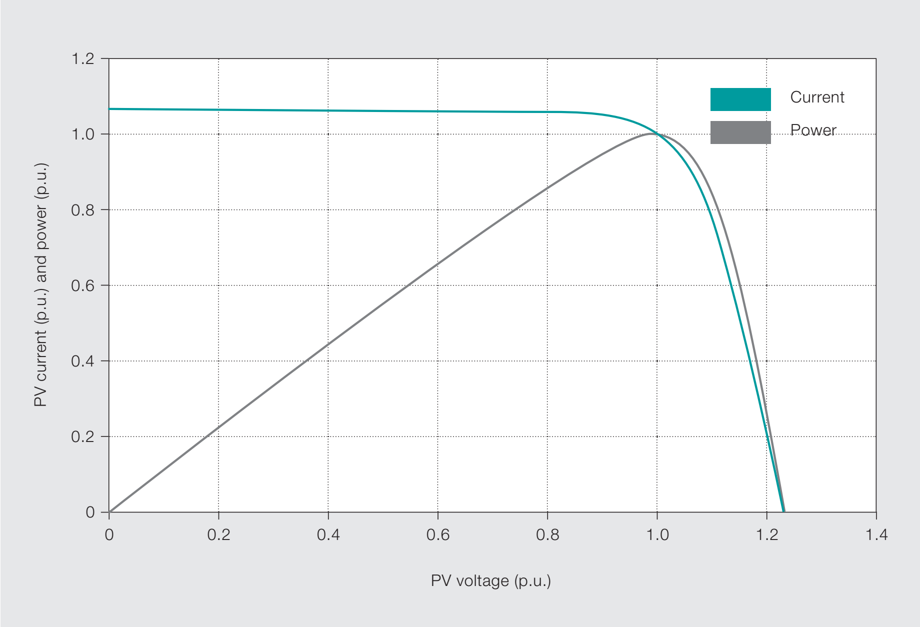
Evolving solutions

Technology trends and design targets for next-generation photovoltaic inverters

JUHA HUUSARI, PAOLO CASINI – Photovoltaic power conversion is a relatively new application area in the world of power electronics. Early photovoltaic conversion technologies were based on motor drives and only recently has the industry seen solutions developed solely for photovoltaic conversion. To maintain a strong presence in today's photovoltaic business, companies must be able to adapt to a constantly evolving market and also be visionary, focusing on key technologies to ensure cutting-edge designs for tomorrow's needs. ABB, with its strong background in power electronics, is not only a leading supplier of photovoltaic products, but also a forerunner in next-generation photovoltaic conversion technology.

1 Characteristic behavior of a photovoltaic power source



Widely adopted feed-in tariffs and other incentives that helped lower the cost of photovoltaic (PV) modules led to a boom in the PV industry between 2006 and 2011, particularly in Europe [1]. However, the sharp reduction of financial incentives has forced the market to adapt – meaning cost has become a key target for new product launches. Research, too, has had to adapt. ABB has been vigorously investigating new developments for PV applications, particularly in PV power conversion systems.

PV power conversion

PV power conversion essentially means efficient and controlled delivery of the electrical energy from the PV modules into the load of the system (in small-scale residential applications, such as heating or lighting) or into the transmission grid (in larger-scale applications). The sun's radiated energy reaching the face of the Earth is captured by the semiconductor junction within a PV cell that generates charge carriers, ie, electrical current, into the system. By its nature the PV cell is intuitively seen as a current source, unlike most electric power sources, which have voltage-source characteristics. This, in turn, requires appropriate measures to reliably control the power generation. Early converters intended for PV applications inherently provided suboptimal performance and even the scientific community struggled to accept the paradigm change with PV conversion control principles [2]. Such performance flaws have since been eliminated.

Due to its nonlinear semiconductor nature, the PV generator yields its maximum output power only when the generator is forced to operate at a specific voltage level → 1. Furthermore, environmental conditions, such as the temperature of the PV cells within the generator as well as the intensity of the arriving irradiation drastically change the electrical properties and the generated power of the PV generator. The generated power increases as a function of decreasing cell temperature and increasing irradiation intensity. Therefore, in regions like northern Europe a PV generator may produce peak power during cold, early spring mornings.

