# IMPEDANCE MATCHING

The Science Behind the Tigo Energy® Optimizer

Tigo Energy has developed a revolutionary solution for harvesting the maximum power available from a photovoltaic (PV) array. Like other distributed balance-of system (BOS) architectures, the Tigo Energy® Optimizer solution extracts energy from each module, virtually eliminating the negative effect of weaker modules on the rest of the PV array. However, the Tigo Energy products do so with unprecedented efficiency and accuracy, with very few incremental electronic components for maximum reliability and minimum cost. This paper will further discuss the novel and patented approach of "impedance matching" implemented in the Tigo Energy solution.

A SOLUTION FOR 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 with Voc of 35V will usually find itself connected in series with 10 or 11 others in the US. For larger installations, several of these strings are connected in parallel to form an array. Because of the serial and parallel interconnection, power output of each module in an array will be affected by the weakest modules (figure 1).

| Ideal Situation | Weak Module Drags Down String | Bypass Diode On |
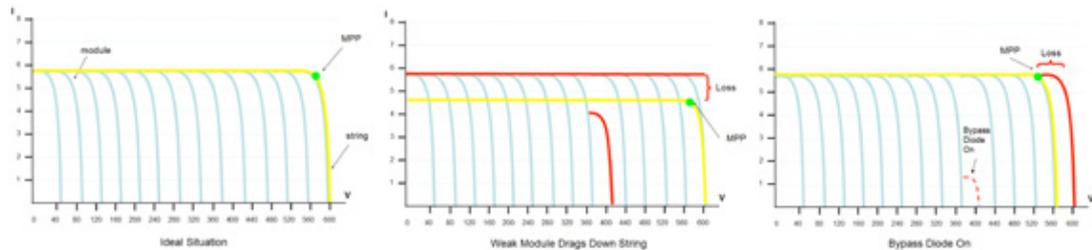
Therefore, it is important for the modules in the installation to be well matched in power rating and from the same manufacturer. Most module manufacturers meticulously flash-test the product after assembly and provide IV curves for each, allowing an installer to greatly reduce the variance between the modules. But is this enough to avoid mismatch losses? After instrumenting many commercial scale, well architected PV projects, Tigo Energy's 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 silicon degradation become evident within weeks leading to significant losses due to environmental mismatch (even without shade). Figure 2 is a graph of a representative installation located in Northern California and taken in the middle of the day in June, 2008 with full sun [1]. The graph plots voltage of each module in a string, one data point per second. If this system were operating at peak efficiency, each of these 170 W multi-crystalline modules would be operating near their Vmp of 24.6V. We would expect 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
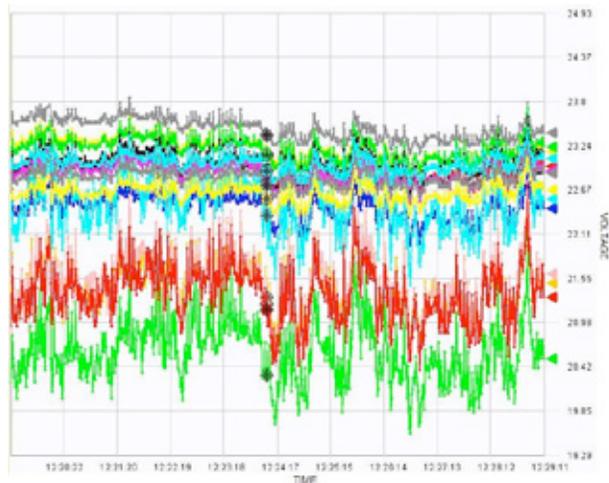

Figure 2 – Voltage distribution of a typical crystalline PV string (Berkeley, CA - 2008)

that it is rare for a module to be working at the maximum power point of the system. Those operating below their individual Vmp see large voltage swings as the inverter adjusts system current while those operating above system are less impacted. [1] (find full text of article at http://www.tigoenergy.com/brochures/PVI_article.pdf)

