

*This paper considers performance, reliability, and regulatory aspects of three-phase grid-tie photovoltaic (PV) inverters and the arrays to which they are connected, with an emphasis placed on systems greater than 100 kW.*

*Development of this class of equipment for the North American market over recent years has resulted in a set of commonly encountered characteristics. These attributes, while acquired through experience and adversity, have led to the present-day condition in which the dominant indices of performance, particularly energy efficiency, have plateaued. While many of the design improvements discussed here have at one time been proposed and even attempted (and often subsequently abandoned), this paper describes the benefit of combining a number of advancements at once and the resultant step forward in improved performance.*

## PV Systems in North America

While high-power PV installations certainly vary in configuration, a typical commercially installed system (Figure 1) consists of the following:

- *PV modules stacked in strings not to exceed 600 V open-load, referenced to ground on either positive or negative leg*
- *A UL1741-certified inverter whose function, in addition to converting direct current to alternating current, is to act as an autonomous generating station; This includes functions as varied as optimally extracting energy from the array to assuring National Electric Code (NEC)-compliant operation for the entire facility.*
- *An isolating transformer to provide galvanic separation of the PV facility from the electric utility, in addition to voltage ratio-changing (This may, or may not, be provided integrally with the inverter.)*
- *Point of common coupling (PCC) to the utility, which may be either a low-voltage ( $\leq 600$  V) distribution system of arbitrary size (with any type or quantity of three-phase appliances) or a dedicated connection to the low-voltage secondary of a medium-voltage utility transformer*

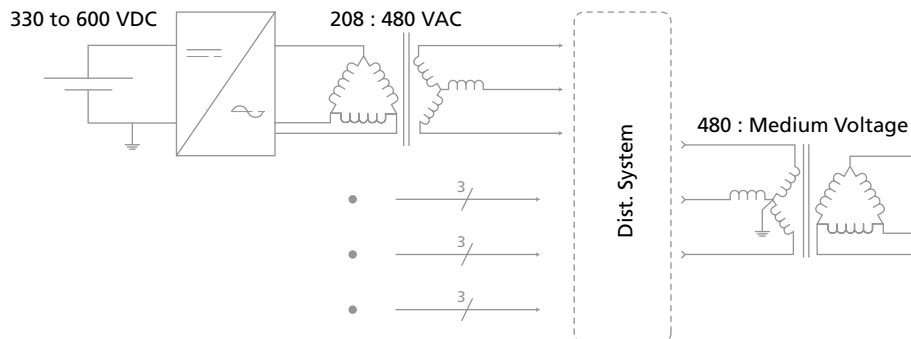


Figure 1. Conventional PV-distribution system connection

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## Possible Improvements

When considering possible performance enhancements for the aforementioned system, one improvement is to remove the transformer. Transformers of this size consume between 1 and 2 points of efficiency. Additionally, they are physically large and, in recent years, ever-growing in cost. However, their removal from the systems described in Figure 1 provides certain challenges. Firstly, their ratio-changing function is quite important. Optimally-loaded PV operational voltages on a 600 VDC limited system run from typically 300 to 500 VDC. Distribution systems in North America that are capable of accommodating these power levels are almost always 480 VAC. The respective DC voltages are far too low to allow direct inversion into 480 VAC. The actual inversion voltage is usually 208 VAC. A high-power, transformerless 208 VAC three-phase inverter is only of use on a relevantly sized 208 VAC distribution system. Such a system requires immense amounts of conductor. (It also requires all other appliances to be 208 VAC-configured). As one would expect, such high-current, low-voltage distribution systems are rare and unlikely to be built purely for the convenience of a PV inverter.

The second challenge associated with removing the transformer is that of proper array referencing. That is, how does one properly reference the PV array (and all its DC distribution equipment) to ground and what voltages and currents are present? There are many ways to get this wrong, and the PV industry is replete with examples of those who failed while trying (with the stories usually ending with multiple, adjacent non-isolated inverters “fighting one another” shortly before failing spectacularly).

As a result, the removal of transformers from commercial PV systems has largely been limited to the following special case. When the PV system and its inverter are so large as to warrant a dedicated and direct connection to a medium-voltage utility transformer as shown in Figure 2, then the ordinarily integrated transformer may be removed from the inverter, leaving just the utility transformer to provide the PV array with all the required isolating characteristics, as shown in Figure 3. This improvement is an important loss-reduction effort, but makes the inverter’s “transformerless” distinction one of merely “less transformers” (as in fewer), not truly “no-transformers.” What ultimately is desired is a system in which an arbitrary number of PV inverters may be placed adjacent to one another (and any other equipment) without the presence of any transformers.

