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A Practical Primer On Motor Drives (Part 8): Power Semiconductors

by Ken Johnson, Teledyne LeCroy, Chestnut Ridge, N.Y.

The preceding parts of this article series have discussed the various winding configurations associated with single-phase and three-phase electrical systems, defined the associated electrical parameters (voltage, current and power) and demonstrated how to measure these parameters using Teledyne LeCroy's Motor Drive Analyzer. These definitions and measurements are essential knowledge for evaluating a motor drive's performance.

Many of the measurements discussed were performed at the input to a motor drive. Here in part 8, we begin to look inside the motor drive to understand its operation by introducing the power semiconductors (also referred to as *power switches*) that control the flow of power to the drive. This section on power semiconductor device physics will be a review for most power electronics engineers. However, for those new to the motor drive field, this section lays the groundwork for a discussion of the power conversion topologies and circuits discussed in subsequent parts of this series.

Drives And Other Power Converters

Power conversion is the conversion of electric power from one form of power (ac or dc) to another (ac or dc), from one voltage to another, or from one frequency to another, or some combination of these conversions. This primer is mainly concerned with one very specific type of power converter—the motor drive.

Typically, the term drive refers to any power converter that transforms one ac or dc line voltage to a different ac voltage or frequency. Motor drives, variable frequency drives, variable speed drives, and inverter drives are all different ways to say the same thing. Drives are sometimes used in non-motor applications such as converting the voltage or frequency produced by a wind turbine.

In addition to drives, there are power converters that perform ac-dc, dc-ac and dc-dc conversions as outlined in the table below. While these power converter categories are beyond the scope of this primer, there are many design techniques and issues that are common across the different power converter categories. Therefore much of the material discussed in this primer will be relevant to designers of other power converter types. That includes the discussion that follows on power semiconductors, which are the basic "building blocks" of any power conversion and drive system.

Table. Power converter types.

Type	Function	Examples
Ac-ac	Conversion of ac line voltage to a different ac voltage or frequency. This is commonly referred to as a "drive."	Motor drives, variable frequency drives (VFDs), variable speed drives (VSDs) and inverter drives.
Ac-dc	Conversion of ac line voltage to a specified dc voltage. Commonly referred to as a "converter," "power supply" or "ac adapter."	Internal and external power supplies for computing and other electronic equipment.
Dc-ac	Conversion of dc voltage to a specified ac voltage and frequency. Commonly referred to as an "inverter".	Inverters used in automotive and other mobile applications as well as solar power inverters. These could also be motor drives (e.g., a battery-powered drill or electric vehicle propulsion motor drive).
Dc-dc	Conversion of dc voltage to a different specified dc voltage. Commonly referred to as a "dc-dc converter".	Includes isolated and nonisolated dc-dc converters used in computing, telecom, networking and many other applications.

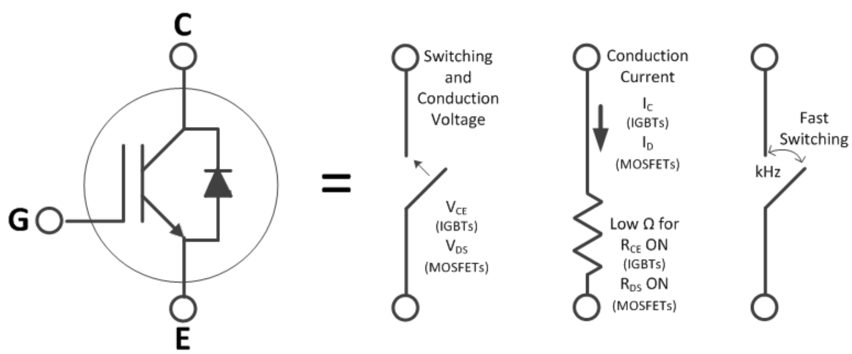
For our purposes, power conversion involves use of fast power semiconductor devices as "switching" devices to enable efficient conversion. In most applications, these devices run at typical switching frequencies from 1 to 100 kHz. In this context, we do not consider a 50-/60-Hz core/coil device such as a line-frequency stepup or stepdown transformer to be a power conversion device.