"TRIAL AND ERROR" MAXIMUM POWER POINT (MPP) TRACKING

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 from the leading inverter manufacturers (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 MPP tracker within the inverter 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 tracker usually applies a "trial & error" algorithm which adjusts its current draw (load) on the system. By measuring the new DC power input, the tracker 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 this 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 (ex. 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.
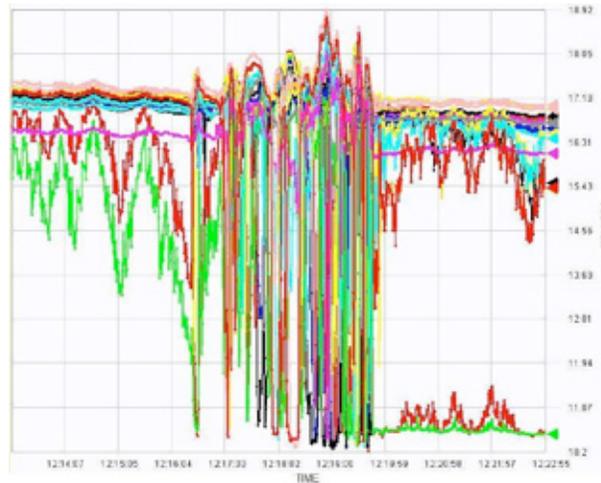

Figure 3 – System impact of a cloud (Santa Cruz, CA)

Figure 3, taken from a commercial installation in Santa Cruz,California during a sunny day in June, 2008 with high clouds (using a string inverter), shows that there are extreme swings in module voltage. This variance exceeds the period of cloud cover and the array remains unstable over the next several minutes. When we look at the IV curves for these 125W multi-crystalline modules, there is almost no variance between Vmp as irradiance varies. Therefore, we should expect to see negligible changes in Voltage with a corresponding reduction in current as a cloud passes through the array. The voltage swings that are present exacerbate module mismatch, create strain on the module diodes and represent inefficiencies (often in excess of 50%) across the array. In a climate where frequent changes in irradiation levels (ex clouds) are normal – such as Eastern US, Germany, and Japan – the inability to maintain Vmp and quickly stabilize the system can greatly compound the energy losses.

IMPEDANCE MATCHING

Once the Tigo Energy team completed the analysis of the data from many large scale "perfect" installations, it was clear that substantial, environmental mismatch was still present. If the Tigo Energy solution could efficiently bring each of the modules to their optimal output point, the large-scale projects could yield up to 8% more energy output while less "perfect" sites could increase energy production by up to 20% more. The key to adding incremental value to PV projects was clearly to develop a highly reliable and efficient (lowest power loss from the panel electronics) solution while minimizing the cost of implementation. The patented, innovative approach to maximizing production output achieves these objectives while also delivering a comprehensive active project management console. The Tigo Energy® Optimizers and the intelligence which resides in the Tigo Energy® Management Unit (MMU) applies Tigo Energy's "Impedance Matching" approach to extract the maximum output from each module. The system is designed as both integrated smart modules, as well as a technology overlay, so that it performs optimally with all new and curent PV systems building blocks (modules & inverters), and is ideal for retrofit installations.

WHAT "IMPEDANCE MATCHING" IS NOT

To best understand the Tigo Energy power harvesting technology, it is important to start with what it is not. While never quantified to the degree which Tigo Energy has accomplished, the industry has known of the mismatch problem since the early days of photovoltaics. Applying MPPT to smaller portions of the array has been known to address the issue but these more distributed solutions have never been able to achieve a positive return on the incremental cost required to implement them in a larger scale project. Simple distribution of existing central inverter functions continues to be attempted with sub-optimal results.

