Exclusive Technology Feature

ISSUE: April 2026

Motor Control For Designers (Part 6): Three-Phase Motor Waveforms

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In the last article in this series,[1-5] we looked at three-phase waveforms as vectors rotating relative to stationary coordinates. This made the phase relationships between vectors explicit. These vectors were depicted in the circuit model of a Y-configured motor (Fig. 4 in part 5, repeated here in Fig. 1) and in a vector diagram (Fig. 5 in part 5, repeated here in Fig. 2). A complete set of vectors required for phase control was also presented (Fig. 6 in part 5, repeated here in Fig. 3).

Engineers more familiar with waveforms in the time domain from oscilloscope screens might prefer seeing these waveforms in time instead. In this part, we'll present the waveforms corresponding to the rotating vectors of a three-phase motor vector diagram**.** We'll then look at the requirements for rotor position sensing under six-step control and drive sequencing for half-wave drive in a three-phase, Y-configured motor and drive sequencing for the delta-configured motor.

This leads to a description of six-step sequencing for three-phase motors with ∆ or Y configured windings with DCM or CCM terminal-pair sequencing. Winding inductance introduces errors that must be compensated for when driving the windings**—**these effects are briefly explained.

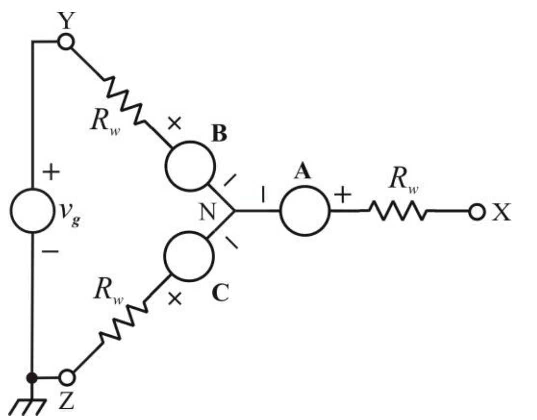

*Fig. 1. Circuit model of a Y-configured motor, with v_ω voltage sources shown as vector phase-winding voltages (to include their phase in the model) of **A**, **B**, and **C**. The winding terminals are labeled X, Y, and Z. The drive source v_g is shown driving terminal pair YZ ($v_Y - v_Z$) while terminal X is open—a DCM drive of the motor. A, B, and C voltage waveforms can be observed on an oscilloscope by probing their associated X, Y and Z terminals while spinning the unloaded, undriven motor.*

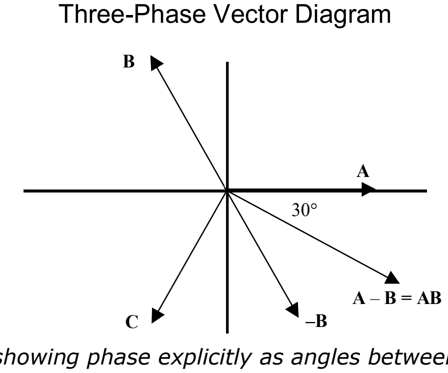

Fig. 2. Vector diagram showing phase explicitly as angles between phase-winding voltages. Vector lengths represent voltage magnitudes; they are equal for an electrically symmetric motor.

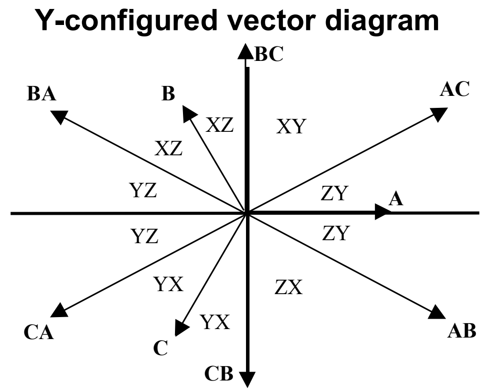

Fig. 3. Complete set of vectors for a Y-configured three-phase motor, showing intervals (steps) between vectors of terminal-pair zero-crossing induced voltages that can be detected for phase control (step sequencing).

Three-Phase Motor Waveforms For Six-Step Control

Waveform representation, with sine-wave motor voltages, is shown in Fig. 4.

