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Aiming for grid parity on utility-scale solar applications

Kleber V. Facchini,
Eaton Corporation

The next generation of utility-scale inverters—stepping up to reduce the cost of solar energy

Contents

Description **Page**

Executive summary 1
Bankability and warranty 2
Utility-scale solar market trends 2
Larger inverter stations 2
Comparison: Sub-MW solution vs. MW solution 2
Fault-tolerant design. 4
Utility requirements and power factor support 5
Maximize reliability. 7
Liquid cooling 7
Components safety margin 7
Parts count 7
MPPT range operation 7
Conclusion 8

Executive summary

The solar industry in the U.S. and worldwide has had strong growth over the past few years. As the industry has grown, installations have increased in size from commercial projects at a few hundred kilowatts, to utility-scale applications at hundreds of megawatts.

Utility-scale projects will help support a true grid parity reality by increasing the scale of energy production. Grid parity will be achieved from volume production increases, affordable equipment, and deployment of solutions that truly optimize system installation and operation.

Today, commercial-grade equipment is being applied to utility-scale installations. Commercial solutions are being adapted to larger-scale projects without being specifically designed for the challenging requirements in utility-scale solar installations. Consequently, designers and installers are challenged to come up with solutions to shoehorn commercial-grade equipment into utility-scale projects.

By adopting solutions that are specifically developed for large-scale installations (>5 MW), installers can avoid extra costs and help propel grid parity. Further, these solutions can help solar customers optimize balance of system (BOS) costs.

This paper discusses the challenges and cost penalties that utility-scale installers face by using commercial-grade inverters in utility applications. It also examines the new Eaton Power Xpert® Solar inverter utility-scale inverter, which is designed specifically for utility-scale applications to reduce plant levelized cost of electricity (LCOE).

Powering Business Worldwide

Bankability and warranty

Owners and investors of utility-scale projects have millions of dollars invested in equipment, making it imperative that key component suppliers are around for the life of the plant to support the project. Utility-scale projects are expected to deliver 25 years of energy production. The reliability of vendors supporting those projects and the availability of replacement parts are crucial to project success. The best warranty and operating performance do not matter if the manufacturer is not around to back it up.

As vendor bankability improves, financing risk is reduced. This leads to lower financing costs and the viability of a greater range of projects.

Long warranty terms (up to 25 years) are unusual in the traditional energy industry. Typically, equipment warranties in traditional energy industries have a lower period and are supported with a detailed service agreement that includes:

- Equipment monitoring
- Local on-the-ground service personnel (support from local technician pool)
- Scheduled preventive maintenance

Shifting to warranties in the solar industry to mirror those in the traditional energy industry overall will help to greatly reduce up-front costs. Further, it will allow developers and installers to focus resources on a robust service agreement, helping to increase the solar plant life.

Utility-scale solar market trends

To reduce overall plant cost of ownership (or LCOE), utility-scale solar customers are implementing a range of measures to control installation, operations, and maintenance costs, while increasing energy production. Key trends adopted in the U.S. market include:

- Lower installation costs—larger inverters with all-inclusive equipment and stations with integrated transformer
- Lower DC transmission costs with a 1000 Vdc system
- Grid-friendly inverters to meet utility-scale requirements
- Increased plant availability with fault-tolerant equipment and maximum equipment reliability

Larger inverter stations

To reduce installation costs, designers and installers are requiring inverter stations, typically in the megawatt range (>1 MW), to include step-up transformer, AC and DC switchgear, and other ancillary components that may be plant specific (SCADA, power controls, and so on).

It is common to find utility-scale installations that bundle a few sub-MW inverters (<1 MW), step-up transformer, and switchgear to create an MW-range inverter station (ranging between 1.5 and 2 MW). This bundle often requires a metal structure or a skid to hold all the equipment together; the skids and equipment typically range from 35,000 to 70,000 pounds, depending on the equipment and the environmental protection requirements. In addition to being heavy, the skids are ungainly from a transportation and handling perspective.

Eaton developed the Power Xpert Solar 1500 kW inverter to be a megawatt-scale solution to specifically address utility-scale requirements. The Power Xpert Solar inverter is engineered to help installers facilitate integration of additional components on the inverter station without needing a skid.

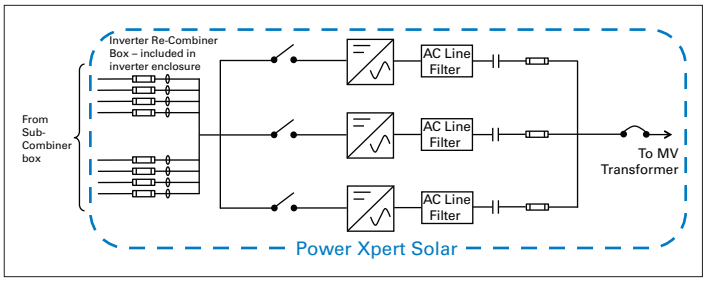


Figure 1. Power Xpert Solar MW Inverter

Figure 1 shows the one-line diagram of the Power Xpert Solar 1500 kW inverter. The 1.5 MW inverter is an all-in-one enclosure that includes equipment from the DC re-combiner box to the AC breaker for connection with the step-up transformer, making it a comprehensive solution.

