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A Practical Primer On Motor Drives (Part 12): Variable Frequency Motor Drives

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As described in the previous two parts on motors, an electric motor operates when an applied rotating magnetic field on the stator causes application of an opposing force to the free-moving rotor that is connected to a rotor shaft that then performs work. Historically, ac induction motors were connected directly to fixed-frequency line voltages, and relatively simple control systems or other mechanical means (a mechanical brake, a valve to adjust fluid flow, etc.) were used to adjust the speed or output.

Often, an ac induction motor was oversized, and the output adjustment was very inefficient. This led, in general, to higher initial purchase and operating costs with relatively poor motor speed and torque control. Dc brushed motors, with inherent capability for independent speed and torque control, were prized for their control capabilities, but suffered from high mechanical complexity, high cost, and low reliability. Permanent-magnet synchronous motors, when connected to a fixed-frequency line voltage, had the same limitations as ac induction motors.

To combine the reliability of an ac induction motor or permanent-magnet synchronous motor (i.e., no carbon brushes that wear) with the variable speed and precise torque control of a brushed dc motor, we use a complex electronic control. Such a control modulates the duty cycle of a pulse-width “digital” voltage signal applied to the stator winding(s) of the motor, and manages the period during which the digital pulse width’s alternate polarity is controlled. By precisely controlling both the pulse-width durations and period, we achieve precise control of the applied stator voltage and frequency.

The systems that provide these pulse-width-modulated (PWM) outputs and control capabilities are known as variable frequency drives (VFDs), variable-speed drives (VSDs), inverter drives, or, more commonly, motor drives, and they use power semiconductors to provide the PWM output signals as described previously. We apply the PWM output voltage signals to the motor stator winding, just as a line voltage would be. Note that a PWM signal has quite different harmonic content and signal qualities compared to a sinusoidal line voltage signal, and this must be taken into account when designing a motor to prevent insulation failure in the motor. Thus, we often label motors designed to work with VFDs as such.

After a brief discussion of VFD uses, this section explains VFD operation including a discussion of VFD architecture and topologies. The latter includes a detailed description of the popular dc bus (link) topologies including the voltage-sourced inverter, the current-sourced inverter, the load-commuted inverter and the matrix converter or cycloconverter. This part also explains the common pulse-width modulation (PWM) techniques—carrier-based and space-vector pulse-width modulation.

VFD Applications

VFDs can be as simple as a single-phase input/output drive with no sensor inputs (“sensorless”) for control of motor speed only. An example is a variable-speed control managing the speed and direction of a ceiling fan. Or, VFDs can be quite complex with three-phase input/output, many precision sensor inputs, and complex algorithmic processing to provide precise speed and torque control in either rotational direction (much like that provided by a brushed dc motor). Such drives handle widely varying loads, and may regenerate power back to the source (e.g., a vehicle propulsion application with regenerative braking.)

By design, ACIMs operate at various speeds using VFDs and thus are a natural fit for many industrial and commercial applications. Often, these motors are oversized and do not need to run at full speed at all times in their intended application. It may also be desirable to control precisely the torque in addition to the speed. Because the power consumption of the motor varies with the cube of the speed, reducing the speed by half reduces the power consumption to one eighth, which is a significant increase in efficiency when a lower rotor speed provides acceptable performance.

In general, we primarily find VFDs paired with larger ACIMs in industrial plants and processes requiring precise speed and/or torque control as well as significant operational efficiencies. VFDs coupled with smaller BLDC or

PMSM motors serve complex control capabilities (e.g., washing machine motor, vehicle propulsion motor) where operational efficiency may not be the highest priority. Of course, the lines blur quite often—small mini-split HVAC compressor motor VFDs deliver both control and efficiency optimization while small refrigerator compressor motors are designed primarily for operational efficiencies.

VFD Operation

All VFDs convert a dc voltage to a pulse-width modulated (PWM) ac signal that is applied to the motor terminals. VFDs operating from a battery input do not require ac rectification, while those that operate from an ac line require rectification and filtering to obtain a stable dc bus.

Fig. 1 represents a typical simplified schematic of the complete power conversion section of an ac-ac three-phase VFD. In a preceding section of this primer, we described the cascade H-bridge power conversion topology (shown with IGBTs; MOSFETs may be substituted). We now more appropriately describe it in the simplified schematic as the "inverter subsection."