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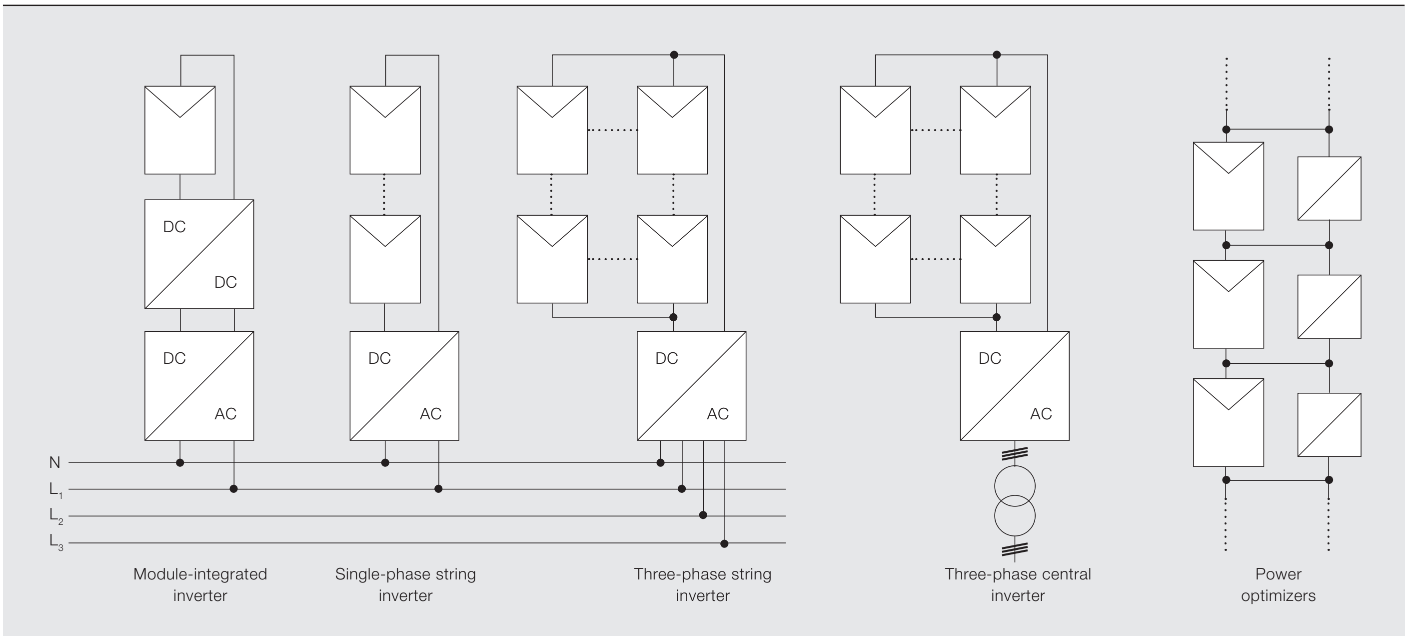
The intermittent behavior of the PV generator is supervised by the power electronic converter processing the generated power of the PV generator. Through a feature known as maximum power point tracking (MPPT), the converter monitors the output power of the generator, adjusting it constantly to the desired level by changing the voltage level of the generator.

The basic building block of a PV generator is the PV cell, roughly 15 cm × 15 cm, with a thickness on the order of 100 µm. A single PV cell typically generates a couple of watts at voltages below a single volt, depending on the size and technology used. Most of the cells are silicon (Si) based, but the entire family comprises other conventional semiconductor materials, such as gallium-nitride (GaN), indium-phosphide (InP) and copper-indium-gallium-diselenide (CIGS), as well as more exotic – namely, organic and dye-sensitized – materials.

Title picture
A 181-kWp PV installation on the roof of ABB factory in Helsinki, Finland.

2 Conceptual photovoltaic power processing converters



Individual cells are joined in a series arrangement to create a PV module (also referred to as PV panel), comprising two to 96 PV cells. This is done because power processing is more feasible with higher voltage levels. PV modules typically range from 5 to 350 W; the large-scale systems are realized with larger, high-power modules. The PV modules are connected in series to form the fundamental unit, a PV string. Due to safety regulations, the maximum voltage of the PV string versus Earth is limited (1,000 V/1,500 V in the European Union; 600 V in the United States), which in turn defines the string's maximum power. One PV string rated for 1,000 V usually provides a nominal DC power of 5 kW. Thus, commercial PV inverters for multiple strings are typically rated for multiples of 5 kW.

