# Technical trends in next-generation solar inverters

**Inverter technology |** Inverters are the subject of intensive ongoing innovation as the range of roles they are expected to play in PV power plant operation continues to grow. Stephan Liese of Fraunhofer ISE scopes out some of the key areas for further technological advancement in the next generation of solar inverters

Towards a global CO2-neutral energy supply, renewable energy sources are becoming increasingly important worldwide. In particular, photovoltaics will take a key role in this context. In recent years, the levelised cost of electricity for PV has dropped massively compared with conventional energy sources [1]. As the key element of a photovoltaic system, irrespective of the power range, the efficiency and reliability of solar power generation are essentially determined by the properties of the PV inverters. As a result of increasing cost pressures, new generations of PV inverters are required, in which not only technical innovations and reliability but also cost optimisation and intelligence play a central role.

## Power density

Power density and power-to-weight ratio already played a major role in inverters at the beginning of their development in the early 1990s. Major technological advances have been made over the last few decades by eliminating circuit topologies with transformers and adding new semiconductor technologies. Not only could the efficiency therefore be brought close to the theoretical limit of 99% [2], but also the power density and power-to-weight ratio could be increased significantly.

The introduction of the latest semiconductor technology has led to a significant increase in power density, particularly in the field of photovoltaic inverters. The introduction of silicon carbide semiconductors has led to higher switching frequencies being realised, thus allowing the passive components, such as inductors, to be reduced (Figure 1).

Due to the increasing market penetration of wide bandgap semiconductors, SiC-MOSFETs are increasingly being used in PV inverters. Wide bandgap semiconductors permit devices to operate at much higher voltages, frequencies and temperatures than conventional silico-based semiconductors.  The combination of silicon IGBTs and SiC Schottky diodes, in so-called hybrid power modules, has already become state of the art in commercially available inverters. Due to the increasing electrification of the transport sector and the resulting volume market for semiconductors in addition to photovoltaics (Figure 2), it can be assumed that prices for SiC semiconductors will continue to fall in the coming years. In the transport sector, power density or power-to-weight ratio is even more important than in the field of photovoltaics. Each additional kilogram of weight saved can increase the range of electric vehicles. As a result, silicon carbide technology within photovoltaic inverters will become state of the art within the next few years. The first manufacturers in the field of PV inverters have already announced devices that are completely based on silicon carbide technology.

Credit Fraunhofer ISE

**Figure 1. Example of weight/volume reduction of inductors**

Semiconductor technologies such as gallium nitride, which are still predominantly used in consumer electronics today, are becoming increasingly interesting for applications in power electronics. By increasing the switching frequency in the megahertz range, weight and volume as well as the associated material costs can be further reduced. In contrast to SiC semiconductors, which are commercially available up to a reverse voltage of 1,700V, commercially available GaN semiconductors are only available up to a reverse voltage of 650V and with a maximum current carrying capacity of 60A, which adversely affects the scalability of the power classes. Due to the high price and low reverse voltage, GaN semiconductors are still mainly used for research purposes in smaller power electronics devices (<5kW). One of the future challenges will be to improve GaN semiconductors for parallel connection

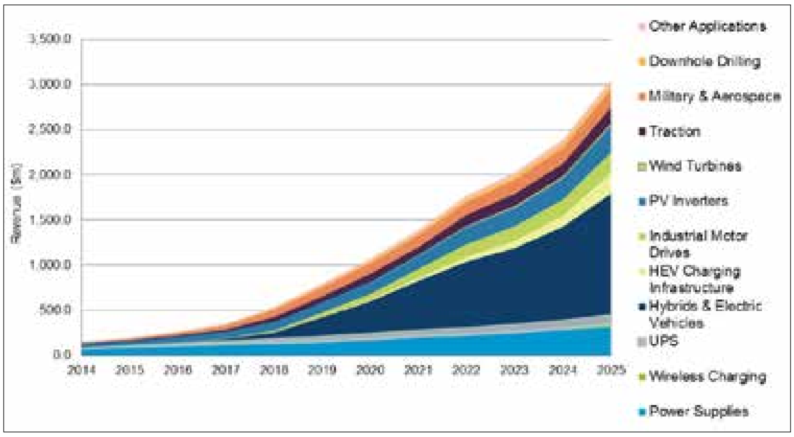



**Figure 2. The SiC power semiconductor market. Source: IHS**

to cover higher power ranges. The high switching frequencies associated with GaN semiconductors will require additional innovative, internal and external EMC device concepts that comply with current standards.

