Tigo Energy® Smart-Curve™
Application Note

Introduction

Smart-Curve technology from Tigo Energy reduces the maximum operating voltage of each module, by limiting its output voltage using electronic settings.

This enables longer strings, as designers no longer need to rate the strings to open circuit voltage and temperature derates. With longer strings, the electrical balance of systems can be streamlined, requiring fewer combiner boxes, fuses, and home run wiring. Overall, this reduces electrical balance of systems costs by approximately 30%. Additionally, with fewer conductors, the system wire losses are reduced by approximately 0.4%. Finally, this design can raise the average string voltage, giving system and inverter designers more options to reduce cost and increase efficiency.

Functionality

Control Mechanism

The voltage out of each Maximizer is constrained to a pre-defined limit, called "Reduced Voc". The voltage control, keeping the voltage below the Reduced Voc during the course of normal operation, is regulated by Tigo Energy's patented Impedance Matching approach. Thus, the mechanism is provided by a proven hardware architecture already used in hundreds of thousands of units deployed worldwide. See Figure 1 demonstrating the electronic I/V curve of Smart-Curve.

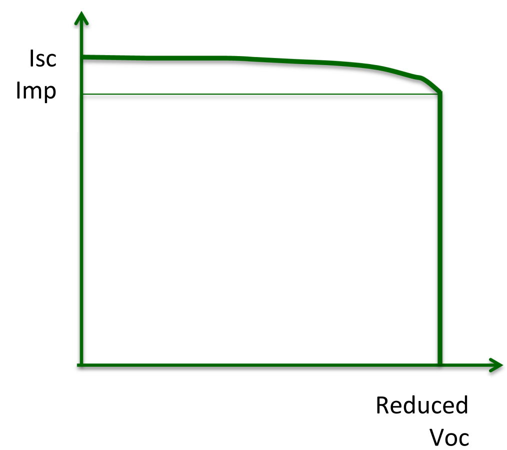

Figure 1: Illustrative PV module I/V curve with Smart-Curve technology

Impact on Module Voltage

The module voltage is independent of the voltage that the Maximizer contributes to the string. So, the voltage potential across a module may still be higher than the voltage limit of the Maximizer (say, on a cold bright morning), but the voltage out of the Maximizer (which is how the string sizing is calculated) will never exceed the pre-set voltage limit. See the block diagram on Figure 2 below. So, for example, the Reduced Voc choice can be below the module's Vmp, without impacting the module's power production.

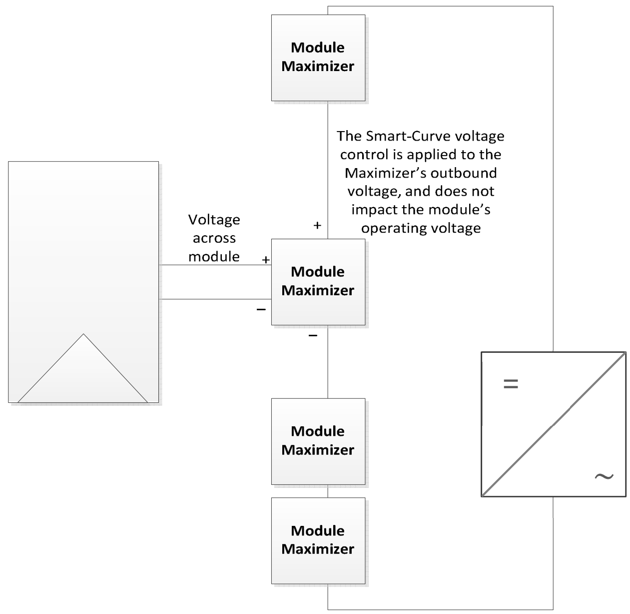

Figure 2: Block diagram of Maximizer and PV module

Behavior under Various Conditions

The voltage limit value does not need to be de-rated for various temperature values. The new Reduced Voc value will be the same at +25C as for -40C. When designing a traditional system one should consider the lowest temperature ever measured in that region, and translate it into a temperature coefficient. This factor can increase up to 30% of module Voc, making the string much shorter than it should be in normal operating conditions. With Tigo Energy, that coefficient vanishes, as voltage is fixed no matter what the ambient temperature is.

