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A Practical Primer On Motor Drives (Part 9): Power Semiconductors As Implemented In Power Conversion Systems

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The review of power semiconductor physics in the last part set the stage for a discussion of the power electronics circuitry found in motor drives. This section does not provide exhaustive technical detail regarding power-electronics designs. Rather, it introduces the common power conversion topologies, explaining in broad terms how they work and the types of outputs they produce.

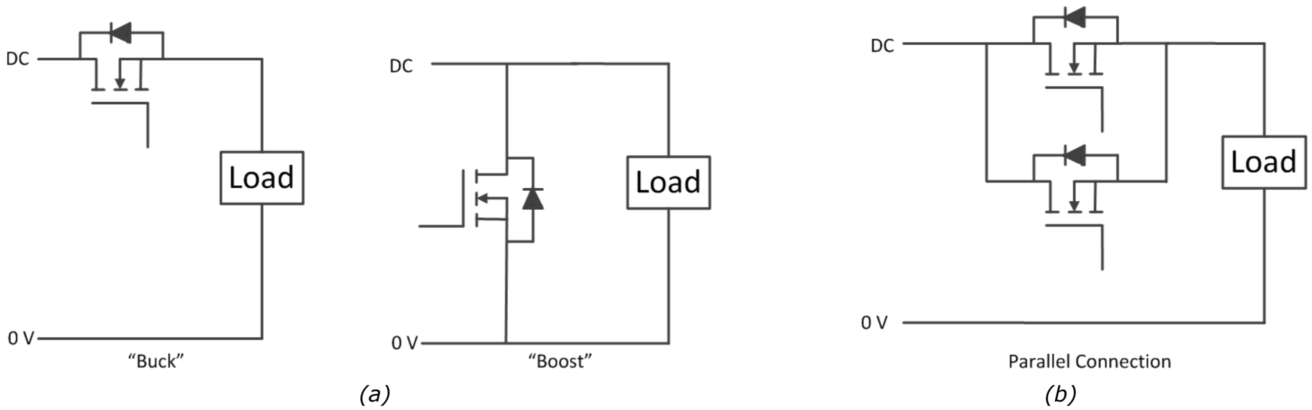
The topology discussion begins with single-device configurations of buck and boost stages, then moves onto the multi-device topologies—the half-bridge and full bridge (H-bridge). The latter subject covers both the standard (single-phase) and cascaded (three-phase) H-bridges with descriptions of both the sine-modulated and six-step commutated PWM control techniques.

Both the half bridge and H-bridges produce two levels of output voltage albeit with different degrees of control over output voltage and current. For those drive application requiring even greater control over these parameters or the ability to reach higher output voltages, there are multi-level topologies, which are also introduced here.

Note that the circuits used to explain the various topologies are greatly simplified. Also for the sake of simplicity, IGBTs are shown as the power switches in all the circuits. However, all of these topologies can use either MOSFETs or IGBTs depending on voltage, current, and other application requirements.

Single Device

Regardless of type, one may connect a single power semiconductor device in series with the load ("buck") or in parallel with the load ("boost"), and may utilize multiple devices paralleled with each other for higher-current operation. Fig. 1 shows "buck" and "boost" configurations each with a single device, and two devices parallel to each other and in series ("buck") with the load.



(a) *(b)*

Fig. 1. Connecting a power switch in series with the load is referred to as a buck configuration, while connecting a power switch in parallel with the load is known as a boost configuration as shown in part (a). Paralleling multiple power switches as illustrated in part (b) allows the power stage to handle higher current levels.

With two devices in parallel, both devices switch identically and together they deliver twice the current of a single device to the load. The PWM and modulating ac voltage for a single device, given a 170-Vdc bus voltage, is shown in Fig. 2.

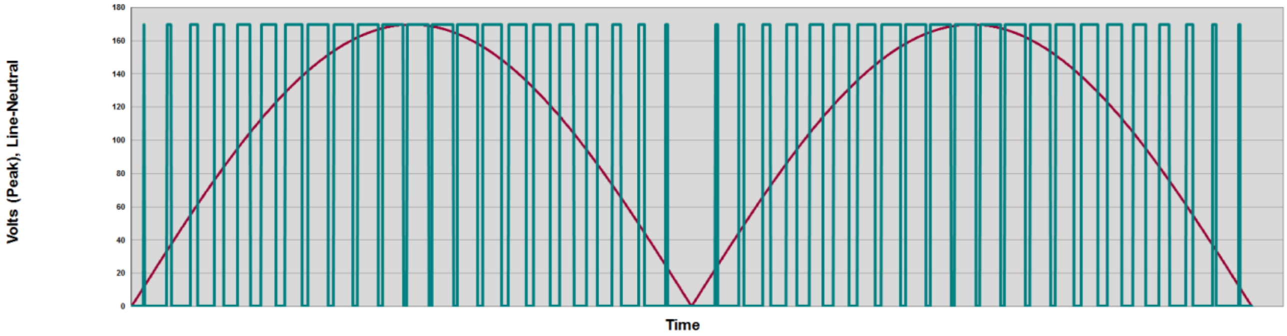


Fig. 2. PWM signal for a single power semiconductor shown with modulating sinewave signal.

Series Connection (Half-Bridge)

One may connect either IGBTs or MOSFETs in series to provide higher-voltage operation and/or ac voltage output biased around zero. This is known as a half-bridge connection. Such circuits serve single-direction control of a load, with the direction of power flow depending on whether we connect the load to the upper rail (dc) or the lower rail (0 V).

Bidirectional control is theoretically possible using some sort of reversing mechanical switch, but doing so mitigates against instantaneous switching of the output polarity to the load without damaging the half-bridge devices, the load (motor), or other parts of the circuit. Thus, bidirectional control with a half-bridge is impractical in most situations.

