor industry for the past 25 years (although we are not yet so bold as to devise the PV version on Moore's Law). As today, less than 0.01% of electricity generated comes from PV installations [1], demand will materialize and the need for public subsidies will decline as the economics improve. This first in a series of papers, we will investigate the steps required to optimize every solar project by presenting parameters for evaluating solutions for the problem areas.

Introduction

As we architect today's installations and compute incentive rebates or project returns for power production agreements, the industry is accepting of a remarkably universal system derating factor that hovers around 22%. On closer examination of how this number is computed, one can find contributing factors such as PV module nameplate DC rating, MPPT efficiency, mismatch, diodes and connections, soiling, inverter conversion efficiency, system availability and shading [2]. To provide an immediate and sustainable benefit to the workings of the PV market, considering the breadth of contributing factors, the answer should be systematic in approach and span the lifecycle of the installation. We began this effort by taking a detailed look at what are considered to be "perfect" installations; commercial scale, flat roof, abundance of sun, no obstructions or shade, architected by installers with impeccable reputation.

Module mismatch

Today's PV systems are typically comprised of modules (panels) serially connected to one another in strings until the voltage maximum is met (600V or 1kV as mandated by the US and Europe respectively). For example, a multi-crystalline silicon module in the US with V_{oc} of 35V will usually find itself connected in series with up to 17 others. For larger installations, several of these strings are connected in parallel to form the array. Because of the serial and parallel interconnection, power output of the each module in the array will be affected by the weakest modules (Figure 1).

Therefore, it is important that the modules in the installation are well matched in power rating and come from the same manufacturer. Most module manufacturers meticulously flash-test the product after assembly and provide IV curves for each, allowing an installer to greatly reduce the variance between the modules. But is this enough to avoid mismatch losses? Our findings suggest that at solar noon on the first few weeks after installation, this is probably sufficient. However, environmental effects such as uneven soiling, temperature variations, slight differences in orientation and property migration of silicon become evident within weeks, leading to significant losses due to mismatch. The graph in Figure 2 depicts a representative example of voltage distribution of a silicon PV string installation in Northern California on a sunny midday in June 2008 [3]. The graph plots voltage of each module in a string, one data point per second.

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Each of these 170W multi-crystalline modules would be operating near their V_{mp} of 24.6V if this system were operating at peak efficiency. We would hope to see a thick straight line above 24 volts – clearly this is not the case. The lower voltage output and high module distribution (up to 15%) represents lost power output. This also illustrates that it is rare for a module to be working at the maximum power point of the system. Those operating below system V_{mp} see large voltage swings as the inverter adjusts system current while those operating above system are less impacted.

The inverter effect

By observing the topology of most installations today, the most widely accepted approach for cost and reliability is to have a central inverter with a variable DC input from the array. The inverter performs the DC to AC conversion necessary to deposit energy production onto the grid. These single or multi-stage conversion processes (DC/DC step-up for isolation and DC/AC) have been optimized over 50+ years, are highly efficient and well accepted by global regulatory bodies and power companies.

The inverter also attempts to keep the array (or string) at the highest power output possible. To find the point at which the entire system can produce the maximum power at the current solar irradiance point, the inverter usually applies a "trial and error" algorithm, which adjusts its current draw on the system. By measuring the new DC power input, the inverter will determine whether to continue the adjustment in the same direction or reverse course. This process is constantly looking for the peak power point but rarely finds the system working at this point (only instantaneously during transitions). There are many variants of the algorithm but with input data limited to system DC voltage and current, all have limited accuracy. The task becomes significantly more complex during times of changing irradiance (e.g. cloud cover, shading), as each module's maximum power point is dynamically moving. System stabilization may take several minutes after a cloud has passed. Because each module has a series of by-pass diodes, a significantly under-performing module can be "turned off" when the current drawn from the inverter exceeds its ability to provide power.