It is NOT "Distributed MPPT"

All power point tracking algorithms are based on a "trial & error" approach of adjusting impedance and measuring the impact to aggregate power output. This is typically implemented at the central inverter for the array. Leading inverter companies have perfected these algorithms to provide very good results with the input parameters available. However, with only the system DC input voltage and power to work with, these trackers have fundamental issues with mismatch and rapid irradiance changes (such as clouds). Modern DC/DC distributed architectures have brought the "trial & error" power point tracking methods to the string and even panel level with the addition of buck/boost transformers and local digital intelligence to increase the granularity of the input to the algorithm. This approach has some positive impact in terms of power point tracking accuracy. However, Tigo Energy has developed a technology which does not implement a distributed "trial & error" approach to finding the operating point of the module. By implementing Impedance Matching, Tigo Energy can more accurately and quickly find the EXACT optimal operating point and avoid putting expensive and relatively low efficiency electronics on each module.

It is NOT a "MicroInverter"

Inverters are available in a variety of capacities from 200 Watts to 2 Mega Watts. These inverter topologies include MPPT, (often a) DC/DC boost stage, and DC/AC inversion functions. By inverting at the highest capacity the system will accommodate, project designers are able to minimize BOS cost (per Watt - see figure 4) and maximize AC conversion efficiency. The concept of AC modules emerged many years ago with the goal of bringing an inverter to each module to increase the granularity of the power point tracking. These smaller inverters have provided some benefit in very small installations for shade mitigation but continue to fall considerably behind larger central inverters in conversion efficiency and cost per Watt at implementation. The Tigo Energy technology is not a micro-inverter. The Company believes that product innovation can achieve much higher (2.5% to 3% more) system conversion efficiencies, increased reliability and lower costs than a traditional inverter topology scaled down to 200W. In addition, Tigo Energy believes that by adhering to today's system partitioning of DC generation and central AC conversion, PV projects are better suited to meet the energy demands of direct DC loads (ex. data centers, manufacturing machinery, and electric automobiles) and the need for energy storage.

Scale Economies for Inverters
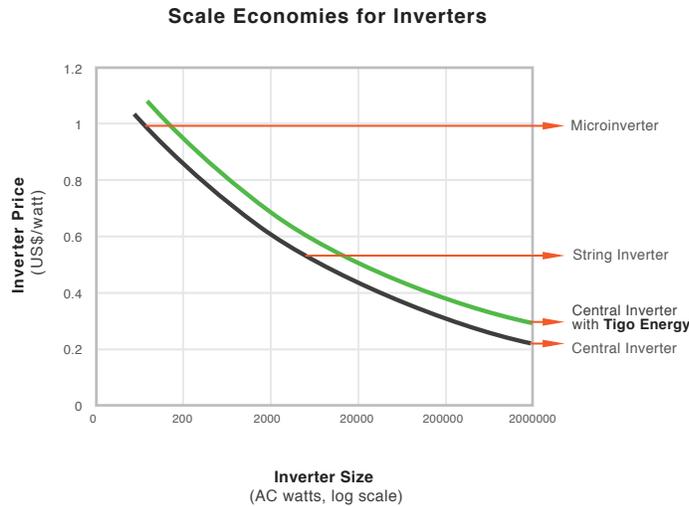
It is NOT "Distributed DC/DC Stage"

In many geographies, string voltage limitations remain relatively low (600V or below) and often require galvanic isolation in the system. For these reasons, many single and three-phase inverters contain a DC/DC boost stage to bring the input voltage to the AC bridge to an optimal point for conversion efficiencies. Several newer module-level power optimization products desegregate this DC/DC function and move it to module. By boosting or bucking voltage at the module level, these solutions implement a localized MPPT algorithm and provide a fixed voltage (either in serial or parallel) to a central inverter. In a market where isolation is required (ex. USA), these solutions can provide a comparable efficiency to a traditional system if used with a specialized transformer-less, MPPT-less, fixed voltage inverter. However, most large scale and European installations have already moved to highly efficient transformer-less (floating) topologies. Implementing an additional DC/DC stage in a transformer-less system or with a standard isolated inverter reduces system efficiency by 2-3%. Worse yet, the power dissipation related to the lower efficiency is transferred to the panels as heat and further reduces their production output. Tigo Energy believes that by innovating rather than distributing the DC/DC boost function, the system can achieve much better end-to-end system efficiency. The Company also works with existing inverters, providing customers with the flexibility to choose best-in-class inverter technologies for any region or application.

