Demystifying high-voltage power electronics for solar inverters

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The movement toward a clean and a sustainable grid is gaining a lot of momentum through advances in distributed energy resources, namely photovoltaic (PV) or solar power generation. Increased efficiency, reduced cost, and reliability are three areas where renewable-energy systems can achieve grid parity.

One of the key subsystems in PV generation is the inverter. Advancements in high-voltage power electronics are resulting in more intelligent, more lossless and smaller PV inverters.

The goal of this paper is to give an overview of the inverter, highlighting the benefits and advancements made in power electronics that have affected PV inverter technology – particularly wide-bandgap solutions such as silicon carbide (SiC) and gallium nitride (GaN).

Power conditioning in PV systems

PV panels made up of cells, connected in series or parallel, represent the front end of a PV ecosystem. These cells convert sunlight to electrical energy at typical efficiencies from 10% to 30%. The power extracted from the panels is DC and needs to be converted to AC, as most of the loads receive power from AC electricity distribution (the electric grid). Conversion from DC to AC power happens in the back end of the PV chain, in the inverter.

To ensure the stability of the power supply, PV generation systems are coupled with large-capacity energy storage to meet peak power loads. This is called a grid tied with an energy storage/battery backup system. This configuration, while complicated, is the trend in modern PV systems. The solar panel uses the charge controller to charge the battery. Typically, energy in the batteries is used either for peak power demand or for emergency backup. If the batteries are fully charged and the demand requires energy exceeding what the PV panels can provide, electricity flows into the grid from the batteries through the inverter.

On the other hand, if the panels produce excess electricity and the batteries are fully charged, then the electricity flows directly into the grid through the inverter. Inverters used in such systems are called grid direct inverters.

Function of the grid direct inverter

Synchronization with the grid is one of the key functions of a grid direct inverter. The inverter needs to generate a sinusoidal AC waveform at a fixed level from the PV panels, which has varying voltages depending on the sun's irradiance, weather conditions and other factors. The output voltage and frequency need to be at a certain level, outside of which the inverter will be unable to connect to the grid.

For example, grid direct inverters for residential systems in the U.S. usually have an output voltage of either 120V or 240VAC with an output frequency of 60Hz. Such stringent requirements are not necessary in inverters for stand-alone systems (where the PV panels connect not to the grid but to DC or AC loads). However, such systems are far less common than grid-tied configurations.

In addition to grid synchronization, the grid direct inverter performs other tasks, such as maximum power point tracking (MPPT), monitoring, protection and communication.

Key inverter components

Regardless of configuration, inverters today are built using high-voltage power electronic components. The key components of an inverter are:

- Power semiconductor switches: insulated gate bipolar transistors (IGBTs), silicon metal-oxide semiconductor field-effect transistors (Si MOSFETs), SiC and GaN
- Gate drivers
- A controller for MPPT and charging energy storage solutions (batteries) – digital or analog

Keeping in mind high efficiency, high reliability and low cost as the key priorities to achieve grid parity, it is imperative to make the right component choices depending on inverter requirements such as power level and rail voltage. Power losses in semiconductor switches and gate drivers are directly related to efficiency. Keeping losses close to zero in passive filtering elements such as capacitors, inductors and transformers is also critical.

Inverter configurations

Figure 1 shows three different inverter configurations. Each one depends on the power levels. A micro-inverter is a low-power configuration ranging from 50W to 400W. A medium power configuration between 1kW and 20kW is called a string inverter, while a high-power configuration greater than 20kW is called a central inverter.