We cannot close both power semiconductor "switches" (conducting) at the same time because a short circuit will destroy both devices. We ensure "dead time" safety margins with more complex switching control. During this dead time, both devices are "open" and non-conducting before switching to their next assigned "open" or "closed" state. Fig. 3 shows the half-bridge configuration.

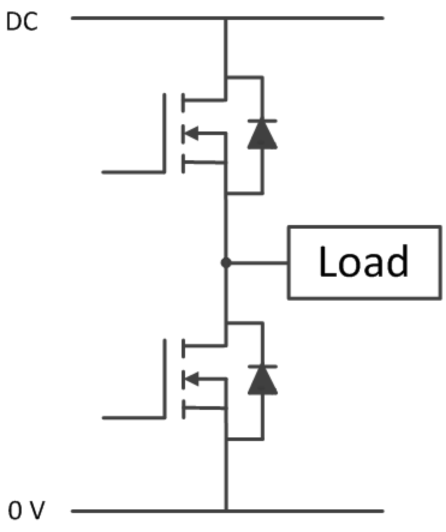
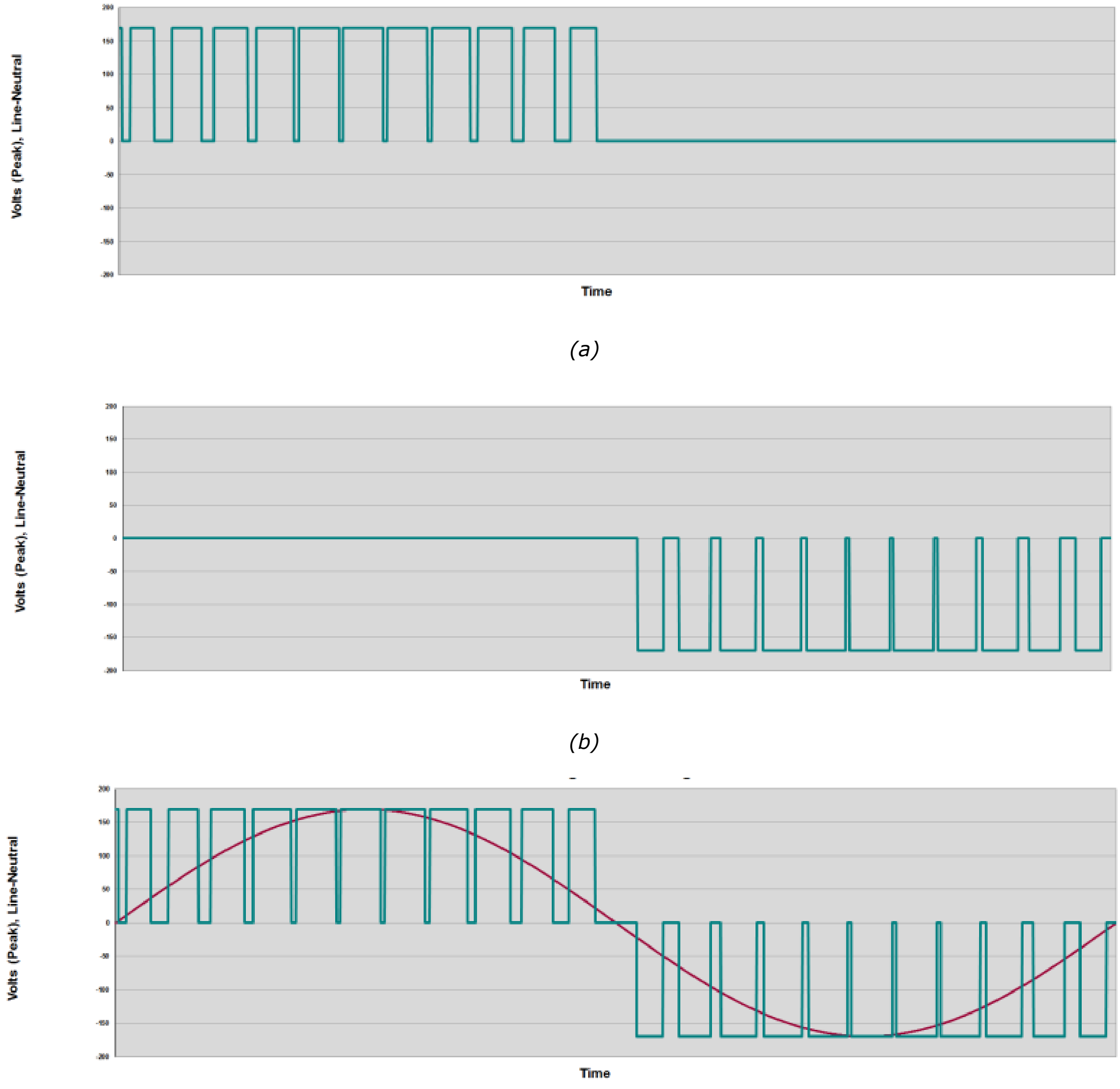


Fig. 3. Two series-connected power switches are referred to as a half-bridge.

As in the single-device example (or parallel-device, single-output example), each device is controlled by a gate-drive signal, although in this case the gate-drive signals are different and independent for each device. Again, while the control system manages the gate-drive switching to generate the appropriate output from the devices for voltage and frequency control, each device continues to be driven from (in this example) 0 to 170 Vdc derived from the 120-V rectified ac. To achieve a sinusoid-like output, switching commences in a "complementary" fashion with one device "off" while the other is "on". The output to the load is the difference between the two IGBT waveforms at any given time.