Power Semiconductor Device Operation

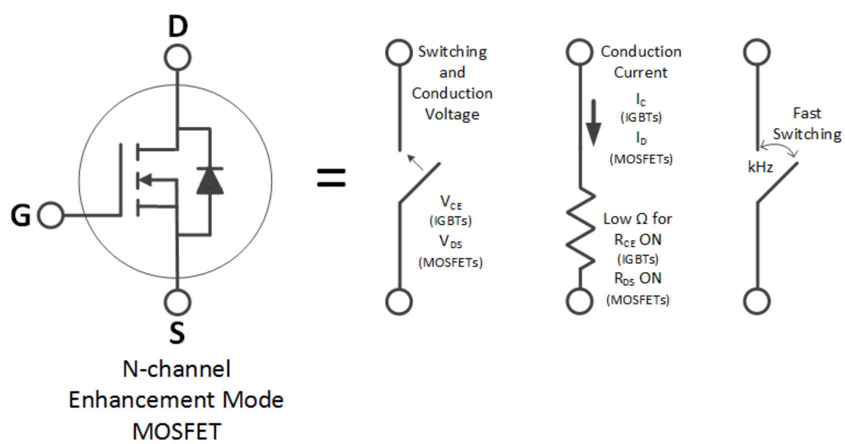
One may consider a power semiconductor device, as used in a power conversion system, as a very fast switch with the following characteristics:

- A rated "withstand" (blocking) voltage that is the maximum open-circuit voltage
- A current-carrying capability
- Low losses when carrying current (low forward-voltage drop, or low resistance)
- A fast switching capability (typically measured in the tens or hundreds of kilohertz).

Fig. 1a shows an insulated-gate bipolar transistor (IGBT) with terminal notations. A metal-oxide semiconductor field-effect transistor (MOSFET) is similar, but has different terminal notations, which are shown in Fig. 1b.



(a)



(b)

Fig. 1. An IGBT symbol (a) and a MOSFET symbol (b) and some of their associated characteristics.

Applying a voltage from the gate to an IGBT's emitter (V_{GE}), or, in a MOSFET, from the gate to the source (V_{GS}) controls the device's switching behavior. This voltage is known as the "gate-drive" voltage. Typically, V_{GE} = 0 V (in an IGBT) means the power semiconductor is not conducting, or is "open."

In power conversion applications, the V_{GE} signal is a pulse-width modulated (PWM) gate-drive signal that switches from 0 V to some upper voltage (typically 3 to 20 V, depending on whether is it is an IGBT or MOSFET, is Si, SiC or GaN, and the intended application). When the V_{GE} voltage is 0 V, the power semiconductor is "open" from the collector (C) to the emitter (E). When it reaches a switching threshold, it conducts (i.e., the "switch" closes) and conducts a high level of current at the defined biased dc bus voltage.

Fig. 2 shows the gate-drive PWM signal as applied at the gate terminal.

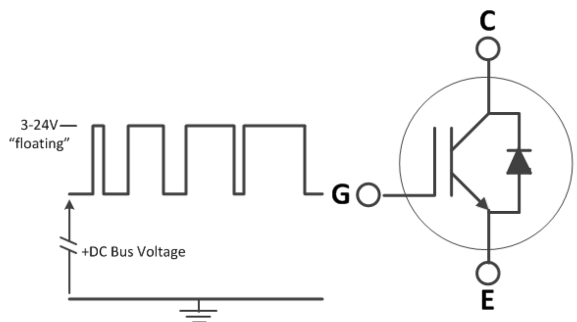


Fig. 2. Gate drive signal for an IGBT.

Note that the power semiconductor device, as implemented in a power-conversion design, is not referenced to ground potential. The gate-drive signal (V_{GE}) and the collector-emitter signal (V_{CE}) are therefore "floating" at half or full dc bus voltage (depending on the design), and this could be several hundred volts. Therefore, take care when probing these signals with an oscilloscope and a probe that has a ground reference (e.g., a typical non-isolated oscilloscope and a typical passive probe).