The inverter includes most of the inverter station components, yielding significant equipment, installation, and handling savings. The Power Xpert Solar inverter includes:

- **Re-combiner box:** The inverter has an integrated re-combiner box that can accept up to 24 DC inputs. Each DC input is fused and includes a current sensor device for optional zone monitoring.
- **Power train section:** The inverter is divided into three power stacks. Each power stack is composed of its own DC switch disconnect, DC/AC converter, AC filter, AC contactor, and AC fuses for protection against catastrophic failure. Each power stack can be individually isolated due to its own DC and AC switches and individually operated for partial-power operation for fault tolerance.
- **AC switchgear:** Industry-leading switchgear provides centralized control and protection of the inverter equipment and circuits. The AC side of the inverter includes a power air circuit breaker that is load-break rated. To enhance safety during maintenance operations and to protect equipment, this breaker provides an extra safety layer on the AC side for fault current capability. The power air circuit breaker can be open/closed remotely and is lock-out/tag-out capable.

The Power Xpert Solar inverter requires one connection between the inverter and the transformer (see **Figure 1**). When multiple sub-MW inverters are used to create an MW-scale inverter station, a special transformer is often required to prevent ground circulating current, or the installation necessitates special switchgear equipment between the sub-MW inverters and the step-up transformer, as the inverters do not include an AC breaker.

Comparison: Sub-MW solution vs. MW solution

A large base of utility-scale projects have used a skidded solution due to a lack of a true MW solution. The Eaton Power Xpert Solar inverter has been engineered to address MW-scale plant requirements.

When a true MW solution is used, fewer parts are required for the inverter station, thus improving system reliability.

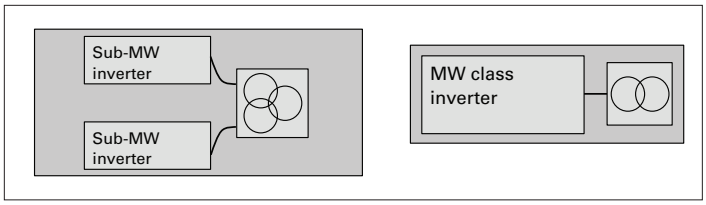


Figure 2. Sub-MW Inverter Solution (Left) and Power Xpert Solar (Right)

Figure 2 shows a skidded solution using sub-MW inverters on the left and the Power Xpert Solar inverter on the right. The dimensions are to scale, so that the footprint area can be compared. The sub-MW installation requires more connections and equipment.

An MW-scale inverter does not require a skid structure; there is only one connection between the inverter and the transformer, and one inverter to install. The following advantages are realized with an MW-scale inverter, such as the Power Xpert Solar 1500 kW inverter:

- Reduced installation time and costs—only one inverter to be installed and one direct connection between the inverter and the transformer
- Shorter lead time—the MW solution needs only a pad-mount transformer
- Reduced equipment space—a smaller pad includes the inverter and the transformer (see **Figure 2**)
- Less equipment—there is no need for AC switchgear between the inverter and the transformer

With one connection between the inverter and the transformer, Eaton designed a throat connection that closely connects the inverter and the step-up transformer (see **Figure 3**). A similar arrangement has been used in Eaton low voltage switchgear for years, yielding a host of advantages:

- Eliminates the use of DLO (Diesel Locomotive) cables between inverter and transformer. For an inverter this size (3000A), there would be approximately 10 x 500 kcmil (Thousand Circular Mils) cable runs per phase and potentially up to 60 lugs
- The connection is made above-grade, so there is no need for cable trenches, reducing the risk of rodents getting into equipment and chewing on cables
- Quicker installation, as the connections are made through busbars and not inside inverters, which may have narrow and small compartments
- An overall cost-effective cement pad solution
- Improvement of overall inverter station efficiency by up to 0.2%

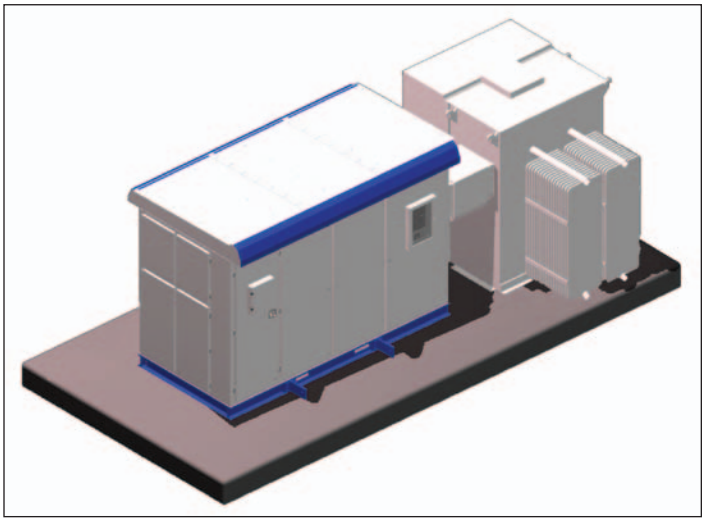


Figure 3. Close-Coupled Solution Between Inverter and Transformer

To demonstrate the advantage of a utility-scale solution that is mounted on a cement pad with a throat connection, **Figure 4** provides a cost comparison between a skidded and a pad-mount solution, using average market pricing. **Figure 4** shows the total cost of equipment, installation, and transportation between the two solutions. The differences in equipment cost largely stem from the skid's metal structure, and price difference between a pad transformer and a special transformer with multiple windings on the low voltage side. When comparing with other solutions, there can be even greater cost differences as these require additional switchgear equipment between the inverter and the transformer.