WHAT "IMPEDANCE MATCHING" IS

The term Impedance Matching is often used in Radio Frequency (RF) applications where it is critical for highest power efficiency and lowest interference. To achieve maximum output of an RF transmitting device the impedance reflected to the transmitter should be equal to the internal impedance of that transmitter. The antenna will tend to have a fixed resistive load so that peak RF power is attained with a characteristic impedance which is identical. For example, examine the case of a power amplifier (PA) with an internal resistance of 50Ω and an external antenna with resistance of 100Ω, both measured at the operating frequency of the circuit (figure 5a). In this configuration, the power output of the PA will be far from optimal. To achieve maximum power output, the amplifier needs to "see" 50Ω on the output side. If 100Ω resistance was added in parallel to the antenna, the PA will achieve its maximum output, but much of this output will dissipate at the 100Ω resistor rather than being transmitted (figure 5b). In order to not waste power through the resistor, a capacitor and coil may be used reflecting "virtual" impedance of 50Ω at the circuit frequency (figure 5c).
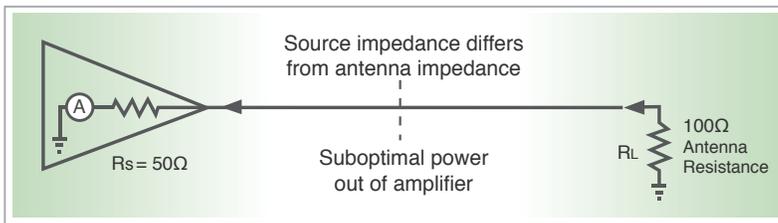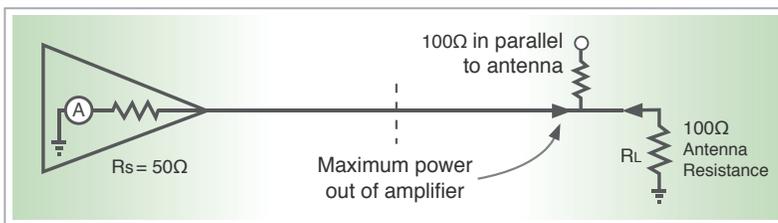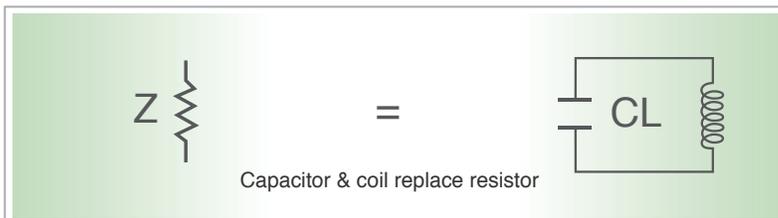

Figure 5a

Figure 5b - RF impedance matching

Figure 5c

Obviously this approach cannot be directly applied to the power electronics challenge within a PV installation. However, Tigo Energy implements this concept in a unique, novel and patented way to achieve maximum harvest from each PV module. The Tigo Energy Optimizer system does not utilize traditional DC/DC or Micro-inverter conversion technology which normally adds additional inefficiency to the array therefore reducing its power output.

