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A Practical Primer On Motor Drives (Part 13): Motor Drive Control Architectures And Algorithms

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Part 12 began the explanation of how VFDs operate by describing their overall operation and architecture, dc bus link topologies, and pulse-width modulation techniques. In this part, the discussion continues with an introduction to the popular VFD control architectures and algorithms.

There are three primary methods for achieving variable-frequency motor control: scalar V/Hz, six-step commutation (also known as trapezoidal control), and vector control. One may implement all of these methods in an open loop (few or no sensor feedback signals from the motor) or closed loop (significant sensor feedback required from the motor) with various algorithms. Each of these control methods will be explored here.

Control Architecture And Algorithm Overview

Fig. 1 shows the hierarchy for the various VFD control architectures and common algorithms.

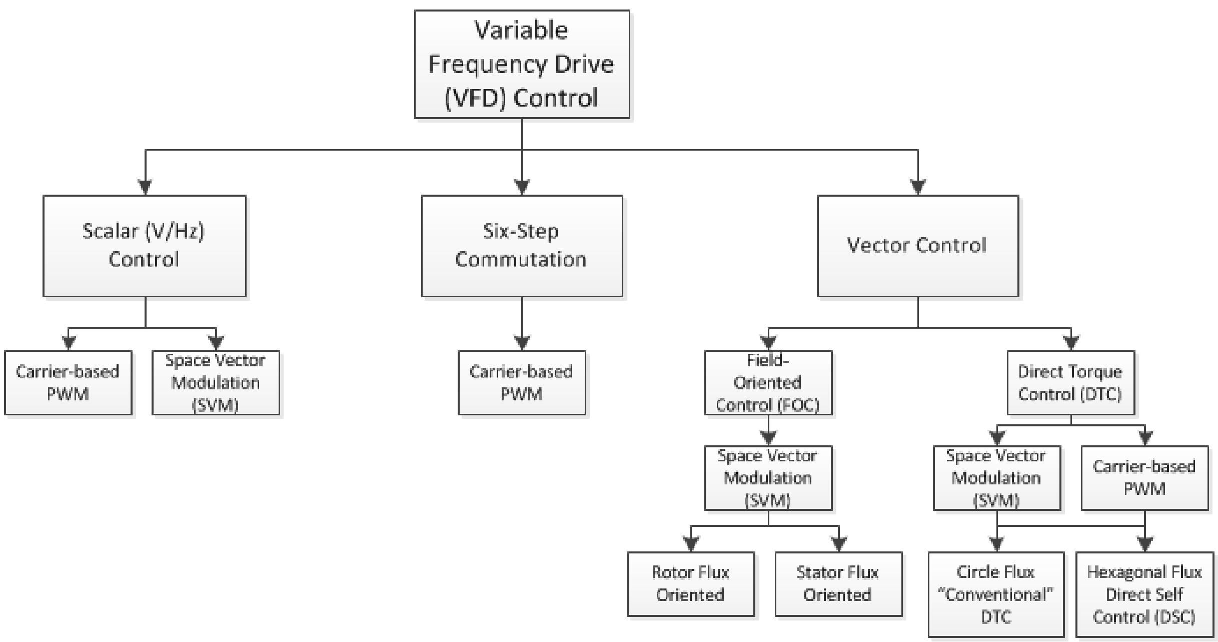

Fig. 1. Common control architecturers and algorithms for variable-frequency drives.

Below in Fig. 2 is a "generic" control block diagram (note that not all control methodologies utilize all of the signal inputs to the control as shown in this figure.)

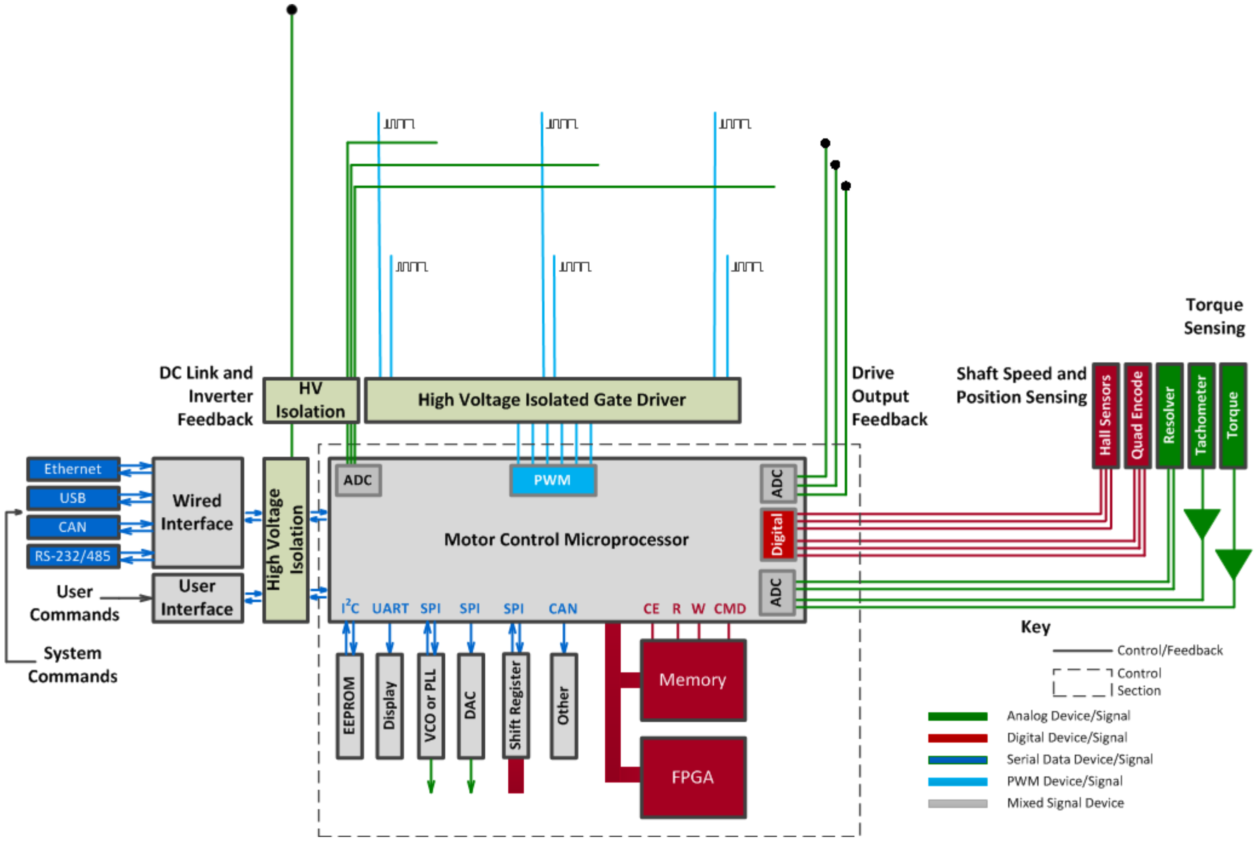

Fig. 2. Generic control block diagram for variable-frequency motor drive.