The three-phase ac line input is rectified by a six-pulse (six-diode) rectifier in the "rectifier section" and filtered to a low-ripple and stable dc bus voltage in the "dc bus" or "dc link" section (the terms are used interchangeably.) Also shown are the signals present in the circuit at the ac line input, dc bus, drive output, and gate drive of the power semiconductor devices. This particular VFD is very representative of most VFD designs and is a class of voltage source inverters (VSIs).

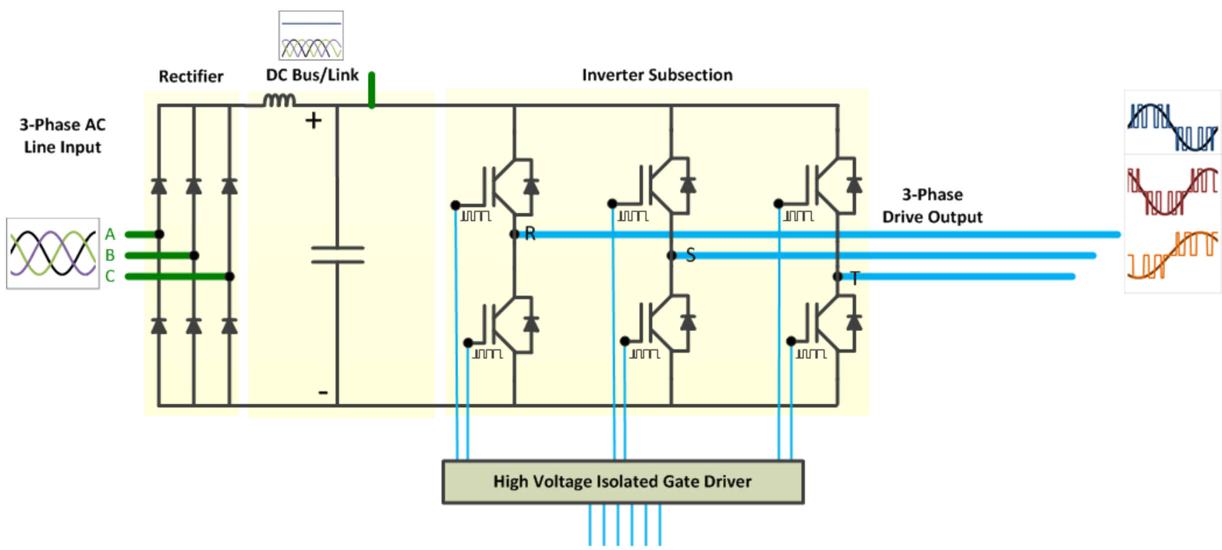

Fig 1. The power conversion section of an ac-ac three-phase VFD rectifies and filters the ac line input to create a stable dc bus voltage, which then powers the inverter subsection.

The input to the VFD is typically a 50/60-Hz, single- or three-phase signal (typically referred to as A, B, and C phases.) It is supplied at a voltage anywhere from a nominal 120 V to a nominal 600 V. While motor drives with higher voltage inputs or outputs (e.g., 4160 V) would likely use a multi-level power conversion inverter subsection topology different from that shown above, the concept is the same.

When applied to the motor winding, the three-phase PWM motor drive output causes a current to flow in the winding. The characteristics and quality of the PWM voltage output signals relate to the PWM control methodology. Varying the PWM signals' width results in more or less voltage applied to the winding. Varying the period of alternation for the upper and lower gate-drive signals determines the frequency of the alternative positive and negative PWM outputs. Combined, the drive output produces signals resulting in the desired speed, torque, power, and efficiency characteristics from the motor.

A high-voltage, isolated gate driver connects the control/logic system to the power semiconductor gate terminal in the inverter subsection. The controls take feedback signals from the motor and other parts of the circuit to calculate how to switch the gates of each power transistor on and off to create the appropriate PWM signal at the power semiconductor output. Because the controls connect to the gate of the power semiconductors, there is no ground reference for many of the signals on the controls; thus, the controls are not at ground potential. Operator-exposed control functions are sometimes isolated with optical links or "floated" in an insulated control connection.