The three waveforms in Fig. 4 show the switching (green trace) of the upper device (part a), the lower device (part b), and the difference between the upper and lower devices (part c; note the overlay in red of the modulating ac sinewave). The load sees the difference between the upper and lower signals with the polarity determined by termination of the load (at the dc bus or the 0-V rail).



(a)

(b)

(c)

Fig. 4. PWM signals for a single-phase half-bridge power stage. The PWM signal for the "upper" semiconductor is shown in (a), while the PWM signal for the "lower" semiconductor is shown in (b). Part (c) shows the combined "upper + lower" semiconductor PWM signal with the modulating sinewave signal.

In the “upper-lower” device output signal, a 50% duty cycle represents a 0-V condition. Note that even though the input was only 120 Vac, the power conversion circuit’s output is 340 Vpk-pk.

H-Bridge (Full-Bridge) Topology

Power semiconductor devices can also be connected in an H-bridge topology to achieve exactly what the half-bridge (series connection) does, but with built-in bidirectional power flow control and the ability to completely interrupt power flow (e.g., stop a motor) or brake a motor in a controlled fashion. Fig. 5 is a simplified H-bridge topology. Note the connection of the load between the series device pairs.

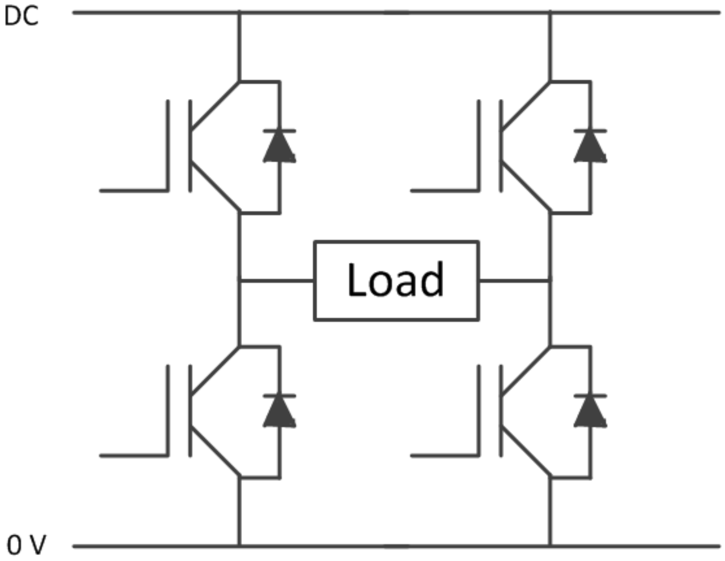
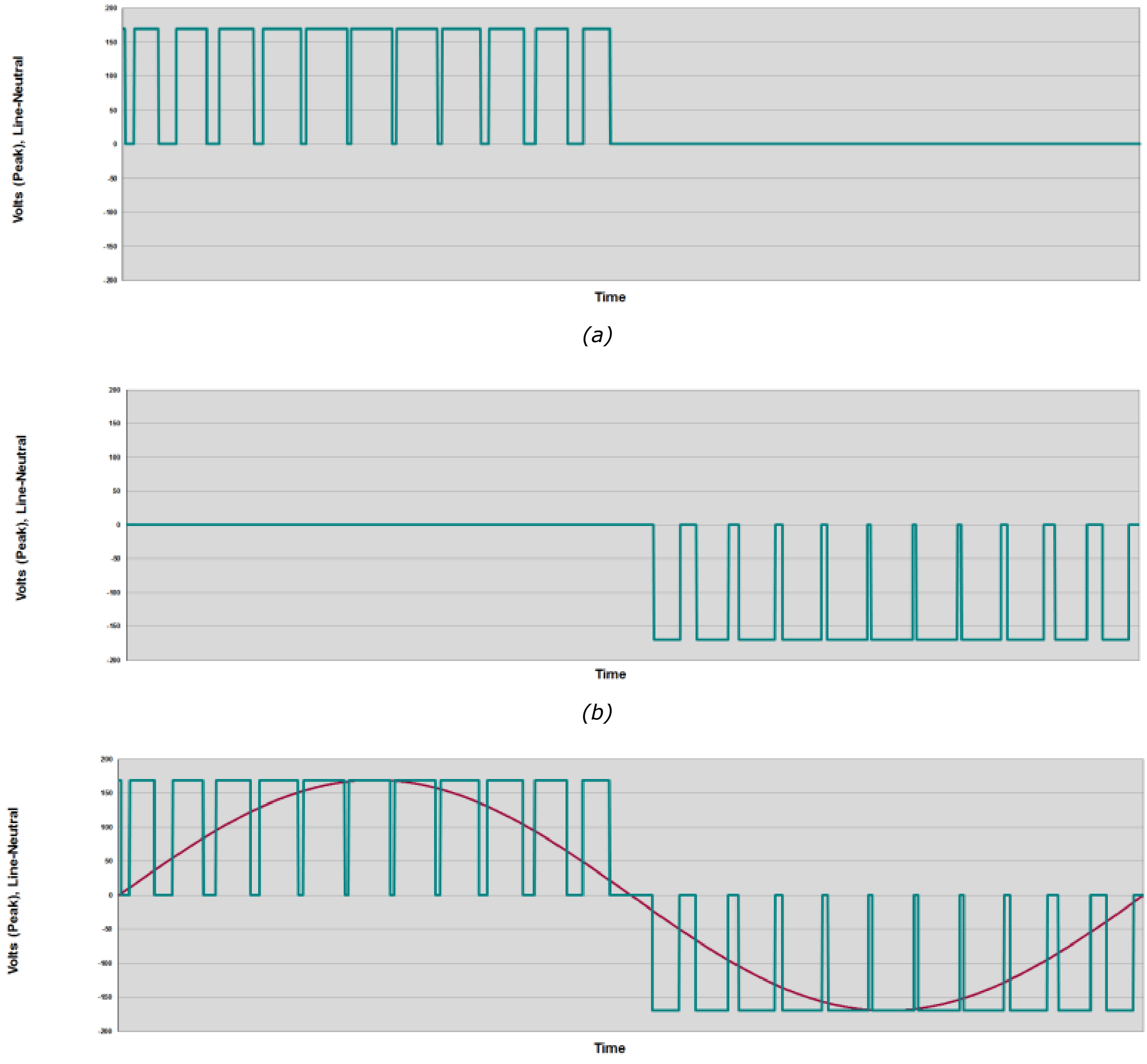


Fig. 5. The H-bridge or full bridge consists of two sets of two power semiconductor devices in series with a load connected across each output.