The motor-control microprocessor system accepts inputs from the motor (speed, direction, position, and torque) and digitizes them for further processing. Drive feedback signals (output voltage or current, dc bus voltage and current, gate-drive signals, etc.) are likewise monitored and digitized. We combine knowledge of the motor and drive operational state with system or user (speed and torque) commands to permit calculation of the necessary gate-drive signals.

Thousands of times per second, these signals switch the transistor devices in the inverter subsection to achieve the appropriate output voltage and frequency to the motor. Thus, a VFD control system is a very complex embedded control with a variety of analog, digital, serial data, and sensor feedback signals on the input/output, and it requires its own debug/validation separate from the inverter subsection before it can be debugged as part of the complete VFD.

An oscilloscope, such as Teledyne LeCroy's HDO8000 series or MDA800 series with eight analog channels with 12-bit resolution, 16 digital inputs, and up to 1 GHz of bandwidth, is ideal given the large number of signals that must be monitored at one time for proper debug and characterization (Fig. 3.)

Fig. 3. Featuring eight analog channels and 16 digital inputs, Teledyne LeCroy's MDA800 series oscilloscope can handle the large number of signals that must be monitored at one time for proper debug and characterization of a VFD control system.

VFD controls differ in the types and quantity of sensor signals that are input to the control system, the complexity of the processing done by the control system, and when output signals are sent to the power-transistor gate drives in the inverter subsection.

Scalar (V/Hz) VFD controls are the simplest type, providing control of voltage and frequency (motor speed) in a simple xV-per-yHz relationship with no possibility of direct torque control. Scalar V/Hz controls are ideal when high quality control is not required and/or where low cost is highly desirable, such as in fan controls and power tools. Scalar controls can use a carrier-based PWM or space vector modulation. Realistically, simple carrier-based PWM would predominate in this type of control.

Six-step commutation controls are used exclusively with BLDC motors. They typically use rotor-position feedback from Hall-effect sensors mounted on the rotor shaft. Sensorless (back-EMF sensing) techniques can help lower costs (with some loss of control at lower speeds). In both implementations (sensored and sensorless), only two of the three windings have a voltage waveform applied at any given time. The result is a trapezoidal (as opposed to sinusoidal) back-EMF (BEMF) waveform that is distinctly non-sinusoidal.

Such a control, while very simple and relatively inexpensive for the level of control it provides, results in more distorted output voltages and applied currents. It also produces high torque ripple and audibly noisier motor operation. It has the advantage of low implementation cost.

Vector field- or flux-oriented controls (FOC) provide instantaneous and simultaneous control of speed and torque. Best known simply as vector controls, they are ideal in complex applications such as pumps, milling machines, elevators, or electric propulsion motors. However, implementation comes at a higher cost due to increased control complexity and motor sensor requirements.

Vector FOCs transform the three-phase ac voltage system of the motor into a two-coordinate vector system that represents the operation of the applied stator magnetic flux field from the perspective of the rotor (rotor flux-oriented) or stator (stator flux-oriented.) They then use this simplified two-coordinate system for calculation of applied voltage before transformation back to a three-phase vector system for calculation of pulse-width-modulated gate-drive signals. Vector FOC controls always use a space vector modulation method for PWM.

As their name implies, vector direct torque controls (DTCs) control torque directly through precision motor-current sensing and a “lookup table” based on various torque hysteresis loop methods. Space vector modulation most often provides gate-drive signal generation. Vector DTC provides control and performance approaching that of vector FOC controls, but with (claimed) lower algorithmic complexity and cost due to the lack of mathematical transformations to the rotor reference frame. In short, they are “good enough” for many applications with potentially lower cost and higher reliability.

Scalar V/Hz Controls

Scalar V/Hz controls, also known as V/f or variable-voltage, variable-frequency controls, manage motor speed as a function of frequency using a simple lookup table. They do not directly control motor torque and have limited ability to control motors at low speeds or under highly dynamic conditions in which torque requirements change quickly. These controls can be either open loop (without sensors) or closed loop (with sensors), depending on the application, cost targets, and requisite control capabilities.

Scalar controls can use either carrier-based PWM or SVM (both of which are sinewave-modulated methods) to control the gate-drive signals. A simple scalar V/Hz open- or closed-loop controller has inherent limitations on control of the motor’s speed or torque, especially under dynamic conditions, but is low in cost.

Fig. 4 shows a sample V/Hz voltage vs. speed (frequency) profile. We program an operating curve into the motor-control microcontroller to govern the operating profile ranging from maximum voltage and speed operation to low-voltage and low-speed cutoffs.

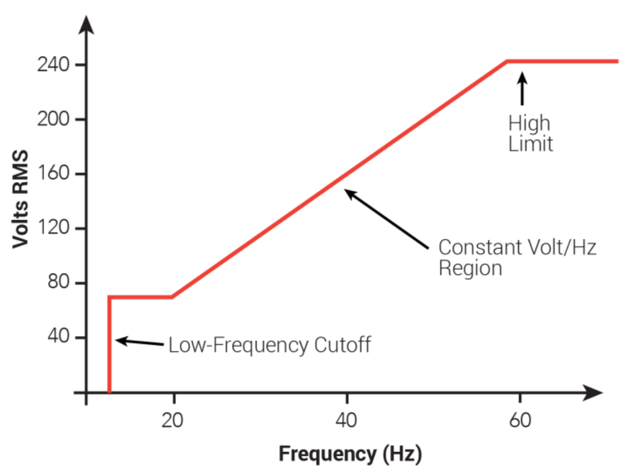

Fig. 4. A voltage vs. speed (frequency) profile for scalar V/Hz control.