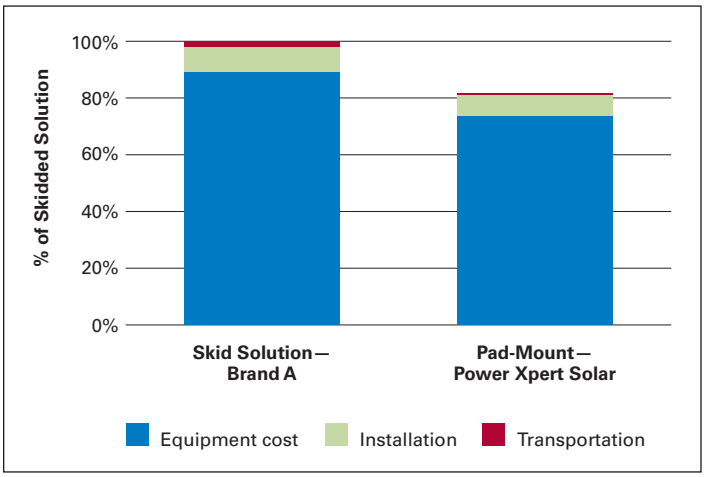


Figure 4. Comparison for a Skidded Solution Using Sub-MW Inverters and Pad-Mounted Power Xpert Solar

A skidded solution is typically used to reduce field installation cost. However, the cost of transportation and installation for the Power Xpert Solar 1500 pad-mount solution is lower than the skidded solution with sub-MW inverters (see **Figure 5**), as an optimized pad-mount MW-scale inverter is used. In other words, a skidded approach reduces installation and transportation costs only when comparing solutions with sub-MW inverters.

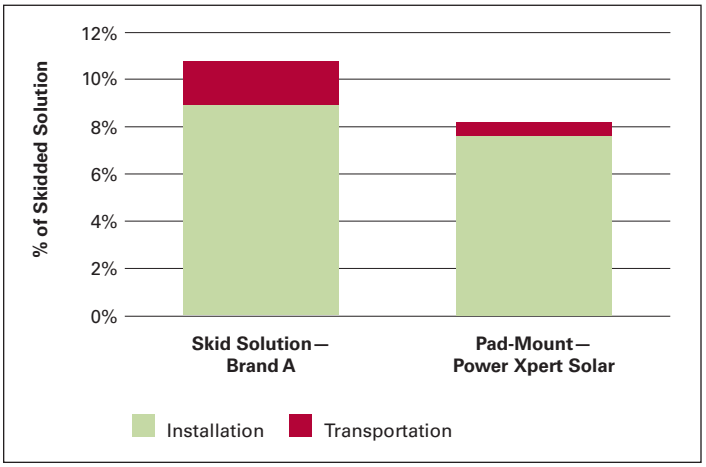
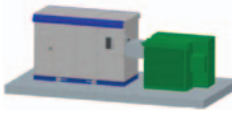


Figure 5. Installation and Transportation Comparison

The Eaton Power Xpert 1500 is doubly advantageous when compared with skidded sub-MW inverters. The Eaton inverter is an inclusive MW-scale inverter and enables installation of the inverter on a traditional cement pad. Further, the Power Xpert Solar (with a total width of 11 ft) enables transportation of multiple inverter units on a single truck.

Table 1. Summarized Comparison Between Skidded and Pad-Mount Solutions

Description	Cost	Equipment Weight (Lbs)	Transportation	Installation	Field Mounting
Skidded	$$$	40,000 to 50,000		40-T Crane	Piers
 Pad-Mount	$	23,000		8-T Boom-Truck	Cement pad

Fault-tolerant design

The Power Xpert Solar 1500 kW inverter has three power stacks (see **Figure 1**). Each one processes 500 kW of power and can be individually isolated and operated. This allows the inverter to operate at partial power in the case of a stack failure. This is critical for isolated solar plants, where parts are not readily accessible should a failure occur. The ability to run the inverter at partial power (if a stack should fail) allows the inverter to capture energy that would otherwise be lost in a non-fault-tolerant design.