For safety's sake, ensure provision of isolation at up to the floating voltage rating in either the oscilloscope or the probe. A high-voltage differential probe provides such isolation. While some low-voltage power conversion designs (<50 V) may be safely probed with an ordinary passive probe and a non-isolated oscilloscope, a high-voltage differential probe may still be desirable for other in-circuit measurements, such as line-to-line voltage ac input or line-to-line drive output probing.

When the gate-drive signal is high, current conducts through the power semiconductor. When the gate-drive signal is low, the power semiconductor "switch" opens, blocking current flow.

If the power semiconductor device in this example is supplied with a 170-Vdc supply voltage (derived from a 120-Vac single-phase full-wave rectified and filtered line voltage) across V_{CE}, then the low-voltage PWM gate-drive signal creates a higher amplitude PWM signal that switches from 0 to 170 Vdc at a switching frequency in the kilohertz range. The gate-drive signal's PWM modulation is determined through a variety of different modulation algorithms programmed into a control system.

The PWM gate-drive signal turns the device on, the device delivers current at the rated dc bus voltage, and then the PWM gate-drive signal turns the device off. The device's output voltage is linearly related to the dc bus voltage and the gate-drive pulse width duration (or duty cycle), and the device's output frequency is related to the duty-cycle crossover point (duty cycle reducing to 0%, and then increasing again). If this PWM device output signal were filtered to remove the higher harmonics, the fundamental (rectified) sinewave would be apparent.

See Fig. 3 below for an example of the output PWM and a representative modulating sinusoidal waveform for a single power semiconductor device controlled as described above.

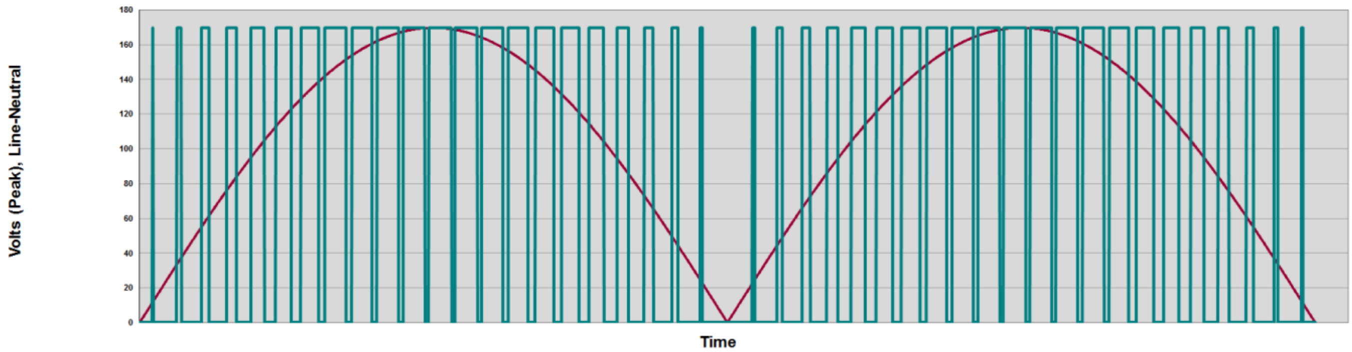


Fig. 3. PWM signal using single power semiconductor with modulating sinewave signal.

Practically speaking and for various reasons, the output PWM fundamental sinewave's (or rectified fundamental sinewave's) peak voltage never approaches the full dc bus amplitude. For the PWM signal, the peak voltage amplitude is typically 85% (or less) of the dc bus voltage, depending on the modulation and control scheme. For the fundamental ac, the peak amplitude would be much less than shown in Fig. 3 above.