We most often find scalar V/Hz controls on smaller and/or lower-voltage ac induction motors (ACIMs) or ac permanent magnet synchronous motors (PMSMs.) The output voltage waveforms appear as previously described (reference the Vector FOC controls section for detailed screen captures.) Each type of motor can use either open-loop or closed-loop control, depending on the application’s needs.

Scalar V/Hz (Open-Loop) Control

An open-loop scalar V/Hz control fits well when minute or fast changes in motor speed are not required, and when the accuracy requirements of speed changes are lax enough not to warrant the higher cost of a scalar

V/Hz *closed-loop* control, which requires a speed sensor and a more complex and costly control system. With no feedback speed sensors on the motor, the PWM voltage signals are determined based on the desired speed and the assumption that the motor will roughly track the voltage vs. speed profile, with any errors in speed considered minor and acceptable.

Torque control happens only under very specific and known conditions, so applications requiring constant or dynamic torque control do not use this method. Typical applications would be in heating, ventilation, and simple (and low-cost) air-conditioning (HVAC) motor applications (e.g., window air conditioners.)

Scalar V/Hz (Closed-Loop) Control

The closed-loop variant of the scalar V/Hz control is essentially the same as the open-loop version with the addition of a speed sensor input to the drive controller. Monitoring of this speed signal provides more accurate values for voltage and frequency, which in turn means better dynamic control and more accurate motor speeds. Torque control improves compared with open-loop controls, but does not approach the performance of a vector control in this regard.

A detailed block diagram of a scalar V/Hz closed-loop control system appears in Fig. 5. From it, one can see the isolation between the gate drive of the MOSFETs in the inverter, the six (three differential-pair) PWM output signals from the control to the VFD, and the speed feedback signal(s) from the motor to the control system.

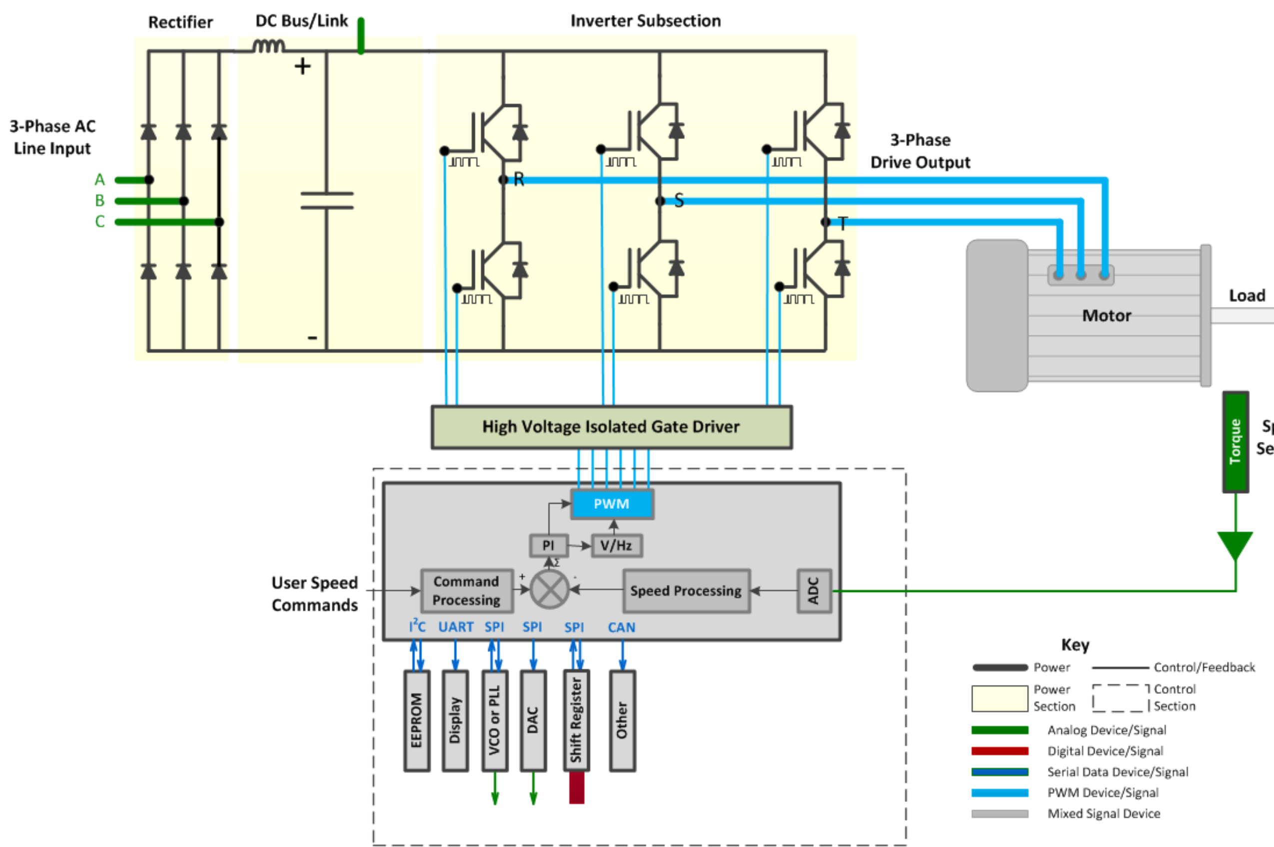

Fig. 5. A scalar V/Hz closed-loop control system employs isolation between the control circuitry and the gate driver and also between the control circuitry and the speed sensor.

Six-Step Commutation (Trapezoidal) Control

Six-step commutation control finds use exclusively with BLDC motors. “Six-step” refers to the number of switching states in the electronic commutation circuit as one rotor magnetic pole rotates 360°. There are six steps because there are typically three Hall-effect sensors that can be either on or off, representing six rotor position steps that require specific stator commutations.

What makes six-step commutation unique is that only two of the three stator motor phases are energized at any given time. Therefore, the back-EMF (voltage) in the stator winding appears trapezoidal when probed from line-to-reference, and for this reason is sometimes referred to as “trapezoidal control” or “trapezoidal modulation.”

The screen capture in Fig. 6 using Teledyne LeCroy’s Motor Drive Analyzer shows the motor drive line-to-reference output voltage and current from a six-step commutated motor drive. Z1 (yellow), Z2 (magenta), and Z3 (blue) are the three line-to-reference voltage waveforms; Z4 (green), Z5 (gray), and Z6 (purple) are the three line currents.