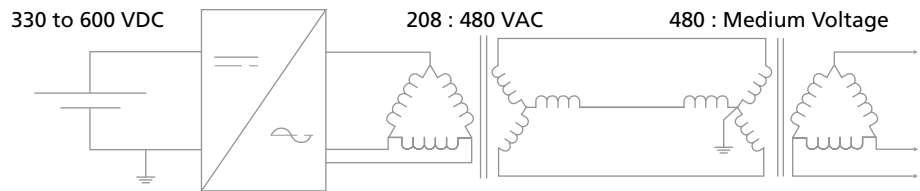


Figure 2. Dedicated PV-utility connection

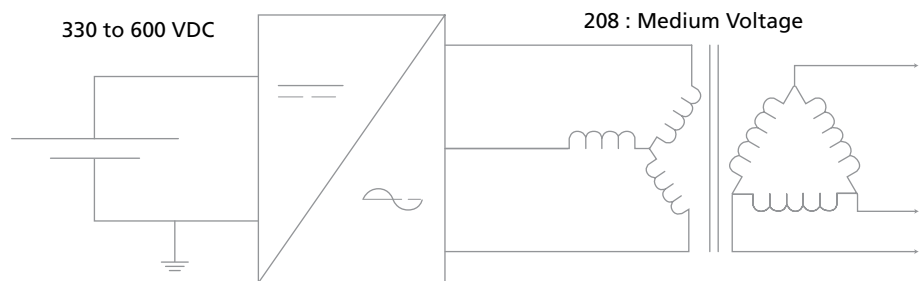


Figure 3. Reduced transformer dedicated PV-utility connection

Aside from eliminating transformers, another likely improvement to commercial PV arrays is to go to higher PV voltages. This would, depending on how the array were wired, reduce DC-side conductor costs and losses. However, under traditional ground referencing of either the positive or negative rail, any increase in voltage would exceed the 600 VDC limits on low-voltage equipment. Given the healthy step in cost to go to medium-voltage equipment, this apparently makes modest PV-voltage increases on traditionally referenced arrays not particularly useful with regard to cost reduction and operational performance.

However, were one to ground the center of a PV array in a “bipolar” configuration, it would be possible to double overall PV voltage before violating NEC low-voltage limits. Even with the previously described benefits, this configuration has never achieved prominence, perhaps due to a lack of interest in pursuing higher-voltage designs among suppliers of inverters.

Coming back to the idea of combining historically proposed, yet seemingly separate improvements, it can be seen that one useful aspect of increasing PV array voltage is to allow for direct inversion into 480 VAC. Once this is done, the ratio-changing function of the transformer is eliminated. At this point, one question remains prior to removing any and all transformers from the PV facility: Can the array be ground-referenced in a way as to avoid having “bad things” happen?

Figure 4 shows such a system with a bipolar-configured array. The intent of this configuration is to provide 1200 VDC maximum differential open-load voltages that do not exceed the 600 VDC-to-ground NEC limits. While processing power, PV array ground referencing comes from a star-point ground on the AC distribution system through the switching action of the inverter. Such an architecture requires a thorough understanding of the inverter’s “common-mode,” or voltage-to-ground, characteristics. Consequently, a truly transformerless PV inverter has a fair amount of additional apparatus and logic not previously seen in transformer-based inverters.