The control system's complexity depends on the control requirements. Simple scalar V/Hz controls use low-speed microprocessors in the embedded control system, are low in cost, and require few feedback signals from the drive or motor. More complicated vector field-oriented control (FOC) control systems can use very high-speed microprocessors (>500 MHz) with many feedback signals.

Instrumenting the motor shaft provides position, speed, or torque values. One may instrument the motor itself for current inputs, temperature, vibration, or other physical characteristics. Some of these instrumented signals serve as feedback to the VFD control system, and some serve only for design validation or test. More complex control systems require knowledge of absolute rotor/rotor magnetic field position for proper operation, and therefore utilize quadrature encoder interface (QEI) or resolver speed, direction, and positions sensors.

A complete drive system showing the complete power conversion section (rectifier, dc bus/link, and inverter subsection), control system, motor, sensors, and interface of all components appears in Fig. 2.

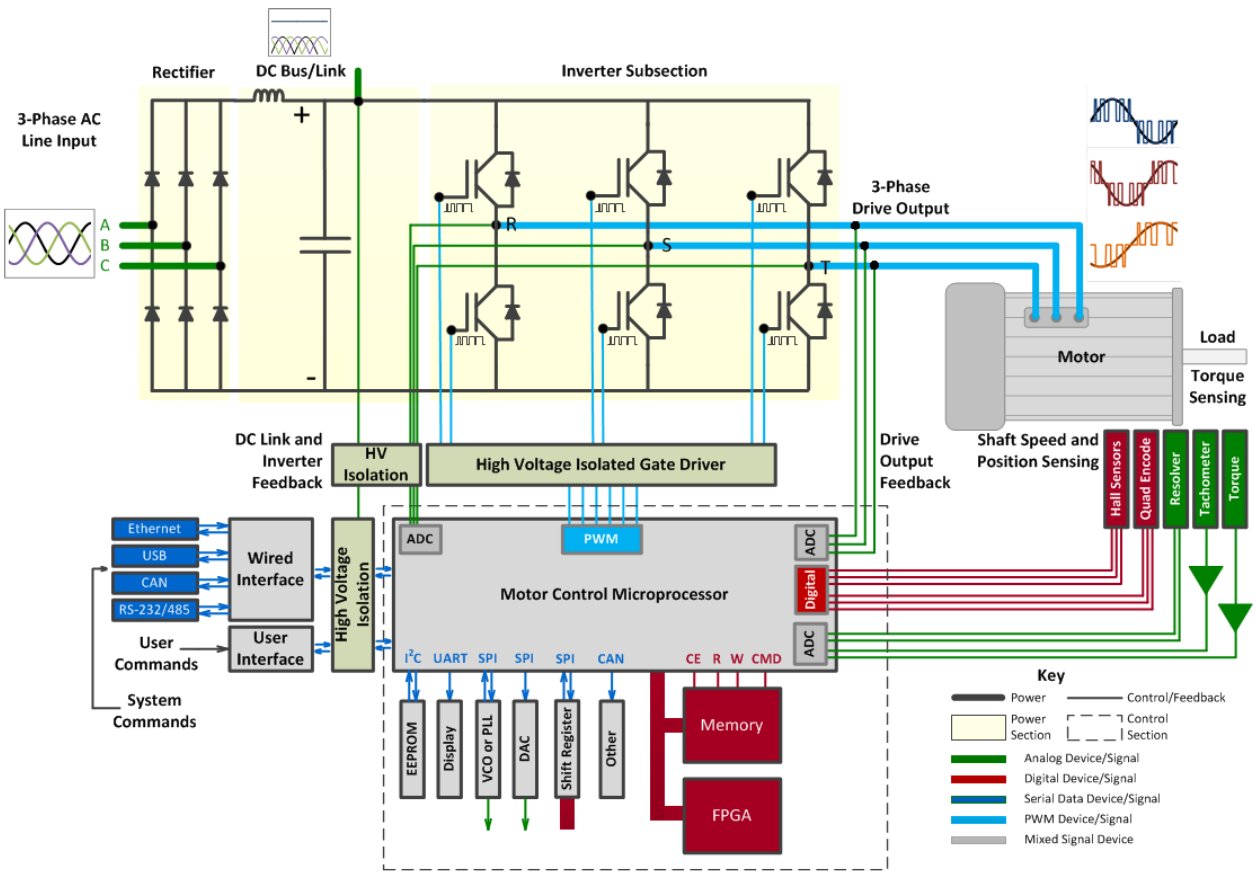

Fig. 2. A complete ac-ac three-phase drive system.