Note that there are six distinct “steps” on Z1, Z2 and Z3: two off steps, one step ramping up, two steps on, and one step ramping down. These represent the six different states in which PWM is not applied, partially applied, or fully applied to that stator coil. The back-EMF influence from a nearby (energized) phase on the adjacent (non-energized) phase results in the “ramp up” or “ramp down” of the peak voltage, and thus the trapezoidal shape.

Fig. 6. Six-step commutation control produces the motor drive line-to-reference output voltages (waveforms on left) and currents (waveforms on right) shown here. The back-EMF influence from a nearby (energized) phase on the adjacent (non-energized) phase results in the “ramp up” or “ramp down” of the peak voltage, and thus the trapezoidal shape.

By sufficiently zooming within the complete trapezoid, one may see PWM waveforms as shown in Fig. 7.

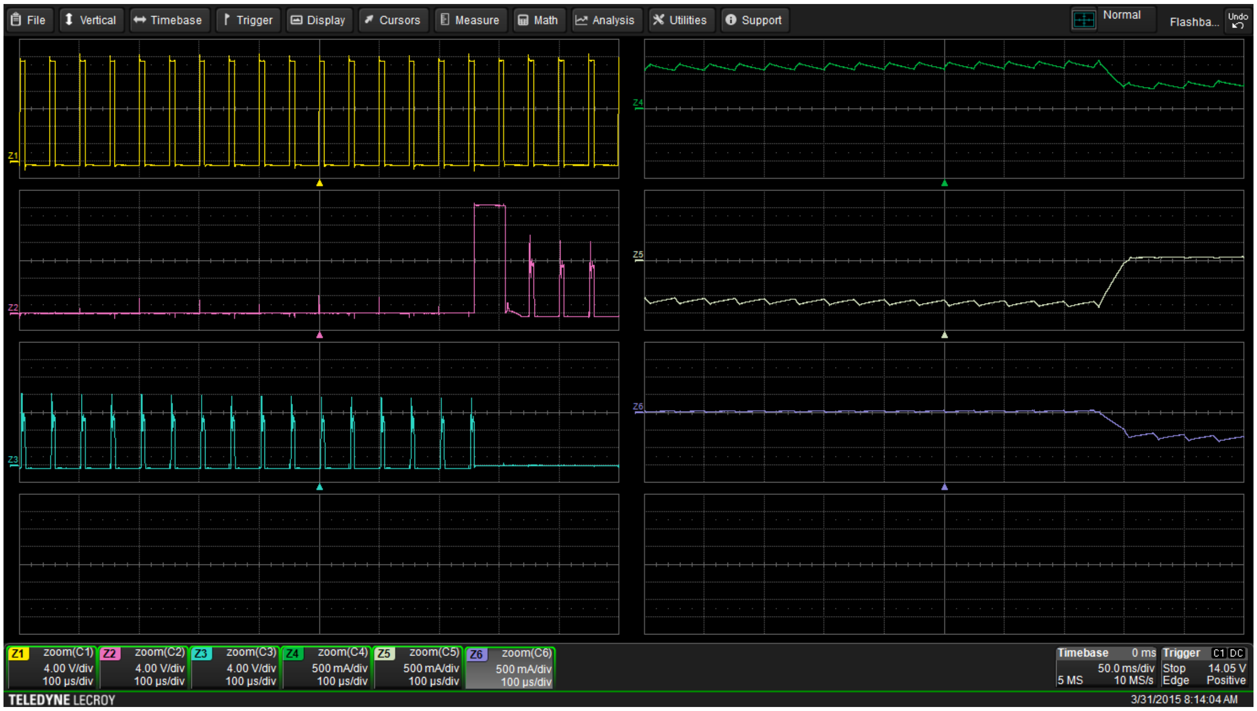

Fig. 7. By zooming in on the trapezoidal waveforms, the underlying PWM signals become visible.

The six-step commutation method reduces cost and complexity compared to the sinusoidally modulated methods, but results in higher torque ripple and more audible noise emanating from the motor.

BLDC VFDs may be closed-loop (sensored) or open-loop (sensorless) systems, with closed-loop systems more common. Hall-effect sensors (typically three) installed in the rotor perform closed-loop sensing to provide feedback to the VFD on both rotor position and direction. The Hall-sensors may be located either 60° or 120° apart.

When the three sensors are spaced 60° apart, we place them on one side of the rotor. At 120° separation, they are equally spaced around the rotor. The screen capture in Fig. 8 shows an acquisition of three line-to-reference six-step commutated voltages signals together with three Hall sensor signals captured using the digital logic (MSO) capability of the Motor Drive Analyzer. Note the time-correlation between the change in Hall sensor logic states and the three difference voltage waveforms.

Note that a line-to-line voltage output always has some voltage present on it since no two lines ever both have a zero voltage level. This is shown in the screen capture in Fig. 9. Note that a differential voltage probe was used to probe the voltage signals in this case.

