Game changers: the rise and rise of 1,500V technology

System architecture | Two years ago, 1,500 volt PV systems were predicted to become the industry standard in the utility-scale segment. Patrick Fetzer of 1,500V pioneer GE looks at how far the technology has come and what further innovations could lie around the corner

Credit: GE Power Conversion

The cost of solar power has plummeted so fast – solar LCOE has come down by some 70% since 2010 [1] – that solar power has already achieved grid parity in many parts of the world. This price pressure is reason enough to fuel innovations across solar plants, such as a shift to higher voltage architecture for achieving system-level cost reduction. And this is indeed what we have seen played out across the market.

When GE launched the world's first 1,500V central inverter in 2012, it was a natural next step for the utility-scale solar market to benefit from the significant cost benefits a voltage increase can bring – just as it had from the previous voltage increase from 600V to 1,000V.

Adopting 1,500V technology for utility-scale solar farms reduces the number of components needed to produce the same power at 1,500V as 1,000V, resulting in a reduction of up to 5% on capex. Supplementary economic savings on operating and maintenance expenditure can also be realised thanks to fewer labour hours needed to maintain fewer inverter units and associated balance-of-system (BOS) components, ultimately bringing value from a long-term opex perspective.

What was once the new kid on the block has rapidly become the industry standard, with 1,000V consigned largely to history for utility-scale solar PV power plants. In 2018 we anticipate more than half of the new central inverter installations for utility-scale projects will be based on 1,500V technology, effecting a tipping point for this now proven technology.

The solar industry has adopted 1,500V as the *de facto* standard system architecture for utility projects

The 1,500V system is already the *de facto* standard system for utility-scale solar projects around the globe, regardless of emerging or mature markets. At GE, we've not only pioneered the technology, we've also been the first to bring it to a range of markets such as the US, India, Japan, Vietnam, Egypt, and Brazil (where we were also the first to obtain BNDES [2] accreditation for 1,500V solar inverters). Today, our global installed base has exceeded 5GW.

Making the shift

We need to remember that new technology cannot thrive in a vacuum – it requires the right infrastructure and environment to support it. So while cost pressures have been a key driver in this recent shift, several other factors also come into play.

Increased plant size

Around a decade ago, the largest size for new plants was 20 to 50 megawatts. This has since increased to the point where it is common to see large utility-scale solar PV projects of over 100MW. This trend towards larger project sizes has enabled the EPCs and developers to capture the full value of the savings on the complete system capex and opex, thanks to the shift to 1,500V systems.

Regulatory changes

A flexible regulatory environment has also been crucial. Over the years, North America's National Electric Code (NEC) has evolved in solar's favour, shifting away from rigid rules to an approach that focuses more on experience and practical application. This flexibility has given companies the freedom to innovate and build game-changing projects – on the condition the finished plant is fully viable. This more flexible regulatory approach has been important for GE, since it effectively lowered the perceived risk of investing in something as yet untested in the field.

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Relevant expertise brings iterative innovation

While 1,500V inverters have been a step change for the solar market, from GE's perspective, this 'new technology' was not, in fact, new. The LV5 1,500V inverters use the same design topology as applied in our proven MV drives – we also leveraged our experience of upgrading LV drives to higher voltages (from 690V to 900V) for the wind market. Bringing proven technology and relevant experience to new applications has allowed us to harness this new technology with less risk.

Technical challenges

While 1,500V technology is hot on the heels of the solar industry, this did not take place overnight.