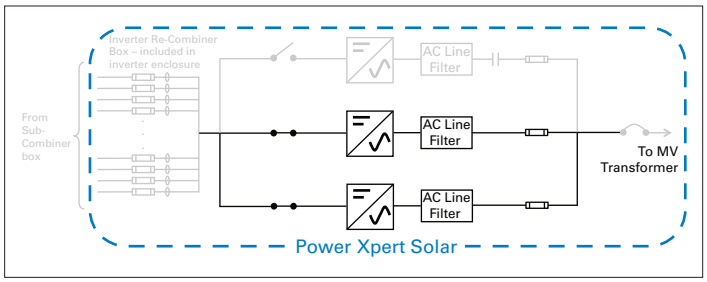


Figure 6. One-Line Diagram Showing Partial Power Operation

Figure 6 depicts how partial power operation is achieved with Power Xpert Solar 1500. If a power stack fails, the DC switch-disconnect opens, breaking both positive and negative DC paths and isolating the DC side of that particular power stack (in this case, the upper stack). The AC contactor also opens to isolate the AC side. In case there is a high current instance from one stack to another due to phase-ground faults, fast semi-conductor AC fuses will clear the fault, protecting the healthy power stacks and avoiding even further damage in the faulty stack.

When sub-MW scale inverters are used to create an MW-scale inverter station, fault tolerance is inherently achieved with multiple inverter units. The inverter units can be individually isolated and operated (see the left side of **Figure 7**). On the other hand, an MW-scale inverter (right side of **Figure 7**) does not achieve fault tolerance inherently because they tend to incorporate larger DC and AC switches and breakers that isolate the entire inverter when open. With MW-scale inverters, the design needs to be engineered to achieve fault tolerance.

The Eaton Power Xpert Solar inverter is designed to allow fault tolerance (see **Figure 6**). However, there are differences between the inherently fault-tolerant design of a sub-MW solution and the Power Xpert Solar fault tolerant design. The main difference is in the way the solar array is subdivided and connected to the MW-scale inverter station.

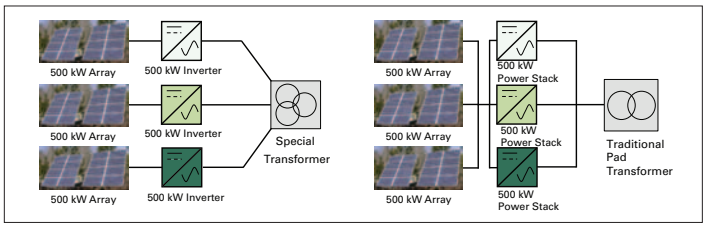


Figure 7. Sub-MW Solution (Left) and Power Xpert Solar (Right)—Fault Tolerance

Figure 7 shows a 1.5 MW solar array that is subdivided and connected to a 1.5 MW inverter station composed of sub-MW inverters (left) and one composed by the MW-scale Power Xpert Solar inverter (right). Note that for the case with the sub-MW inverters, the 1.5 MW array is subdivided into three 500 kW arrays; in this case, each 500 kW inverter is connected to one-third of the array. On the other hand, when using the Power Xpert Solar, the array is not subdivided and all the home-run cables of the array connect into the inverter re-combiner box, and power is distributed internally to the three power stacks.

If one 500 kW inverter fails, the system automatically loses access to one-third of the 1.5 MW array, making it a 1 MW array. On the other hand, using the Power Xpert Solar inverter, if one power stack fails, the system still has access to the full 1.5 MW array. This scenario is better shown in **Figure 8**.

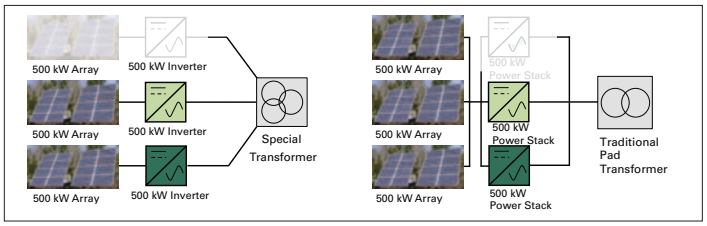


Figure 8. Resultant Scenario Upon Failure of One-Third of Power Processing Capacity—Sub-MW Solution (Left) and Power Xpert Solar (Right)

Note that the Power Xpert Solar 1500 inverter has the ability to optimize power from the entire array, even with a power stack failure (see **Figure 8**). A sub-MW solution, however, is not able to optimize power from the entire array, upon failure of one-third of processing power.

In order to better quantify this advantage, consider the following hypothetical situation for the same array shown in **Figure 9** and **Figure 10**, assuming that in a given day there is only 900 kW of peak power and that the 1.5 MW inverter station loses one-third of its power processing capacity.

