Maximizing Energy Harvest

The Roles of Predictive IV and Impedance Matching in PV Array Optimization

INTRODUCTION

Today's PV systems are typically comprised of panels serially connected to one another in strings, with several of these strings connected in parallel to form an array. Due to the nature of PV modules connected in series, the lowest-performing module will impact the performance of the entire array unless optimized. This paper will outline the causes for underperformance of PV arrays, describe the superior technologies available to minimize its impact in the form of Impedance Matching and Predictive IV, and help the reader validate the solution with independent tests that they can perform.

IV Curves

The need for optimization can be understood by examining module IV curves and the way modules behave when connected together in series. Kirchhoff's current law determines that in a closed electronic circuit, where all components are connected in series, current should be identical. For example, in a simple PV array with a single string connected to an inverter, every module should have the same current as its peers. However, under certain conditions, some modules can only carry a smaller amount of current.

The following example shows the IV curves of 2 identical PV modules; one exposed to high irradiance (*A*) and the other exposed to low irradiance (*B*).

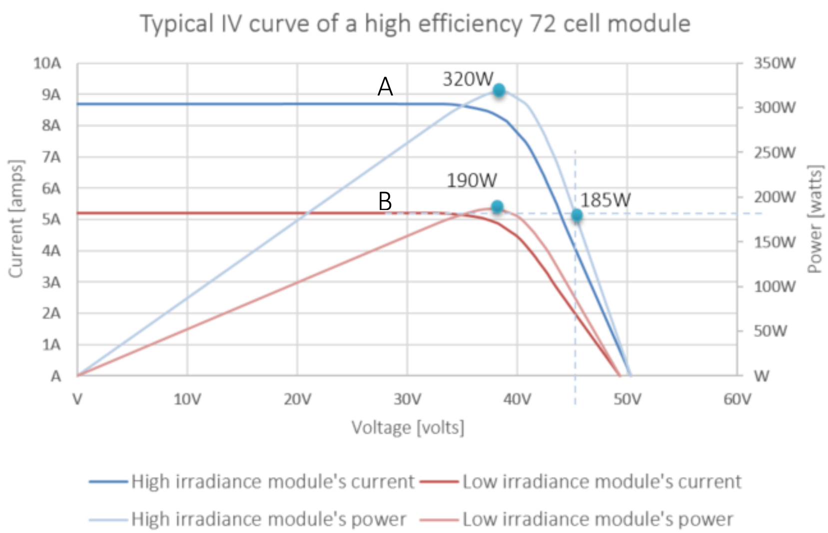

Figure 1: Example of 2 identical PV modules exposed to different irradiance levels: module A exposed to high irradiance, and module B exposed to low irradiance

Since the same current should apply to both modules, the Maximum Power Point Tracker (MPPT) at the inverter or charge controller can select between module *A*'s power point (high irradiance, around 8.7A), module *B*'s working point (low irradiance, around 5.2A), or any point in-between.
At 8.7A, the strong module, *A*, produces its maximum power, however the weaker module, *B*, is completely bypassed (no point on its IV curve that matches 8.7A). At 5.2A the weaker module, *B*, is at peak power, however the stronger module, *A*, can only produce ~185W. With module-level optimization by Tigo, each module (A or B) can produce its maximum available energy, independently of the other modules in the string. The result in this example can be quantified for all 3 options by summing the available power from both modules:

With a string current of 8.7A: 320W + 0W = **320W** (strong module's output + weaker modules' output)
With a string current of 5.2A: 185W + 190W = **375W**
With a string optimized by Tigo: 320W + 190W = **510W - conversion efficiency (~0.5%-1.5%) = 505W**

The next chapter will discuss the reasons for underperformance.

MISMATCH: THE INHERENT PROBLEM OF PV SYSTEMS

Mismatch in the context of PV systems is used to describe deviation in performance between PV modules in an array. Mismatch can have a significant impact on a PV system's power production, even in an unshaded array. When modules are not performing identically, the strong and weak modules have different power curves. When an inverter chooses a single operating point for multiple modules, compromises between strong and weak modules must be made. Also, since module IV curves change dynamically and independently throughout the day, it becomes even more challenging for a central inverter to achieve the maximum energy yield from the array.

Some sources of mismatch cannot be prevented through good design practices or component selection. The following section briefly describes the common sources.

Out of the box mismatch

The sources of mismatch below influence production from the very minute the system gets commissioned.