The graph shown in Figure 3 is taken from another commercial installation on the California coast on a sunny day in June 2008 with high clouds (using a string inverter). It is clear from the graph that there are extreme swings in module voltage exceeding the period of cloud cover, causing the array to spend the next few minutes trying to stabilise. A look at the IV curves for these 125W multi-crystalline modules reveals that there is almost no variance between V_{mp} as irradiance varies. As a cloud passes through the array, there should be negligible changes in voltage with a corresponding reduction in current. The wild voltage swings that are present exacerbate module mismatch, create strain on the module diodes and represent enormous inefficiencies (often in excess of 50%) across the array. In climates such as Eastern US, Germany and Japan where frequent changes in irradiation levels (e.g. clouds) are normal, the inability to maintain V_{mp} and quickly stabilize the system can greatly compound the energy losses.

System visibility

Much of the production losses occur as environmental factors and system wear take their toll on the PV array. Understanding the time-based degradation of the system requires an ability to measure the power output over long periods of time and correlate this data to expectations from seasonal irradiance and weather conditions. There are many system monitoring solutions available today, including instruments to read the DC input and AC output of the inverter, and a gateway to send this information via the internet to the consumer. The data is useful in understanding how much power is being generated by the system and how much money is being saved on the power bill. However, from this information it is extremely difficult to detect reoccurring power losses caused by gradual soiling, shading, heat patterns, or module defects. Pinpointing the offending modules so that proactive maintenance can be performed requires more granular solutions, which could possibly add cost to the system, thus outweighing the utility. Figure 4 shows a string in which one of the modules had a permanently active bypass diode, thus halving its power production. The installation had been active for almost one year and the installer and consumer believed the system was running at peak efficiency based on the data read at the inverter.

Addressing BOS inefficiency

Our research on real-world system characteristics, and efforts to solve some of the fundamental problems by modifying the PV system architecture lead us to the assertion that there is anywhere between 6% and 20% performance improvements readily available. Through deploying a combination of new technologies, more granular system monitoring and event-based system maintenance, these improvements can be attained in new installations. Determining which technologies and the granularity/frequency of monitoring and maintenance will depend on an economic metric that balances front-end capex, cost of ownership (risk and reliability), and incremental energy production. The ideal scenario is one that does not impact costs (either capital or operating), but which returns this upside power generation.

A more efficient production scenario could be attained with "perfect" site selection, advanced tracking systems to ensure optimal orientation, daily module cleaning to eliminate soiling, and regular proactive tree trimming. However, it is likely that the cost of such measures outweighs the value of the incremental production and severely limits many potential installation sites in