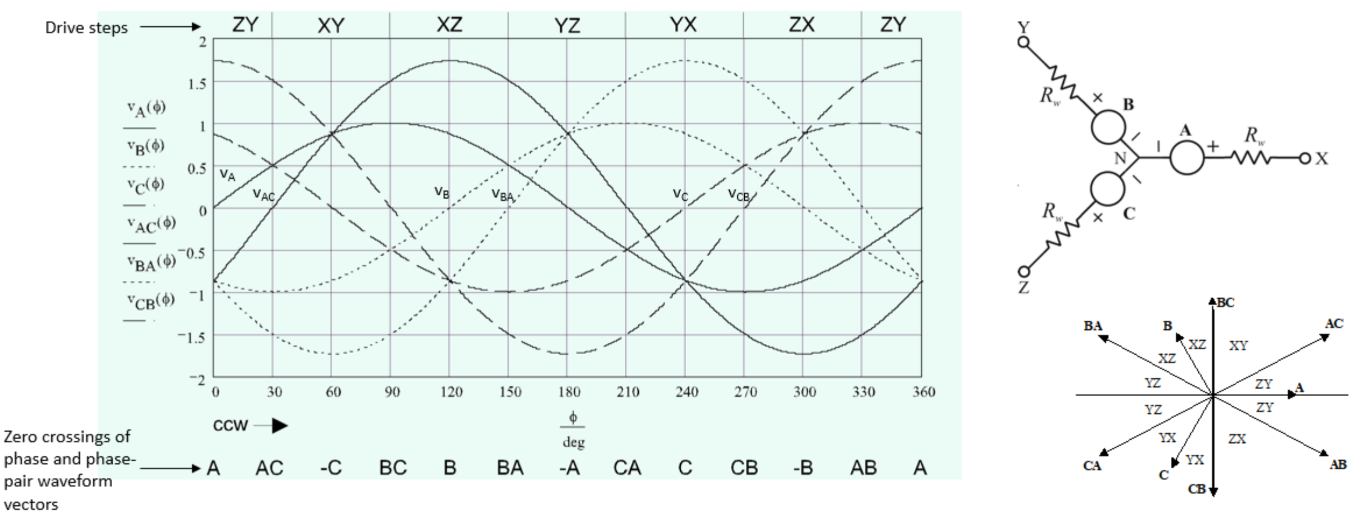

Fig. 4. Phase-winding waveforms (v_A, v_B, v_C) and terminal-pair (v_{AC}, v_{BA}, v_{CB}) waveforms for a three-phase motor, plotted against electrical phase ϕ. The intervals are shown for six-step phase control. Rotation is CCW from left to right, drive steps of terminal pairs straddle their peak voltages as shown above the graph, and the phase and phase-pair waveform vectors are at their 0° phase as indicated below the graph.

For Fig. 4 the vectors are rotating CCW. The positive zero-crossing (or 0° +zc) of **AB** (at –30° relative to A) occurs 60° before the XY drive step begins, at +30° relative to A. The drive terminal pairs shown above the graph are phased to drive a given phase at maximum voltage for maximum torque. For instance, drive of XZ, which peaks at 120° spans from 90° to 150°.

Induced voltage as observed in Fig. 4 is maximum during flux zero-crossings because $v_\omega = d\lambda/dt$ is maximum there. (For example, when v_{AC} is maximum, the corresponding flux of that phase-winding is crossing zero and its slope is maximum in magnitude.) Thus, v_ω leads λ by 90° and drive is applied when v_ω is maximum. (If the motor-drive controls its output current as a current source, then torque is controlled directly by i_s, and this current is made to be in-phase with v_ω for maximum real transfer power.)

Zero-crossings in Fig. 1 are labeled on the bottom row below the graph. Drive intervals or "steps" are shown on the top row.

Applying the motor drive voltage to terminal pairs is the "drive". Because there is one source per phase-winding, which source is driving with which polarity is determined by the sequencing. Three phase-windings and two (+ and -) polarities give six possible drive states. If a source has the options of + or -, then CCM drive results. With three source outputs: +, open circuit (oc), and –, DCM six-step drive is sequenced.