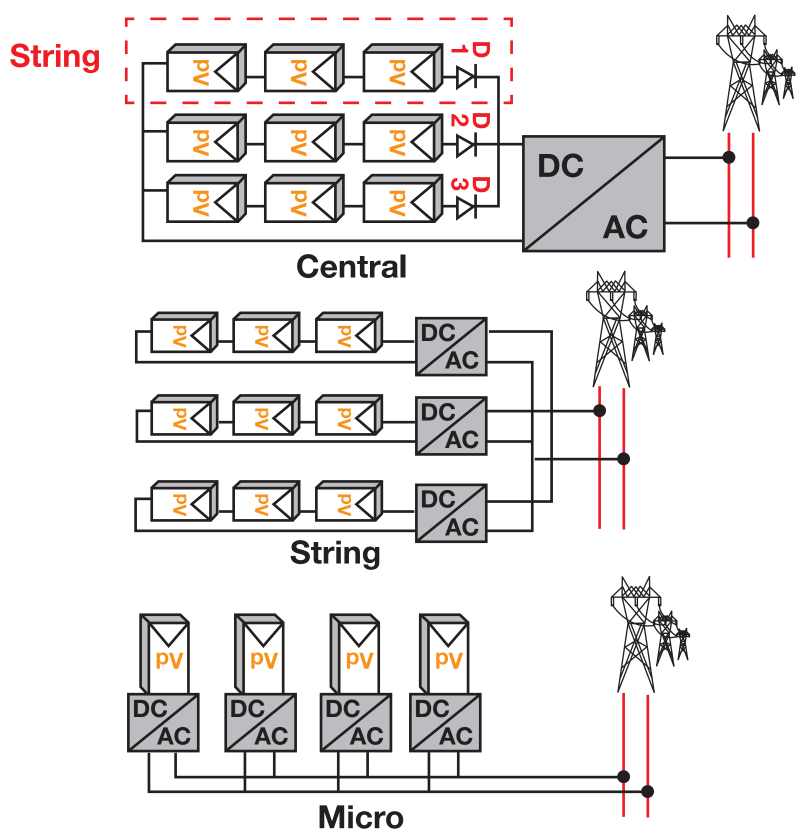

Figure 1. *Different inverter configurations.*

All inverter configurations follow the same methodology for power conversion and similar requirements: an integrated solution to lower system/overall cost, high efficiency, small size and increased lifetime (20 years). There are also variations in MPPT and power-conversion topology to maximize inverter efficiency. The choice of power electronics components varies by configuration as well.

Here are the main features of the three inverter configurations:

- Micro inverter:
  - Integrates a separate inverter and MPP tracker in each solar panel
  - No DC cabling, but requires extensive AC cabling
  - More efficient than string inverters
  - Only economical for small systems

- String inverter:
  - Solar panels are connected serially (strings)
  - Uses multiple inverters for example, one per string
  - Good efficiency, because every string can operate in its maximum power point

- Central inverter:
- Several strings (serially coupled solar panels) are connected in parallel
- Uses only a single inverter for a set of solar panels
- Special diodes are required to enable different string voltages, but diodes cause losses
- Not all solar panels can be driven to their maximum power point

Among the three configurations, the string inverter is by the far the most popular. String inverters are very scalable and economical for both residential and commercial applications.

Inverter stages

Fundamentally, the function of an inverter is to convert DC to AC in addition to monitoring MPPT and sinusoidal wave shaping. For a grid direct inverter, the input voltage usually needs to be above the output AC voltage (grid voltage). For example, generating a sinusoidal waveform of 230VAC requires an input voltage higher than 400VDC. The problem is that PV modules often deliver lower voltages than what the digital-to-analog converter requires. The way to resolve this is to use a boost DC/DC converter as the first stage [1].

DC/DC stage

In order to maximize the performance of the PV panels, the front end of the inverter is a DC/DC stage where a digital controller performs MPPT. The most common topology is a non-isolated DC/DC boost converter. The MPPT algorithm ensures that maximum power is drawn accurately and quickly when there is varying irradiance. The inverter also ensures an appropriate grid-compliant voltage.

The inverter configuration dictates finer control of MPPT. Micro inverters connected at the back of each solar panel can achieve the finest control and enable MPPT at a modular level. The less granular solution is a string inverter connected to a series of modules. This inverter has a sophisticated controller (usually digital) that performs similar MPPT. Although less granular, string inverter solutions usually have the largest cost advantage, a key metric in the solar industry.

The digital controller is also responsible for pulse-width modulation (PWM) in the primary side. PWM takes place using gate drivers. Depending on the inverter configuration, isolation may or may not be needed.

In all inverter configurations, the DC/DC stage uses high switching frequencies. However, the rail or DC link voltage could vary from as low as 200V to greater than 1kV depending on the inverter configuration. For voltages around 600V or below, Si MOSFETs are a good fit for DC/DC conversion.

Since reduced size is becoming a trend, especially in string and micro inverters, GaN is being adopted in micro inverters because of its ability to switch at frequencies close to 1MHz. On the other hand, for voltages higher than 600V, SiC MOSFETs are becoming more popular. Depending on the topology, single, dual or half-bridge MOSFET drivers are used with fast propagation delays and high drive currents.

