Photovoltaic converters: challenges for the next decade

Prof. Johan Driesen, K.U. Leuven, Heverlee, Belgium

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ABSTRACT

Power generation is a rapidly changing process. Owing to evolutions in power electronics, sustainable electricity generation and consumption came to the fore and now it is nearly impossible for photovoltaics to operate without this technology. This holds true for efficient consumption such as plug-in electric and hybrid vehicles or compact efficient lighting. Power electronics need to be taken into account in relation to grids, for example in novel voltage-source HVDC connections. Photovoltaic energy conversion requires power electronics in order to adapt the floating DC-output to a fixed DC-level and typically further to a grid-compatible AC electricity. These converter (mainly inverter) technologies have evolved considerably over the past few years, in much the same way as has PV cell technology, but in a much less apparent fashion. It is, however, expected and required that the technologies will evolve even further to meet the demands of the future market and the electricity grid to which they will be connected. This article intends to give an overview of the challenges ahead for power electronics in photovoltaic energy conversion.

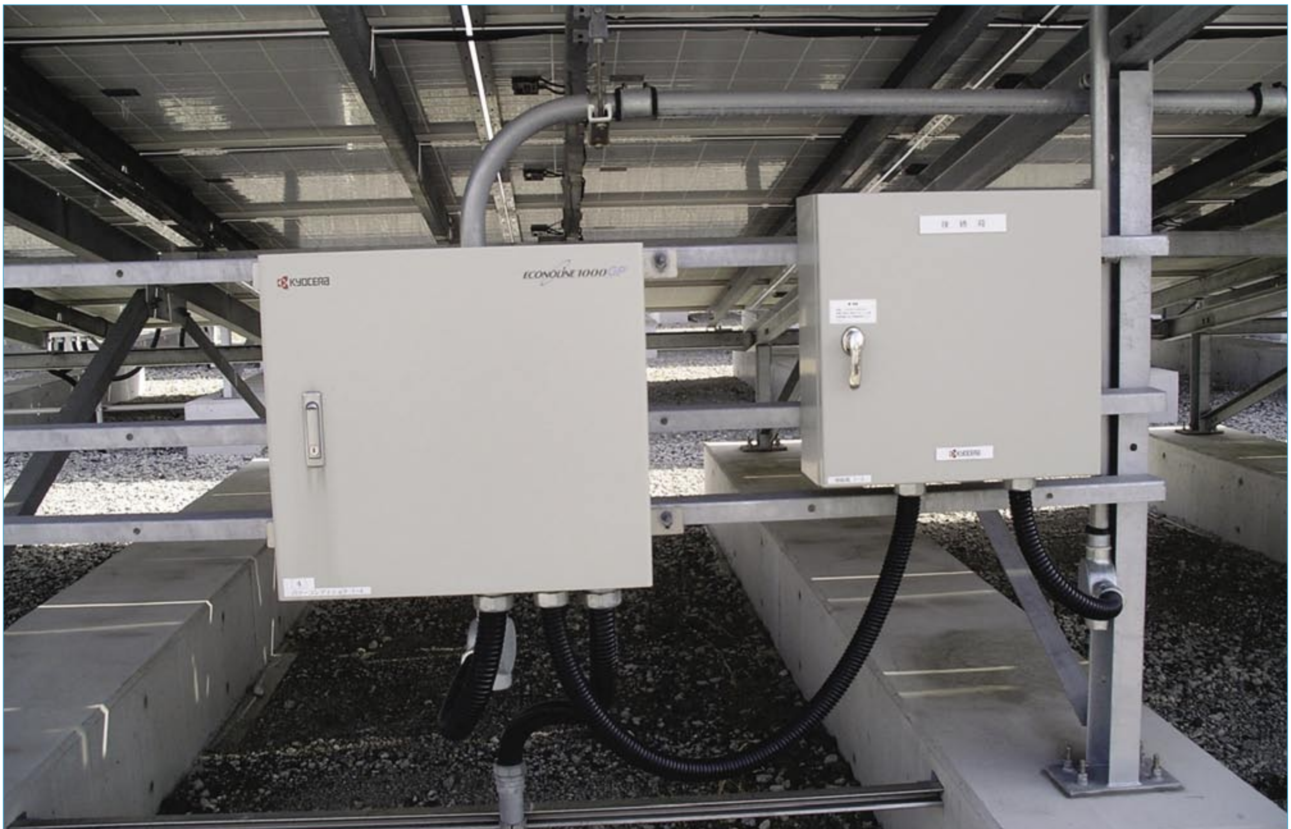
Technological challenges

Novel components and higher switching frequencies

The vast majority of power electronic circuits in use today convert electrical power from one form to another through modulation involving switching. Such circuits also contain a considerable amount of passive components such as inductors, capacitors, performing filtering, galvanic separation or energy buffering functions, as well as interconnectors. Additionally, (digital) electronics provide control at different levels ranging from switching timing to high-level energy flow management and active protection.