PID

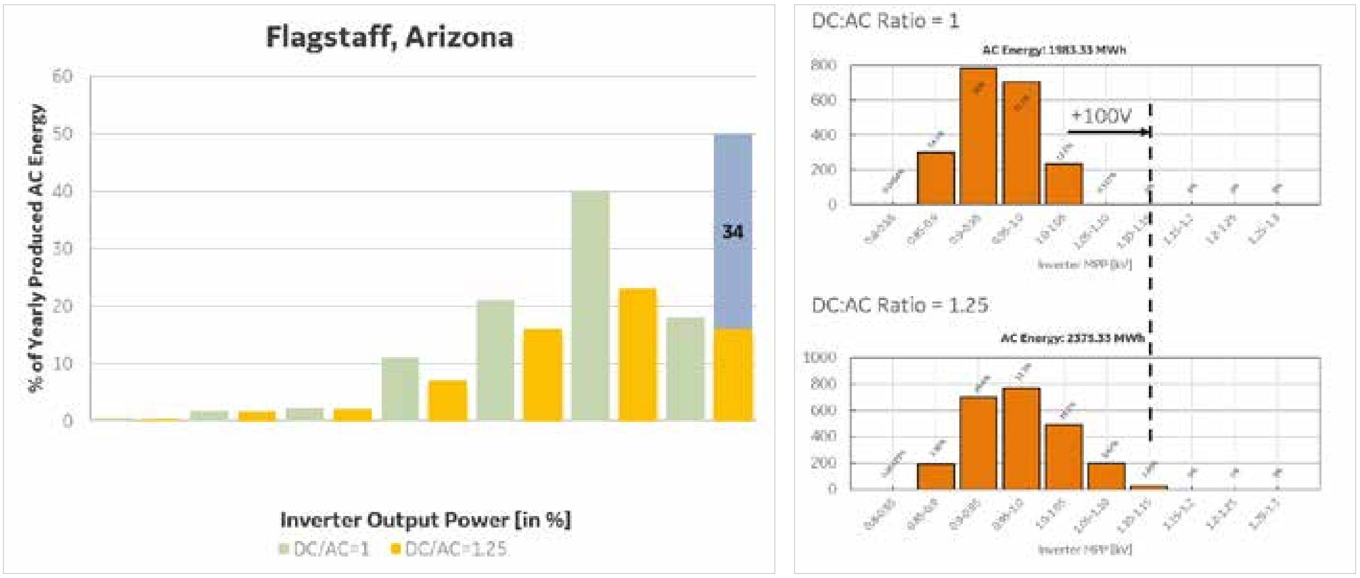
While the industry was becoming increasingly convinced that the shift to 1,500V was one worth making, concerns remained – for example, around the risk of potential-induced degradation (PID). PID is a phenomenon that can affect PV panels and cause up to 80% in power losses. Since PID can be triggered by high voltages, panel manufacturers were naturally wary of 1,500V systems.

However, the availability of anti-PID modules has reassured the industry that, in terms of 1,500V systems, PID is not a cause for concern. Similarly, comprehensive tests have demonstrated that it's possible to reverse the effects of PID during the night using charge equalisers that apply an opposite bias to the inactive panel which cancels out reversible PID.

Inverter performance under high voltage

As costs of panels plummet, plant developers have oversized the PV array to maximise the annual energy production per inverter station, thus DC/AC ratios are on the rise – from 1.1 about five years ago to what will be the highest ratio of 1.7 in 2019.

A DC/AC ratio is the measure of PV power versus that of the inverter – a DC/AC ratio of 1.5 means there is 50% more power available from the array than the inverter can convert into the grid. Higher DC/AC ratios also push inverters to operate at significantly different conditions compared to what they were



Both figures showcase the simulation of a PV plan in Flagstaff, AZ, with a DC/AC ration of just 1.25 compared to a plant with a DC/AC ratio of just 1 in the same location. The figure on the left shows the AC energy produced in percent; the figure on the right shows the AC energy produced in absolute terms.

designed for between five and 10 years ago, when DC/AC ratios were around 1. This results in additional stress to inverters as they are now operating at higher power levels and at full capacity for longer portions of the day.

The increased DC/AC ratio forces inverters to operate away from the Maximum Power Point (MPP) of the array. Instead, inverters move the DC voltage operating point higher to effectively 'clip' the extra energy provided by the PV array. This issue exists in both 1,000V and 1,500V systems, which have higher DC/AC ratios. Since inverters' switching losses are directly proportional to voltage, higher voltage levels result in greater losses and technically lower efficiency than if an inverter were operating at the lower DC voltages of PV plants with smaller DC/AC ratios.