The Fig. 4 graph is an equivalent representation of a vector diagram. The advantage of the vector diagram is that it is less cluttered for phase analysis. What is appealing about the waveform representation of Fig. 4 is that waveforms are less abstract to many engineers, like oscilloscope displays.

For CW rotation, go from right to left on the graph, and zero-crossing polarities invert (+zc → –zc). Although induced voltages are plotted against electrical phase θ_{el}, at a constant speed, it is proportional to time: $\theta_{el} = \omega_{el} \cdot t$, and the Fig. 4 graph θ_{el}-axis is also a scaled time-domain axis.

Rotor Position Sensing

To drive the windings at the right phase for field-orientation, the rotor position θ_{me} needs to be sensed to align torque angle δ at 90°. Commonly used sensors are Hall-effect devices (HEDs), optical interrupters, or the motor induced voltage v_{ω} (winding-sensed, or "sensorless").

For 60° el phase resolution of six-step control, three sensors are required. HEDs can be driven by rotor magnets, with output waveforms shown in Fig. 2. Magnets are located so that they trigger a rising edge from HEDs A, B, and C at the 60° el angles of phase-windings U, V, and W. This placement centers the drive of a step at its 90° el angle for maximum torque.

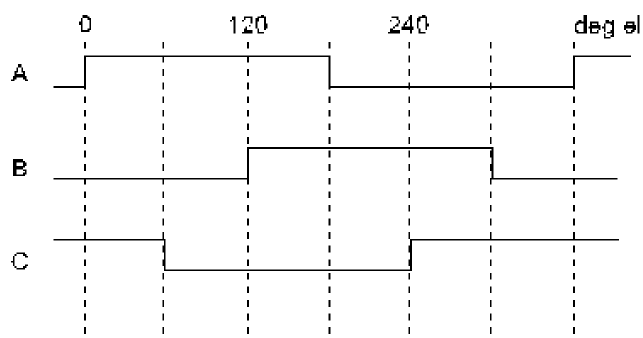

Fig. 2. Digital rotor position sensor waveforms for six-step phase control.

Six-step phase switching has 60° el resolution. Sine-wave induced-voltage waveforms result in torque ripple of (1 – cos(30°)), or about 13%. The drive phasing is exactly field-oriented only at the centers of each of the six steps and the torque angle δ varies within each step by ±30°. This is acceptable for many applications. Many PMS motors have trapezoidal $v_{\omega}(\theta_{el})$ and no torque ripple results.

Position sensors are a design nuisance and they can be avoided by sensing the induced-voltage waveforms at open motor terminals, such as for Y-configured motors with an open terminal in the six-step drive sequence. The induced voltage has the exact phase information.

However, v_{ω} amplitude varies with motor speed, and at low speeds its amplitude is also low and zero-crossings are hard to detect. In this *low-speed region* of operation, there are various schemes to overcome this deficiency of *winding-sensed* or "sensorless" phase control.

Half-Wave Drive

The simplest driver circuitry for motor-drives has unipolar flux, unipolar winding currents or *half-wave drive*. The typical scheme has center-tapped phase-windings with center-tap returned to the supply V_g and each end connected to a power switch to ground. Each switch selects the polarity of flux applied by the winding.

A three-phase Y-configured motor neutral node N is connected to V_g for half-wave drive and has the sequencing shown in Table 1. Motor terminals are ±U, ±V, and ±W. Sensor outputs from Fig. 2 are positioned so that the logic of the sensor decoding corresponds as given in Table 1 with the phase-winding electrical phase. (Note: U, V, and W correspond to X, Y, and Z as given above. In the motor literature, these labels are arbitrary but their sequence matters.)

Unipolar drive simplifies drive circuits but it is not optimal in that utilization of each phase-winding is only half; the full winding is driven only half the time. Full-wave drive doubles motor power and torque density.

Table 1. Drive sequencing for three-phase half-wave drive.

Electrical phase, deg	Drive	Sensor decoding
0	U	A·/B·C
60	V	A·/B·/C
120	W	A·B·/C
180	/U	/A·B·/C
240 (–120)	/V	/A·B·C
300 (–60)	/W	/A·/B·C

Delta-Configured Motor Windings

Besides the Y configuration, there is the Δ configuration, shown in Fig. 3 driven in DCM, with the X terminal open.