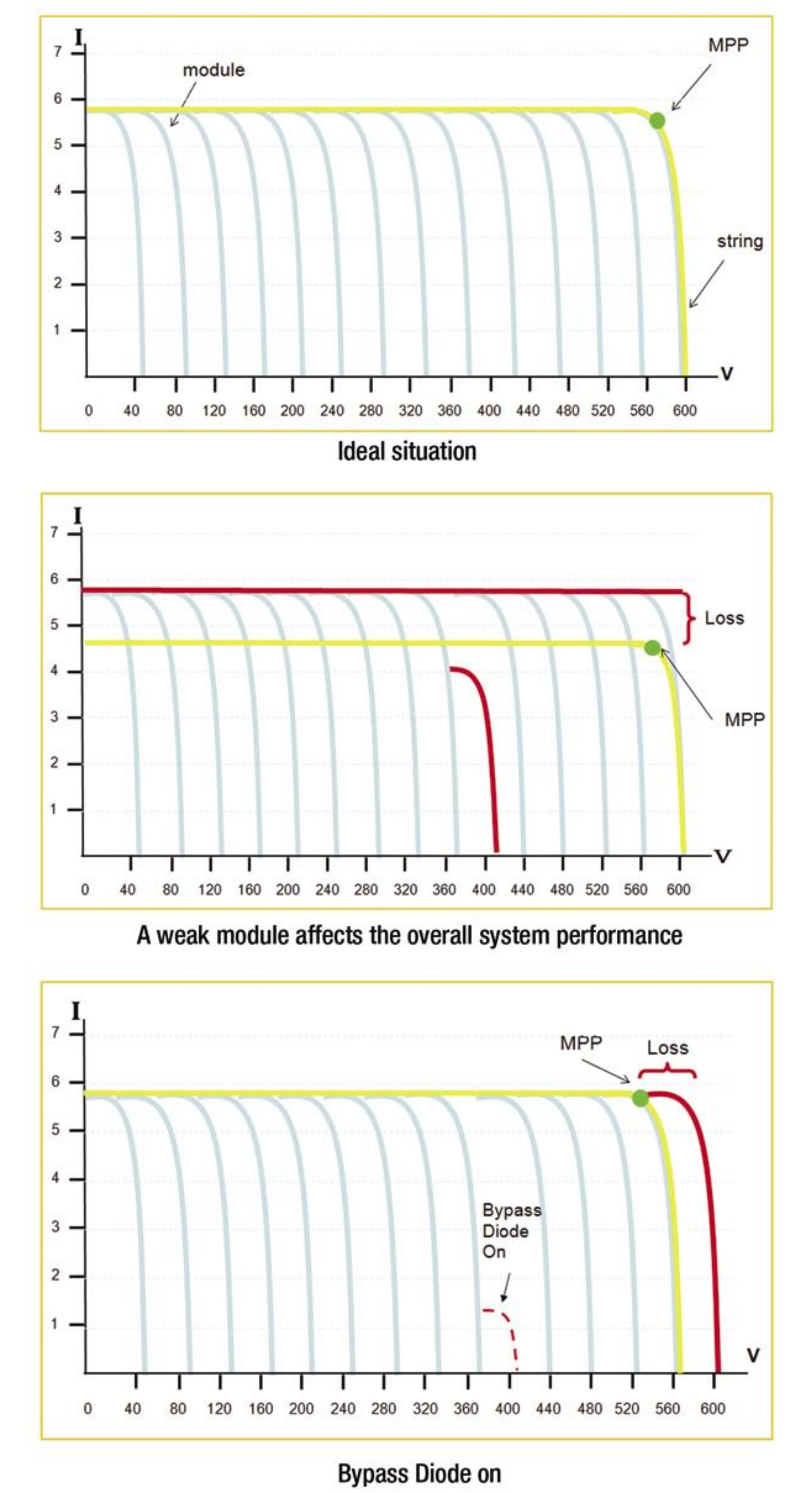

Figure 1. Effect on power output in presence of weak module.

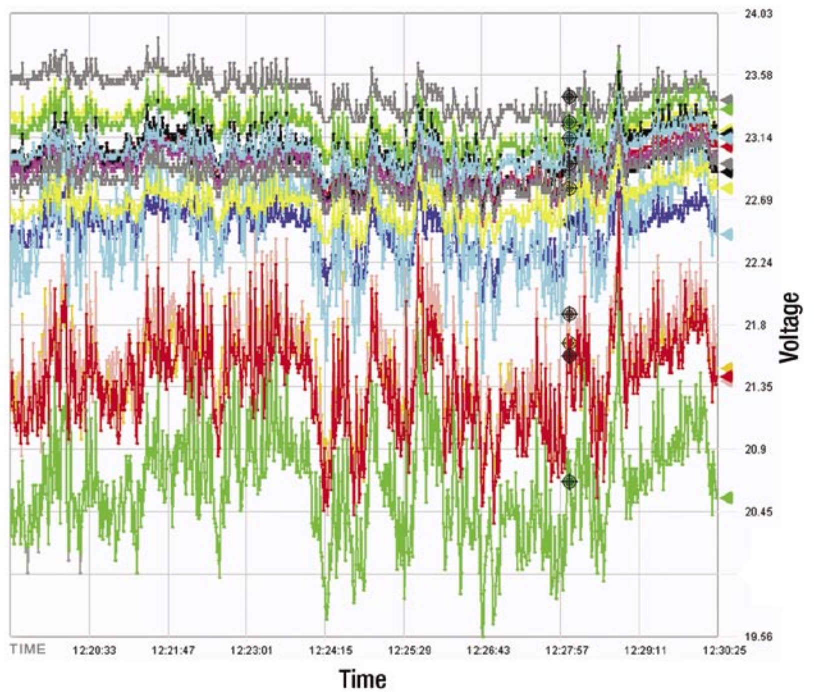

Figure 2. Voltage distribution of a typical silicon PV string.

close proximity to the existing grid. If we are able to architect a low-cost dynamic system that extracts maximum power from each module, we can greatly reduce the system drain from weak modules and ensure a stable array during shading and cloud cover. Strong modules will provide power above their rating while weaker panels will contribute what they are able and will be not be disconnected via the bypass diode. The effort and expense in matching the modules (both in orientation and in manufacturer model number) can be practically eliminated.