A simulation of a PV plant in Flagstaff, Arizona, with a DC/AC ratio of just 1.25 – compared to a plant with a DC/AC ratio of just 1 in the same location – resulted in higher DC operating voltages (100V), and inverters operating at 100% power while 'clipping' extra energy for 34% of the operating hours in a year.

However, some may argue that if the inverter is at 100% capacity and is in fact clipping extra power, then an inverter's efficiency at 100% power is no longer important. This may be true from an Annual Energy Production (AEP) standpoint. But as the inverter is delivering all the power it can, efficiency still plays an essential role when we examine the wear-out mechanisms of an inverter.

The CEC (California Energy Commission) efficiency weighing factors predominantly favour the 75% loading point – which is weighted with 53% of the final CEC efficiency value we commonly see on inverter datasheets today – while the efficiency at 100% inverter loading only receives 5% weighting. This made sense back in the day when oversizing the PV plant beyond what the inverter could handle was prohibitive due to the high PV module cost, so DC/AC ratios were generally around 1.

Indeed, this CEC weighting was also justified, as when we look back at our Flagstaff, AZ simulation with a DC/AC ratio of 1, 40% of AEP was produced with the inverter loaded around 75% of its full capacity, so naturally the efficiency at that point would be very important to extract maximum value of the PV plant. With a DC/AC ratio of just 1.25, the amount of AEP generated with the inverter at 75% drops from 40% to over 25%, while the percentage of AEP delivered with the inverter near or at 100% capacity jumps from just under 20% to a whopping 50% of all the energy produced in a year.

While it goes without saying that inverter efficiency is still a very important metric, our focus at GE has evolved to the point at which the inverter is performing near or at full-power capacity – and at higher DC voltages due to the clipping effects of higher DC/AC ratios. What's more, it is effectively generating 50% or more of the year's energy under those conditions, compared to just 18% or less a few years ago. Therefore, inverter thermal cycles and the overall higher losses and subsequent generated heat and temperature increases are at the core of our requirements to ensure a more reliable and lasting solar inverter for our customers.

Although higher DC/AC ratios are pushing the boundaries of 1,500V inverter performance to new levels, the advent of DC-coupled energy storage architectures could very well have a reversing effect. As the industry sets its sights on capturing the otherwise clipped energy of high DC/AC ratio PV power plants with energy storage systems connected in parallel to conventional solar inverters, the coordinated operation of solar inverters and battery DC/DC converters will bring the DC voltage operating point back down to the MPP, effectively returning solar to its roots and extracting the maximum available energy from the solar plant.

Upgrade the supply chain

In fact, the main challenge of shifting to this particular innovation wasn't the technology per se, but rather market forces.

For a 1,500V inverter to capture the full benefits of the new technology, you need 1,500V modules and BOS components to support it. Gaining buy-in from the entire supply chain was crucial, so it was gratifying to see tier-1 module manufacturers come on board very quickly, gaining certification and manufacturing 1,500V modules on a commercial scale. In terms of upgrading BOS system components, these have been relatively easy to develop and bring to market.

However, upgrading the ratings takes time and naturally requires industry investment. So while adopting 1,500V technology does eventually offer a capex advantage, the costs of developing the technology when it was initially launched were relatively high. This explains why, in highly price-sensitive markets where capex counts for more than opex, there has been a slow initial take-up. India is one example of this – however, the latest trend for large solar parks has seen the market shifting to 1,500 volts.

Partnership for proof-of-concept

The difference between ideas that thrive long term and those that fall short comes down to the reliability and credibility of the technology when applied to projects in the field and at scale. Fostering partnerships throughout the chain – from developers to end users – was essential for getting the pilot project off the ground. The ultimate goal however, was to unleash this technology at scale – and for that we needed to win the support of technology consultants, certification bodies and investors.

Multiple inverter players were forced to exit the market during the solar industry's rise, and left gigawatts worth of stranded assets. As choosing a lesser-known partner could leave a project with potentially bigger problems down the road, solar companies are also looking at a potential partner's corporate profitability and bankability as well as the sound technical solution they can provide.