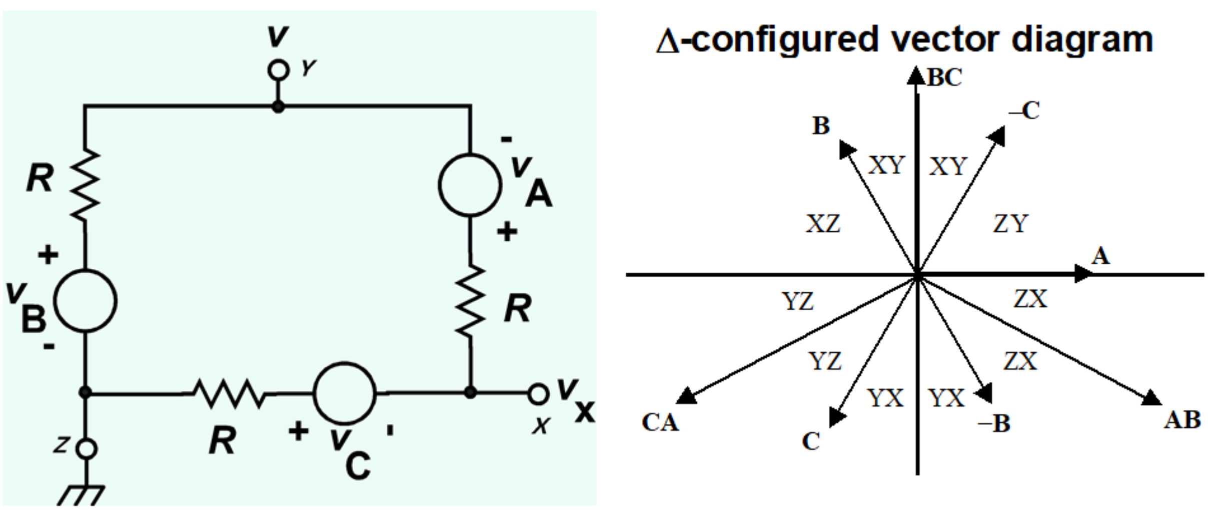

Fig. 3. A Δ-configured three-phase motor with X terminal open for DCM drive. The vector diagram is similar to the Y configuration, but shifted in phase.

The Δ-configured DCM drive sequence (commutation) is given in Table 2.

Table 2. Drive sequence for Δ-configured motor.

Drive vector	Drive terminals	Switch to next step on +zc of
A	XY	B
–C	XZ	–A
B	YZ	C
–A	YX	–B
C	ZX	A
–B	ZY	–C

The Δ-configured DCM drive is in phase with the phase-windings. The two series phase-windings A and C, in parallel with B, have the same voltage magnitude and phase: **B =** – (**A** + **C**). The Δ terminal-pair voltages equal the phase-winding voltages. When phase-winding **X** crosses 0° el, then 60° later it is driven.

The relationship between Δ and Y configurations is not only one of a phase shift in the terminal-pair vectors. The impedance also differs in that the Y-configuration $Z_Y = 3 \cdot Z_\Delta$. Thus the Y configuration is more optimal as a higher-voltage, lower-current configuration than Δ.

Three-Phase, Six-Step Commutation

Six-step sequencing for phase control of phase-windings U, V, and W has 60° el phase resolution and four possible drive schemes: Δ or Y with DCM or CCM terminal-pair sequencing. For DCM, one terminal is open in each step—like the "three-state" or open-collector drive of some digital bus drivers, with states H, L, or open. Phase detection for DCM sequencing uses the induced voltage of

$$\mathbf{U} - \mathbf{V} = \sqrt{3} \cdot \hat{v}_U \quad \angle -30^\circ$$

For CCM switch sequencing, all terminals are driven in all steps and have only "two-state" drive: H or L. The CCM Y-configured induced voltage is

$$\mathbf{U} - \tfrac{1}{2} \cdot (\mathbf{V} + \mathbf{W}) = \tfrac{3}{2} \cdot \mathbf{U}$$

Table 3 lists the order of sequencing of steps for both DCM and CCM drives, which result in different drive waveforms, shown in Fig. 4, and are named by their approximations to square- and sine-wave shapes. In Fig. 4, phase-winding current waveforms are either "sine-wave" (CCM Y, DCM Δ), or "square-wave" (DCM Y, CCM Δ).