N-Channel And P-Channel Devices

Control over the power semiconductor's electrical properties is achieved via addition of dopant impurity materials to the base semiconductor material (e.g., silicon). These additives cause the semiconductor to contain an excess of free current carrying "charge carriers". When doped with a material that supplies more free charge-carrying electrons, the semiconductor becomes n-type. When doped with a material that supplies more free charge-carrying holes, it becomes p-type.

The charge-carrying material defines the "majority carrier" or "channel" of the power semiconductor, and the direction of current flow: thus, we refer to devices as either n-channel or p-channel. However, when we employ MOSFETS in power conversion applications, the lower on-resistance and improved efficiency of n-channel devices makes them a heavy favorite over p-channel devices.

For IGBTs, p-channel (minority-carrier) devices are the more efficient of the two. Power-conversion designs are simpler when using a mix of n-channel and p-channel devices, based on circuit location and activity, but it is typically desirable to trade off design complexity for greater overall efficiency by using just one type of device in the entire design.

Power Semiconductor Device Materials

Power semiconductors are made with silicon (Si), or, more recently, a "wide bandgap" material such as silicon carbide (SiC) or gallium nitride (GaN). The term bandgap refers to the energy between the conduction and valence bands of the semiconductor material, which is the energy required to generate electron and hole movement. Wider bandgap devices impart useful attributes to a power conversion design, but add cost, design complexity, and EMI/RFI issues. They also may decrease system reliability.

Traditionally, power semiconductor devices have been based on Si. However, Si has limited blocking voltage when deployed in a (majority-carrier) MOSFET, and $R_{DS(ON)}$ increases with blocking voltage, making MOSFETs mostly unsuitable for ≥600-V applications. This generally relegates MOSFETs to ≤300-V applications. In (minority-carrier) IGBTs, the blocking voltage is higher (1200 V or more) with an approximately constant on-state voltage, but there are significant switching losses and high tail and reverse-recovery currents after switching, which reduces the converter's efficiency. This restricts IGBTs mostly to 600-V class equipment applications.

Compared to Si, wide-bandgap materials provide higher (breakdown) voltage ratings, faster switching speeds, lower leakage currents at high temperatures, and lower thermal resistance (for SiC). Faster raw device switching speeds translate to rise times in the low-nanosecond range, though deployment in power conversion devices are at much slower speeds to limit harmonics issues and reduce the risk of “shoot-through” (short circuiting, which leads to device failure).

The high blocking voltage and higher-temperature performance provides for better reliability and more compact designs and smaller heat sinks. Higher switching frequencies reduce losses during switching and reduce the size of dc bus/link filter components (e.g., capacitors and inductors). Thus, power conversion systems that use wide bandgap power semiconductors have reduced weight, higher power density (due to smaller size) and higher efficiencies.

Design challenges include mitigation of higher manufacturing cost, lack of long-term data on field reliability, a small knowledge base for implementation, and more parasitic and EMI effects in board layout.

SiC and GaN are the two wide-bandgap materials seeing commercial usage in MOSFETs and IGBTs. Compared to Si, SiC has 10x the blocking voltage, lower on-resistance, higher-temperature performance, and greater inherent cooling. We now see more use of SiC in IGBTs, which makes possible 15-kV devices for utility applications, opening new applications for solid-state distribution transformers and other utility grid-connected equipment in the 15-kV class. GaN has performance similar to SiC, but breakdown voltages that will likely limit it to <600-V applications.

With the advent of wide-bandgap materials, rise times are becoming faster and switching losses are falling in power conversion designs. However, faster rise times increase the risk of catastrophic failure and produce more EMI/RFI emissions. In general, the wide bandgap materials’ faster rise times impact the switching and conduction-loss measurements for individual devices more than the overall drive system output. While it is helpful to understand fully a power semiconductor device’s capabilities, it may often be prudent not to push these devices to their limits in a power conversion system for reasons of cost, reliability, and emissions.

Power Semiconductor Device Types

One may construct a power conversion circuit using a variety of power semiconductor device types, depending on the input/output voltages, surge power ratings, continuous power ratings, and application.