VFD Architecture And Topologies

All VFDs have much in common. The essential elements that describe the VFD power conversion section are:

- Input-output voltage ratings
- DC bus (link) topology
- Power semiconductor components used in the inverter subsection
- Inverter subsection topology.

The essential elements that describe a VFD control and software section are:

- (Gate-drive) pulse-width modulation (PWM) techniques
- Motor drive control architecture and algorithms.

Input And Output Voltage Ratings

The input to the VFD can be either single- or three-phase ac, or dc (e.g., from a battery.) In the case of a dc input, the dc bus topology could change slightly because filtering is not required on a rectified ac input, and some load limiting might be necessary to prevent too much current being drawn from the battery too quickly.

The output of the VFD is nearly always three-phase, even with a single-phase input. The three-phase input to ACIM, PMSM, or BLDC motors makes control simpler and efficiency higher, which overrides any additional up-front cost for a three-phase motor winding compared to a single-phase winding. The exception would be very simple loads (e.g., fans and blowers) that run at low power levels, do not require much speed control, and/or have simple speed control requirements, and serve highly cost-sensitive applications.

Some specialized applications that require high redundancy (aircraft systems, military systems) may utilize more than three phases, but this is uncommon.

DC Bus (Link) Topologies

The dc bus stores energy for input to the inverter subsection. Enough energy should be stored so that the dc bus is "stiff" (i.e., stable) and does not change voltage appreciably under load. Ideally, the dc bus is free of ripple and well isolated from changes or perturbations in the line input. Ripple on the bus may indicate inadequate mains (line) supply, poor inverter design, or problems with the inverter operation, and engineers often monitor the dc bus ripple to correlate it with other VFD behaviors.

We supply dc bus voltage data to the motor drive as a feedback signal. For instance, knowledge of the dc bus voltage and the switching times of the inverter drive circuit facilitate calculations regarding the ac output voltage, which is critical feedback for more complex drive-control systems.

If the input comes from a battery or stepdown ac power supply, the dc bus voltage may be relatively low (≤50 V.) From 240-Vac single-phase inputs, it may be as high as 340 Vdc, or 690 Vac (using three-phase 480-Vac rectified outputs.) Vehicle propulsion systems commonly use dc buses (batteries) in the range of 300 to 500 Vdc. The maximum dc bus voltage for a 600-V class device is 976 Vdc (based on 600-Vac +15% overvoltage rating, three-phase.)

The dc bus voltage is the highest possible (common-mode) voltage present in the circuit, and voltage probes or cables connected to the dc bus or inverter subsection must be properly isolated with a common-mode voltage safety rating equal to or greater than the dc bus voltage.

The three main topologies for the dc bus are:

- Voltage-sourced inverter (VSI)
- Current-sourced inverter (CSI)
- Load-commuted inverter (LCI)
- Matrix converter (MC) or cycloconverter.

Voltage-Sourced Inverter

In all VSIs, the dc bus stores energy as voltage in a capacitor in parallel with the inverter subsection. Typically, we place an inductor in series with the capacitor to perform harmonic filtering. VSI designs are the simplest and most cost-effective in motor drive applications. VSIs deliver higher-performance motor control (faster peak current deliveries and therefore better ability to dynamically control motor torque), lower harmonics, and higher power factors on the mains input.

All of these are important considerations for industrial power usage. Additionally, phase conversion (from one-phase to three-phase ac) is possible with a VSI drive, important for lower-power motor drive applications. Most VFDs are VSI-based, and all further discussions in this document will assume VSI architecture for the motor drive.

Current-Sourced Inverter

In a CSI, the dc bus stores current in an inductor. CSI response times are slower due to the delay in delivery of current from the inductor to the inverter subsection input. CSIs also require a different PWM signal that contributes to higher harmonics on the mains. Lastly, the limitations of the CSI require a higher-cost design to mitigate the performance issues. We rarely see CSIs used in motor drive applications.

Load-Commutated Inverter

An LCI uses thyristors (SCRs) and therefore cannot use PWM signaling for the output voltage. Historically, LCI applications were limited to soft starts of very large motors, and it is no longer widely used with the advent of IGBTs of higher power and voltage.