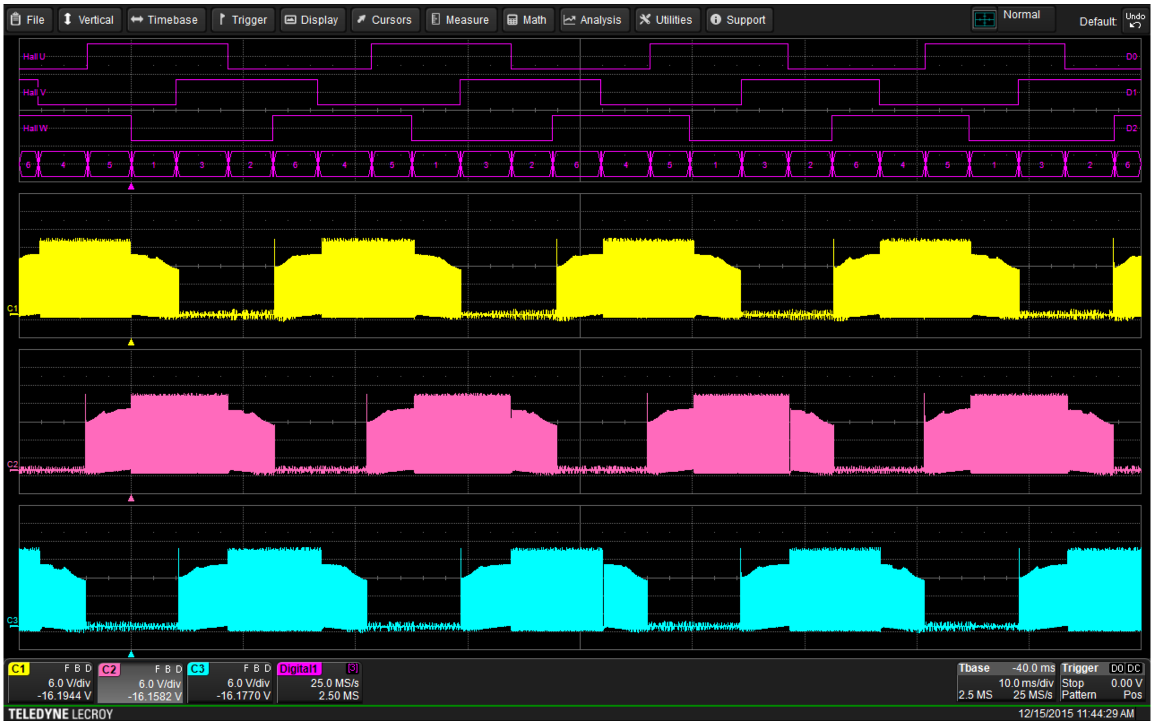

Fig. 8. Line-to-reference six-step commutated voltages signals together with their three Hall sensor signals.

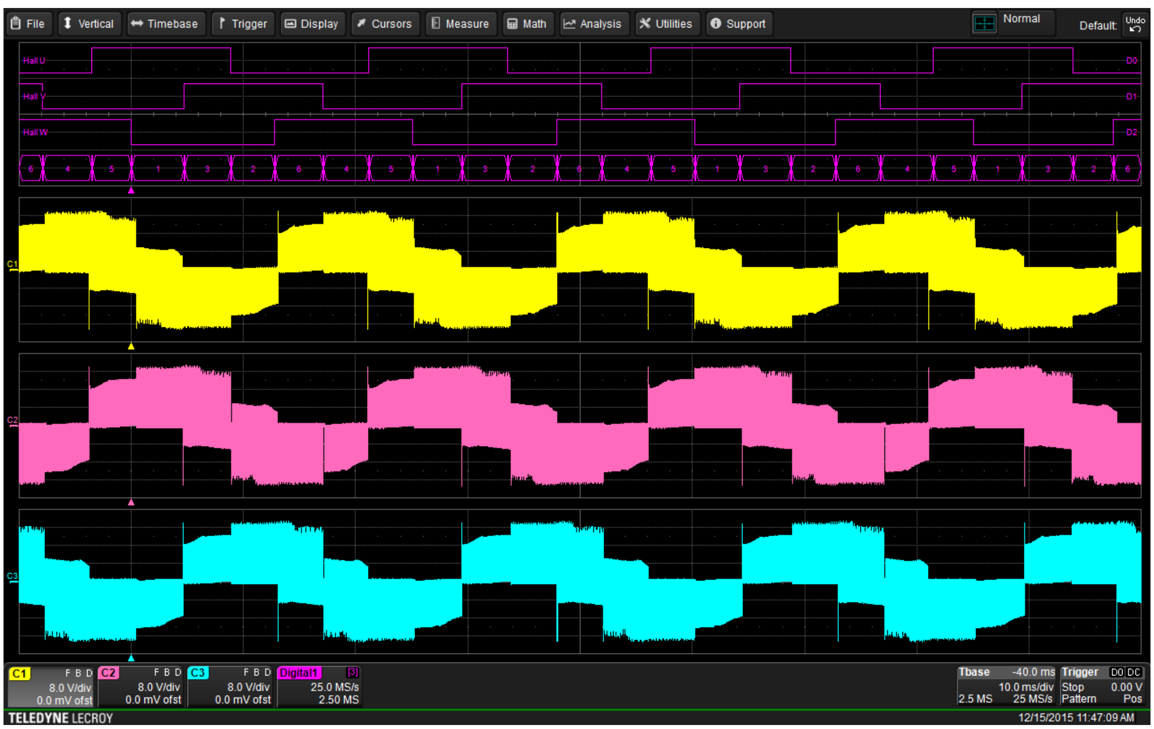

Fig. 9. Line-to-line six-step commutated voltages signals together with their three Hall sensor signals.

The Fig. 10 screen capture shows an acquisition of two of three line-to-line drive output voltage signals (Z1, or yellow and Z2, or magenta) with two drive output motor line-current signals (Z4, or gray and Z5, or green); the three digital Hall-sensor traces (Hall U, V, and W, yellow traces); and the torque sensor signals (Z7, or red.)

In this case, only two of the three voltage and current signals were acquired because a two-wattmeter method measured drive output power. Note how the Hall-sensor signals overlap with the voltage switching, and the resultant torque ripple (high and low frequency.)

Fig. 10. Two of three line-to-line drive output voltages (Z1, yellow and Z2, magenta) with drive output motor line-currents (Z4, gray and Z5, green); digital Hall-sensor signals (Hall U, V, and W, yellow traces); and torque sensor signals (Z7, red) are shown for a six-step commutated closed-loop (sensored) control system.

Open-loop (sensorless) systems infer locations of Hall sensors based on back-EMF sensing from the voltage signals. They provide reasonable control and have lower cost, but the motor must be spinning for back EMF to be developed. Therefore, sensorless systems are not well-suited to motors that operate at low speed or require control at startup.

A detailed block diagram of a six-step commutated (brushless dc) sensored control system appears in Fig. 11. From it, one can see the isolation between the gate drive of the MOSFETs in the inverter (though on a low voltage drive, these would not be necessary), the six (three differential-pair) PWM output signals from the control to the VFD, and the Hall sensor speed/position feedback signal(s) from the motor rotor to the control system.