The power converters processing the generated power are typically categorized as follows: micro-inverters, generally interfacing one to four PV modules into the AC grid; string inverters, 1- to 3-phase inverters interfacing one to 20 PV strings; and, finally, 3-phase central inverters usually rated above 100 kVA → 2. In addition, there is a niche group of power optimizers that are add-on, low-power DC-DC converters intended to fine-tune the generated power in existing PV strings. Excluding power optimizers, ABB provides converters and solutions for all of these application areas.

Plant-level features

Traditionally, PV installations were realized with the highest possible inverter rating relative to installation size: Small installations with micro-inverters and, respectively, larger systems with high-power inverter stations. This concept is changing as the industry experiences a trend of high-power systems being built with string inverters. The factors driving this include higher power output as distributed inverters perform fine-granular maximum-power extraction as well as lower installation costs. In addition, during inverter failures only a restricted part of the installation stops producing power. As a result, the importance of string inverters is increasing.

Another interesting development emerging in PV applications for larger systems is the inclusion of environmental measurement data to enhance near-future prediction and power output. Through monitoring, eg, the cloud movement near the PV power plant, the centralized controller can, in advance, guide the inverter(s) within the plant to adjust their operation, ie, to improve the MPPT operation. Additionally, this information can be used to predict the available short-term power, benefitting the grid operator.

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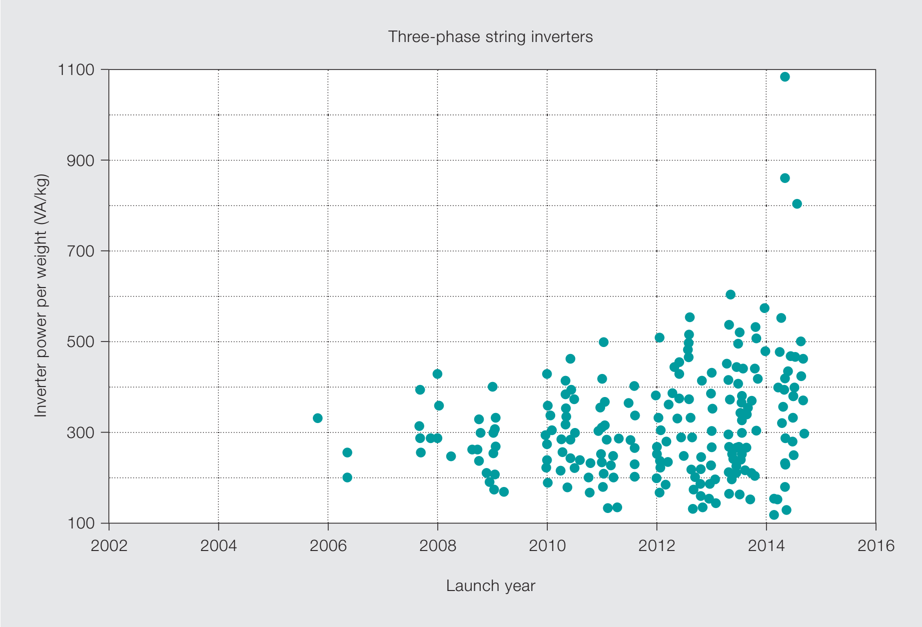
3 Evolution of power density in wall-mountable, transformerless PV inverters



relevant information, such as historical energy output. Again, such information aids the grid operator in dealing with demand-power balancing.

Emerging semiconductor devices

The heart of a PV inverter is the bridge of fast-switching semiconductor devices that, together with passive energy-storage elements, enable power processing. While the clear majority of PV inverters utilize Si devices, lately the industry has seen the emergence of silicon carbide (SiC) devices. Able to withstand higher voltages and temperatures and to switch faster than Si counterparts, the SiC device enables more compact and more efficient power processing converters [3]. However, SiC technology is expensive and the long-term reliability of SiC components remains an open question. These drawbacks notwithstanding, SiC devices can be seen as an integral part of PV inverters in the coming years, as demonstrated through ABB's research [4] as well as products utilizing SiC technology.

The benefits of GaN technology compared with SiC are still being debated within the industry. It is claimed that GaN devices enable ultrafast switching action, thereby providing greater benefits in efficiency and power density. However, practical demonstrators validating these claims are yet to be announced.