1. **Cloud shading and refraction**

   Changes in power (both increases and decreases) due to clouds passing over an array. Clouds block direct normal irradiance when passing over an array, and can lead to significant mismatches in insolation. Also, as clouds move off of the array, they can cause "edge effects", or spikes in power up to 125% of an array's maximum power as it receives both direct irradiance and reflected sunlight from the cloud. Since cloud effects happen quickly, central inverters may struggle to address them effectively.

2. **Residential Market: Built-in Mismatch**

   Research has shown that the USA residential roof space is limited in its ability to accommodate traditional solar arrays. Out of 100% of the pitched rooftops, which are 92% of the entire residential roof space), less than 25% can support solar systems with no mismatch.

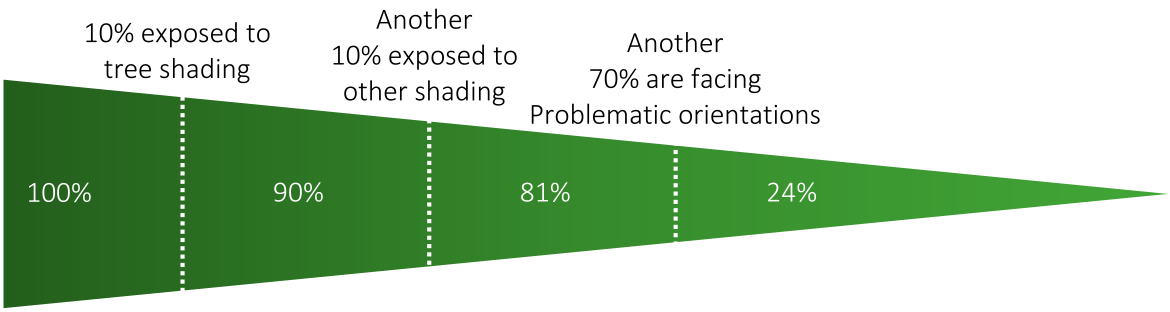

Figure 2: Analysis showing most residential rooftops in the US are not adequate for traditional solar, source: GTM Research

   Increasing the addressable market demands for a solution solving built in mismatch, which occurs due to obtrusive shading.

3. **Manufacturing mismatch**

   Differences in module output driven by manufacturing variance, such as flash test measurement error and differences in cell temperature. Since no two cells are identical, manufacturers "bin" their modules, selling them in ranges of power (typically +/-1.5% to +/- 5%). Some installers may re-bin their modules before installation to sort them into tighter groups, but the small gain in performance generally does not outweigh the additional labor cost to test and sort the modules.

4. Thermal gradients
   Temperature differences between modules within an array. Modules towards the edge of an array receive greater air flow and run cooler than modules in the center of the array (or at the bottom of a tilted ground-mounted array.) Since most crystalline silicon modules have a thermal coefficient of approximately 0.44% per degree Celsius, a 20°C delta in temperature leads to a 9% difference in power output between hot and cold modules.

Mismatch developed over time

The sources of mismatch below start influencing production at different times, which depends mostly on the quality of the modules, and partially on other system components and workmanship.

1. Failed bypass diodes
   Bypass diodes typically fail in the closed position, creating a low resistance path for current to flow around a group of cells in the module. A shorted diode reduces a module's voltage while under load by one third (in a 3 diode module.) Since this represents approximately only 2-3% of a string's voltage, it is within the margin of error of measurement equipment. The direct loss of energy, plus mismatch in power across parallel strings, leads to losses around 0.5% of system power. Failed diodes can easily go undetected for the life of the system without module-level monitoring.

2. Uneven soiling
   Environmental soiling of modules. Uneven soiling changes the insolation that each module receives, leading to differing levels of power production. It can also create "hot spots" on the module due to higher resistive losses, further reducing module efficiency. Typical losses due to soiling range from 1% - 4%.

3. Voltage drop
   Mismatch in string voltage due to long conductor runs between strings and inverters. Parallel mismatch is not as detrimental as series mismatch, but the losses still accumulate.

4. Variable degradation
   Silicon modules degrade over time at different rates. NREL's analysis of module degradation showed that most modules degrade at a rate of up to 1% per year, but some were between 1-4%. Weaker modules can also produce extra heat, which further accelerates degradation.