GE's century-long history in the energy sector has played a key role in convincing partners to embrace the new technology and co-launch our 1,500V pilot project in the US. This became our proof of concept that demonstrated the cost-effectiveness and overall value that 1,500V technology could bring.

Again, cost

The solar industry's unique cost pressures meant that for 1,500V systems to be viable, they needed to deliver lower cost from day one, which is always a challenge when going up against the de facto standard that already enjoyed a dominant large volume in the market. We saw this as one of our biggest challenges to 1,500V adoption.

Inverter costs are 90% related to the supply chain, so at GE we focus on increasingly standardising our multiple inverter and converter product offering with common building blocks. This delivers a double benefit: first, it drives volume into fewer components, allowing our suppliers to focus manufacturing efficiencies into a reduced component portfolio, thereby reducing supply chain costs. Second, it further streamlines our engineering focus onto fewer components and building blocks which are in turn used in a wider application set. This accelerates continuous improvement as various industrial segments benefit from learnings and enhancements developed from other application areas.

In short, by shifting to the 1,500V standard, the main challenges revolved around commercial availability of the components, long-term reliability and potential technology risks. As we have seen, these uncertainties have been addressed, but also continue to evolve as the industry develops. Nevertheless, there have not been any persistent issues that would be considered a long-term concern.

While the debate over central versus string inverters goes on, GE's product development strategy continues to be focused on reliable, efficient, cost-effective central inverters. That is not to say that there isn't a place for string inverters. However, for large PV plants, we believe that central inverters are more cost effective during the construction and commissioning phase in terms of capex and deliver a better return on investment over the lifetime of the project in terms of opex. What's more, we've been observing a growing trend to both centralise the physical location of string inverters, and increase their nominal power rating. In doing so, the industry is reinforcing that DC power collection is more cost effective than AC power collection – and, that a larger string inverter is potentially more cost effective and delivers better performance than a smaller equivalent unit.

As we look to the future of solar energy, we continue to evaluate higher voltage systems, novel materials, disruptive new power collection systems and opportunities to deliver more value to our customers – with intelligent features that will drive down capex and opex alike.

Is another voltage upgrade on the cards?

There will always be a demand for lower cost of energy, and even higher voltage systems may be one way of achieving this – the history of the solar industry thus far is testament to that. So how high could the voltage go? Developers are already considering the possibilities of moving to over 1,500V systems – essentially combining DC-DC string inverters with a single medium voltage converter – which would deliver an upgrade to 2 to 2.5kV. The attraction is clear: a reduction in losses, higher power single inverters, reduced BOS components and costs – basically all the same advantages that the shift to 1,500V gave. However, this would no longer be classified as 'low voltage' so this MVDC concept may present additional challenges.

Yet while a MVDC configuration would be a more efficient, cost-effective system, there are some significant barriers to upgrading beyond 1,500V configurations. Regulation is one of them. In Europe, rollouts would be limited by the low-voltage limit, which is currently set by the IEC at 1,500Vdc. Going beyond this to 2,000 or 2,500 volts would be classified as medium voltage. This would then subject the technology to an entirely different set of standards, which would significantly increase the cost of development. Moreover, an upgrade to MVDC would trigger the same supply chain constraints experienced in the shift from 1,000 volts to 1,500 volts. In other words, the industry would need to address the challenge of upgrading both modules and BOS components cost effectively and to scale.

There's every possibility that a strong demand for higher voltages would trigger regulatory changes. However, in the short term, 1,500V remains the most enticing prospect and an obvious choice for new solar projects. It all comes down to cost: what is viable is whatever can drive the cost down fast – and a shift to MVDC may not drive this cost down fast enough.

To be sure, the challenge of providing higher and higher value at lower cost is something the industry must continue to overcome. But I believe there are many ways to drive costs down:

Increase inverter size

Across the industry, inverter sizes are getting bigger. While the industry standard sits at around 2 to 2.MW, we're now regularly seeing sizes of 3.5 to 5MW. There are also instances of combining two or more inverters and one transformer together to create a 5 to 10MW megawatt or even larger central solar power conversion stations.