Photovoltaic inverters can basically be divided into two categories. On the one hand there are string inverters in the range up to around 125kW and on the other hand there are central inverters starting with several hundred kilowatts of power up to the megawatt range. In string inverters, multi-level topologies have established themselves as state of the art. The related introduction of a large number of voltage levels leads to an additional reduction of the passive components in the output filter, in addition to the increase of the switching frequency by new semiconductors. However, multilevel topologies with an increasing number of voltage levels have the disadvantage that their operation is associated with a considerable additional effort of circuit and control technology. The so-called three-level topologies offer a good compromise in terms of complexity and power density. The combination of multi-level topology and the latest semiconductor generations in combination with high switching frequencies will not only continue in the field of string inverters, but will also increasingly find its way into the field of central inverters. In the case of central inverters, the trends are clearly moving in the direction of even higher power and input voltages. Research projects are already being undertaken that significantly reduce the size of central inverters due to semiconductor technologies and innovative design concepts (Figure 3) [3].

## Increasing the power to weight ratio

The cost breakdown of PV inverters shows that the actual power electronics with their semiconductors and their control contribute only about one third of the total costs. The vast majority of the costs, up to 70%, are associated with the mechanical and electromechanical components. The mechanical components include the housing, which consists mainly of die-cast aluminum or sheet metal, depending on the performance class, the aluminum heat sinks, which are partly integrated into the housing structures, and the supporting structures. The inductors, PCBs and connectors can be assigned to the electromechanical components. With the exception of inductors, which are becoming increasingly small due to higher switching frequencies in conjunction with new semiconductors, only a few technological innovations have been produced in all other areas, which make a significant contribution to costs.


**Figure 3. Demonstrator system of a modular, highly compact 1MW battery inverter using SiC-MOSFET's**

A small number of inverter manufacturers, for example, are already using the first polycarbonate housings, which reduce the use of materials and contribute to cost reduction. New material combinations with regard to the housings and adapted production processes can thus meet EMC requirements on the one hand and on the other hand, these innovations also promise considerable cost-cutting potential in the future.

As far as cooling is concerned, the so-called concept of the "hot core" has recently been investigated experimentally within the research project "PV-Pack" [4]. The aim of the project is clear from its name: "PV Pack: Optimised cooling, packaging and assembly technologies for efficient, fast-switching and highly integrated PV inverters in the 10 to 40 kW power range." To achieve this, a highly qualified consortium was formed, comprising SMA Solar Technology, Fraunhofer Institute for Manufacturing and Applied Materials Research (IFAM), Phoenix Contact and Fraunhofer ISE. Due to the thermal insulation of the heat sink, increased temperature levels can be achieved, which, especially in conjunction with SiC semiconductors and their operating temperatures of up to 200°C, allow a more efficient use of the heat sinks and semiconductors. The use of composite materials can further reduce the material costs of the heat sink and thus increase the power-to-weight ratio. Furthermore, different temperature zones have been introduced in the concept, which means that electronic and electromechanical components with lower temperature requirements can be used, which in turn has an impact on costs (Figure 4).

The connection of cooling and housing is state-of-the-art in the field of string inverters and at the same time includes the supporting structure of the inverter. Within the above-mentioned research project, these two components were completely decoupled from each other, which in turn allowed the support structures to be viewed separately. In the future, multi-functional lightweight construction concepts could be used here, for example with integrated heat transfer mechanisms or with partial

**Figure 4. PV-Pack 70kVA PV inverter with new cooling concept**

electrical conductivities, which would allow a more effective use of the installation space.

Considering the costs and the associated use of materials, there is still considerable potential for optimisation in this area to bring further innovation. Here the emerging mass market for electromobility could have a massive impact on cost-cutting potential too. To increase the power-to-weight ratio, however, it is not enough to focus solely on the above-mentioned points. PV inverters and the associated power electronics also require a number of additional components, which are usually purchased separately. For example, EMC filters, capacitors and a whole range of circuit breakers can fall under this range. In the future, these components should also be investigated more intensively to determine to what degree an increase in the power-to-weight ratio can be achieved and how this can also contribute to cost optimisation. Particularly with the introduction of 1,500V technology in the field of string inverters (>50 kW) and for some time already in the field of central inverters, it can be seen that a considerable number of parts and components are not yet commercially available for the increased voltage resistances, especially for string inverters, and that they have to be developed partly on request.