Matrix Converter

An MC or cycloconverter eliminates the dc bus and uses a direct connection from the ac rectified output to the inverter input. We find applications for MCs in HV power line switching or frequency conversion, or small-range control of relatively large motor loads (e.g., ship propulsion) where the efficiency or harmonic advantages of eliminating the dc bus are relatively high compared to the control drawbacks.

Power Semiconductor Devices

As described in a prior section, motor drive inverter subsections use either MOSFETs or IGBTs. Both device types are widely used, with MOSFETs typically found in 240-V (and lower) input drives and IGBTs in 380- to 600-Vac input drives for cost, reliability, efficiency, and other reasons.

Devices incorporating wide-bandgap materials, such as SiC or GaN, have faster rise times; expect to see them used more often in drives for efficiency reasons. For semiconductor-device analysis of switching and conduction losses, engineers want higher-bandwidth voltage and current measurements. For measuring drive outputs, lower bandwidth works well enough because the fastest wide-bandgap materials are rarely deployed at their highest speeds due to reliability or EMI/RFI emissions issues.

VFD Inverter Subsection Topology

We discussed basic power conversion topologies in a prior section. Single-phase VFDs use H-bridge topologies while three-phase VFDs use cascaded H-bridge topologies. Both topologies result in two-level output signals.

Other topologies provide more than two levels, as described previously. Most VFDs paired with motors in the 600-V class and lower use two-level cascaded H-bridge topologies. Although additional levels add cost and complexity, they achieve lower output harmonics or better speed/torque control.

Pulse-Width Modulation Techniques

Voltage output from the VFD is controlled with various modulation schemes, all of which result in simple one-level PWM gate-drive signals (one per power semiconductor device) and one-level (or sometimes more than one-level) signals at the output of each phase of the motor drive. When the output voltage is viewed line-to-line, these one-level line-reference signals are two-level line-to-line signals.

The PWM drive's output signals vary in quality based on the control and modulation technique chosen for the drive. In general, customers refer to these different control techniques as one of many different "sine-modulated" techniques or a "six-step commutation" technique. A sine-modulated technique applies voltage to all three phases at once, whereas a six-step commutation technique applies voltage to only two of the three windings at any given time.

The one-level PWM gate-drive signals are determined and generated through a simple carrier-based method or through a more algorithmically complex space vector (pulse-width) modulation (SVM or SVPWM) method. Carrier-based PWM methods are simpler to program and implement and cost less (because they require less processing to generate the PWM signal), but have higher harmonic content.

SVM methods require more implementation skill, cost more (due to higher microprocessor speed and cost in the VFD's embedded control system) and lower harmonic content. SVM methods are a necessary component of the vector FOCs, which provide the most advanced control capabilities, and are also simpler to employ in a multi-level (>2-level) inverter.

Carrier-Based PWM

Typically, in a carrier-based PWM implementation, the carrier (high) frequency is a triangle wave and the modulating (low-frequency speed control) signal a sinewave. This is a common approach in simple scalar V/Hz (sine-modulated) and six-step commutated controls. Sinusoidal intersective carrier-based PWM method is the most widely used in new designs.

Sinusoidal, intersective carrier-based PWM employs a constant-amplitude, high frequency (~1 to 100 kHz) carrier and a low-frequency control signal (~60 Hz, or whatever the desired VFD output frequency may be, with a fixed or varying amplitude). The intersection of the modulating sinewave with the carrier frequency creates the width-modulated signal. See Fig. 3 for a simple example of PWM for a single power semiconductor device in which the PWM signal has a 50% duty cycle at 0 V of the modulating signal.

The carrier frequency is either a triangle or a sawtooth waveform; the choice of waveform defines the intersection with the modulating waveform for purposes of width determination. The example shown above is for a triangle waveform, but the frequency used was <<1 kHz (i.e., illustrative only) so that the signal could be more easily viewed with a lower-frequency modulating signal.

As described earlier, for half- or full-bridge power conversion systems, the upper and lower devices switch independently. Thus, the PWM waveforms for each device become slightly more complicated to "view" and understand how they relate to the power-conversion device or drive output, but the basic concept is the same.