However, there's a limit as to how big these inverter configurations can become. Bear in mind that, so far, the number of panels does not change. So there will come a point when the distance the cabling has to cover to reach the inverter is so great that the resulting power loss eliminates the cost benefit of using a large inverter block. However, we continue to be amazed by the ingenuity of our customers as they continue to push up the centralised inverter megawatt rating from single-digit into double-digit territory, and thanks to our modular LV5+ inverter building block, we're able to deliver on any requested rating.

Improve inverter efficiency

If we do hit a size limit, the next step will be to redirect efforts into pushing the efficiency levels of the inverter itself. This could be achieved through better cooling mechanisms or by developing better semi-conductors, for example. Using new materials is another possibility. Silicon carbide (SiC) takes the best features of diamond, one of the toughest materials in the world, and combines them with the properties of silicon, which is inside every computer and smartphone. Based on the inverter demo tested in the field, it has achieved 99% weighted EU power conversion efficiency – a rating that is unrivalled in the solar industry.

Although introducing disruptive technology like SiC takes time, I'm excited about the prospects this technology will bring once the SiC manufacturing industry scales up to enable a cost-competitive position at commercial scale.

Opex optimisation

While higher plant voltages can improve capex and overall LCOE, additional efforts can be taken to reduce a PV plant's opex when a plant is in operation. For example, by leveraging GE's low-maintenance air-filtration technology developed for our high-efficiency gas turbines, to also reduce or sometimes eliminate air-filtration maintenance in our air-cooled solar inverters.

As a matter of fact, opportunities also exist after sunset. During the night, inverter transformers are normally connected to the grid and consume 'no-load' power from the power grid – which typically costs more than the low PPA rates a site receives today for its PV power generation. These power losses add up to costs over the lifetime of the PV plant.

That is why we have come up with the night-time disconnect feature for the medium voltage step-up transformers in our LV5+ Solar Power Stations. Thanks to the integrated solution with smart controls borrowed from our wind converter experience, the LV5+ Solar Power Station can intelligently connect and disconnect the transformer from the grid during periods without solar power (i.e. during night-time periods). This feature, based on GE's estimates, can save a couple of kilowatts each night per solar power station, ultimately saving up to 15GWh for a 100MW solar plant [3] over its lifespan.

Emerging new tech

Two new developments are transforming the profitability of solar plants right now. The first is in energy storage, with the latest innovations enabling better energy management that increases the plant's operational efficiency. The second is in digitisation – and here's where the effects are potentially far-reaching. Unplanned downtime is hugely costly, and ever-increasing plant sizes are making it harder to locate and identify faulty equipment. Digitalising a plant makes it possible to automatically identify equipment issues before they affect overall performance. As a result, plants can shift to a predictive maintenance model, minimising downtime and reducing maintenance costs in the process. Asset performance management (APM) systems have also made it possible to monitor plants remotely – and run analytics that allow operators to fine-tune assets for optimal performance. The result is higher productivity and lower costs overall.

I strongly believe all of these innovations will happen before any shift to using MVDC system configurations in particular. The potential for these innovations to continue lowering LCOE is great – so great, in fact, that I would question whether there's any chance of MVDC system configurations ever taking off at all. But with clarity on the regulatory requirements for 2 to 2.5kVdc systems and availability of PV modules at these higher ratings, MVDC central inverters could be the next technology shift to contribute in lowering the LCOE of solar. ■

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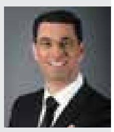

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References and notes

[1] International Energy Agency, 2017, 'World Energy Outlook 2017', https://www.iea.org/Textbase/npsum/weo2017SUM.pdf
[2] The Brazilian Development Bank (BNDES) is the main financing agent for development in Brazil. The Bank offers several financial support mechanisms and enables investments in all economic sectors.
[3] Based on a 100-megawatt plant for 25 years in southern USA.