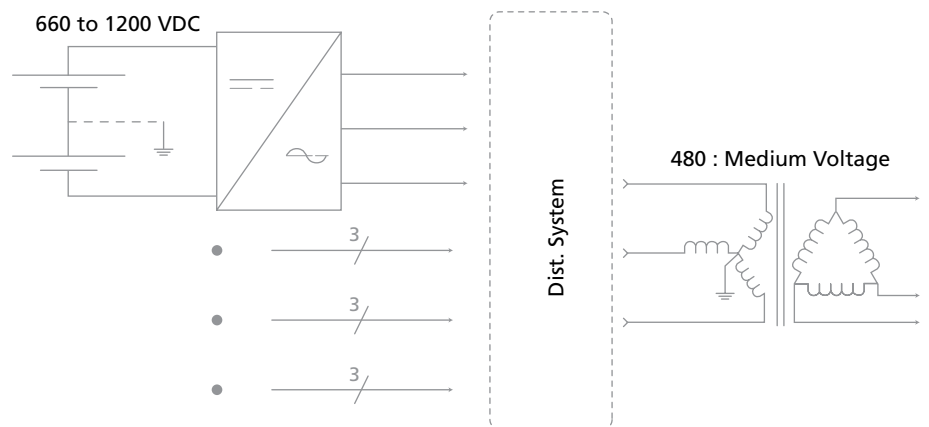


Figure 4. Bipolar transformerless PV-distribution system connection

## High-Voltage Design and Reliability

One benefit conferred by a successful bipolar transformerless configuration is much better efficiency. Of course, efficiency is not the only concern. A classical and reasonable interpretation of competing design constraints does suggest that designs so tailored for one element (in this case efficiency) might suffer in other areas, such as reliability. The effort to prove that this is not necessarily the case brings us to another historically relevant proposal.

Liquid cooling has a less-than-wonderful reputation in the North American PV industry due to past failed designs. Despite the constant and pervasive reminder from the automotive world, liquid cooling remains largely un-adopted.

In what must surely seem to be a completely separate issue, industry-recommended reliability improvements for inverter designs have repeatedly suggested ending the reliance on one component especially: electrolytic capacitors. These not-particularly robust components have remained attractive for their large capacitance and low cost. Physically large inverter bus work layouts, as are often seen in air-cooled designs, require a great many capacitors distributed over their surfaces. Electrolytic capacitors offer a cost-effective solution to the need for distributed, high-capacitance designs, and are prevalent in both North American and European equipment.

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Liquid-cooled cold plates, with heat-removal capabilities far exceeding that of air-cooled heat sinks, allow for physically compact inverter layouts with a vastly reduced number of capacitors (sometimes just one). With reduced numbers comes the budgetary latitude to purchase high-performance film capacitors. The reliability benefit is twofold: elimination of the electrolytic capacitors themselves and engine parts-count reduction.

More importantly, a physically compact, liquid-cooled inverter allows for low levels of “parasitics.” These undesirable and at some level unavoidable physical characteristics limit the performance and reliability of switching devices by causing transient voltages during switching. Low-parasitic design (a consequence of the physical compactness made possible by liquid cooling) allows for selection of efficiency-optimized switching devices without the high-transient over-voltages and resultant low reliability seen in larger engine layouts. Advanced cooling techniques not only allow for the removal of the suspect electrolytic capacitors, but also permit the use of higher voltages with efficient switching devices, which in turn allow for transformerless operation. As stated in the introduction, by adopting many simultaneous design advancements in combination, we are able to realize substantial benefits relative to any one of them. Efficiency, in this case, need not come at the expense of other design constraints, such as reliability.

## Other Design Characteristics

As in other power-conversion applications, one of the fundamental choices a PV inverter designer faces is that of switching frequency. The choice of switching frequency permeates almost every aspect of performance. For PV inverters, this includes efficiency, cost, ripple rejection, size, control stability, audible noise, and utility-connection performance.

The conventional wisdom that higher frequency is better does generally hold true for PV inverters. However, characteristics of the high-power PV application have conspired to hold historical switching frequencies at relatively low values, usually below 10 kHz. The reasons for this are many, but often were driven by the large IGBT modules employed on air-cooled designs. These modules, when switched normally (hard switched without additional soft-switching apparatus), lead to relatively high dynamic losses (losses during turn on and turn off). Additionally, the large base plate area of these modules (on the order of 6 by 6) causes asymmetric heating of the many die placed internally—propagating the use of otherwise larger-than-necessary modules due to thermal-margin concerns. Aside from thermal margin, efficiency concerns often dictate the selection of operating frequency in an effort to limit loss.

At this point, the troubles for a designer saddled with relatively low switching frequency are just beginning. *Line reactors* are the series inductors that reside on the phases between the inverter and the utility as the leftmost inductors shown in Figure 5. As an essential design element, they serve several purposes—one of which is to minimize the injected ripple current to the utility. Injection of high-frequency currents into the power system is undesirable (to put it politely), and can cause numerous problems for utilities and their customers.