The main types of power semiconductor devices in use today are:

- Power metal-oxide-semiconductor field-effect transistor (power MOSFET)
- Insulated-gate bipolar transistor (IGBT)
- High-voltage (HV) IGBT
- Insulated-gate commutated thyristor (IGCT) or gate-turn-on thyristor (GTO)
- Silicon-controlled rectifier (SCR, or thyristor).

Fig. 4 illustrates the tradeoffs in switching frequency, breakdown voltage, and current-carrying capability between the different silicon power semiconductor devices. In the context of power conversion, all of these devices may alternatively be described as power switches.

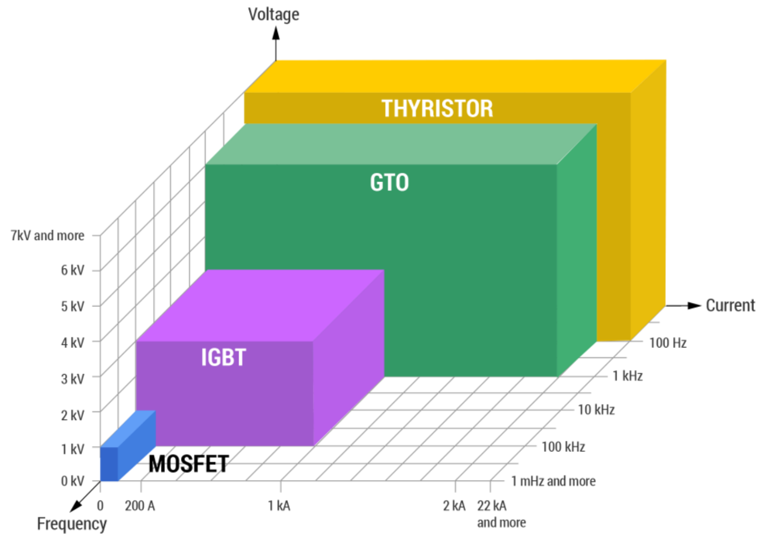


Fig. 4. Comparing breakdown voltage, switching frequency and current-carrying capability of silicon power switches.

Wide-bandgap materials (SiC and GaN) are attractive because they expand the application range of MOSFETs and IGBTs and incur lower switching losses (if implemented at maximum capabilities). As a result, wide-bandgap devices can alter the tradeoffs shown above.

Power MOSFETs

Power MOSFETs made of silicon typically have blocking voltage ratings up to 600 V and are used for switching voltages at roughly 300 V or less, especially with inductive loads that can impose large overvoltage conditions (up to 2x). Although current-carrying capability is in the tens of amps, paralleling devices makes for higher currents. These devices exhibit high switching frequencies (>100 kHz), high efficiencies (especially at low power levels), and reasonable costs.

Typical applications are in 120-/240-V switch-mode power supplies, lighting ballasts, dc-dc converters, and low-voltage (<50 V) or low-power 120-/240-V motor drives. The upper end of the voltage range for power MOSFET use is likely at about 500 V in solar photovoltaic (PV) inverter applications.

Power MOSFETs have a source and a drain that are connected to individually and highly doped regions that are separated by the body region. Current flow is across the drain and source when the gate-source voltage (V_{GS}) is correctly biased. MOSFETs may be n-channel or p-channel. In an n-channel MOSFET, the source and drain are "n+" regions and the body is a "p" region; the opposite is true for a p-channel MOSFET. This defines the direction of current flow when the device is biased.

MOSFETs may be either enhancement-mode or depletion-mode types. Enhancement-mode MOSFETs are normally off at zero gate-source voltage (V_{GS} = 0 V), whereas depletion-mode MOSFETs are normally on at V_{GS} = 0 V. Most MOSFETs used in power conversion devices are n-channel (majority carrier) enhancement-mode MOSFETs because n-channel MOSFETs have a third of the on-resistance of p-channel MOSFETs and are thus more efficient.

Fig. 5 shows the electrical symbols for n- and p-channel enhancement-mode MOSFETs.