As with the half-bridge, we accomplish control using complementary switching of the power semiconductor devices in the circuit. However, the complementary switching is now coordinated among series devices that could be in different series device pairs. The “upper” device switches only for positive voltage and the “lower” device switches only for negative voltage.

The three waveforms in Fig. 6 show the switching (green trace) of the upper device (part a), the lower device (part b), and the sum of the upper and lower devices (part c). (Also note the overlay in red of the modulating ac sinewave in part c.) The load sees the sum of the upper and lower device signals.



(a)

(b)

(c)

Fig. 6. PWM waveforms for a single-phase H-bridge topology resemble the waveforms of the half-bridge. Shown here are the PWM signals for the "upper" semiconductor (a) and "lower" semiconductor (b). Part (c) shows the combined "upper + lower" semiconductor PWM signal with the modulating sinewave signal.

Fig. 7 shows the same type of single-phase signal acquired on channel 1 of a Teledyne LeCroy 12-bit oscilloscope.

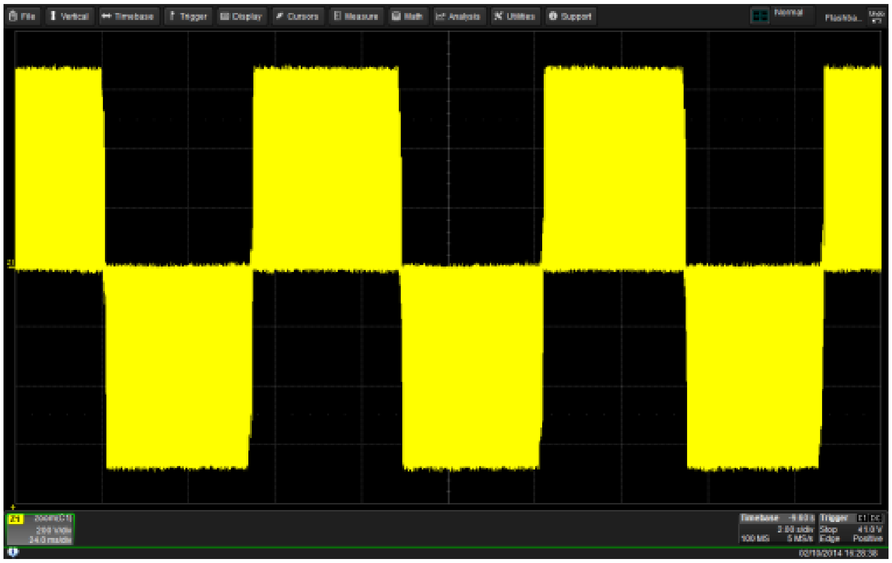
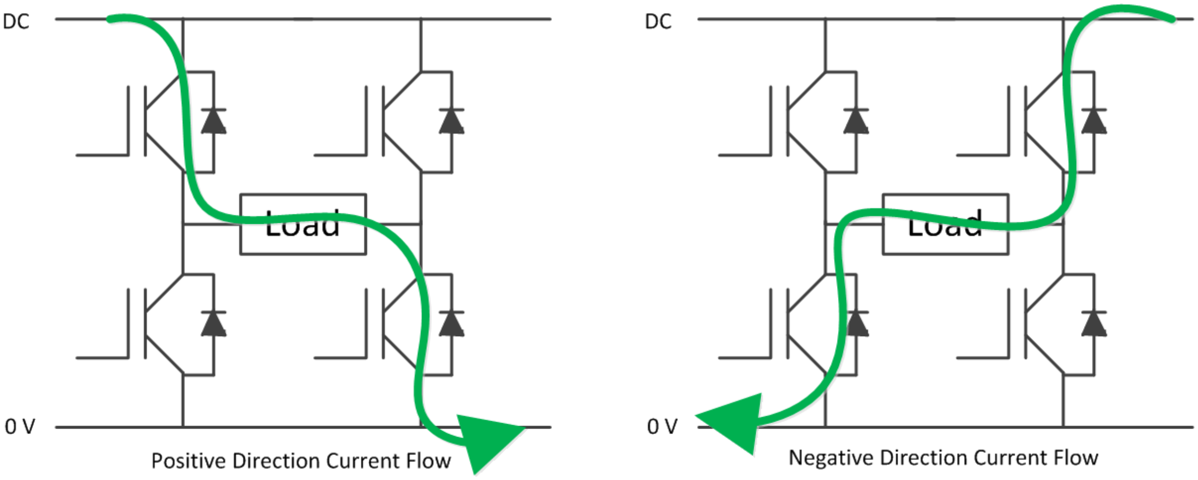


Fig. 7. An output waveform produced by an H-bridge. Because of the +Vdc and –Vdc levels, the H-bridge is also referred to as a two-level inverter or two-level drive.