The circuitry in the Tigo Energy® Optimizer has three main functions. The first is analog sensing by components which accurately measure the module voltage, current and temperature. The Optimizer contains a communications module (either wireless or PLC) which transmits the input parameters and receives the operating point from the MMU. Finally the Optimizer contains the "impedance matching" components to control the output of each module, ensuring that it is contributing the most energy possible.
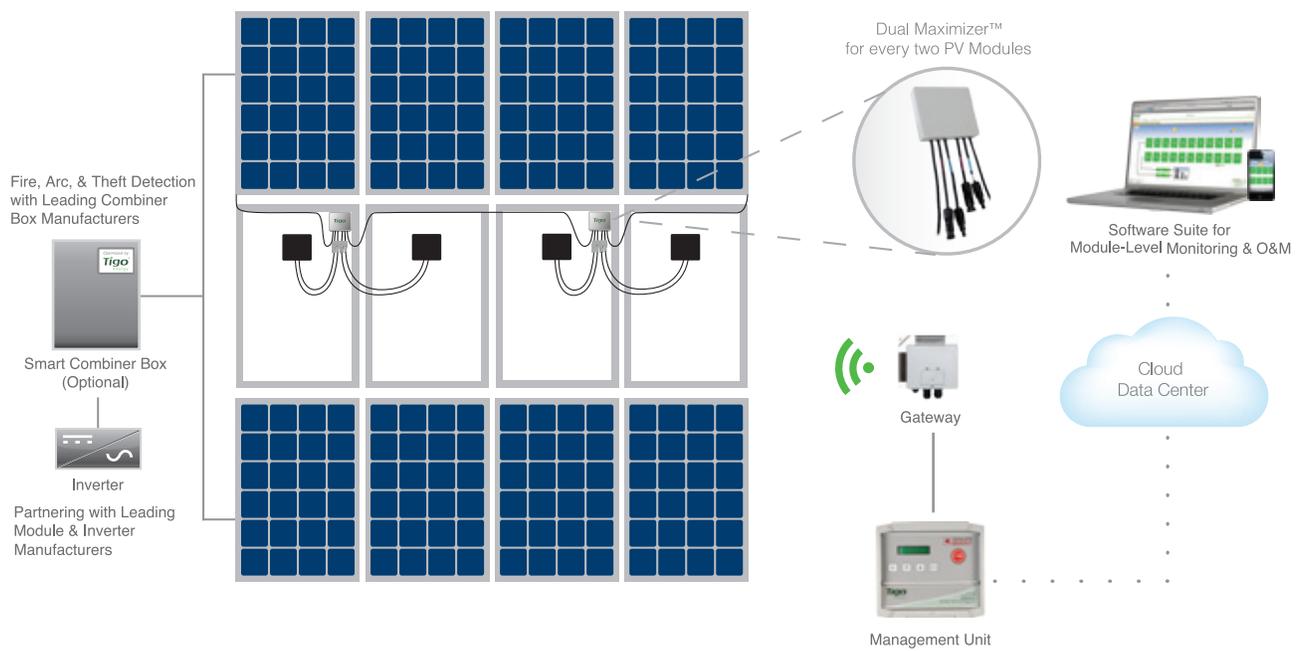
Figure 6 - Tigo Energy system configuration

The process starts with the Optimizer sensing the input parameters at each module. This information is transmitted from each module in the system to the MMU. The MMU collects voltage, current, and temperature of each module. The central processor at the MMU is able to obtain the exact I-V properties of each module (including its desired Vmp), calculate their impedance matching factors and transmit these back to the Optimizers. With access to the input variables, computation of the operating point to maximize the output of the module and the string has been derived by several mathematicians. While Tigo Energy uses an optimized formula for the specific Optimizer implementation, an example of such an equation is on the following page [2] ...

Nomenclature

M	Number of rows in an array
N	Number of columns in an array
W	Maximum Power (W)
W(1)	Maximum Power generated by an array with no cells shadowed (W)
W(2)	Maximum Power generated by an array with some cells shadowed (W)
A.W	Loss in Maximum Power generated by an array due to shadow effect (W)
Pm,n	Potential at the junction (m,n) (V)
Jm, n	Current through the junction (m,n) (A)
V	Array voltage (V)
Vm,n	Voltage across the solar cell (m,n) (V)
Im,n	Current through the cell (m,n) (A)
(Voc)m,n	Open circuit voltage for solar cell (m,n) (V)
(Iph)m,n	Short circuit current for cell (m,n) (A)
(Is)m,n	Diode saturation current for cell (m,n) (A)
(Rsh)m,n	Shunt resistance directly across the diode for cell (m,n) = 1000 O,
(Rs)m,n	Series resistance for cell (m,n) (fl)
n	Ideality constant
Tm,n	Operating temperature for cell (m,n) = 300 °K
e	Electron charge = 1.6022xl0"19 Coulomb
k	Boltzman's constant = 1.3806xl0"23 Joule/°K