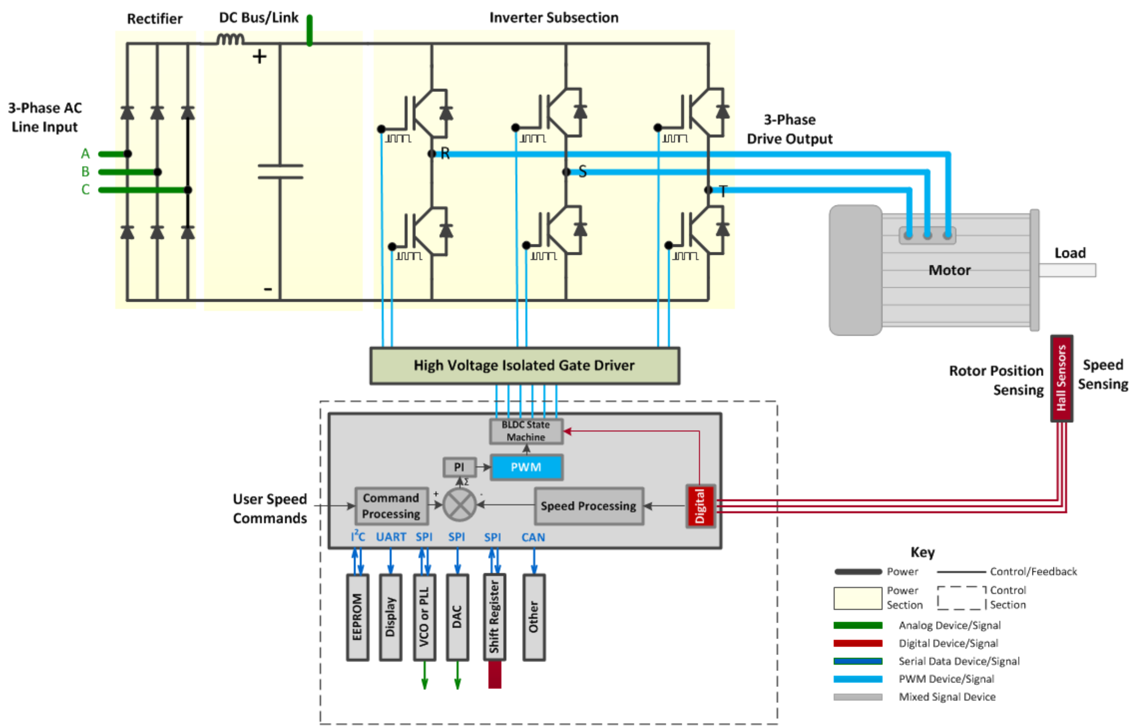

Fig. 11. A six-step commutated (brushless dc) sensored control system.

Vector Flux- (Or Field-) Oriented (FOC) Control

Achieving more accurate dynamic speed control calls for use of a more complex control scheme with ac induction motors (ACIMs) or permanent magnet synchronous motors (PMSMs.) Vector FOCs simplify the three-phase rotating voltage and current vector system at the drive output to a stationary two-vector system that rotates under changing load, speed, or torque. This is very similar to the classic and simple method of controlling a brushed dc motor with separate field (stator) and armature (rotor) applied magnetic fields, except that one may use an ac motor that has more reliability and efficiency.

There are two methods of vector FOC control—stator flux-oriented and rotor flux-oriented. They differ in the number of transformations performed on the three-phase rotating vector system. It is more intuitive to understand and apply algorithmic calculations from the perspective of the rotor, so this method is nearly universally used and will be the only method discussed. This method is referred to as a rotor flux-oriented vector FOC and is the more complex of the two methods.

In a rotor flux-oriented vector FOC control scheme, a mathematical matrix transformation decouples the magnetization (speed) producing (direct) currents in the stator from the torque-producing (quadrature) currents so that we may independently control speed and torque for the highest performance. We know this transformation as a dq0 transformation, or sometimes as a Park transformation.

The vector FOC operates in this manner:

- The system either directly monitors or infers applied three-phase drive output signals and currents from known gate-drive switching behavior and dc bus voltage values.
- The system performs two matrix transformations (an αβ, or Clarke, and a dq0, or Park) of this data to transform the rotating vector system in a stationary reference frame to a stationary vector system in a rotating reference frame (i.e., the rotor.)

- The control system calculates the next required voltage values in the dq coordinate system (rotating reference frame.)
- The calculated direct (d) and quadrature (q) values are then transformed back to a three-phase rotating voltage vector system in a stationary reference frame.
- Gate-drive signals are calculated and supplied to the power semiconductors in the bridge, which results in drive output PWM waveforms.

The calculated d and q values in the control system comprise a single motor stator voltage vector of d and q magnitudes (V_D and V_Q) and a single motor stator current vector of d and q magnitudes (I_D and I_Q.) These are dc values in a steady-state situation (no changing load, speed, or torque), but they dynamically change over time as the load, torque, and speed of the motor change.

We show a summary of the signals at each stage of the transformation and inverse transformation in the block diagram (Fig. 12.)

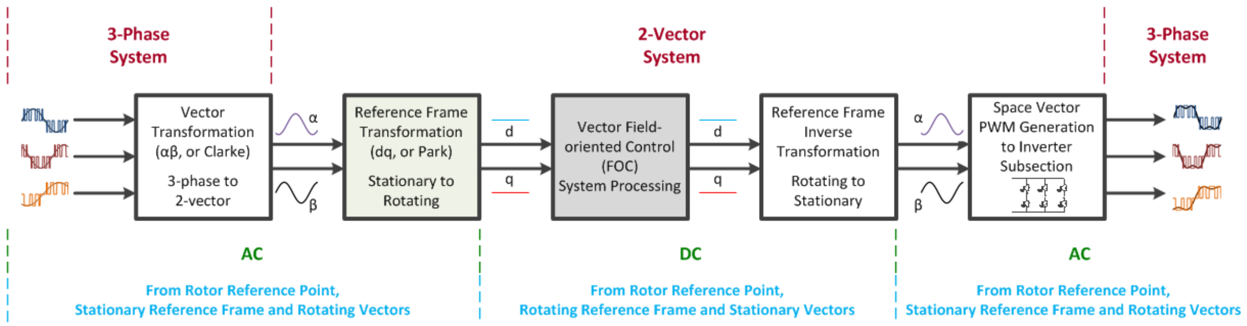

Fig. 12.In a rotor flux-oriented vector FOC control scheme, a mathematical matrix transformation decouples the magnetization (speed) producing (direct) currents in the stator from the torque-producing (quadrature) currents so that we may independently control speed and torque for the highest performance. We know this transformation as a dq0 transformation, or sometimes as a Park transformation.

The V_D, V_Q, I_D, and I_Q values provide important information to the vector FOC control engineer. For instance, the ripple of the I_Q stator current correlates with torque ripple (lower torque ripple is better; engineers design for low torque ripple.)