Because the digital PWM output from an H-bridge has "two levels" (+V_{DC} and -V_{DC}), it is sometimes known as a "two-level inverter" or "two-level drive." As with the half-bridge, the H-bridge design outputs 340 Vpk-pk, but each device is switching only half the time lowering the total switching losses compared to the half-bridge.

For current flow in a positive direction through the load, the upper-left and lower-right devices conduct current while the others are "open." Current flows through the load as shown in Fig. 8a. For current flow in the negative direction through the load, the upper-right and lower-left devices conduct current while the others are "open," as shown in Fig. 8b.

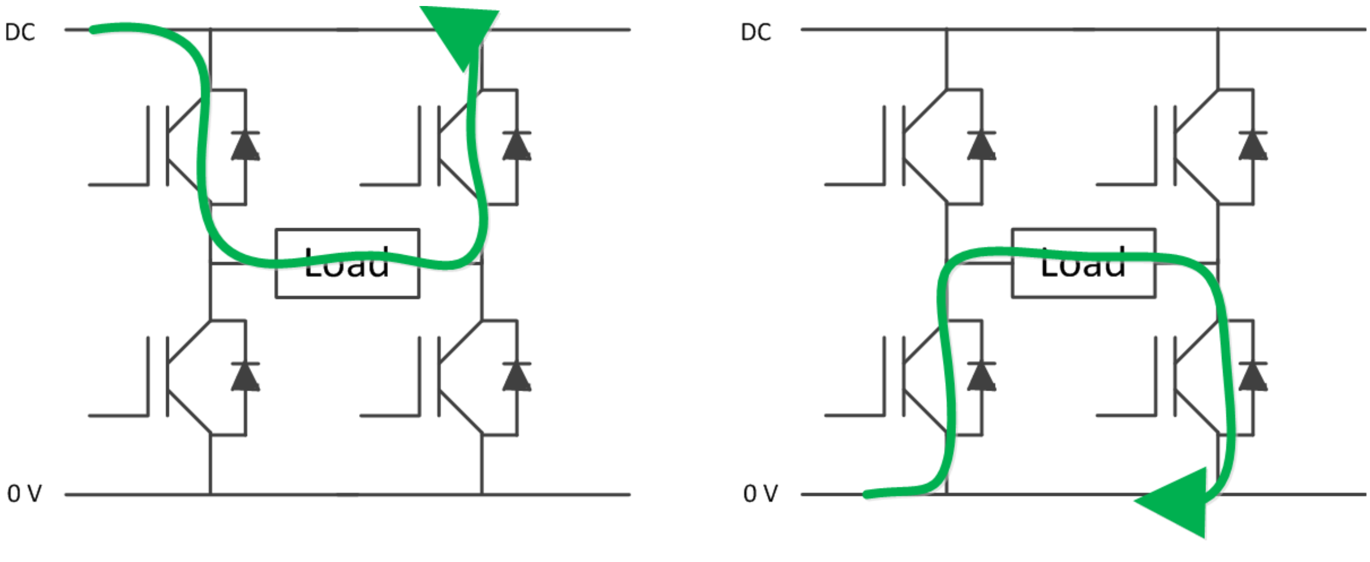


(a) *(b)*

Fig. 8. Current flow in an H-bridge.

To brake a motor in a controlled fashion (i.e., not instantaneously removing power or flipping the polarity) when the motor is moving in a positive direction, one would configure the devices so that both upper devices conduct current while both lower devices stay "open" to block current flow. Thus, both motor terminals are at Vdc (avoiding further application of power) while allowing power flow from the motor back into the circuit.

To achieve the same result for a motor moving in a negative direction, both lower devices conduct current while both upper devices remain "open." Both motor terminals are thus at ground potential, braking the motor's movement. These two cases appear in Fig. 9.



(a)

(b)

Fig. 9. Current flows within an H-bridge during controlled braking of a motor. When the motor is running in a positive direction, the H-bridge is configured so the upper devices conduct while the bottom devices block current (a). When the motor is moving in a negative direction, it's the lower devices that are conducting (b).

To maintain the motor in a "stopped" position, all devices are set to "open."

Cascaded H-Bridge Topology

An H-bridge provides bidirectional control of a single-phase load. To achieve bidirectional control of a three-phase load, the cascaded H-bridge is a popular topology. This topology appears in Fig. 10.