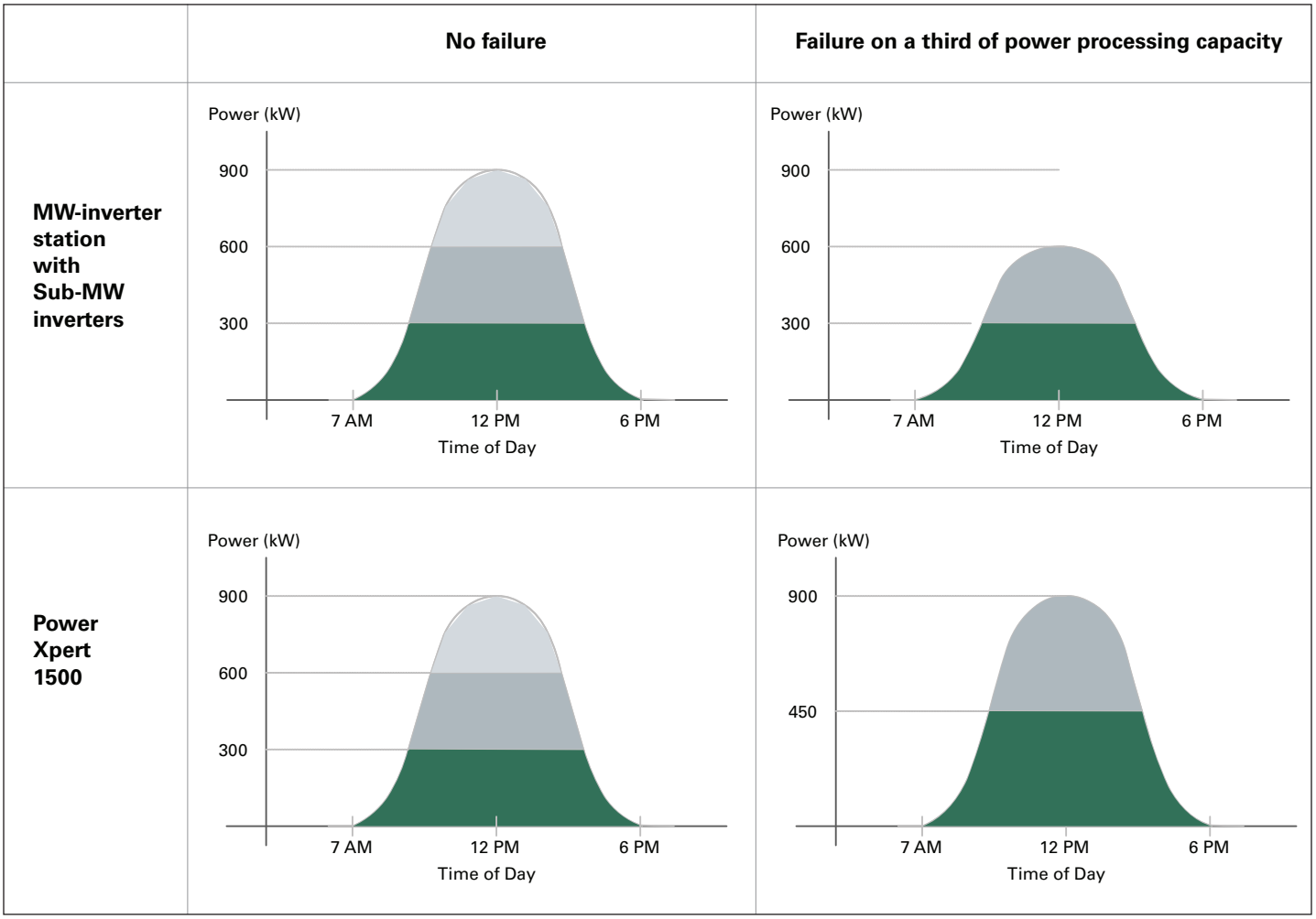


Figure 9. Power Production Upon One-Third Power Processing Failure

Figure 9 compares the difference of power production (and energy harvest) between sub-MW inverters and Power Xpert Solar MW-scale inverter. Note that in the latter, there is no loss of power production upon loss of one-third of power processing capability, whereas with a sub-MW inverter solution, the system is capped at 600 kW, as the sub-array connected to the failed 500 kW inverter is completely untapped and is not producing power. **Figure 10** shows the energy harvest improvement with an MW-scale inverter (blue shaded area), such as Power Xpert Solar fault tolerant design.

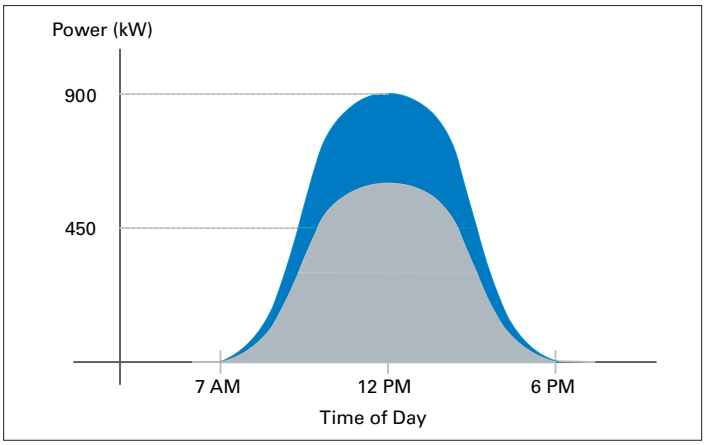


Figure 10. Energy Production Improvement When Using Power Xpert Solar 1500, for the Scenario in Discussion

Utility requirements and power factor support

Utility companies are looking for renewable power plants to work similarly to conventional plants, which typically use a synchronous generator. This means that there is an increased pressure for solar plants to meet interconnection requirements with regards to voltage and frequency disturbances and reactive power support.

The Power Xpert Solar optimized ride-through capability sustains a zero voltage event up to one second, and meets the prominent code requirements in place in the U.S., to name a few: California Independent System Operator (CA-ISO), North American Reliability Corporation (NERC) and Electric Reliability Council of Texas (ERCOT). See **Figure 11** for some of the voltage and frequency ride-through requirements in the U.S. and Power Xpert Solar inverter capabilities.