This effort must start with greater granularity in addressing maximum power point tracking (MPPT). Methods have been devised to narrow the scope of the tracking algorithm from the array (central inverters), to a single string (string inverters), to the module (micro inverters). These solutions reduce the complexity of the task by addressing fewer modules, or even a single module (an array of cells), which can incrementally improve tracking performance. However, these solutions equate to more inverters in the system, as the entire inverter architecture (including the DC/AC conversion function) is replicated to achieve greater MPPT granularity. System architects continue to struggle with the cost and reliability implications of such approaches relative to the incremental returns.

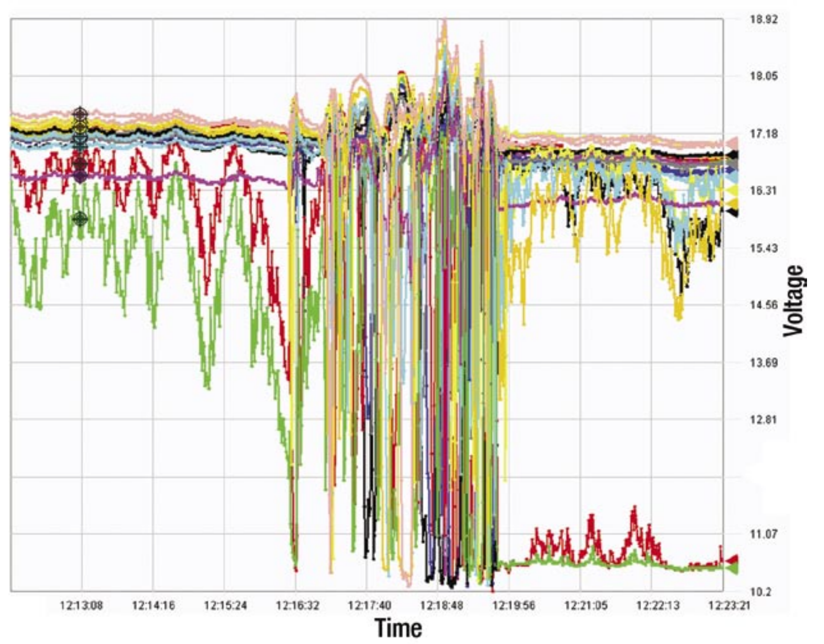

Figure 3. System impact of a change in irradiance (a cloud).

Monitoring module performance

Other more selectively distributed solutions are emerging, designed to address these cost and reliability concerns. They are based on the theory that finding the optimal operating point for a given module (or even cell) can be attained quickly with access to a wider range of tracking data. With system knowledge of real-time module performance data (IV), performance data of adjacent modules and system heuristics computed over previous days and weeks to understand recurring shading events, more accurate tracking algorithms can be developed that communicate an operating point directly to the module.

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Understanding this system data also facilitates a monitoring solution that moves far beyond today's products. If the collection mechanism is already in the system for MPPT, the same data can be provided to the installer or consumer without additional cost. The system owner or integrator could not only see how much power is being generated, but how each module in the system is functioning. Simple applications could be developed to create alerts and dynamic system maps to recommend when service such as cleaning, tree trimming or warranty replacement should be performed on unusually weak modules. This level of visibility and related maintenance procedures can assist with more targeted manual system adjustment and warrantee work to reduce annual performance degradation factors.

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Loss limitation

When considering which BOS system or enhancement to deploy, the system architect will initially consider power output gains from greater efficiencies.