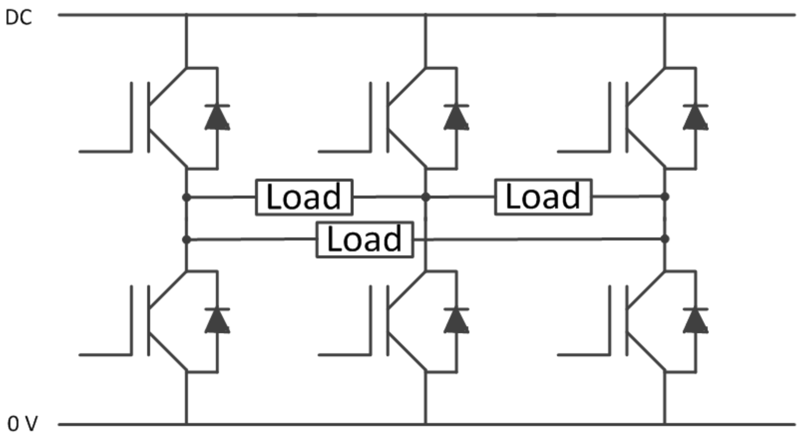


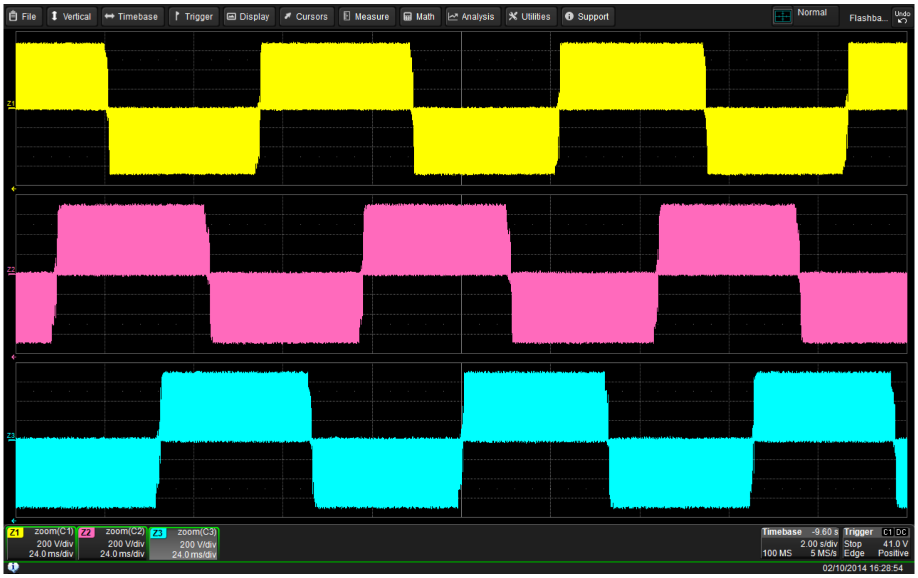
Fig. 10. The cascaded H-bridge provides bidirectional control of a three-phase load.

Note that increasing the number of output phases from one to three means only two more devices in the circuit. Thus, users of the cascaded H-bridge accrue all of the benefits of three phases (higher power levels, improved control capabilities, etc.) while only increasing power semiconductor device costs by 50%.

The control of the gate-drive signals and the device output operation for the cascaded H-bridge is very similar to that of an H-bridge with some exceptions. First, the output voltage now consists of three separate "line-to-line" voltages (sometimes referred to as U to V, V to W, and W to U; or R to S, S to T, and T to R). Fig. 11 is a screen capture of these three line-to-line waveforms taken with a Teledyne LeCroy 12-bit oscilloscope.

Secondly, the device switching behavior remains complementary, but the control is more complicated given the more complicated interactions among all the switching devices. Finally, the device switching control can be either through a three-phase, sine-modulated (carrier-based or space-vector) control scheme or a six-step commutated control scheme. Fig. 11 shows a sine-modulated control scheme.

As with the regular H-bridge topology, some refer to the cascaded H-bridge as a "two-level inverter" or "two-level drive." A cascaded H-bridge, built from either MOSFETs or IGBTs, is probably the most common type of inverter topology for creating three-phase output voltages to run 600-V class or lower-voltage products.



Z1 zoom(C1) 200 V/div 24.0 ms/div
Z2 zoom(C2) 200 V/div 24.0 ms/div
Z3 zoom(C3) 200 V/div 24.0 ms/div
Timebase -9.60 s 2.00 s/div 100 MS 5 MS/s
Trigger C1 DC Stop 41.0 V Edge Positive
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Fig. 11. The cascaded H-bridge produces three line-to-line outputs.

Sine-Modulated Cascaded H-Bridge

As with the H-bridge (single-phase) example, any two devices in series cannot both be "on" at the same time. Otherwise, operation of the complementary gate-drive switching is very similar.

Consider a desired ac waveform as shown in Fig. 12 with line-to-neutral voltages V_{R-N}, V_{S-N}, and V_{T-N} at a time t=0. At a given time for such a three-phase waveform, voltages will be generated so that the individual phases (the mid-point of each half-bridge in the cascaded H-bridge) is either sinking or delivering current, resulting in a three-phase current flow through the cascaded H-bridge as depicted in Fig. 13.

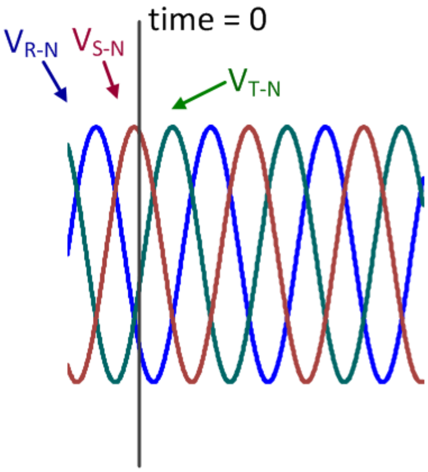


Fig. 12. The three-phase ac waveforms shown here may be generated using a sine-modulated cascaded H-bridge.

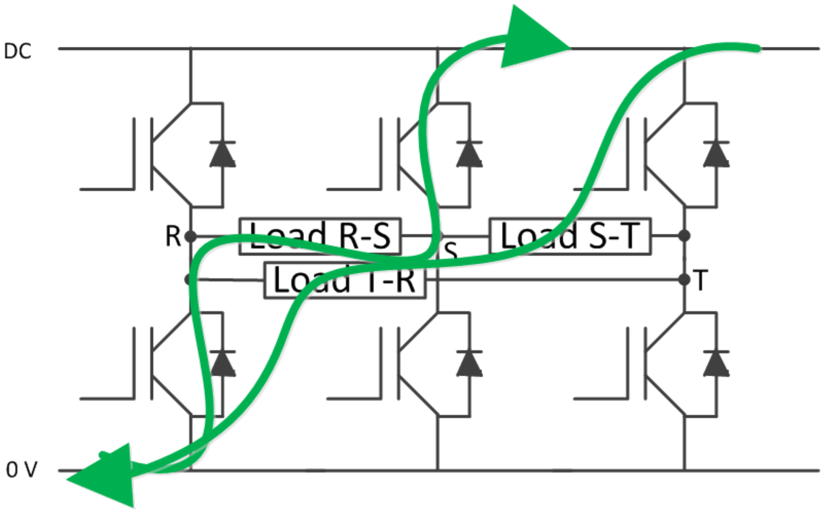


Fig. 13. Current flows in the cascaded H-bridge at t = 0.

