



Getting to a Cleaner Future

Design challenges and solutions

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Renewable Energy is the key to a cleaner future and solar energy is leading the way. Designers of solar inverters face a multidimensional challenge to ensure solar power continues to meet the growing demand for clean energy. This article explores these challenges by comparing the latest solutions in terms of efficiency, weight, cost and reliability, and shows that flying capacitor topologies can offer unique opportunities for system optimization.

Climate change is one of the key challenges facing today's society. The global demand to fight rising carbon dioxide levels, pollution, and to reduce our dependency on fossil fuels, is driving governments towards a clean energy future. Research Institutions and Industry are working to identify and deploy new ways to meet the growing demand for clean energy.

Renewable power is the key to a clean energy future, already providing almost 25% of the global power demand, and solar power is the fastest growing part of the renewable energy landscape. In recent years, more solar generation capacity has been added than fossil fuel and nuclear power combined, and almost twice as much as wind power. Solar power generating capacity grew to 48% of all new power installations during 2019-2020, and countries such as Germany, Italy, Greece and Chile are already producing almost 10% of their national demand. Huge investments continue to be made in all segments of the solar market, including the consumer, industrial and utility sectors.

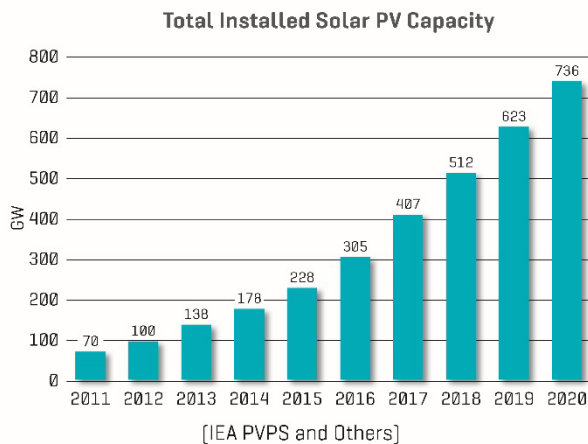


Figure 1: Total installed solar PV capacity

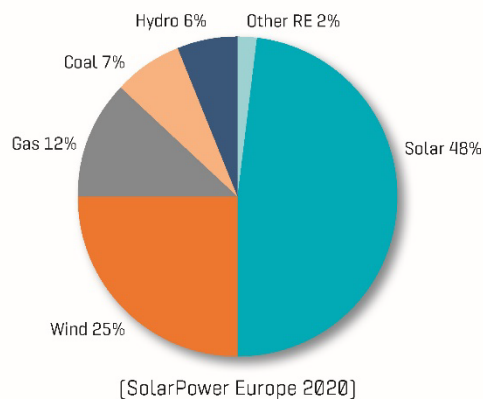


Figure 2: Power capacity installed in 2019

Over 700 GW of solar power has been deployed globally, with more than 100 GW being installed during 2020. Both cumulative and annual power installation are forecast to double in the next 5 years. The majority has been in utility-scale systems (>100 kW) but, increasingly in recent years, the consumer market has seen significant growth, especially when coupled with storage systems. Utility-scale systems are split between central-inverter and string-inverter systems. Historically, central-inverter systems have received the majority of investment. However, string-inverter systems are expected to become the dominant type in the next 5 years due to falling costs, increased flexibility and ease of maintenance. Central-inverter systems are based on multiple PV panels feeding into a single large inverter hub. In contrast, string-inverter systems place the inverters together with smaller “strings” of PV panels. These sub-systems are then combined before output. Consequently, as demand grows, additional string-inverter sub-systems can easily be added. As string inverters are usually modular in design, maintenance typically involves simple replacement of the failing inverter module. Local storage of replacement modules means problems can be quickly resolved. This helps ensure security of power supply, thereby minimizing brown- or black-outs.

High efficiency, maximum power capability, low weight and high reliability are some of the critical requirements designers need to consider to support these key string-inverter system features. High efficiency is needed to maximize the power generated from the PV panels and minimize power loss. This helps reduce heat-sink requirements and system weight. Maximizing the power generation per inverter reduces the number of modular sub-systems required for a given power output. This reduces the footprint of an overall sub-system. Low system weight ensures that inverters can be easily installed and replaced, without the need for special lifting equipment. This enables quick system installation and a rapid response to system failures, especially in difficult-to-reach locations. High system reliability helps reduce maintenance requirements, even when systems are working in harsh environments, further improving longevity of supply.