Tigo Energy tested the Smart-Curve feature in a temperature chamber. Results show that the unit's output voltage does not vary when it is under load in cold temperatures. Figure 3 displays a snapshot from a four hour soak at -35°C that demonstrates that temperature is not a factor in the voltage output, which is set to 30V in that case.

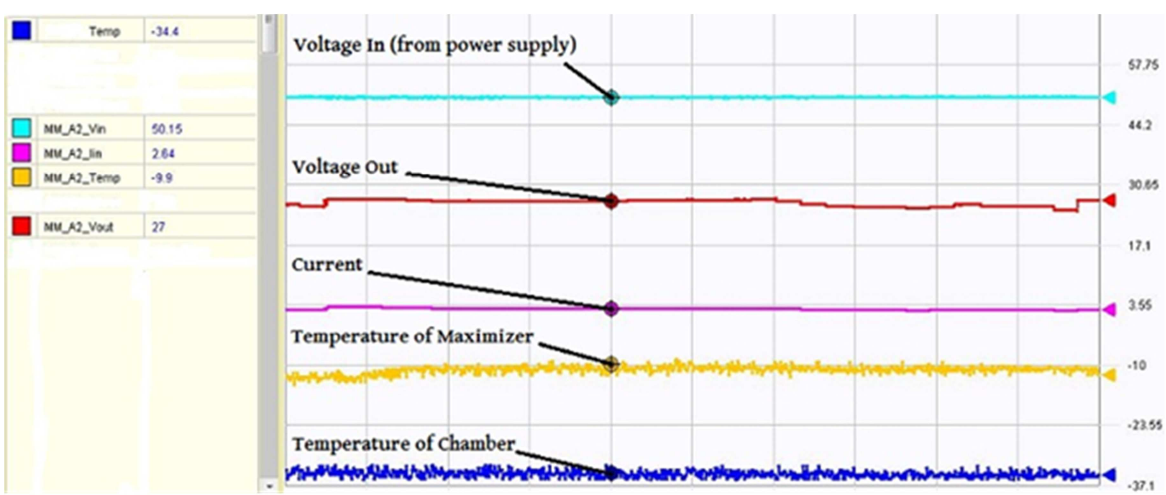

Figure 3: Smart-Curve function tested in thermal chamber for low temperatures

NOTE: This system is operating under MMU control and is therefore attempting to find the power-point of a fixed system, this causes the operating values to be skewed somewhat. Regardless of operational values, output voltage always stays at, or under the set value of 30V.

Plausible Failure Modes

The following graph on Figure 4 shows a PV system's response to various disturbances while maintaining the Reduced Voc. The first incident is a simulated loss of an inverter. When the load is lost, the inverter stalls out, or some other disturbance causes the DC line to go to open circuit, the system will respond by going to the Reduced Voc value. The second incident displays an AC outage event; much like a DC open circuit event, the panels go to Voc, while the Maximizers only allow Reduced Voc to pass through. The third case is the Tigo Energy PV Safe feature. This demonstrates that the Tigo energy system can be deactivated either on site or remotely, thereby shutting the panel voltage down to zero volts while the panel is still producing full Voc.