To achieve the current flow shown in Fig. 13, the devices switch as follows:

- Upper R device is "off"
- Lower R device is "on"
- Upper S device is "on"
- Lower S device is "off"
- Upper T device is "on"
- Lower T device is "off".

Six-Step Commutated Cascaded H-Bridge

In a six-step commutation scheme, we apply voltages across only two of the three phases at any given time, with six "steps" for one complete commutation period. The six steps are typically determined by reading embedded Hall sensors placed in the motor's rotor. These Hall sensors generate high/low signals that, when read as a 3-bit pattern, define a pattern (000 and 111 excluded) that dictates when to apply the phase voltages. During this voltage application, the amount of voltage applied is controlled using pulse-width modulation.

For example, Fig. 14 shows the six steps across the top. The R, S, and T phase upper and lower devices appear as either on (high) or off (low).

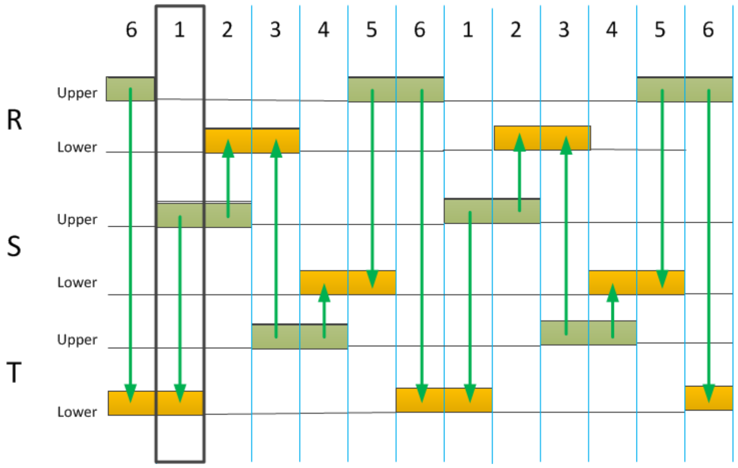


Fig. 14. This diagram shows the conduction states of the six switches in a cascaded H-bridge during implementation of a six-step commutation scheme.

If you look at step 1 (outlined in Fig. 14), phase R is not energized, and phase S and T are energized. According to the diagram above, the device switching should be as follows:

- Upper R device is "off"
- Lower R device is "off"
- Upper S device is "on"
- Lower S device is "off"
- Upper T device is "off"
- Lower T device is "on".

In this particular step of the six-step commutated scheme, current flow will be as shown in Fig. 15.

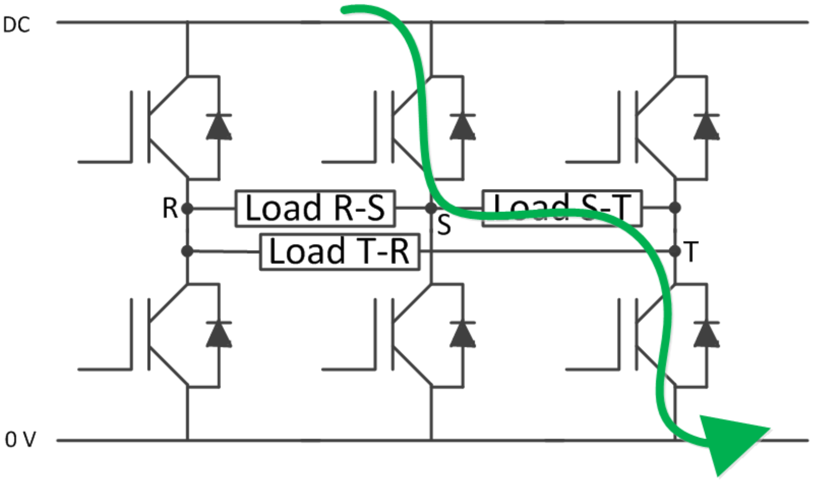


Fig. 15. Turning on the upper S switch and lower T switch during step 1 results in the current flow shown here.

Six-step commutation is very common for smaller brushless dc motors as it is less expensive to implement and performs reasonably well, but does result in high torque ripple and higher audible noise during operation (compared to sine-modulated methods). Waveforms look very different as well compared with sine-modulated waveforms (as shown later).

Multi-Level Topologies

As circuits progress from a simple single device (or multiple devices in parallel with a single output), to series device connections (half-bridge) to H-bridge and then to cascaded H-bridge topologies, each succeeding topology offers more voltage control and range, more current-flow control, and multi-phase control. However, there are still only a maximum of two levels for the output voltage for the H-bridge and cascaded H-bridge topologies.

However, multi-level topologies provide more output control for the digital PWM voltage levels, achieving >2 levels. Why might one want >2 digital PWM levels?

- To reduce harmonics on the output
- For better and smoother motor control (e.g., less torque ripple)
- To achieve voltage levels that are higher than possible with a 1200-V- or 6000-V-rated IGBT.

In terms of the last point, we typically use IGBTs (and all power semiconductor devices) well below their breakdown voltage rating to ensure greater field reliability. For instance, a 1200-V IGBT in a cascaded H-bridge with a 480-V rectified input would see a maximum voltage of 679 Vdc (without overshoot). Developing a drive for a 4160-V (nominal voltage) motor is beyond the capability of a single 3300-V device because the dc bus voltage would be 5.884 kV in this case. However, this is within the capability of two (or more) 6000-V devices.