DC/AC stage

Figure 2 shows the block diagram of a starting inverter with the DC/AC stage marked in red. The rail voltages are around 600V to 1,200V, particularly in string and central inverters, making IGBTs the preferred choice for switching. The gate drivers needed to switch these IGBTs require advanced features such as desaturation, short-circuit current protection, Miller clamping and negative voltage handling. In addition, these drivers need to be galvanically isolated. This is explained in a later section.

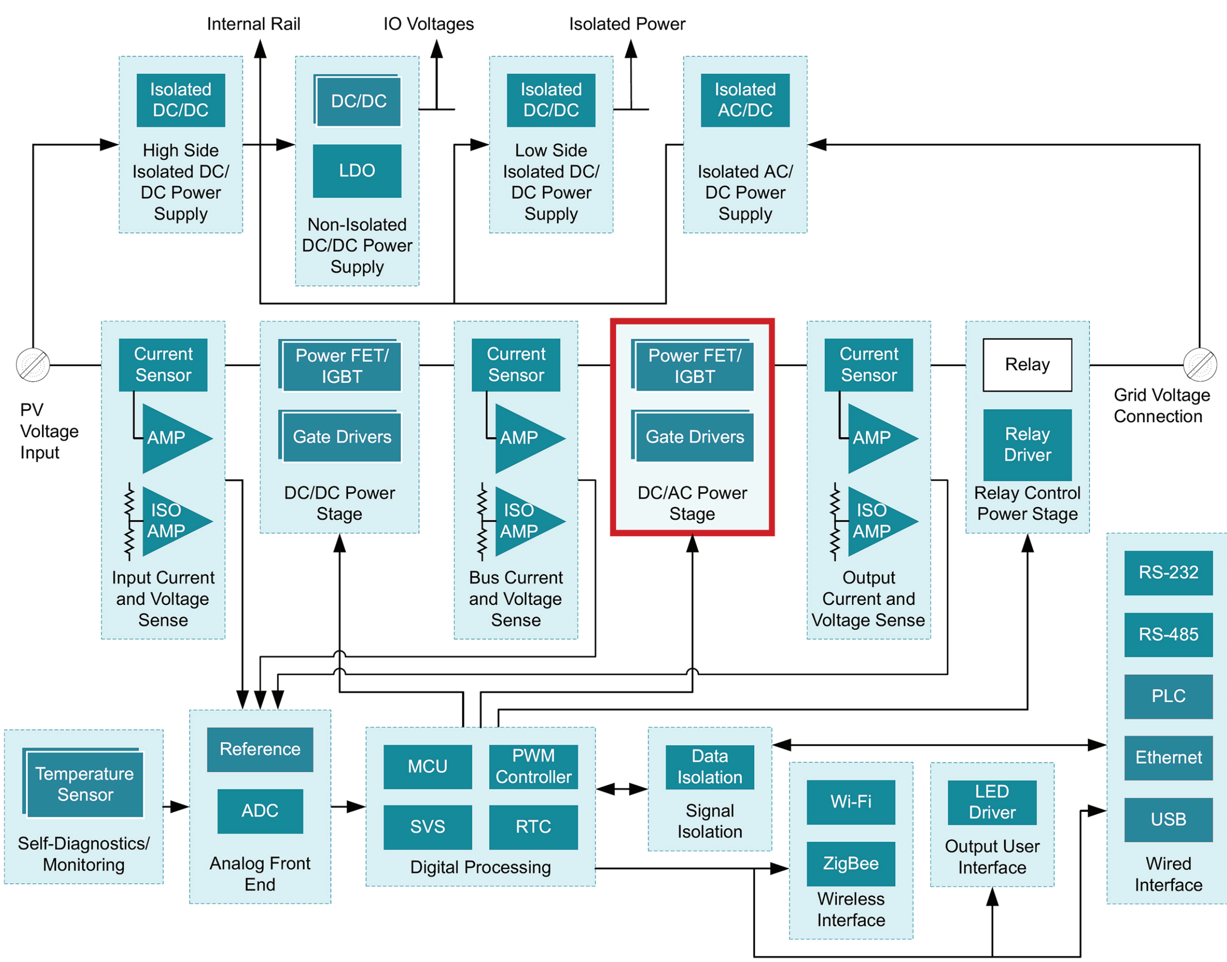

Figure 2. *. Block diagram of a string inverter.*

Why is SiC the right choice?