Vincotech's latest generation of power modules for the solar market introduces new design concepts which specifically target these design requirements – high efficiency, maximum power density, low weight and high reliability. Careful selection of innovative topologies and the latest semiconductors enables significant system level benefits. The following detailed analysis of the power conversion steps in an inverter system shows how and where Vincotech's latest modules are addressing these design requirements and the system benefits provided.

Power electronics for 1500V multistring inverter systems

PV Inverter systems require DC/DC boost converters, as part of the Maximum Power Point Tracker (MPPT), to adjust the PV panel output voltage to the required DC-link voltage level. This is then input into DC/AC converters which deliver the solar energy to the public grid.

Various topologies can be used for the booster and inverter stages and in the next two sections these are compared in terms of efficiency, cost and system benefit.

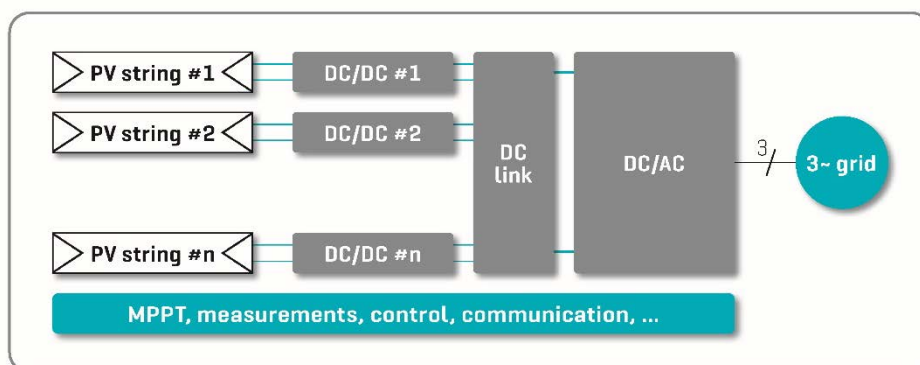


Figure 3: High level block diagram of PV inverter

Cost and performance comparison of boost topologies

Two-level and three-level symmetric boosters are commonly used in the input stage of the inverter, and three-level flying capacitor boosters are starting to be used in the latest systems.

2L

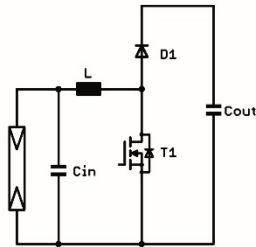


Figure 4:
two-level boost circuit

3L-sym

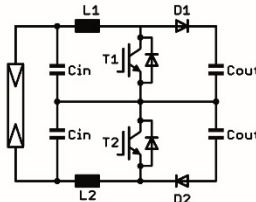


Figure 5:
three-level symmetric
boost circuit

3L-FC

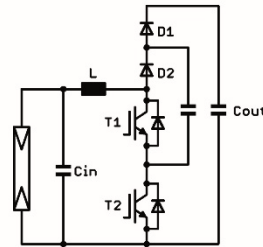


Figure 6:
three-level flying
capacitor boost circuit

Three-level topologies introduce an additional third voltage level. This reduces the voltage across the boost inductor, boost switch and diode to half the value required for two-level. Consequently, for a given ripple current, the inductor can be reduced to half its value when compared to a two-level topology. The overall inductor volume, weight and cost is therefore reduced. This is an additional system benefit which should be kept in mind as it is not considered in the following power module cost benchmark.

In the symmetric boost topology the third voltage level is created by splitting the boost circuit into a 'symmetrical' positive and negative part. The additional third voltage level is generated by splitting the input and output capacitors (C_{in} , C_{out}) and connecting them to the neutral point. The pulse-width modulation (PWM) pattern needs to be adjusted to ensure symmetry of the neutral point.

In the flying capacitor boost topology, the third voltage level is generated, as the topology name indicates, by a floating or flying capacitor (C-FC). The flying capacitor is charged to half of the output voltage. A key advantage of flying capacitor topology is the "artificial" increase of inductor current frequency. In case of three-level flying capacitor, the inductor current frequency is doubled compared to the semiconductor switching frequency. This leads to smaller, lighter and cheaper inductors. Also, only one boost inductor is required whereas a three-level symmetrical booster requires two.