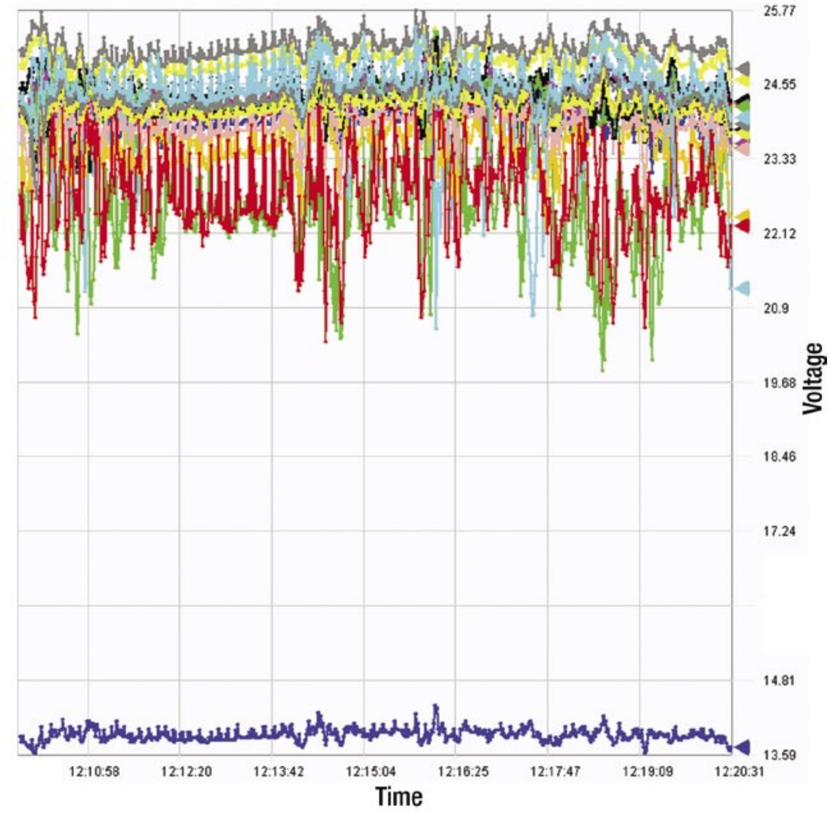

Figure 4. A disconnected module.

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Upside potential will vary considerably based on location/orientation, weather patterns, potential obstructions, tendency for module soiling, and site security. However, it is also important to observe potential impacts to conversion efficiencies that may result from any repartitioning of the inverter functions. Today's central inverter implementations utilize extremely efficient conversion techniques limiting losses to below 5%. Any reduction as a result of additional conversion stages or cost tradeoffs will offset the production gains and must be considered. Clearly, the most effective way of determining the overall system gain is with a side-by-side comparison within the same installation environment relative to a conventional system over a statistically relevant period of time. Partitioning a larger installation to evaluate several combinations over a portion of the lifecycle can result in long-term data collection benefitting this and future projects.

Risk and reliability

Diligent evaluation of risk and reliability of new BOS solutions will also be a key determinant of which solutions are deployed. While today's system reliability has yet to be field tested over the ten to twenty-five year warranty periods, it is critical that any new system components meet or exceed the reliability standards of today's solar modules and inverters. Any incremental per-module electronics should be minimized to reduce reliability, physical stress, thermal impact and the incidence of failure. Particular attention should be paid when devices inherently susceptible to failure (such as DSPs, microcontrollers, motors and moving parts) are introduced into the system. While these devices need not be completely avoided, the costs of redundancy, failure, repair and replacement must be factored into the project's rate of return. Effective deployment of a monitoring system with visibility to the device could serve to immediately identify the cases of failure, ensure that immediate warranty work is performed, and return the system to its optimal production levels.

BOS cost considerations

Last (but certainly not least) are the cost implications of new BOS components. An increase in capital or operational expense must be accompanied by a 1 to 1 ratio of production returns to maintain the project rate of return. At or below this ratio, the BOS element will likely never gain critical mass as it also poses the inherent risk of an unproven solution. As new technologies re-partition the traditional solution and eliminate unnecessary redundancy, new installations will potentially reap incremental power production with very little additional up-front capital expense relative to today's installations. Further integration work across the system by existing industry leaders can continue to improve the initial costs over time.

Conclusion

The system approach to maximizing power output is gaining with several new entrants in the PV market. We are seeing the emergence of new approaches that should be carefully considered with tangible data and side-by-side comparison in a variety of environments. Combined with the advances in module costs and efficiencies, we see another opportunity for innovative project managers to quickly reduce the cost of solar power production, approach grid parity, and continue the demand for PV deployment that will fuel continuous growth for the industry.

References

[1] http://www.solarbuzz.com/StatsMarketshare.htm

[2] http://rredc.nrel.gov/solar/codes_algs/PVWATTS/version1/derate.cgi

[3] http://www.tigoenergy.com – to request password for full installation details, data set and graphing tools.

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