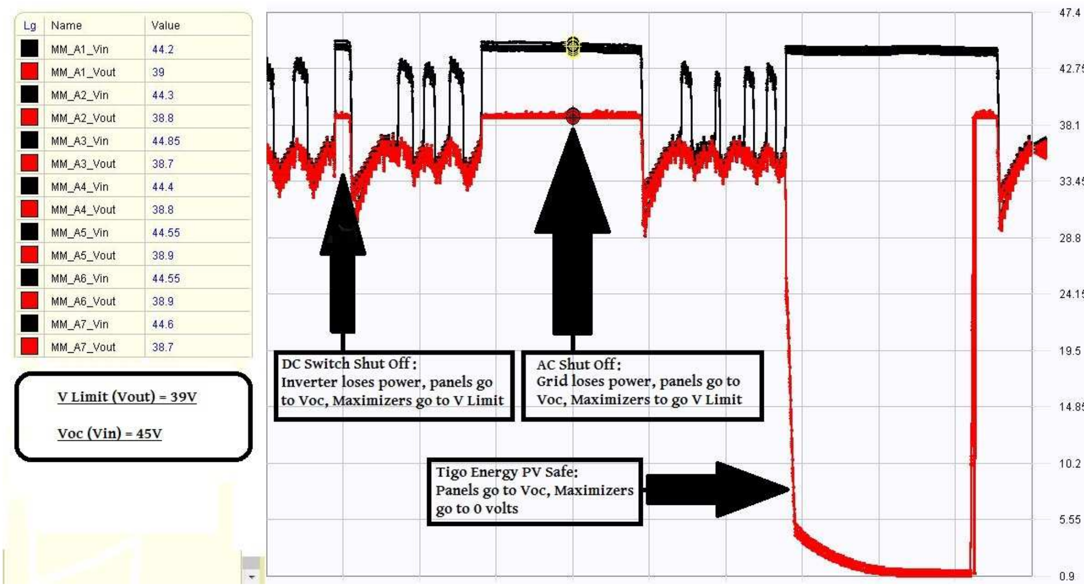

Figure 4: Smart-Curve response to system disturbance

Other failure mechanisms and Smart-Curve feature response are in the following table.

Failure	Response
MMU malfunction	Maximizers will continue to produce power while staying at V limit value
GW malfunction	Maximizers will continue to produce power while staying at V limit value
Grid outage	Maximizers will stay at V limit value
Inverter malfunction	Maximizers will stay at V limit value
Maximizer malfunction	Maximizer will go to 0V (Type A) or Voc (Type B), see details below

Maximizer malfunction have a few possible triggers, and only two possible results. Given failure mode Type A, Maximizer will short the output and disconnect PV module from the string. Other failures modes, Type B, Maximizer will become a traditional non-smart PV module.

In Type A failure, no danger whatsoever to exceed maximum allowed string voltage, as Maximizer effectively disconnects the PV module from the string and therefore that module is not contributing any voltage or current to the string.

In Type B failure, the Maximizer is inactive in a way that doesn't enable it to perform optimization. PV module will be connected to the string as if the Maximizer does not exist, which mean no voltage constrain. PV module will provide voltage that reaches as high as Voc. Vmp/Voc in most PV modules is around 0.8. Tigo Energy sets Reduced Voc at 6% above Vmp, which turns this ratio to 0.94. Maximum Voc allowed for Smart-Curve enabled Jbox is 52V, effectively means that only 7V will be added to the string voltage in case this type of failure occurs. The new design rule with Smart-Curve considers maximum string voltage to be as high as the inverter maximum voltage for MPP tracking. This voltage is averaging around 40V below the allowed maximum string voltage, and in extreme cases goes to minimum of 25V. Adding the 7V resulting from Maximizer malfunction will always leave a safe buffer, and keep string voltage 30+V below the maximum allowed string voltage.

Impact on System Design

With a lower maximum voltage from each module enabled by Smart-Curve, system engineers can install longer strings than possible with traditional system design guidelines. This UL certified Smart-Curve technology provides more flexibility in design (more options for string length), reduces overall string count, and enables a tighter DC voltage range for the inverter.

Note that the Smart-Curve technology does not impact the minimum string sizing, as the Maximizer does not boost voltage.

String Design

The impact on string design is best shown through an example. We will use a typical 72-cell (280-watt peak) crystalline silicon module, in a 600V system application. The module and inverter specifications are given below.