The following benchmark compares the two-level, three-level symmetric and three-level flying capacitor topologies in terms of cost and performance for a 40-45 kW boost leg in a 1500 V multistring solar inverter.



Chipset	two-level	three-level symmetric	three-level flying capacitor
Si/SiC hybrid	not examined because efficiency meets not the requirement		950 V fast Si IGBT 1200 V SiC diode
Full SiC	1700 V SiC MOSFET 1700 V SiC diode		1200 V SiC MOSFET 1200 V SiC diode

The efficiency and cost comparisons (figures 7 & 8) show that the full SiC two-level booster has the lowest efficiency and the highest price. The hybrid chipset was not evaluated as it would have had an even lower efficiency in this frequency range. In addition, 1700 V blocking voltage might be too low for 1500 V systems when cosmic radiation requirements are considered and using 2200 V components would further reduce the efficiency and increase the module cost.

The comparisons also show that the three-level flying capacitor (FC) booster has a higher efficiency than the symmetric booster. Since both topologies use the same components, they have the same module price.

The hybrid Si/SiC flying capacitor booster has the highest efficiency up to 50 kHz inductor current frequency. Above 50 kHz, the full SiC flying capacitor booster has the highest efficiency, but also a higher price than the hybrid circuit.

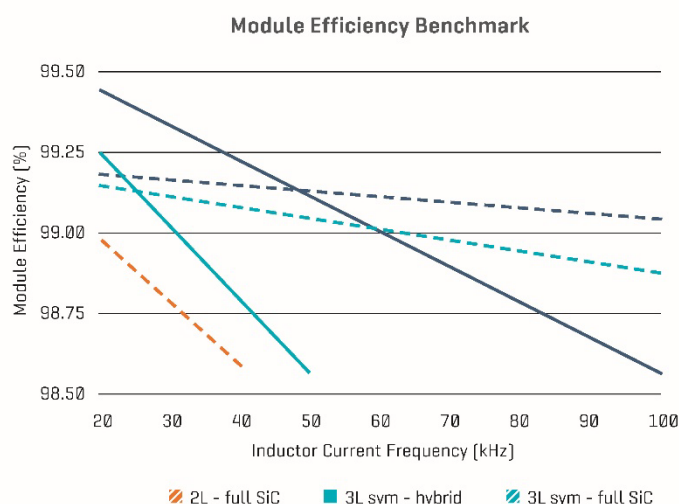


Figure 7: Module efficiency benchmark – conditions:
 $V_{in} = 760 \text{ V}$, $V_{out} = 1200 \text{ V}$, $P_{dc} = 42 \text{ kW}$

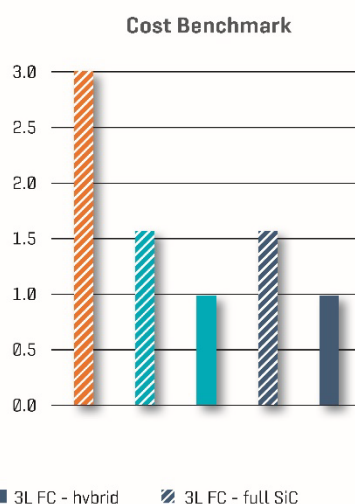


Figure 8: Module cost benchmark

Consequently, it is clear that the flying capacitor topology has best price/performance ratio compared to both the two-level and three-level symmetric topologies. For systems up to 50 kHz inductor current frequency, hybrid three-level flying capacitor topology offers the best price/performance ratio, whereas above 50 kHz, full SiC has the best efficiency.

Cost and performance comparison of inverter topologies

Many different inverter topologies have been proposed in the past. NPC and ANPC are widely used in 1500 V multistring inverters. Mixed voltage NPC (MNPC) is still used in residential and commercial 1000 V systems, but is gradually being replaced by NPC. Three-level and four-level flying capacitor inverters are starting to be used in the latest systems.

NPC, ANPC and flying capacitor topologies provide a higher system blocking voltage than the individual components. For example, an NPC using 950 V components will provide 1900 V blocking voltage. If a four-level flying capacitor topology is used in 1500V PV inverter, components with only 650 V blocking voltage are needed. Typically components with lower blocking voltages are faster, have lower switching losses and are usually lower cost.