While SiC devices are already technologically mature, GaN devices are not. At present, there are only a handful of GaN products on the market and, furthermore, no high-current power modules are available. This is also due to the property of the lateral GaN semiconductor junction, which makes paralleling many GaN chips difficult, thus hindering the production of high-current modules. With single-packaged GaN chips it is possible to reach power levels of roughly 20 to 30 kW; at higher power levels modules are required.

Power density in string inverters

Over the past 10 years, the design targets for PV string inverters have been changing dramatically. The first-generation designs targeted high energy yield with multiple isolated MPPT converters. The second-generation designs maximized conversion efficiency, followed by third-generation single-stage systems. Current design targets are now lower cost and higher power density. Each of these posed different challenges to power electronics designers.

The power density concerns arise from various needs: For safety reasons, the industry has adopted a weight limit of 75 kg for each cabinet to be carried by two people. For wall mounting, there are also limits regarding the weight capacity of the mounting structure and the wall itself. Another driver is the lower transportation cost per installed Watt.

The evolution of the power density of commercial wall-mountable, transformerless three-phase PV string inverters weighing less than 75 kg shows that inverter manufacturers are putting increasing effort into maximizing the power density → 3.

The power density of PV string inverters has definite limitations. Typically the passive filtering elements make up a significant part of the system weight, but the heat transfer solution, the enclosure itself and various protection devices also add considerable weight. Many of these restrictions cannot be changed – for example, the enclosure thickness and the use of certain protective means are defined in standards (eg, in IEC 62109). The higher the power level, the bulkier the protection means becomes, thus resulting in a heavier enclosure to support the weight and to provide an adequate ingress protection (IP) rating.

A modern-day feature that has emerged in PV applications is the connection to various cloud services.

The challenge of reaching a higher power density will push designers to look for more innovative system solutions and foster the use of next-generation semiconductor components.

Utility-scale PV solutions

Although technological developments have been seen throughout the entire PV industry, the utility segment has had the most impressive pace of innovation. Since the early stages of the modern PV market the evolution of utility-scale PV inverters has been driven by the optimization of the PV plant's production efficiency and total cost of ownership (TCO), that is, the summation of the initial capital expenditure (capex) and the operational expenditures (opex) sustained during the life of the plant.

Most of the efforts by the inverter industry in the past 10 years have been aimed at improving the inverter's power conversion performance, which has resulted in increased efficiency values up to 98 percent weighted and 99 percent peak. But the unavoidable asymptotical efficiency trend and the modest incremental gain of the financial return in relation to the added cost of better-performing topologies and control techniques has gradually brought attention to the reduction of the TCO.

Innovation at the inverter level is seen as a means to drive down the cost of the balance of system (BOS), which represents 60 percent of the cost of a utility PV plant, compared with less than 10 percent of the cost incidence of the inverter itself. A few years ago the progressive adoption of the 1,000 V system voltage from the 600 V system voltage allowed a 25 percent reduction of the DC BOS. The PV industry is today on the verge of a similar change with the upcoming 1,500 V module technology, which will revolutionize the utility inverter offering by requiring a significant review of the electronic and electromechanical components and topologies deployed in PV inverters.

The other component of the TCO is operation cost. The typical annual operation and maintenance cost of a PV plant is roughly equal to 1.5 percent of its initial capex cost and a significant part of it is represented by the maintenance required by traditional air-cooled PV inverters, especially when installed in remote and hostile conditions. Throughout the 20 years of expected field life the opex becomes a major contributor to the cost of the plant. Combining the need to reduce maintenance costs with reduced logistic costs and ease of installation creates another driver for the evolution of utility-scale inverters' mechanical packaging. The sudden switch to outdoor inverter enclosures in several utility portfolios was the initial move in this direction that will continue with the development of innovative, low-cost maintenance cooling solutions. The traditional air cooling of IP20 inverters, with their periodic maintenance to clean air filters and decontaminate electronics exposed to the direct air flow, is gradually moving to sealed-enclosure solutions IP54 or IP65 rated with liquid or 2-phase cooling solutions.

An additional benefit of smarter packaging and cooling technologies is increased power density, which results in reduced logistics and installation costs. This is particularly important as utility demand shifts to emerging markets, where installations are needed in remote areas.

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