5. Accumulated wear and tear
   System problems that build up over time, such as mechanical or electrical faults. Module components can age and crack, humidity can short exposed connections, and thermal changes can separate mechanical connections.

To summarize mismatch

Mismatch occurs in systems of all sizes, from residential, to commercial, to utility scale, and typically results in a 2-5% energy loss in a new, unshaded array, with further losses growing over time. However, these losses can be recovered by using module-level power electronics, such as the Tigo Smart Modules. By keeping each module working at its individual peak power point, module-level power optimizers can increase the energy output of any solar array, as demonstrated in the introduction.

The next chapter is going to discuss the innovative technologies mitigating mismatch.

THE SOLUTION: PREDICTIVE IV AND IMPEDANCE MATCHING

Tigo's TS4 platform is the only MLPE in the market utilizing Predictive IV (PIV, patent pending) and guarantees the highest ROI. To overcome the challenges forced on a PV system, mismatch mitigation solutions have been available in the market for at least seven years now. DC-DC optimizers, micro inverters, multi Maximum Power Point Tracking (MPPT) inverters; all exist to address the same problem, with different system architectures and topologies. Tigo provides a revolutionary approach that intelligently predicts the most optimum settings allowing each PV Module to generate the maximum energy.

The Tigo system architecture is identical to a string inverter's architecture, allowing the optimizers to remain in a complete bypass mode until mismatch occurs that requires its intervention. It does not rely on distributed DC/DC stage or DC/AC conversion, which allows for the lowest duty cycle among all other leading solutions in the market. Because of these guiding principles of operation, Tigo optimizers achieve maximum energy harvest with 99.5% conversion efficiency and the lowest heat dissipation at the back of the module.

Predictive IV

Predictive IV (PIV) is state of the art technology that evolved from Impedance Matching and years of research. Predictive IV incorporates MPPT and Impedance Matching techniques as well as historical module behavior statistics to predict the optimum settings for a module to generate maximum energy. The result is a more robust and accurate module-level optimization, with greater energy yield.

PIV parameters are set locally, thanks to advanced predictive analysis capabilities. It is completely independent of any other module in the string as well as of the inverter. Operating locally allows for very high speed monitoring and therefore highest accuracy in real-time response to any variation of the PV module's behavior. This guarantees the highest operational efficiency as well as maximum energy generation from any string of modules.

Additionally, PIV technology enables selective deployment of optimization. PIV accommodates partial placement as needed, and can be applied to any module in a single string, minimizing the number of optimizers needed to harvest the maximum available energy. In other words, any PV Module in a string that is exposed to shade, higher temperature, or has a higher mismatch characteristic with other modules can be outfitted with a PIV optimizer. This will ensure the module's own best performance, and equally important, that it will not limit the production of the other, unshaded PV modules in the string.

Figure 3: With Predictive IV in a single string only shaded modules require optimization

Predictive IV comes as a standard feature in each TS4 cover with optimization capabilities, i.e. TS4-O and TS4-L, and is available today. The TS4 is a unique hardware-software platform combination in the industry, replacing the traditional PV modules' junction boxes with two key components. The first is a universal TS4 base, which connects to the module and incorporates the power cables (like a regular Jbox). The second is a matching detachable cover that houses the application electronics. Together they form a new generation of junction boxes; flexible, replaceable and upgradable, accompanied by a powerful PV 2.0 communication-centric architecture backend.

Impedance Matching

Like batteries, PV modules are connected in series. When all the modules are producing the same amount of power the array is producing optimally. However, when one module underperforms it not only outputs less, it also drags down the other modules in the string.

It is easy to think of solar modules as pipes. Perfect modules have a larger pipe, while underperforming modules have a smaller pipe. When connected together the narrower pipe constricts the flow of energy through the array, and loses power by heating up the module. This can result in significant power losses and panel damage.

Impedance Matching technology corrects for mismatch issues between modules by opening up a current tunnel to allow some current to bypass an underperforming module. The tunnel's diameter is dynamic and opens only as much as needed. The underperforming module will continue to contribute its power to the string, but will not restrict the flow of the other modules.