The calculations made by vector FOCs require high processing power, and therefore the microprocessor in the vector FOC control system is likely to run at speeds in the hundreds of megahertz. In turn, general-purpose control debugging calls for an oscilloscope with a bandwidth of at least 1 GHz. It also requires a measurement of speed, direction, and absolute rotor position using a quadrature encoder interface (QEI) or a resolver. The absolute rotor position provides the basis for calculation of the rotor magnetic field position, which is a necessary step for proper calculation and application of the appropriate stator voltages.

The screen image in Fig. 13 shows the motor drive line-to-reference output voltage and current from a small, sensorless vector FOC drive output. Any "sine-modulated" drive output (including simple Scalar controls) would look very similar. The three line-to-reference voltage waveforms are Z1 (yellow), Z2 (magenta), and Z3 (blue) while the three line current waveforms are Z4 (green), Z5 (gray), and Z6 (purple).

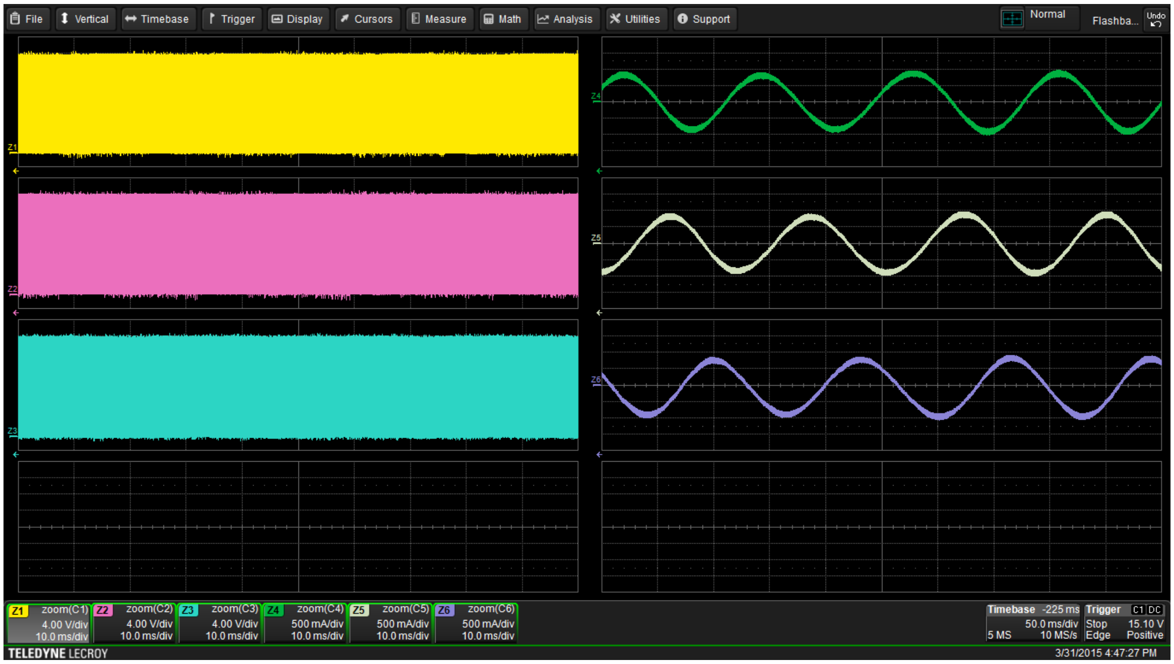

Fig. 13. Motor drive line-to-reference output voltages and currents from a small, sensorless vector FOC drive output.

Zooming in clearly reveals the PWM voltage waveform as shown in Fig. 14. Note the sawtooth-shape within the output current waveforms—this can be clearly seen with the Motor Drive Analyzer's 12-bit resolution.

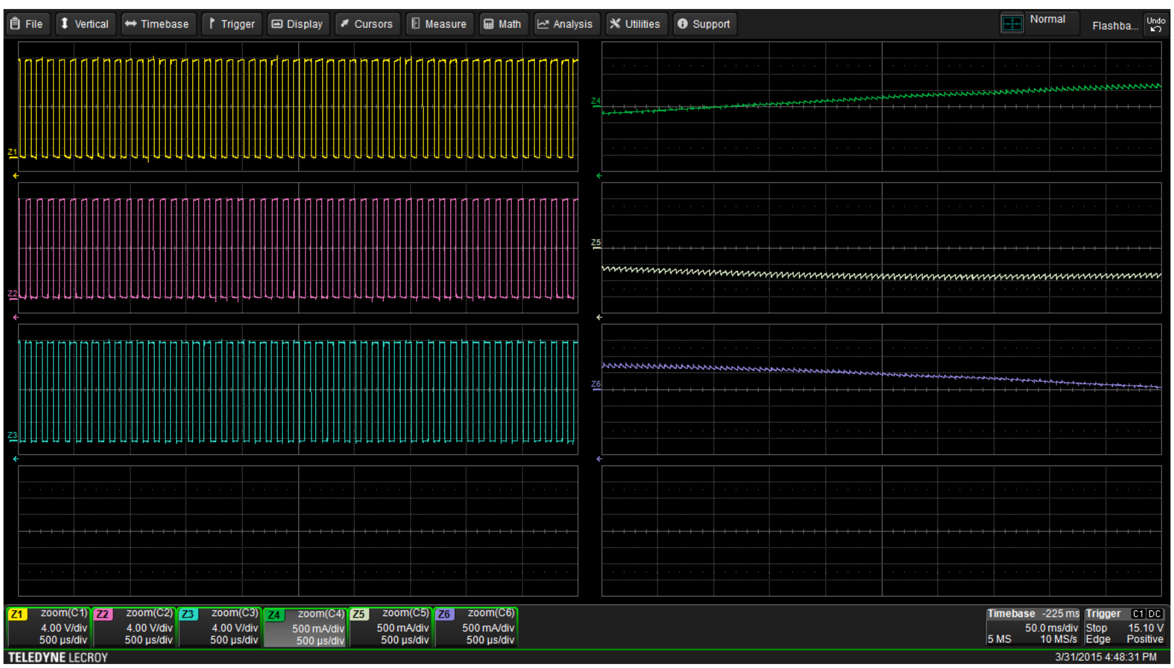

Fig. 14. Zooming in on the line-to-reference output voltages reveals the PWM voltage waveforms and the sawtooth shape of the output current waveforms.