Traditional String Design	Value
Max power voltage (Vmp) at STC	35.2V
Open circuit voltage (Voc) at STC	44.8V
Modules per string (traditional design)	11 modules

With traditional string sizing, the maximum string size is defined as the maximum voltage (600V) divided by the voltage overhead of each module (Voc at the coldest temperature at the installation location). Using a 13% temperature estimator, the voltage overhead for each module is 50.6V, and so strings cannot be any longer than 11 modules (600 / 50.6 = 11.85).

However, with the Smart-Curve technology, the strings get longer. For the module above, Reduced Voc value will be 37.3V. In other words, the Maximizer would prevent the output voltage from ever going above 37.3Vdc, at any insolation or temperature level. Now, the strings could be designed up to the maximum operating voltage of the inverter using the new Reduced Voc. With a typical inverter voltage of 550Vdc, the maximum string length would grow to 14 modules (550 / 37.3 = 14.86). These strings of 14 modules are 27% longer than the 11-module strings in the traditional design.

Smart-Curve String Design	
Inverter’s maximum DC input voltage	550V
Reduced Voc	37.3 V
Modules per string (with Smart-Curve)	14 modules
Improvement in string length	27%

Electrical BoS Cost Impact

To see the benefits of these longer strings on the electrical BoS, we will continue the example with the 280-watt module (similar ratios will be true with most modules).

Assuming a 1 megawatt (DC) array, this will require 3,572 total modules. At strings of 11 (the traditional design), the modules will be wired into 325 total strings. Assuming a 16-pole combiner box, this array will require 21 combiner boxes. With the Smart-Curve technology, the strings can be lengthened to 14 modules each – again, a 27% improvement. This means that the same 3,572 modules can be connected in just 255 strings. Assuming the same 16-pole combiner box, this array will only require 16 combiner boxes; 23% fewer than the traditional array. Furthermore, not only are the combiner boxes reduced, but all the home run wiring, fusing, and corresponding labor are all reduced by 23%. Given a typical electrical balance-of-system cost of approximately $0.20-0.25, a 25% improvement represents approximately $0.06-$0.07 in up-front cost savings from the Smart-Curve technology.

In addition to the electrical system cost reduction, longer strings have a number of other design benefits. They can give system designers more options for string layout, more optimally fitting strings to a given area. For smaller systems, the option to go to longer strings can help expand the system size beyond what a traditional array could address.

Minimum String Voltage

With longer strings, the minimum string voltage also increases. Continuing our example with the standard modules, the longer strings of 14 modules will raise the minimum string voltage to 394Vdc. This compares very favorably to the original string of 11 modules, which would have a minimum string voltage of 309Vdc.

With higher minimum voltages, the inverter will reach turn on voltage earlier and have a longer operating window. Additionally, inverter manufacturers have more options for improving the design and performance of their inverters.

Energy Production Impact

The Smart-Curve can improve the total energy production of the system, when all factors are taken into account. We will describe each factor in detail below.

Power Point Tracking Impact

There is no impact on the module's power point tracking with the Smart-Curve technology. This includes zero impact on the inverter's MPPT algorithm, as well as the Maximizers' Impedance Matching algorithm.

As noted above (see Figure 2), the voltage out of the Maximizer is completely separate from the voltage across the module. So even if the value of Reduced Voc is below the module's Vmp, the module can still operate at its own peak power voltage, while the Maximizer reduces its voltage contribution on the string.

Line Loss

In addition to reducing the electrical BoS cost, the longer strings also improve the line losses, making the energy impact of the system (factoring in the efficiency of the Maximizer System) equivalent to traditional system, not counting the benefits of optimization.

The other benefit of fewer home runs is the fact that the resistive losses of the strings are also 25-30% lower. The current for each home run will be the same in each scenario, but with Smart-Curve there are fewer home runs, and subsequently fewer line losses. With typical line losses of approximately 1.5%, a 25-30% reduction results in a ~0.4% improvement in system efficiency.