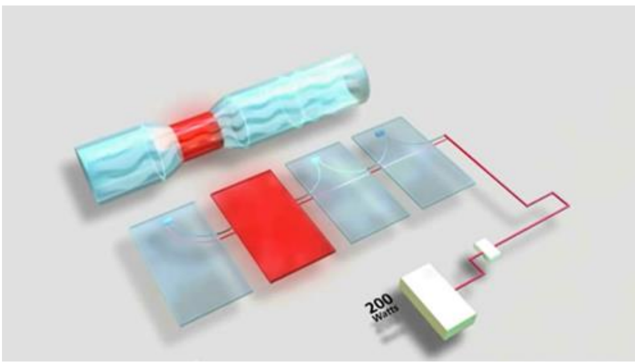

Figure 4: Four (4) PV modules connected in series, one of them is underperforming and limits the current

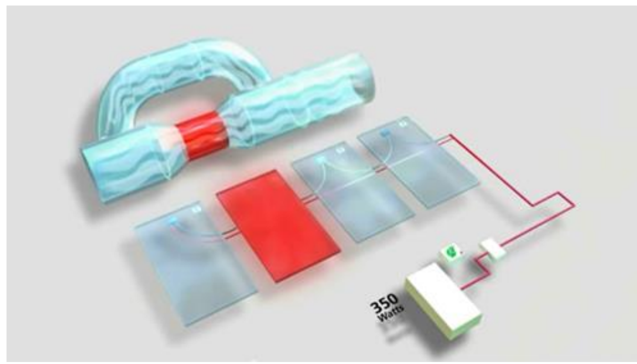

Figure 5: The current that cannot flow through the underperforming module is bypassed by the optimizer

These diagrams illustrate the current tunnel in a Tigo optimizer or Smart Module system. Because of the Impedance Matching circuitry, the shaded module is able to contribute its optimal output without restricting the maximum available string current. As a result, the shaded and unshaded modules in the string can operate at their maximum power points, harvesting the most out of the PV array.

Testing Selective Placement

Tigo has demonstrated an unparalleled boost in performance with partial placement of PIV by optimizing a single shaded PV module with TS4-O, in a string of eight (8) modules. The module was shaded as shown below, and performance with a TS4-O cover was tested against a TS4-D cover (diodes only; no optimization capabilities).

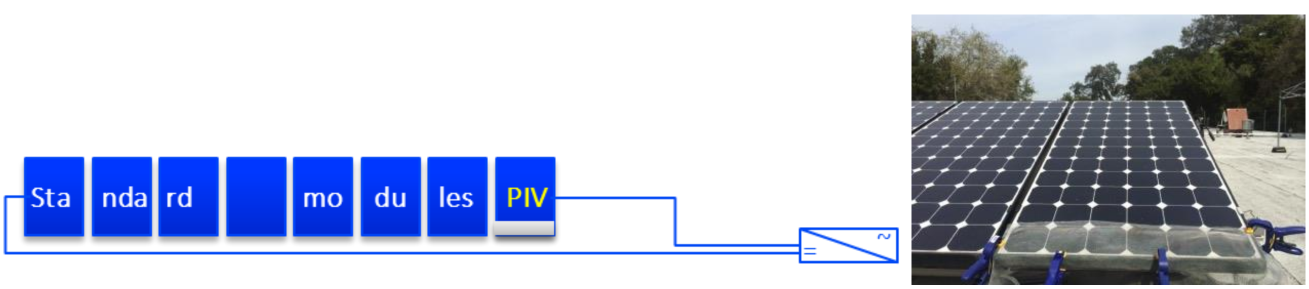

Figure 6: Testing selective deployment experiment setup, one shaded module with TS4-O / TS4-D to measure the energy output with and without PIV