As mentioned earlier, there is a strong push toward higher system efficiency, longer lifetime and compact solutions. Unfortunately, MOSFETs and IGBTs are approaching their theoretical limits. IGBTs currently used in high-voltage (>650V)/high-power applications are already being stretched to their absolute limit at voltages above 1kV.

SiC FETs have superior material properties such as low on-resistance, high thermal conductivity, high breakdown voltage and high saturation velocity compared to silicon. All of these characteristics result in an efficient, robust and compact system with reduced cooling needs. SiC FETs are built into high-power DC/AC stages, either as several FETs connected in parallel or as a module.

SiC cannot do it alone

SiC switches need to be turned on and off for efficient power transfer through a gate driver as dictated by the controller for any given topology. The gate driver acts as an interface between the controller and the power device. Given the superior characteristics of SiC FETs, defining the requirements for gate drivers becomes very critical [3].

One unique feature for a SiC gate driver is fast overcurrent protection, versus desaturation for an IGBT gate driver. For the same rated current and voltage, an IGBT reaches the active region for significantly lower collector-emitter voltage (VCE) (typically 9V) compared to a SiC MOSFET. IGBT self-limits the current increase. In the case of SiC, the drain current (ID) continues to increase with the increase in the drain-to-source voltage (VDS), eventually resulting in faster breakdown. It is therefore critical for a SiC gate driver to have fast protection and therefore fast fault reporting, typically 400ns [3].

The gate voltage must have high dv/dt to accommodate the high switching speeds of SiC, implying the need for a low impedance driver for robust operation. Since SiC and IGBTs are used in high-voltage/high-power applications, almost all of the gate drivers are isolated. **Table 1** is a comparative analysis among Si MOSFET, IGBT and SiC gate drivers.

Power Switch	MOSFET	IGBT	SiC
Switching frequencies	High (>20kHz)	Low to medium (5-20kHz)	High (>50 kHz)
Basic protection	No	Yes – Desaturation, Miller Clamping	Yes – Current sense, Miller Clamping
Max Vdd (power supply)	20V	30V	30V
Vdd range	0 to 20V	-10 to 20V	-5 to 25V
Operating Vdd	10 to 12V	12 to 15V	15 to 18V
UVLO	8V	12V	12 to 15V
CMTI	50 to 100V/ns	<50V/ns	>100V/ns
Propagation delay	Smaller the better (<50ns)	High (not critical)	Smaller the better (<50ns)
Rail voltage	Up to 650V	>650V	>650V
Typical applications	Power supplies – Server, datacom, telecom, factory automation, onboard and offboard chargers, solar u-inverters and string inverters (<3kW), 400-12V DCDC - Auto	Motor drives (AC machines), UPS, solar central and string power inverters (>3kW), traction inverters for auto	PFC – Power supplies, Solar inverters, DCDC for EV/HEV and traction inverters for EV, motor drives, railways

Table 1. *Comparison of SiC to MOSFET and IGBT iso drivers.*

In addition, all gate drivers and controllers need to power up at the highest level of efficiency using isolated power supplies. These supplies are usually flyback converters or general-purpose PWM converters.

Need for isolation

Galvanic isolation is a technique to isolate functional sections of electrical systems to prevent current flow between them. This prevents no direct current or uncontrolled transient current from flowing in between the two. However, data and energy need to flow through this galvanic isolation barrier. This barrier is based on optical, magnetic or capacitive isolation technologies. Of these, capacitive and magnetic isolation allow data to be transmitted through the barrier digitally. Capacitive isolation, like magnetic isolation has digital circuits for encoding and decoding the incoming signals to pass through the isolation barrier. Also fundamentally capacitors do not pass DC signals and can only pass AC signals. That makes it inherently the right choice for isolation. Finally, they are not susceptible to magnetic noise while maintaining high data rates and keep the power consumption low.

Particularly for SiC power switches, capacitive isolation is the preferred choice for SiC gate drivers due to its high data rate and high noise immunity (also called common mode transient immunity) above 150V/ns.

In general, there are two types of galvanic isolation, basic and reinforced. Choice of the type is dictated by the standards and certification requirements for the inverter in the region it is sold.

Summary

TI offers several isolated gate drivers for power switches, including the ISO545x/585x, UCC21521C, UCC2122x and UCC53xx for efficient and reliable solar power conversion. Digital controllers such as TI's Piccolo™ and Delfino™ families from the C2000™ platform of real-time controllers are available for efficient PWM and MPPT control along with analog controllers such as the UCC28C45 and UC2845 for auxiliary power supplies.

References

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