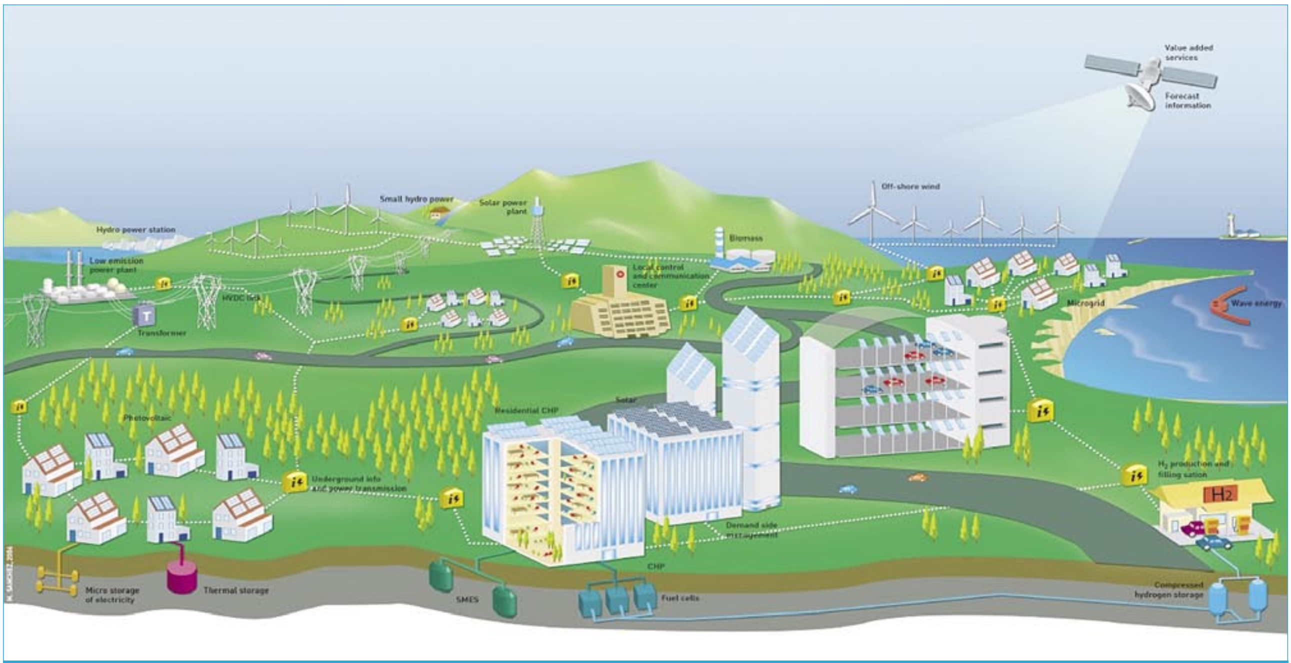
Switches in use today are Si-based components such as power-MosFets of IGBTs. Novel switching components are under development; however it seems that it will be some time before they will become suitable for mass production. These switches will be based on wide band-gap semiconductors such as SiC or GaN. SiC-based diodes are readily available, having been experimented with for quite a few years, but they still prove difficult to produce. GaN should be easier to process, but is still evolving towards relatively low switching frequencies from its original application domain of high-frequency telecommunications.

The advantages of these new components are that they are more efficient (lower losses in switching as well as conduction losses); they sustain elevated



Courtesy: Prof. Johan Driesen.

Figure 1. Inverters installed in the shadow of a PV array.



Source: European Technology Platform Smart Grids [1].

Figure 2. Artist's impression of the future Smart electricity Grid.

temperatures and are able to switch at considerably higher frequencies; and they are more abundant in different ranges up kHz to the MHz range, compared to the currently common lower kHz range. Nevertheless, this increased switching frequency (and its harmonics) can be regarded as a disadvantage as well, since electromagnetic compatibility problems will increase. Design of the inverter circuits will have to account for the radiative effects causing disturbances and additional losses. Whereas power electronic circuit design has been using analogue circuit techniques, high frequency or even microwave design knowledge will now have to be applied.