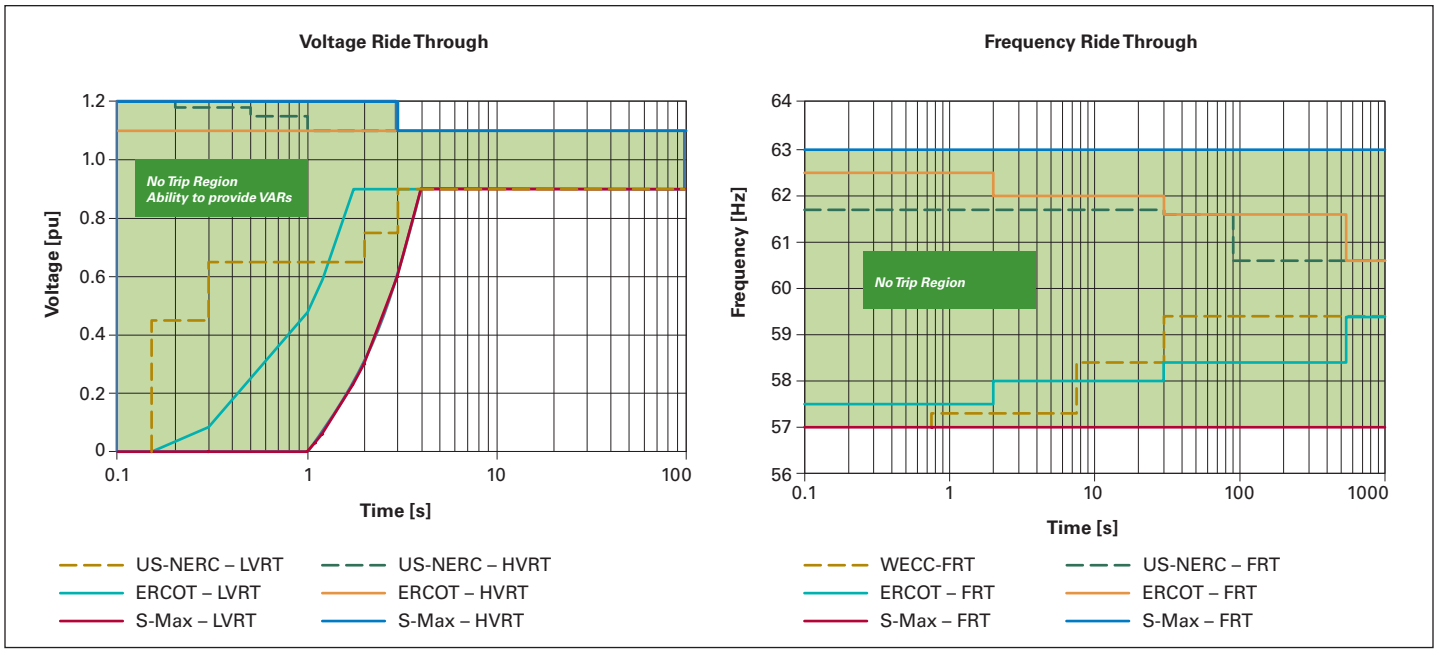


Figure 11. Voltage and Frequency Ride-Through Requirements for CA-ISO and ERCOT and Power Xpert Solar 1500 Capabilities

Providing reactive power support at rated power is also critical. The Power Xpert Solar 1500 kW inverter supports up to a ±0.91 power factor range at full power (full MW). When power factor support is required, this is crucial to keep installation costs in check.

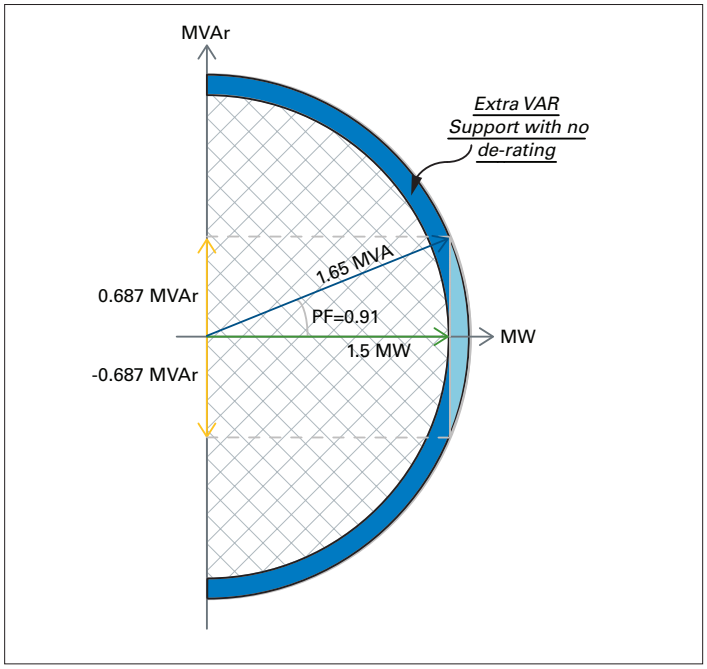


Figure 12. Inverter Power Characteristic Curve—Power Factor Support and Inverter Apparent Power Capability