Line reactors are heavy, expensive, and lossy. Ideally, one would choose one of high inductance in an effort to minimize ripple levels and core loss. Unfortunately, switching frequencies below 10 kHz present a sort of “no man’s land” for elegant magnetic design. The switching-frequency current ripple, and therefore core-flux ripple, is simply too high to affordably block with the line reactor alone. The usual solution is to go with a relatively low-inductance line-reactor design, suffer a majority of the consequential loss in the form of high-frequency heating, and make up the rest of the ripple-reduction task with other filter elements. Those other elements are shunt capacitors (usually connected in delta) and another inductor. The three elements make up an LCL filter as shown in Figure 5.

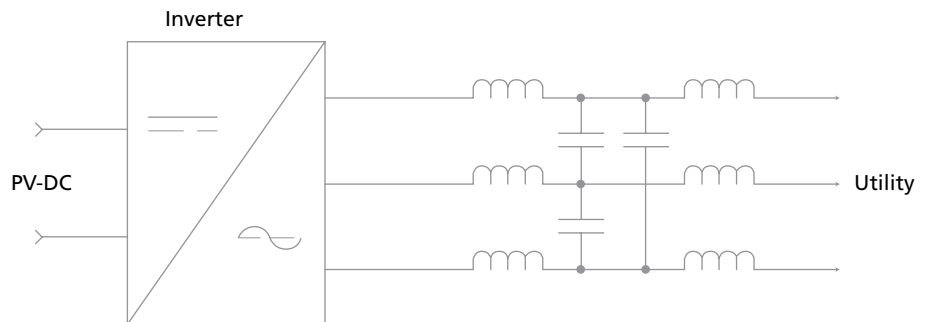


Figure 5. LCL ripple-rejection filter

The capacitors that comprise the “C” of the LCL filter, in an effort to maximally attenuate the effect of high-ripple currents on the power system, historically have been large, occasionally approaching a milliFarad. Line-frequency current is only kept to barely reasonable levels by the fact that the capacitors are operating at 208 VAC—such capacitances at 480 VAC would result in absurdly high currents. It is worth noting that even if an inverter is itself operating largely free of harmonics, other harmonic sources in the distribution system can load up these capacitors with harmonic currents (such as can happen to deliberately applied power factor correction capacitors).

The second “L” in the LCL filter is required to complete the ripple-rejection recipe. It is often provided by the leakage inductance of the integrally provided transformer. Adding to the already substantial difficulties of removing transformers from old PV inverter designs is that, without the transformer, some other magnetic component must be put in its place.

A typical admittance-gain curve for an LCL filter whose inverter is operating at 7 kHz is shown in Figure 6. The attenuation level of ripple currents created from the high-frequency applied voltage of the inverter is shown with the vertical line.