The impetus to aim for still-higher frequencies is that any volume and weight reduction linked to the reduction of the characteristic values of the required inductors and capacitors would mean an easier life for many people. Imagine thin, lightweight inverters softly buzzing in cabinets hanging somewhere on the wall, instead of the current heavy, bulky and cumbersome inverters. An illustration of this effect is the size difference between a 50Hz system and a high-frequency galvanic separation transformer. High-frequency inductors are built around core materials such as ferrites, which will need further development when the move to the MHz range takes place. Classical conductors can no longer be used due to troublesome skin effects.

The temperature and reliability challenge

Current power electronics technology and PV inverters in particular can be developed further still, even with Si-based components and kHz-range switching frequencies. In green power conversion, the overall system efficiency of the panels and associated control algorithms including maximum power point tracking (MPPT) are paramount. The role of the inverter is often underestimated in this sense, as traditionally this circuit is optimised alone and rated on performance, rather than for the entire conversion chain with realistic influx. Experience from other application domains (mainly electric drives) has shown that there is still a quite a bit of room for improvement, for instance at partial load performance. Rated performances were typically not mentioned and weighted efficiencies composed of measured values at different conversion levels rarely used.

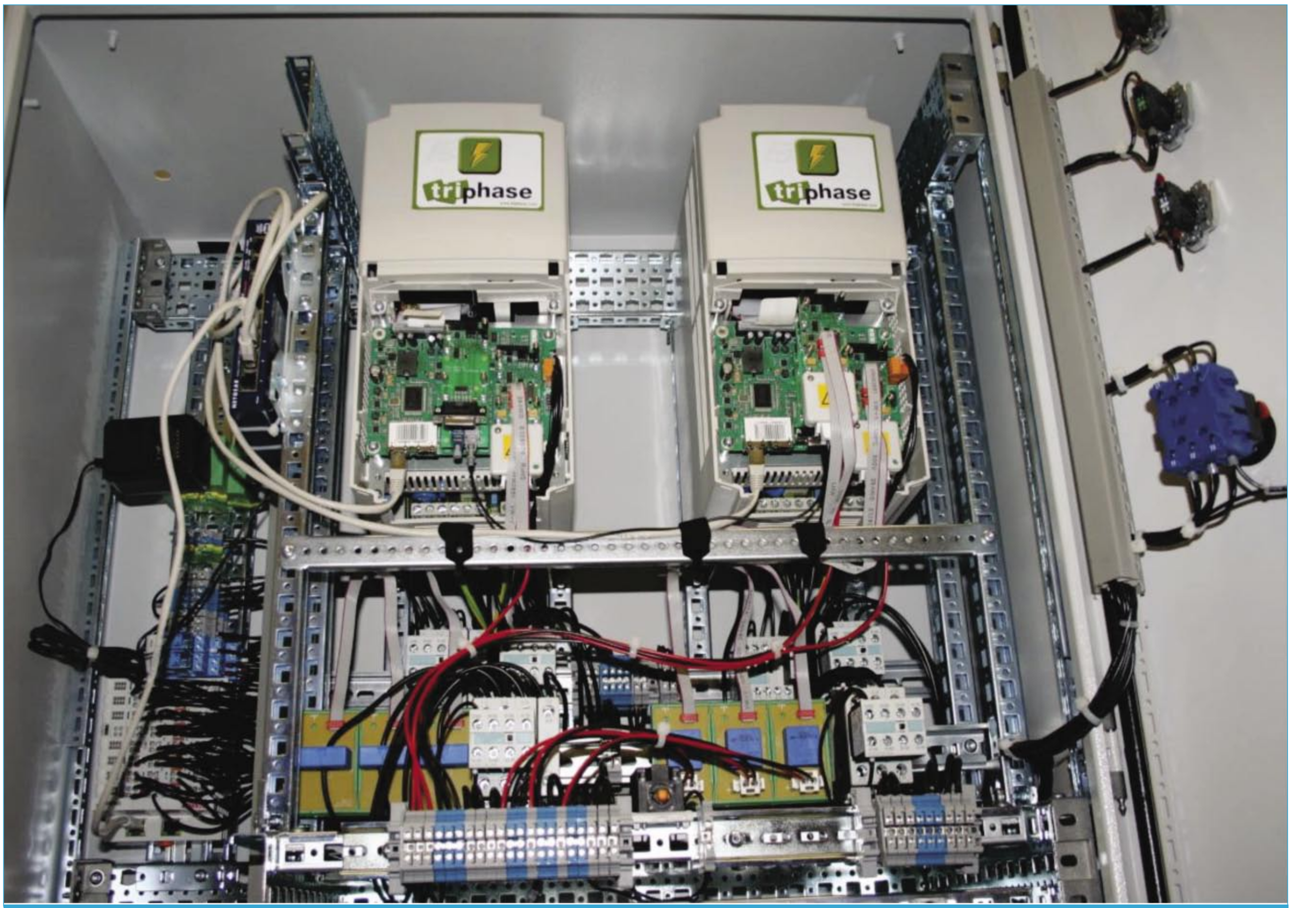
Nevertheless, in grid-connected systems, the changing grid conditions have an effect on voltage levels, which can vary between ±10%, and can lead to voltage harmonics and imbalances and neutral conductor leakage for three-phase systems. It has been observed that these power quality issues can affect the inverter's internal losses and decrease the efficiency by several percent. Additional functionalities such as reactive current injection also come at a price, and can lead to a need for enhanced efficiency validation techniques.