Figure 12 shows the power capability for both active and reactive power of the Power Xpert Solar 1500 kW inverter. From the figure, the capability of the inverter is such that it simultaneously sustains:

- 1.65 MVA
- 1.5 MW
- ± 687 kVAR

In other words, there is no inverter de-rating for reactive power (VAR) support (up to a ± 0.91 PF range). Some solutions rate the inverter at unity power factor, thus a power de-rating occurs if any power factor support is needed. So, in order to truly compare Power Xpert Solar 1500 inverter with other inverters in the market, the following calculation is useful:

- True $MW=P_{@PF=1}*PF_{operational}$
- Power Xpert Solar 1500 kW inverter yields:
  True MW=1.65 MVA*0.91=1.5 MW
- Typically, the following is true: True MW=1.5 MVA*0.91=1.36 MW

Therefore, when comparing inverters for a project that needs power factor support, based on the above equations, it is concluded that Power Xpert Solar 1500 inverter yields 1.5 MW at ± 0.91, whereas others yield 1.36 MW at the same power factor level (± 0.91).

To further illustrate this advantage, consider a hypothetical example of a 20 MW solar plant to be installed in California or Arizona (under CA-ISO or APS jurisdiction), which must meet ± 0.95 PF support at POI (Point of Interconnection). The designer of this plant will need to address the PF support requirement by means of reactive equipment support (STATCOM, shunt reactive banks) or size the solar inverters accordingly to provide the needed reactive power at the POI. The total needed VARs at point of interconnection (POI) (not considering collector losses) for this example is about 6.6 MVAR ($20\ MW*\tan(\cos^{-1}0.95)=6.6\ MVAR$).

If the designer is using Power Xpert Solar inverter for this plant, a calculation shows that there will be about 13 inverters on this plant (20 MW/1.5 MW), with a total VAR capability of 8.93 MVAR (0.687 MVAR * 13). Therefore, meeting the needed VAR support at the POI for this example, with a 2.3 MVAR of spare to address collector reactive losses.

On the other hand, if the choice is to use inverters that do not have VAR capability at full rated power, there will be a need of about 14 inverters (20 MW/1.5 MW*0.95) with a total VAR capability of 6.9 MVAR. Therefore, an extra inverter station is needed. Another inverter station includes inverters, transformers, associated AC and DC switchgear, and a skid if using sub-MW inverter solution.

Typically a plant also needs to overcome AC collector reactive losses, so there would be a need for more than 6.6 MVAR in order to meet the requirement of ±0.95 at POI.

Maximize reliability

The reliability of a solar plant is directly connected to its equipment life and robustness. Plant operators indicate that inverters often cause downtime in a solar plant. In order to increase reliability for solar inverters, parts count should be reduced and the design safety margin of the components must be increased.

Power Xpert Solar 1500 inverter has been designed to address parts count reduction and increased design safety margins on its components:

1. Liquid cooling reduces footprint, number of fans, and insulated-gate bipolar transistors (IGBTs)—better thermal management increases the usage factor of a specific device.
2. Enclosed controls and power electronics in a dust-free environment.
3. Significant design safety margins for components (switches, capacitors, IGBTs).

Liquid cooling

Cooling methodology varies among suppliers and somewhat depends on inverter size. Small inverters tend to be air cooled. As power levels increase, the benefits of liquid cooling come into play. Liquid cooling can more effectively maintain optimum component temperatures. In utility-scale applications where high ambient temperatures are more common, liquid cooling can increase component life (and thus reliability), which offsets a small increase in upfront costs for liquid cooling.

Air cooling requires moving massive amounts of air, and greater airflow results in larger amounts of debris. Liquid cooling is more effective at reducing debris buildup both in the filters and the inverter's interior compartments.

Beyond increasing component life, liquid-cooling systems also tend to last longer. Properly rated pumps can replace multiple fans (present in air-cooled systems), dramatically decreasing parts count.

Components safety margin

Well-designed components are key to supporting inverters slated to operate in desert conditions for the next 25 years. Otherwise, failures and nuisance trips can occur, jeopardizing energy harvest. Conservatively rated components in the Power Xpert Solar inverter are designed to withstand harsh environmental conditions.

Table 2 shows the design criteria and associated design margin for the components included in the high current path. These are the components that will work the hardest, as they will experience full inverter rated voltage and current while subjected to extreme weather conditions.