The tradeoff for more voltage levels is higher control complexity of all of the modulation signals, which requires more processing power in the control system. Thus, >2-level topologies are very unusual unless one of the above requirements justifies the need.

A common three-level topology is a neutral-point clamped (NPC) topology. The schematic in Fig. 16 reveals that the topology consists of two cascaded H-bridges connected together.

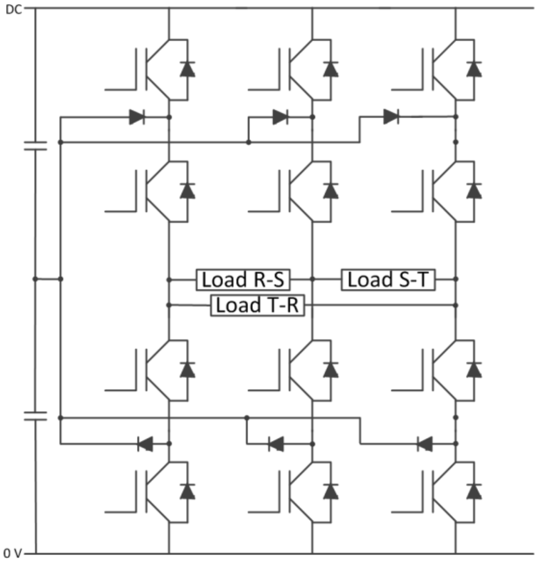
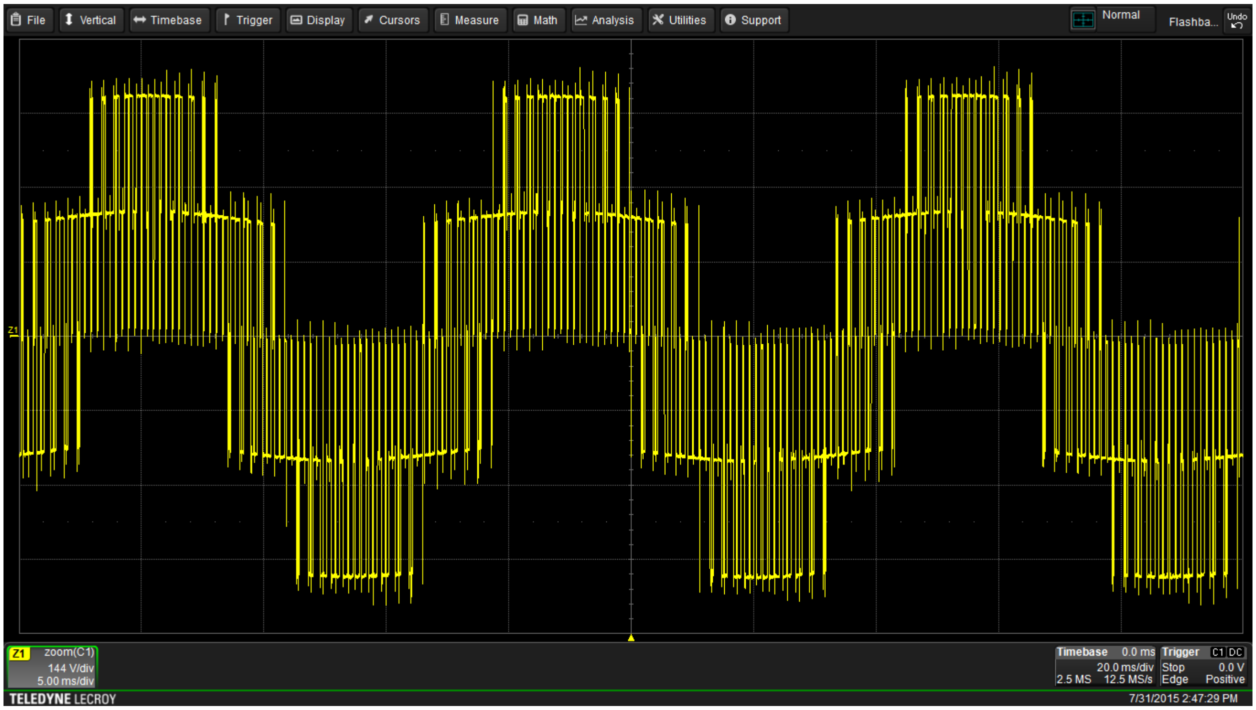


Fig. 16. The neutral point clamped topology is a common three-level topology in which two H-bridges are cascaded.

An example of an output signal produced by an NPC topology (when probed line-to-line, or U-V, V-W, or W-U) appears in Fig. 17.



Z1 zoom(C1)
144 V/div
5.00 ms/div

Timebase 0.0 ms
20.0 ms/div
2.5 MS 12.5 MS/s

Trigger C1 DC
Stop 0.0 V
Edge Positive

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Fig. 17. Output waveform produced by an NPC converter probed line-to-line.

More than three levels is also possible—the concept scales up to five, seven, or more levels, but at the cost of increasing control complexity. Topologies of more than three levels are unlikely to see much use as wide band-gap (i.e., higher voltage) IGBTs of SiC become more prevalent. Such devices offer significantly more than 6-kV breakdown (withstand) voltage and make possible 15-kV converters with a three-level, NPC-type topology.

It is possible that such topologies will become more common for >15-kV voltage applications (e.g., 35-kV distribution voltages, which might be used in a 34.5-kV to 480-V stepdown solid-state distribution transformer).

Conclusion

This latest part has reviewed the common power conversion topologies starting with the simplest, single device types and progressing through the increasingly complex, multi-device configurations that are commonly used for motor drives. In the next part, we'll turn our attention from these power electronic circuits to the motors that will serve as our loads. 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.