The current-voltage relationship for a single diode solar cell (m, n) in an array can be obtained as follows:

$$f\left(V_{m,n}, I_{m,n}\right) = 0$$

or

$$I_{m,n} - \left(I_{ph}\right)_{m,n} + \left(I_s\right)_{m,n}\left\{exp\left[\left(\frac{e}{nkT}\right)\left(V_{m,n} + I_{m,n}(R_s)_{m,n}\right)\right] - 1\right\} + \left(\frac{V_{m,n} + I_{m,n}(R_s)_{m,n}}{(R_{sh})_{m,n}}\right) = 0$$

Figure 7 - A sample example equation for finding Vmp

About the algorithm:

This algorithm displayed above is for demonstration purposes only and may not represent the actual algorithm used by Tigo Energy. Tigo Energy reserves the right not disclose protected intellectual property.

The calculated Vmp point for each module is used to calculate impedance matching factors and transmit these back to each Optimizer. Impedance matching circuitry presents a virtual impedance to each module that is equal to the internal impedance of the corresponding module making it possible to extract the maximum energy from every module. As presenting a resistive impedance would obviously create power loss, the circuitry implements this in a more innovative manner. Through a combination of a FET and small capacitor, the Optimizer creates a "current tunnel" such that each module can operate at its optimal voltage and current while not affecting the max power string current, such that Imodule + Itunnel = Imp (string) = Iout. Each module is thereby able to contribute its maximum output without affecting other modules in the string. String current remains at its optimal point as supported by the highest performing modules in the string and the inverter receives a normalized string IV curve for accurate MPPT (no false peaks).
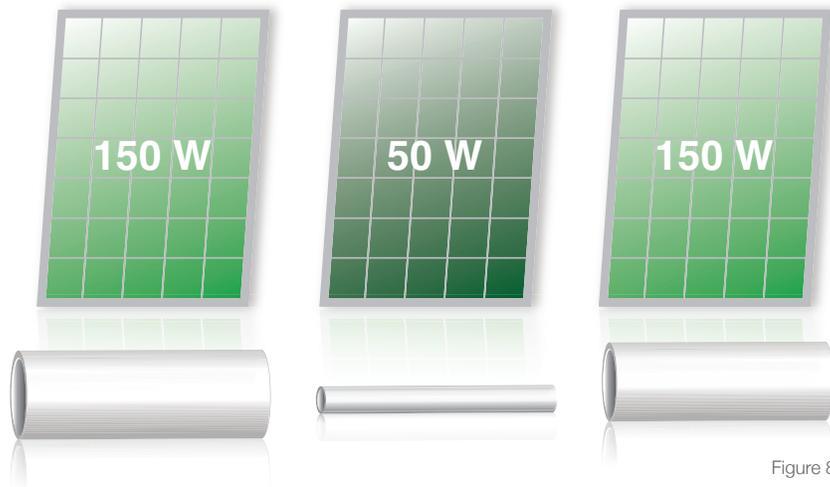
IMPEDANCE MATCHING IN PRACTICE

Figure 8

As described in pervious articles, equally sized modules can have different generating capacities depending on the amount of available irradiance and PV material properties. Differences can result from varying levels of shading and soiling; temperature differences; and silicon aging.