In an attempt to decrease losses, enhanced switching techniques and low-loss passives are being researched. Techniques to optimize the operational losses of the system can be further implemented. It is important to note that lower losses can help control the internal temperature and hence simplify cooling, yielding an indirect volume and weight reduction, as well as cooling fins and fans shrink.

The evolution towards wide-band gap components is important as these components can sustain higher operating temperatures, possibly up to 200-300°C, it is said. In applications such as hybrid cars where elevated temperatures occur, this is a clear advantage. But is this feature necessarily an advantage for inverters in PV applications? Classical PV inverters can have a higher internal temperature level within the switching components. With an unchanged outside temperature, higher temperature gradients exist, yielding smaller heat exchangers to evacuate the losses. This reduced volume advantage has a downside, however, as internal PV-inverter components should eventually work at a considerably elevated temperature. Currently available passive components and circuit assembly techniques are not yet suited for these conditions. In fact, the characteristic values of the inductors and capacitors can heavily detune when exposed to a large temperature range, causing a totally different system performance and efficiency, making it even more difficult to keep up correct functioning. Obviously, in special PV applications such as CPV, the higher temperature conditions will be welcomed.

Keeping temperatures under control is not only an efficiency-related issue, but could more importantly be considered an inverter longevity issue. As today's PV modules can easily last a 20-year lifetime of operation, it makes sense to be able to expect the same lifespan from inverters. In practice, however, some installations require additional insurance to cover the cost of replacing the power electronics after a couple of years. Thanks to technology evolution, the new state-of-the-art inverter will typically be a better performing one and hence energy-wise it will be an improvement. From a customer's perspective, though, this is not an ideal situation as not everybody performs regular checks on the system's state of operation.

Inverters, though statically mounted, operate in permanently changing external conditions invoked by the day-night and seasonal cycles. This reliability challenge occurs elsewhere in many different power electronics applications, and is certainly within the focus of research. However, there



Courtesy: Prof. Johan Driesen – EU-FP6-VSYNC project, [2].

Figure 3. Internal view of a power electronic system coupling a distributed energy resource and storage units to the grid.

are not many small-scale implementations of switching power electronics – especially not on the electricity consumption side – that are foreseen to be in quasi-continuous operation for several decades as is the case in renewable electricity generation.

When these technological evolutions are all brought together, perhaps a bright future for efficient 'hot' panel integrated modular inverters will come about. Obviously, the PV-module technology will evolve as well, imposing new challenges upon the power electronic inverter. CPV brings in power at a different scale, while multi-layer cells working in different conditions perhaps require a more enhanced MPPT. The characteristics of organic cells can be completely different from semiconductor cells, so why should the inverter be the same?

Changing role in the Smart Grid

Additional functionalities for the PV inverter

After discussing the 'internal' evolution of the PV inverter, one would almost forget that next to the PV-modules, the output side of the inverter is also changing spectacularly. Several trends force the electricity grid to rethink itself. In the frame of this article, one is inclined to think that only the move towards a more decentralised sustainable electricity production is driving this, but one should not underestimate the impact of the implementation of liberalised energy markets that demand more flexibility of the system. The consumption of electricity will increase in the coming time, despite the ever-more efficient power consumption. One of the drivers of this growth is the move towards cleaner energy forms, examples of which include electrothermal processes instead of gas combustion, or new loads such as heat pumps, charging electric vehicles, etc.

In future, the electricity system will see co-existence of large plants of a new generation, such as clean coal units, with decentralized generators and next-generation loads, probably augmented with energy storage systems. This sketch of the future poses many different technical and operational challenges to the electricity system, which will be built around an intelligently operating "Smart Grid" [1]. Making all of this work together at an affordable price is perhaps the biggest challenge of all.