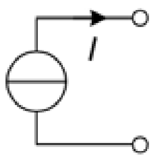
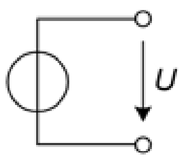
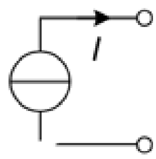
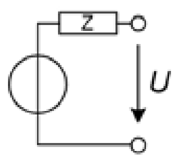
## Reliability and intelligence

The main failure causes of PV inverters in terms of power electronics are nowadays either the power semiconductors or the capacitors. In the future, it must be ensured that either the reliability of these two components is increased or the power electronics is empowered to make intelligent statements about state of health of the inverter or these two components. Fault-tolerant PV inverters can also help to ensure system services by, for example, only operating at reduced power, depending on the fault. In the age of industry 4.0, a whole series of innovations are still needed at this point regarding monitoring, in order to increase the internal intelligence of PV inverters. One look at some wind turbine manufacturers, which are already a considerable step further along this particular line, is enough.

Photovoltaic inverters are normally dimensioned for a lifetime of 20 years, although it must be taken into account that this calculation "only" takes the hours of sunshine into account. In recent years, however, the devices have increasingly been taking over various system services that are otherwise provided by conventional generators; in order to be able to provide such services on a permanent basis, the devices must also be dimensioned for night-time operation. As a rule, the ancillary services are grid-supporting methods, such as frequency support via active power or voltage maintenance via reactive power.

Due to the implemented control technology, most inverters can only function as current sources and thus

**Table 1. Operating modes and behaviour of inverters. Source: Fraunhofer ISE**

| **Operation Mode** | *Grid-feeding* | *Grid-forming* | *Grid-supporting* | *Grid-sustaining* |
|---|---|---|---|---|
| **Grid** | interconnected grid | island grid | interconnected grid | *interconnected grid or island grid* |
| **Application** | grid with a high share of rotating generators | grid is formed by one inverter | grid with a high share of inverters | *Inverter-dominated grid / no rotating generators* |
| **Source characteristic at fundamental oscillation (50 Hz)** | current source<br>$Z \to \infty$ | voltage source<br>$Z \to 0$ | current source<br>$Z \to \infty$ | *voltage source with virtual impedance*<br>$Z = R + j\omega L$ |
| **Equivalent circuit diagram** |  |  |  |  |
| **Droop Control** | no | no | P(f), Q(U) | f(P), U(Q)<br>[grid-compatible] |

contribute to the maintenance of the electricity grid only to a limited extent. However, due to the increasing penetration of feed-in inverters into the power grid and the displacement of "conventional" rotating machines such as synchronous generators, it will be necessary in future for the inverters themselves to ensure the maintenance of the grid.

Typically, PV inverters operate in grid-feeding operation. Due to the increasing multifunctionality of inverters, e. g. with inputs for photovoltaics and connection options for batteries, these devices usually have two operating modes. This includes on the one hand grid-parallel operation and on the other hand island operation. In grid-parallel operation the inverter is synchronised with the grid voltage and grid frequency and feeds a current into the grid. Therefore the source characteristic is a current source. This operation mode is called "grid feeding". In island operation, however, the inverter forms the grid voltage and frequency of the island grid. The source characteristic is a voltage source. The current is determined by the connected loads. This operation mode is called "grid-forming".

With the increasing number of inverters feeding the interconnected grid and the reduction of synchronous generators, the need to control the grid voltage and frequency by the inverters is increasing. The operation mode of inverters that operate in an interconnected grid or island grid is called grid-sustaining. This operation mode demands complex and universal control algorithms which are currently under development and are still being used for research purposes. In the future, this functionality should be implemented as a standard feature in multi-function devices, battery inverters and photovoltaic inverters, so that PV can also contribute to the full supply of renewable energies, even if limited by the available power, to maintaining the grid.

Furthermore, the increasing interconnection and digitalisation of renewable energy plants will become increasingly important, especially with regard to the fluctuating generation of electricity from PV and wind. Often, the electricity generated is not consumed directly on site, but has to be transported where it is needed. The additional expansion of electrical storage facilities will help to bring production and consumption closer together. Precise acquisition and control of power flows is essential. In order to ensure this and not endanger grid stability, the communicative capabilities of the devices will play an increasingly important role in the future, especially with the superordinate grid operators, in order to optimally control the power flows in the grid. ■

## References


[1] https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf

[2] https://www.ise.fraunhofer.de/content/dam/ise/en/documents/press-releases/2009/press-release-fraunhofer-ise-sets-a-new-world-record.pdf

[3] http://netfficient-project.eu/

[4] https://www.ise.fraunhofer.de/en/press-media/press-releases/2017/photovoltaic-inverter-with-highly-integrated-concept-promises-lower-costs.html


## Author


Stephan Liese joined the Fraunhofer ISE in Freiburg in 2011. Starting from the development of software for power electronic devices he has managed several industrial and public projects related to this topic. Since 2015 he has been the head of the "Modelling and Control of Converter Systems" team and since 2016 the head of the "Distributed Generation and Storage" group within the Power Electronics and Grid Technologies department.