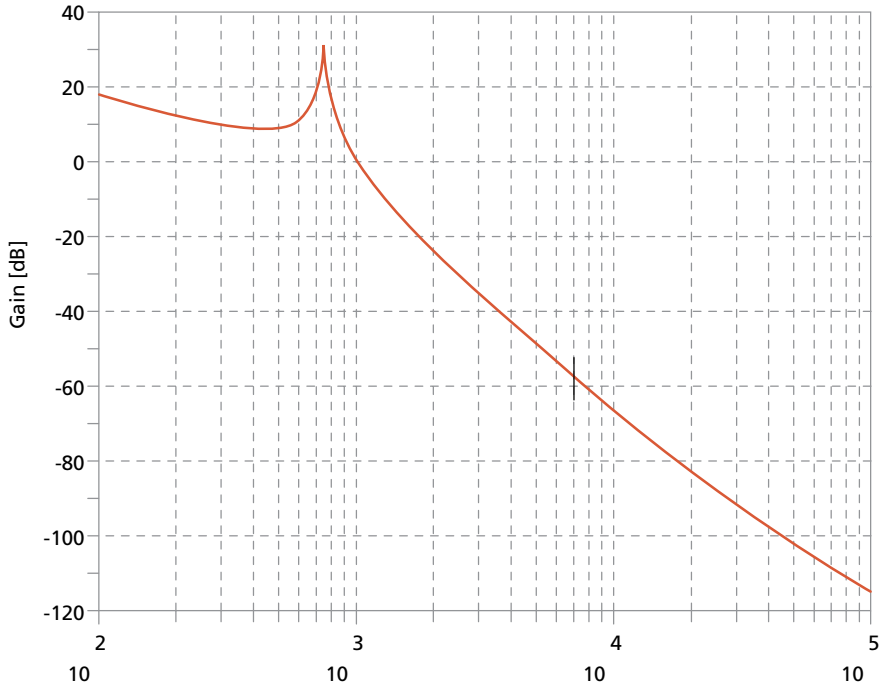


Figure 6. Ripple-rejection filter gain for 7 kHz inverter

The selection of components made possible by the imposed choice of switching frequency leads to a sort of design cul-de-sac. Firstly, omission or attempt at component capability reduction of the LCL filter may adversely affect ripple rejection. Secondly, attempts to damp the system with resistive elements (in concert with the delta-configured capacitors) may result in unacceptable loss. The lack of possible damping results in an unstable region of operation, shown by the high-gain spike in Figure 6, that can interfere with the inverter controls.

Now let's consider a filter design whose corresponding switching engine is capable of operating above audible frequency (18 kHz). The admittance-gain curve of such a filter is shown in Figure 7.

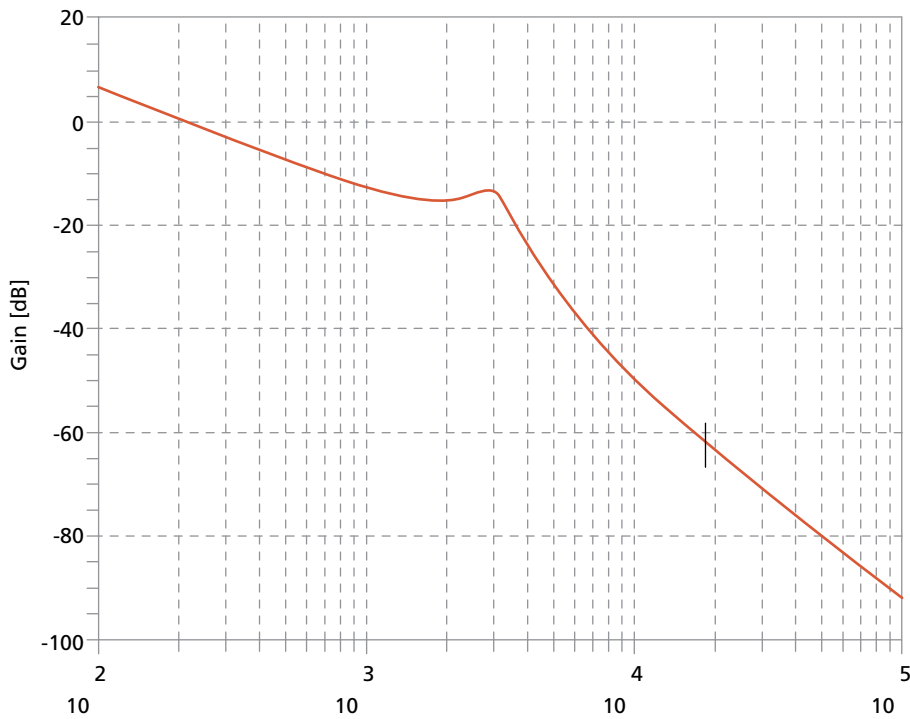


Figure 7. Ripple-rejection filter gain for 18 kHz inverter

This filter has line reactors of much higher inductance and whose primary loss constituent is from line frequency currents, as the high-frequency flux ripple is quite small. Additionally, the system can be damped with resistors (not shown in Figure 5) with inconsequential loss. The second “L” in the LCL is served by power-system source impedance and does not need to be specifically included. The filter is inherently stable and presents no control-system difficulties. Additionally, the degree of attenuation is greater than the earlier example. Put simply, higher switching frequency allows for a whole range of new approaches regarding the design of virtually all engine hardware.

Ultimately however, what is most pleasant about higher-frequency operation is quite simply that you cannot hear it.

## Conclusion

This paper has shown that within the confines of what is deemed conventional inverter design, considerable improvements are attainable by a thorough reassessment of the entire set of systems that has comprised PV inverter products for many years. Doing this results in a considerable improvement in overall efficiency of 1 to 2 points, quieter operation, a smaller footprint, and potentially lower DC-distribution costs due to a reduction in the amount of required wiring.

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