By observing the IV curves, if the array control is working to maximize current, the voltage output of the weaker panels will drop (as the string current is higher than the optimal operating point of the weak panels and thus the weaker panel is forced to reduce its operating voltage point below Vmp). The optimal path for the weaker panels is described by (B) in figure 9 but the actual path the panel is forced to take is (A) which is resulting even lower power output for that panel and the whole array (analogous to the leaking). Figure 10 shows typical voltage measurements of interconnected (series) modules controlled by a central inverter, sampled synchronously every second. This particular data was captured in Berkeley, California during the summer of 2008. One can clearly see the voltage difference between the strong and weak panels in the array.
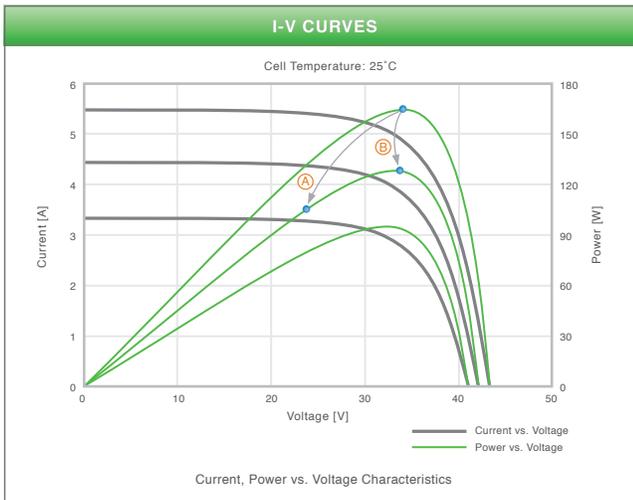
Figure 9 I-V & Power Curves

These effects have a "positive feedback" behavior, an undesirable system instability where "A" creates more of "B" which in turn creates even more of "A". In the series connected PV case, less power output harvested from the solar panels will leave more of the available power on the panel creating heat. That additional heat will further decrease the power harvested from the panel which again will create more heat on the panel. The result is a feedback loop that negatively impacts overall power production.
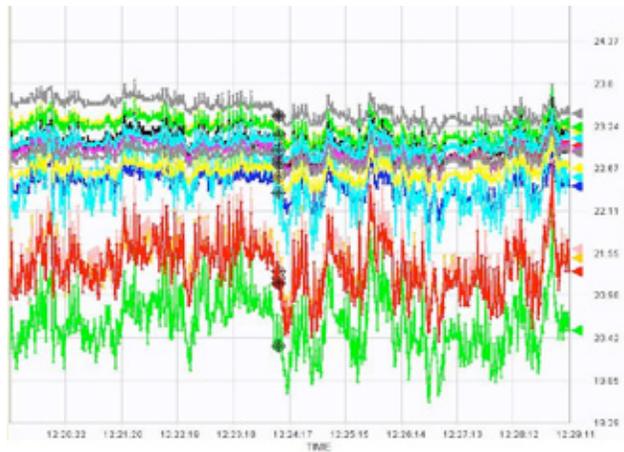
Figure 10

This technique is not only used on the weakest panel on the array but to almost every panel. Each panel in the array will have an "impedance matching" circuit, which can be programmed independently to carry current around the modules to extract their maximum energy harvest without affecting output of other modules in the string. The amount of current going around each panel is calculated by the MMU using information from each Optimizer on panel voltage, current and temperature. By changing the current flow through the panel the voltage on the panel can be readily adjusted so that the panel voltage is moved to its optimal operating point (Vmp).