If the voltage is sensed line-to-line instead of line-to-reference, the output voltage appears as a two-level signal, as shown in Fig. 15, with Z1 (yellow) the R-S voltage, Z2 (magenta) the S-T voltage, and Z3 (blue) the T-R voltage (R, S and T are abbreviations for the three-phase drive output.)

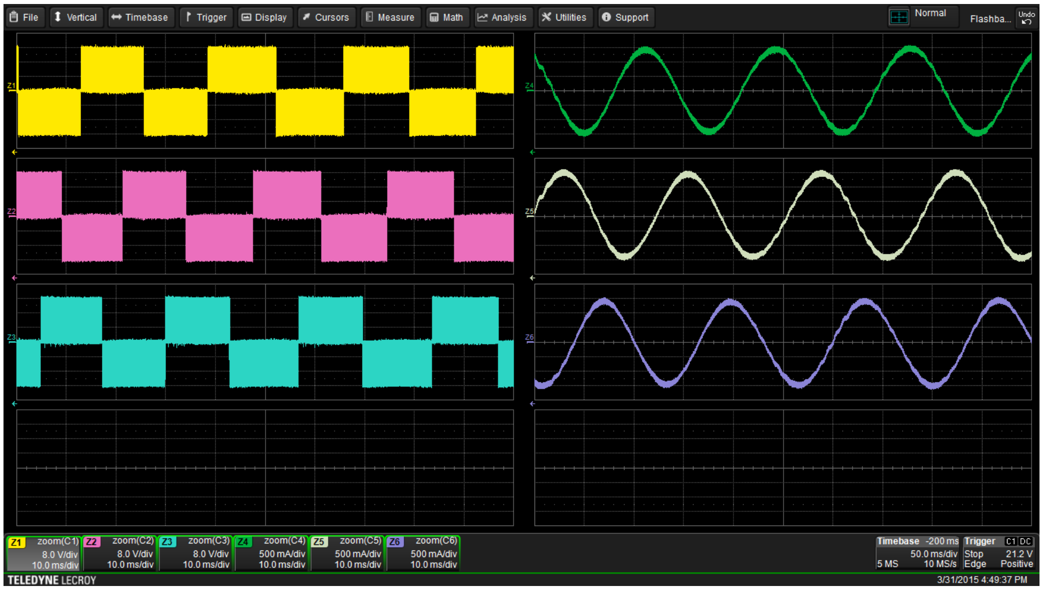

Fig. 15. Sensing the output voltages line-to-line in a sensorless vector FOC drive output causes the output voltages to appear as two-level signals.

In the typical block diagram for a vector FOC drive system in Fig. 16, note the quadrature encoder or resolver signals (either one may be used) for rotor position and speed that serves as input to the controller, and the dc bus voltage and current sensing.

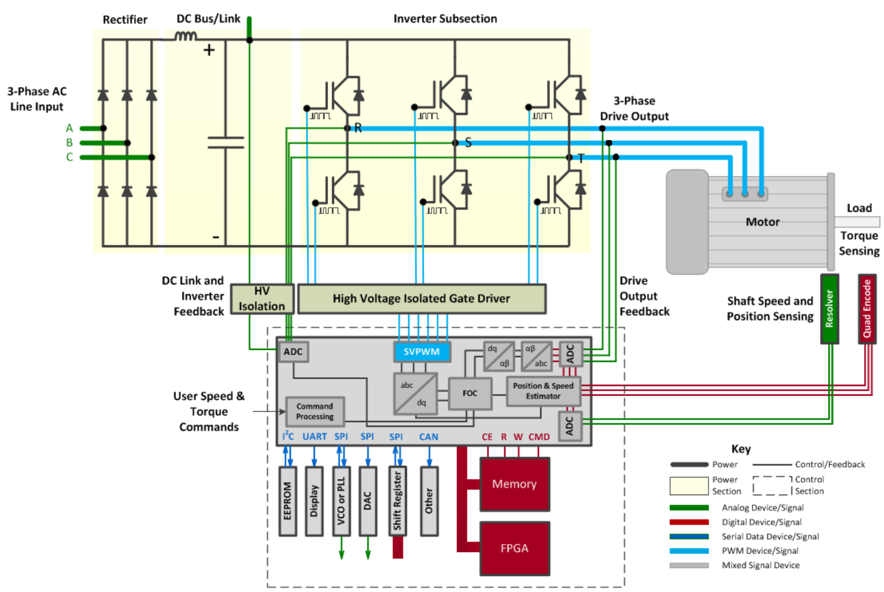

Fig. 16. A vector FOC drive system with quadrature encoder or resolver signals and dc bus voltage and current sensing.

Vector Direct Torque Control (DTC)

Direct torque control is also a vector-control technique, but it does not utilize real-time monitoring of rotor position and speed. Instead, it uses a look-up table to compare directly measured or derived values of motor torque and stator magnetic flux (via measured motor drive output stator currents) with control or user inputs and lookup tables. Then, it performs calculation of gate-drive PWM signals using a space vector modulation technique.

Vector DTC provides control and performance approaching that of vector FOC controls, but with (claimed) lower algorithmic complexity and cost due to the lack of mathematical transformations to the rotor reference frame. In short, they are "good enough" for many applications with potentially lower cost and higher reliability. In general, vector FOC controls are more common on PMSMs; direct torque control might be more common on large ACIMs.

All varieties of vector DTC use the same core principles for control—direct sensing detects two of the three drive-output line currents with the third inferred. The system compares a torque estimate calculated from the sensed current values to the desired torque. If the estimated and desired torque values differ by more than an acceptable hysteresis value, the controller calculates a ΔTorque value used for subsequent calculation of stator voltages via a lookup table.

The lookup table contains a pre-defined set of values for three-phase stator voltages depending on the input ΔTorque and calculated stator flux inputs. The output values from the lookup table determine the gate-drive signals for the inverter subsection.

Vector DTC has some advantages over vector FOC in that it may provide faster control of speed and torque. But it also has disadvantages such as limited control at zero or low speeds.

Conclusion

This part described the three main methods for achieving variable-frequency motor control: scalar V/Hz, six-step commutation (trapezoidal control), and vector control. Discussion of the later included vector flux- (or field-) oriented (FOC) control and vector direct torque control. Both open-loop (sensorless) and closed-loop (sensor-based) methods were described.

In part 14, we return to the subject of power measurement, exploring how to make power measurements on distorted signals such as PWM waveforms and drive outputs. 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.