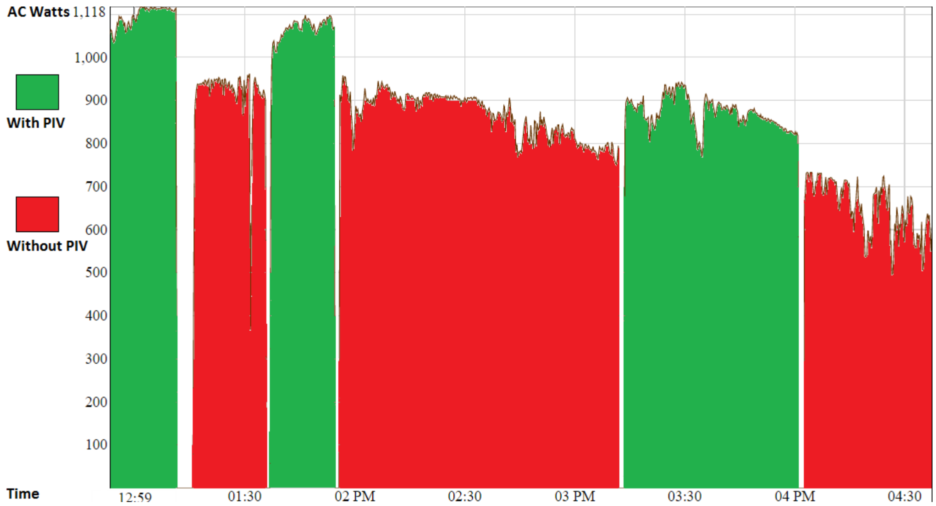

Figure 7: Measurements of selective placement experiment, taken by an AC meter. Greater energy yield with PIV is highly noticeable.

Results were measured with an AC meter at the inverter and can be seen above. Energy recovery reached a peak of 18.5%, validating feasibility as a stand-alone solution for shade mitigation on PV systems.

THE RESULTS: INDEPENDENT TESTING

The technology is continuously being validated by Tigo and its customers, as well as by independent research facilities. In this final chapter, we'll display results from two of these labs: National Renewable Energy Laboratory and Photon.

NREL

In 2014, the National Renewable Energy Laboratory (NREL) performed an assessment of PV installations with Tigo. The focus of the study was to estimate lost system performance due to partial shade and performance improvement from module-level electronics. Analysis of over 500 systems found an average power loss of 8.3% from partial shading, which would have increased to 13% without optimization. They estimated that module-level optimization can recover on average 36% of power lost to partial shade.

Actual system performance was compared to estimated unshaded performance to determine energy lost and energy recovered.

The complete article is available here.

PHOTON

PHOTON Laboratories performed several tests with Tigo optimizers and found increased energy harvest in all shaded scenarios. The charts below represent two typical residential shading scenarios, where Tigo and its competitors mitigated mismatch to increase production.

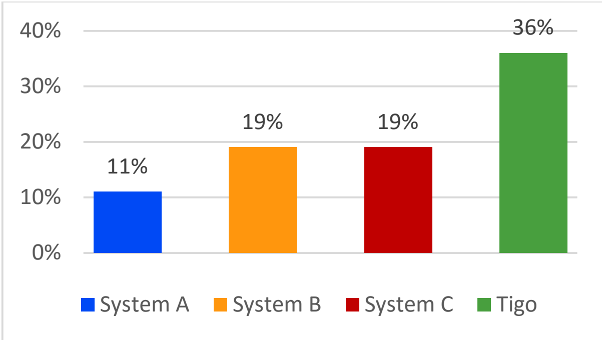

Figure 8: Results in partially shaded arrays (pole), source: PHOTON, Nov 2010

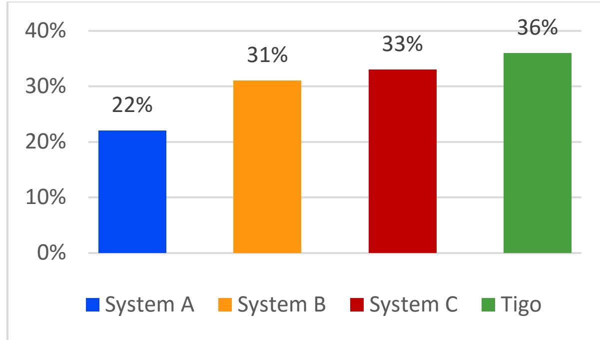

Figure 9: Results in arrays with horizontal shade, source: PHOTON, Nov 2010

In the first shade test, a pole was placed in front of the modules, casting shade that slowly moves across the array as the sun travels throughout the day. In the second test, a static horizontal shade element was placed across the modules. In both cases Tigo optimizers generated more energy than non-optimized and competing solutions. The result is similar to NREL's analysis.

Summary

The Tigo TS4 based optimization solution utilizes revolutionary Predictive IV, allowing it to quickly respond to changing conditions. It brings each module to its optimal power output point, recaptures energy lost due to mismatch, and increases total energy production.

PIV works with the majority of standard off-the-shelf inverters and battery chargers on the market and does not require any specific installation setup, commissioning, or operational consideration.

Tigo's PIV based solutions guarantee the highest ROI compared to any other DC optimizer or micro inverter in the market today from ANY vendor. TS4 optimizers equipped with the state-of-the art Predictive IV are available today from leading module manufacturers.