NPC and ANPC topologies have similar losses, and therefore efficiency, when used in systems driving predominantly non-reactive loads. However, the ANPC has clear efficiency advantages for $\cos\phi < 1$ and, for the sake of completeness, bidirectional operation. The losses in NPC and ANPC are concentrated in the semiconductors operated with high frequency PWM. These components are subject to conduction and switching losses. In most cases, the temperature of the fast switching semiconductors limit the maximum module output power.

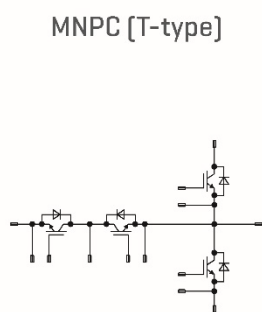


Figure 9:
MNPC inverter topology

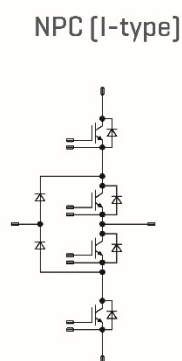


Figure 10:
NPC inverter topology

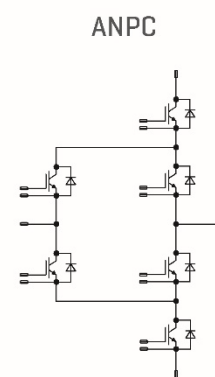


Figure 11:
ANPC inverter topology

In general, the losses in a flying capacitor inverter are distributed evenly across all components. This means a flying capacitor inverter has a lower junction temperature than NPC or ANPC for the same output power. Alternatively, a flying capacitor inverter enables a higher output power at same junction temperature as NPC & ANPC.

The flying capacitor inverter also supports full reactive power and bidirectional operation. A more detailed description of the operation of flying capacitor inverter topology is provided in reference [2].

3L-FC

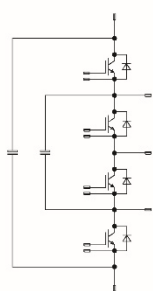


Figure 12:
3-level flying capacitor inverter topology

4L-FC

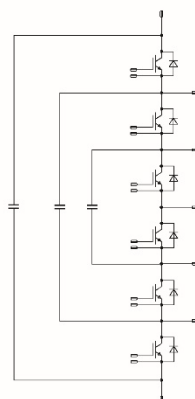


Figure 13:
4-level flying capacitor inverter topology

A key advantage of flying capacitor inverter, as with the flying capacitor booster, is the “artificial” increase of inductor current frequency. For a three-level flying capacitor topology, the inductor current frequency is double the semiconductor switching frequency and, in the case of four-level, it’s triple. The inductor size can be drastically reduced or, by keeping the same inductor current frequency, the semiconductor switching frequency can be reduced by factor of 2 or 3 respectively. This reduces the switching losses and results in a higher efficiency than NPC and ANPC.