Table 2. Power Xpert Solar 1500 Inverter Components Design Criteria

Component	Design Criteria / Safety Margin	Operated at
DC switch disconnect	Rated at 1500 Vdc	850 Vdc operational
	Load break capability up to 4 times rated current	1000 Vdc open circuit
	Breaks both positive and negative polarities	Opens/closes upon critical faults and inverter service (seldom operation)
	Rated for 10,000 operations	
DC bus capacitors	Film type	850 Vdc operational
	Rated at 1200 Vdc	1000 Vdc open circuit
	Protected by NEMA® 4 cabinet (water and dust free)	
	Cooled by liquid cooling loop	
IGBTs	Rated at 1700 Vdc	850 Vdc operational
	Rated at 150°C maximum Tj	1000 Vdc open circuit
	Protected by NEMA 4 cabinet (water and dust free)	Maximum Tj of 100°C
	Liquid cooled	
AC contactor	Rated at 600 Vac	320 Vac operational
	Rated for 5 million operations	Opens and closes on a daily basis
AC capacitor	Film type	320 Vac operational
	Rated at 525 Vac	66% current margin
	Internal fuse for protection—fail open in case of high current/temperature	
AC breaker	Rated at 600 Vac, 3200A	320 Vac operational
	Eaton power-air circuit breaker	3000A maximum
	Load break capability up to 4 times rated current	Opens/closes upon critical faults and inverter service (seldom operation)
	Rated for 15,000 operations	

Parts count

A liquid cooling system keeps internal parts cooler, enabling a higher usage factor and reducing the number of parts. For instance, Power Xpert Solar inverter uses fewer IGBT devices, as its cooling efficiency is higher than an air-cooled system. In an air-cooled system, there will typically be more IGBT devices as current needs to be kept lower per IGBT device, due to the low cooling efficiency of an air-cooled system.

The Power Xpert Solar inverter also reduces the amount of components and connections on the inverter station without requiring special multiple winding transformers. Higher-inverter station reliability is an added benefit of having a higher power density system.

MPPT range operation

The Maximum Power Point Tracking (MPPT) range of an inverter directly impacts plant energy harvest, as this will dictate how long the inverter stays online during the day and also its point to shut-off upon abnormal conditions, such as extreme irradiance. The wider the MPPT range of a given inverter, the higher the energy harvest, especially in hot climates.

Conclusion

Solar inverters are crucial to the success of utility-scale solar installations. Designers and installers have been using commercial-grade inverters for utility-scale plants due to a lack of robust, utility-scale equipment. Yet, a MW-level, utility-grade inverter can help reduce overall equipment, installation, and commissioning costs.

The following hypothetical example is useful to better understand the full advantages in a utility-scale plant using Power Xpert Solar 1500 kW inverter.

- Plant size: 20 MW
- PF requirement at POI: ±0.95
- Grid requirements: CA-ISO requirements for plants above 20 MW
- Solution A uses inverter stations with skidded, sub-MW inverters, and solution B uses Power Xpert Solar 1500 inverter

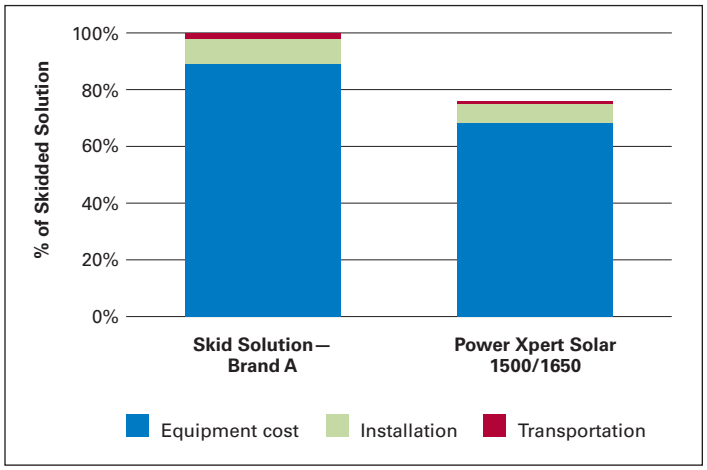


Figure 13. Cost Advantage When Using Power Xpert Solar Inverter

Figure 13 shows the cost advantage of using Power Xpert Solar 1500 inverter. The cost advantage of utility-scale Power Xpert Solar solution is roughly 25% when compared with a solution with skidded sub-MW inverters, due to:

- Fewer inverter stations (inverter and transformer)
- No inverter de-rating for power factor support
- Savings introduced by usage of pad-mount and throat connection design

Table 3. Power Xpert Solar Inverter Features and Its Contribution to Lower LCOE

Description	CAPEX (Capital Expenditure)	OPEX (Operating Expenses)	Energy Yield (Energy Produced)
1.5 MW block and true 1000 Vdc operational capability	▼		▲
Traditional pad-mount transformer	▼	▼	
Eaton's AC and DC portfolio BoS solution—"one stop shop"	▼	▼	
Integral liquid-cooled design	▼	▼	▲
Design for service and Eaton's comprehensive field support		▼	▲
Remote connectivity	▼	▼	▲
High efficiency (98% CEC, including ALL auxiliary losses)	▼		▲
Fault tolerance (ability to operate at partial power)		▼	▲
Components operation margin		▼	▲

Table 3 summarizes Power Xpert Solar inverter features designed to help lower the LCOE of a plant. Power Xpert Solar inverter allows developers, installers, and owner/operators to optimize costs and reduce the price of energy. The market is on a run for grid parity, and true utility-scale solutions like the Eaton Power Xpert Solar inverter are crucial to that end.

Eaton Corporation
Electrical Sector
1111 Superior Avenue
Cleveland, OH 44114 USA
Eaton.com

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