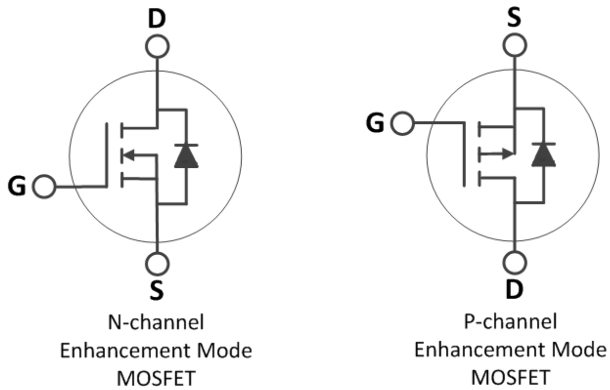


Fig. 5. MOSFET symbols.

IGBTs

IGBTs have blocking voltage ratings of ~1200 V and switching frequencies of 1.5 to 10 kHz (in silicon). High-voltage (HV) IGBTs can reach up to 6000-V blocking voltage (typically implemented in designs at half this voltage for reliability reasons). Lower-voltage IGBTs can be cascaded to achieve similar ratings (though with higher design complexity). Current-carrying capability is in the hundreds of amperes. Due to their higher blocking voltage and ruggedness compared to MOSFETs, one often finds IGBTs in 600-V class motor drives, propulsion ("traction") motor drives, uninterruptible power supplies (UPSs), and welding systems.

In power conversion applications, IGBTs are minority-carrier (p-channel) devices. Fig. 6 shows the electrical symbol for a p-channel (minority-carrier) IGBT.

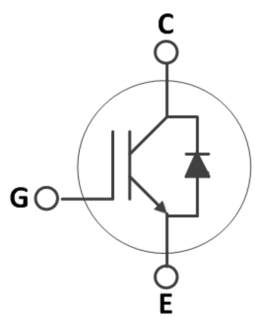


Fig. 6. P-channel IGBT symbol.

Note that in an IGBT, the source and drain are known as a collector (C) and emitter (E).

IGCTs, GTOs, And SCRs

Historically, IGCTs and GTOs have been the preferred power semiconductor for medium-voltage (2.4 kV to 7.2 kV) ac induction motor drives. These devices have blocking voltage ratings up to 6000 V and a simpler and more-efficient architecture for higher power ratings, but a much slower (<1 kHz) switching frequency compared to IGBTs. However, slower switching matches up well with higher voltages because problems often result from attempts to switch high voltages at high speeds.

SCRs can switch only once per power cycle—they can switch on at any point in a cycle but cannot switch off until a zero crossing occurs. This makes their switching frequencies very slow, making them suited for very high-voltage transmission and distribution applications, but less so for drives and other lower-voltage power conversion applications.

Conclusion

This section reviewed the various types of power semiconductor devices or switches that are employed in power converters. The principles of device operation were explained, their capabilities were discussed, and their typical applications were noted. The performance benefits of the newer, wide-bandgap devices versus the more established silicon devices were also discussed. This material lays the foundation for a discussion of power stage topologies in the next section (part 9) and subsequent discussions of motor drive circuitry. For a full list of topics that will be addressed in this series, see part 1.

About The Author

Kenneth Johnson is a director of marketing and product architect at Teledyne LeCroy. He began his career in the field of high voltage test and measurement at Hipotronics, with a focus on <69-kV electrical apparatus ac, dc and impulse testing with a particular focus on testing of transformers, induction motors and generators. In 2000, Ken joined Teledyne LeCroy as a product manager and has managed a wide range of oscilloscope, serial data protocol and probe products. He has three patents in the area of simultaneous physical layer and protocol analysis. His current focus is in the fields of power electronics and motor drive test solutions, and works primarily in a technical marketing role as a product architect for new solution sets in this area. Ken holds a B.S.E.E. from Rensselaer Polytechnic Institute.

For further reading on motor drives, see the How2Power Design Guide, locate the "Power Supply Function" category, and click on the "Motor drives" link.