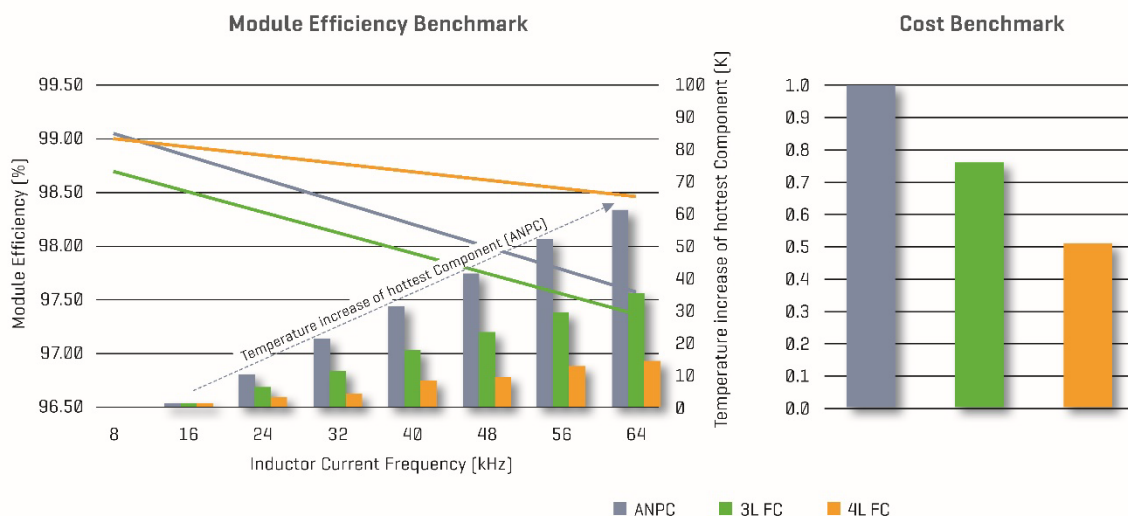


Figure 14: Module efficiency benchmark - conditions:
 $V_{dc} = 1350\text{ V}$, $V_{ac} = 460\text{ V}$, $P_{ac} = 117\text{ kW}$ per phase, $\cos\phi = 1$

Figure 15: Module cost benchmark

The efficiency comparison (figure 14) shows that an ANPC operated at 16 kHz inductor current frequency has same efficiency as four-level flying capacitor inverter at 32 kHz. By moving from ANPC to four-level flying capacitor the inductor current frequency can be doubled. Consequently, the inductor volume and, to a first approximation, the inductor cost can be reduced by 40%. In addition, as shown in the cost comparison (figure 15), the power module cost for a four-level flying capacitor is 50% that of the ANPC, which results in a significant system cost reduction.

High reliability is another key design requirement in PV inverters. The temperature of the hottest component of 4-level flying capacitor operated at 32 kHz inductor current frequency is only 4K higher than the ANPC operated at 16 kHz. Nevertheless, any temperature rise has effect on module lifetime. Vincotech's recently introduced new advanced die attach technology addresses this and increases the reliability at higher junction temperatures. Accelerated lifetime testing confirms that the new technology increases the module lifetime at 150°C junction temperature by at least 10 times.

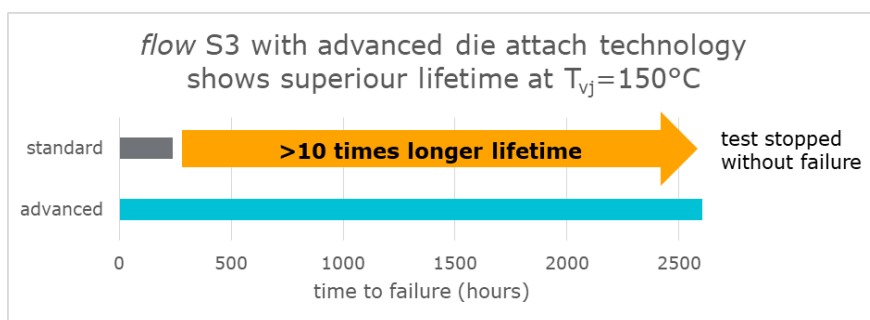


Figure 1: Result of accelerated lifetime test of standard and advanced die attach technology



Summary and solutions for high power multistring inverters

The performance and cost comparisons clearly show that the flying capacitor topology, in both booster and inverter, provide significant efficiency improvements, module and system level cost savings, and weight reduction in the inductor and heat sink requirements. These new topologies provide designers of next generation PV inverter systems with solutions to address the critical design requirements of high efficiency, maximum power density, low weight and extended reliability.

Vincotech offers a broad range of power modules optimized for the solar market. Combining symmetric boosters (LR6x family) or flying capacitor boosters (LS6x family) with ANPC inverters (LQx9 family) or the flying capacitor inverters (LMx9 family), Vincotech provides fully optimized and tailor-made solutions for 1500 V systems.

With these innovative technologies, Vincotech is providing solutions to help us get to a cleaner future.



References

- [1] "Symmetrical Boost Concept for Solar Applications up to 1000V", Temesi, Frisch, 01/2009
- [2] "Flying Capacitor Topology for Ultra Efficient Inverter Applications", Frisch, Temesi, 01/2021
- [3] "The Advantages and Operation of Flying-Capacitor Boosters", Antoni, 10/2020
- [4] Figure 1: Statistics from IEA PVPS report "Trends in Photovoltaic Applications 2020" (International Energy Agency, Photovoltaic Power Systems, Technical Collaboration Programme)
- [5] Figure 2: Statistics from SolarPower Europe 2020 report