For grid-coupled photovoltaic inverter systems, this synergy will have important consequences. In the past, when the penetration of such systems on the grid was low, they did not have much of an effect on the overall workability as they silently injected power without a care for voltage stability and the related reactive power exchange. The extent of the required conservative safety principles consisted of a "shut down and back off in case of an incident" philosophy. The evolution of wind power and its impact on the transmission grid in many European countries has shown that the ever-increasing share of decentralised generation systems, mostly with power electronic interfaces, should obey a more limiting grid code as soon as a critical level is reached. They are also asked to provide grid support by delivering so-called "ancillary services", such as stabilizing the voltage by injecting reactive power, ride-through incidents, etc. Unfortunately, determining that critical level proves to be an extremely difficult exercise.

PV systems are often more dispersed and connected to the distribution system, which is totally different in nature from the meshed, high-voltage transmission grid. Since the distribution feeders are radial and mainly made of cables, keeping the voltage profile under control is a more complicated challenge. This necessary form of grid support can only be successful when additional functionalities are added to the PV inverters. Ride-through of transients such as voltage dips is a minimum requirement; contribution to voltage profile stabilisation is due to follow soon.

To implement this, the converter technology will have to be adapted up to a certain point. The changes to be applied are not dramatic: firstly, the power (current) rating of the grid-connected front-end will have to be increased to allow for the additional reactive currents and short-term enlarged injections. The power required to do this will have to come from internal energy storage, mainly implemented with supercapacitors and possibly batteries such as Li-types or hybrid storages. Using the latter has additional benefits in terms of power smoothing, for example. However, it should be noted that storage integration is still a technical challenge and a control challenge in delivering balance (long-term) and stability by creating "virtual inertia" (short-term) [2].

Towards aggregation of systems

Finally, a higher level of control will have to be added on top of all these changes inside individual converters. The current PV converters are in general undispatched, meaning there is no supervisory adjustment to the operation from a control centre; hence they inject power when there is solar input. Since the level of sunshine is geographically dependent in an area the size of a typical distribution grid section, the injection can be massive with destabilizing consequences when the local loads do not pick this up and the power cannot be exported to the rest of the grid. As such, a partial curtailment of solar electricity production will sometimes be unavoidable. Obviously this should stay compatible with the liberalized market and be an exception to the rule to as great an extent as possible, but these actions can be beneficial as it is a remunerable grid support service.

The coordination of solar power injection should not stay limited to emergency measures. In general, it is a good idea to aggregate distributed energy resources, including active loads such as remotely adjustable heat pumps or charging electric vehicles. When a good portfolio is gathered, the aggregated energy balance is smoothed, becomes more predictable and may even be adjustable. Such a joint configuration can be considered a 'Virtual Power Plant' (VPP). With such a tool in hand, true market participation will become a reality. To make this possible, the smart grid will need dependable intelligence and communication. Within this setting, the aforementioned storage may also play a role in making the power injections controllable and time shiftable.

Conclusion

Power electronics as implemented in photovoltaics will evolve significantly over the coming years. On the one hand, novel components force a rethink of the entire circuit and its components. Classical systems need to enhance their reliability. On the other hand, additional control features have to be implemented in order to stay grid-compatible (and market-compatible). But perhaps the most important challenge has not yet been mentioned – the challenge of keeping this evolution affordable. The massive deployment of the technology scale-advantages will probably keep the price low, but is there actually an alternative?

References

[1] European Technology Platform's *Smart Grids* [available online at http://www.smartgrids.eu].

[2] "Virtual Inertia" research project [available online at http://www.vsync.eu].

About the Author

Johan Driesen received his M.S. degree in electrotechnical engineering from the K.U. Leuven, Belgium in 1996. His Ph.D. degree, also from the K.U. Leuven, focussed on the finite element solution of coupled thermal-electromagnetic problems and related applications in electrical machines and drives, microsystems and power quality issues. Currently, he works as an associate professor and teaches power electronics and drives at the K.U. Leuven. From 2000-2001 he was a visiting researcher in the Imperial College of Science, Technology and Medicine, London, after which he worked at the University of California, Berkeley, USA. His current area of research is in distributed energy resources, including renewable energy systems, power electronics and its applications in drives, electrical transportation and power quality.

Enquiries

Prof. Johan Driesen
K.U. Leuven
Department of Electrical Engineering, Research group Electrical Energy ESAT-ELECTA
Kasteelpark Arenberg 10
B-3001 Heverlee
Belgium

Email: johan.driesen@esat.kuleuven.be
Website: www.esat.kuleuven.be/electa