For example, for a half-bridge implementation, there is an upper and lower device, and the two devices switch in a complementary fashion to create the full output waveform. This is shown in Fig. 4 with the upper device PWM waveform shown at the top, the lower device PWM waveform shown at center, and the total output (upper minus lower) PWM waveform and modulating waveform shown on the bottom (the carrier-frequency waveforms are omitted in this example, but they are the same as in the single-device example shown above.)

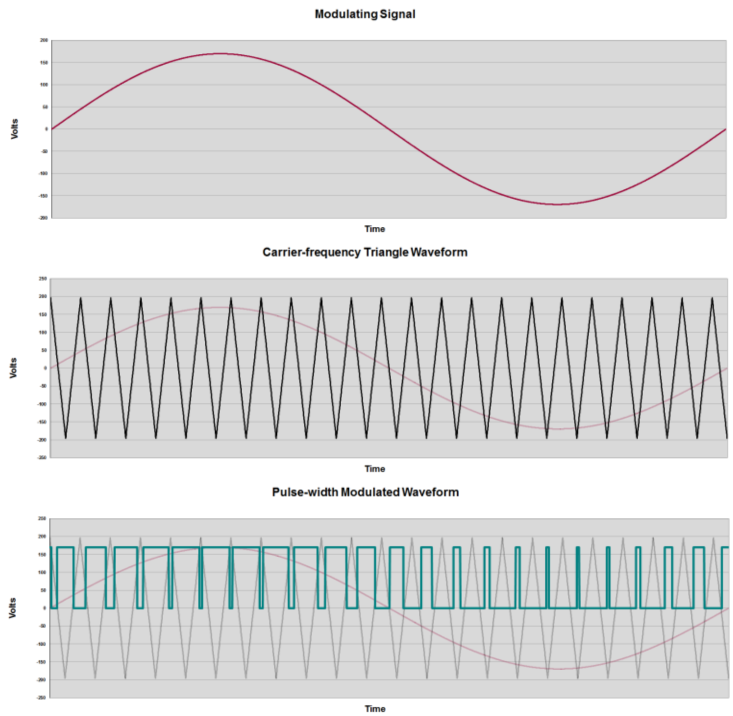

Fig. 3. In this example of sinusoidal, intersective carrier-based PWM, a low-frequency sinewave representing motor speed modulates a high-frequency triangle wave.

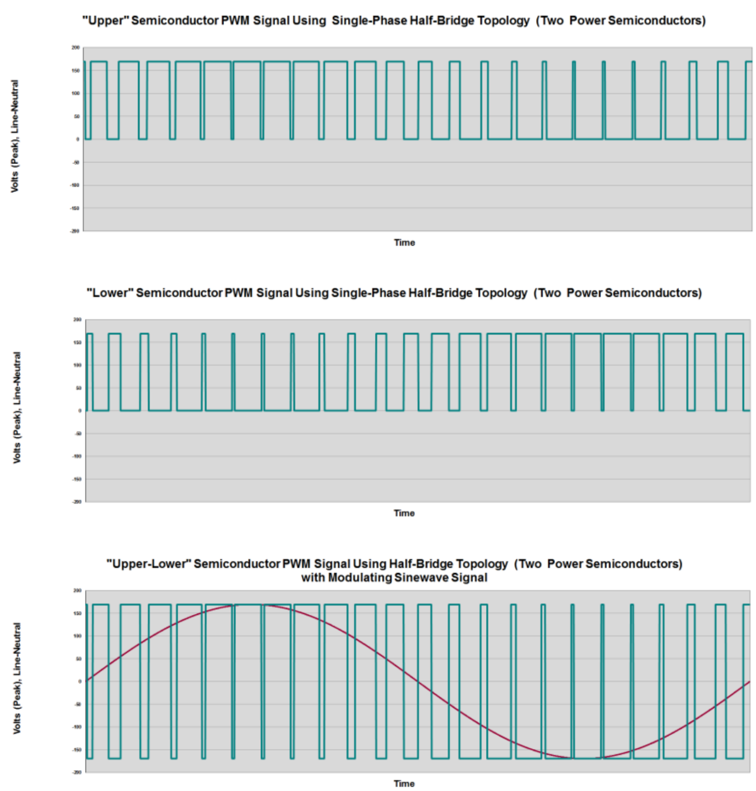

Fig. 4. PWM waveforms for a half-bridge implementation.

For a full-bridge (H-bridge) design, the upper and lower waveforms and output PWM waveforms appear as shown in Fig. 5.