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┌─────────────────────────────────────────┐
│  Synchronously measure voltage (V), current (I),  │
│      and temperature (T) at each panel            │
└─────────────────────────────────────────┘
                    │
┌─────────────────────────────────────────┐
│  Communicate readings to Maximizer Management     │
│    Unit (MMU) via wireless or DC power line       │
└─────────────────────────────────────────┘
                    │
┌─────────────────────────────────────────┐
│  ┌───────────────────────────────────┐  │
│  │  MMU calculates I-V statistics for each panel │  │
│  │      (see sample equation in Fig. 7)          │  │
│  └───────────────────────────────────┘  │
│  ┌───────────────────────────────────┐  │
│  │  MMU calculates optimal working point         │  │
│  │       for each panel (n, m)                   │  │
│  └───────────────────────────────────┘  │
│  ┌───────────────────────────────────┐  │
│  │  MMU calculates required virtual impedance    │  │
│  │  Z(n, m) =  (I(m),  Vmp(n,m), Imp(n, m))      │  │
│  └───────────────────────────────────┘  │
└─────────────────────────────────────────┘
                    │
┌─────────────────────────────────────────┐
│  Communicate operating parameters to each         │
│    Optimizer (via wireless or DC power line)      │
└─────────────────────────────────────────┘
                    │
┌─────────────────────────────────────────┐
│  Optimizer reflects Z(n, m) to each module        │
│     i.e. Z(1, 1) to panel 1 in string 1           │
└─────────────────────────────────────────┘
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In a large system, where many strings are connected in parallel, the Tigo Energy solution also acts to minimize mismatch between strings. In most situations, string voltage, although variable, is almost identical as the average temperature across all strings is similar. As each module is operating at its max power point, Vmp of each module is almost identical. String voltages in this condition are within a small distribution and thus a constant voltage across the parallel string is not creating a reduction to any one underperforming string (as opposed to the conditions without the Tigo Energy® Optimizer). In the unusual case when a subset of modules in one string are heavily shaded such that voltage output of an individual string is affected, the impedance matching effect creates the equivalent of a tunnel across the strings so overall system loss is eliminated. [3]

Summary

ADVANTAGES OF IMPEDANCE MATCHING RELATIVE TO ALTERNATIVES
(DC/DC buck boost, distributed MPPT or micro-inverters)

Very minimal electronics at the PV module level for:
- Best reliability
- Lowest cost
- Smallest footprint

Highest average efficiency at the module (statistically 99.5%):
- Best overall conversion efficiency of distributed solutions
- Lowest heat dissipation at the panel (often lower than that of today's diodes)
- Avoids heating of the modules and associated output degradation
- Enables polycarbonate housing - no additional grounding
- Simple integration in existing module junction boxes

Smallest change to today's array configuration (inverter, module wiring and BoS):
- No need to move inverter to fixed voltage (wasteful in energy as it adds an additional conversion stage)
- No need to stop inverter MPPT
- Great solution for retrofit of existing arrays
- Validated interoperability with proven inverter suppliers

Software controlled operation:
- Lowest cost and highest harvest accuracy
- Flexibility to adapt to new technologies and configurations
- Eliminates complex processing at the module

No trial and error algorithm at the module level
- Precise calculation of impedance matching factors by sophisticated, patented approach

In summary, the Tigo Energy impedance matching solution uses a combination of real-time module and string-level information to accurately compute the optimal operating state of each module. It readjusts the module by a process of impedance matching. The Tigo Energy solution is able to quickly and dynamically find the maximum operating state for each panel and maintain system stability during cloud cover or shading. By implementing this statistically 99.5% efficient approach to power harvesting, financial productivity can be maximized throughout the life of the system.

References:
[1] Arditi S, Krisa J. Maximizing PV solar project production over system lifetime lifetime.
Photovoltaics International, Second edition; November 2008.
[2] Gautam NK, Kaushika ND. An efficient algorithm to simulate the electrical performance
of solar photovoltaic arrays. Centre for Energy Studies, Indian Institute of Technology,
Hauz Khas, New Delhi, India; 2002.
[3] Revolutionizing Large-scale PV Projects. InterPV; November 2009, p. 51-55.
[4] From Passive Monitoring to Active Management.InterPV; February 2010, p. 82-87.ww

Tigo Energy, Inc.

P: +1.408.402.0802
F: +1.408.358.6279
www.tigoenergy.com

Headquarters:

420 Blossom Hill Road
Los Gatos, California
U.S.A.

Offices:

Frankfurt, Germany
París, France
Monza, Italy
Tokyo, Japan
Tel-Aviv, Israel

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