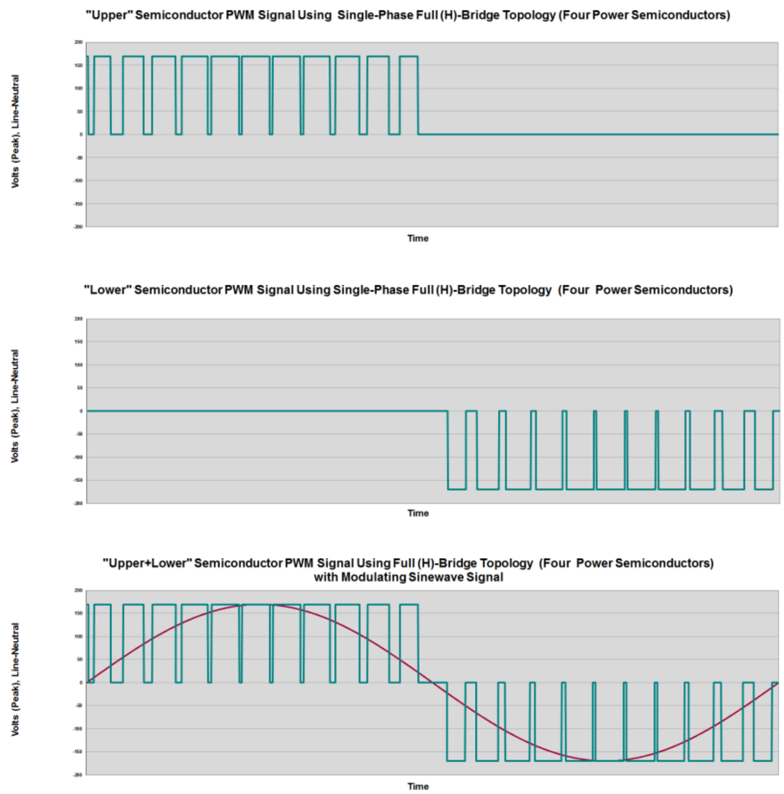

Fig. 5. PWM waveforms for a full-bridge (also known as an H-bridge) implementation.

Typically, for a three-phase (e.g., cascaded H-bridge) design, we create one modulating signal in the microcontroller and then phase-shift that signal by 120° and 240° to create the other two modulating signals for the other two phases. Therefore, there are three PWM waveform sets in this case, as shown in an earlier example.

Note that both series power semiconductor devices in a half-bridge, full-bridge, or cascaded H-bridge topology cannot be switching on at the same time, so some minimum "dead time" before and after switching is built into the controls to avoid such a condition, which causes "shoot through" and device failure. The result of this dead time can be seen in the lower waveform in Figure 5.

Space-Vector (Pulse-Width) Modulation

In SVM, we use a matrix transformation to transform a three-phase voltage signal corresponding to the rotating stator magnetic field into a single rotating "space vector" in a two-dimensional reference frame. This simplifies calculation of a single voltage magnitude and angle, which is then inverse-transformed back to a three-phase voltage signal from which we generate the gate-drive PWM signals.

This is an algorithmically more complex modulation scheme compared to a conventional carrier-based PWM, but it allows suppression of certain harmonics, improving the VFD's harmonic performance. SVM may be employed in either a scalar V/Hz control system (in place of a carrier-based PWM scheme) or in a vector (field-oriented or direct torque) control. It is required in the latter because vector controls require generation of a referenced space vector as part of their control system.

There are several variants of space vector modulation based on the alignment of the pulse widths within a defined "time slot." The alignment can be center-aligned, left-aligned, or right-aligned. The choice of alignment depends on available processing power and the importance of harmonic suppression (some alignment methods require less gate switching, and so create less harmonic content on the VFD output.

A more detailed explanation of how space vector modulation works is beyond the scope of this document. Regardless, the VFD PWM output signals look essentially the same as with carrier-based PWM modulation schemes.

Conclusion

This section introduced VFDs, describing their overall operation and architecture, dc bus link topologies, and pulse-width modulation techniques. In part 12, the discussion of VFDs continues with an overview of control architectures and algorithms including an explanation of scalar V/Hz, six-step commutation, vector flux- (or field-) oriented and vector direct torque control. 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.