Table 3. Three-phase, Y-configured six-step DCM and CCM drive sequencing.

Electrical phase, deg	Square-wave drive phase sequence		Sine-wave drive phase sequence	
	+	–	+	–
0			U W	V
30	U	V		
60			U	V W
90	U	W		
120			U V	W
150	V	W		
180			V	W U
210 (-150)	V	U		
240 (- 120)			V W	U
270 (-90)	W	U		
300 (-60)			W	U V
330 (-30)	W	V		

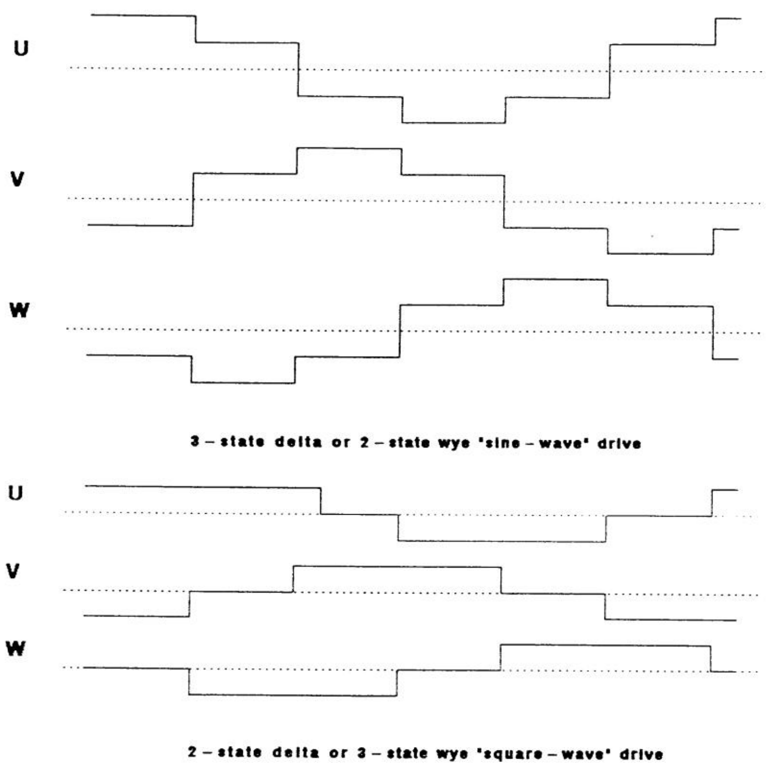

Fig. 4. Four combinations of Y or Δ configuration and DCM (three-state) or CCM (two-state) drive result in two different drive waveshapes, labeled by their waveshape approximations.

Each has three levels, but sine-wave drive has two levels in each half-cycle while square-wave has only one. Which drive is optimal is chosen based on the waveshape of v_ω of the motor. A perfect fit would result in zero torque ripple.

For CCW rotation of drive vectors, a CCM drive step commences 60° after the v_ω positive zero-crossing (+zc) of the phase-winding. In Table 3, when U is at 60°, U(+) and VW(−) drive is applied. Square-wave DCM drive steps start 30° el after phase-winding v_ω +zc. When W is open, U(+) and V(−) drive is applied at 30° of U.

The challenge in these cases is to offset drive phase from zero-crossings, and various circuit schemes have been invented, though vector addition or subtraction solves the problem without phase-locked loops or other circuit complications. Happily, sine-wave drive phase-steps start in phase with the phase-windings.

For each half-wave of drive waveform, the sequences are the same with inverted polarity of drive. For DCM Y drive at 30°, UV is driven and 180° later in the opposing half-cycle at 210°, VU is driven. Also, permuting phase sequence (swapping two motor terminals) reverses the direction of the sequence and the direction of rotation.

A three-phase, full-wave DCM Y-configured PMS motor has optimized drive for trapezoidal (flat-top) phase-winding induced-voltage waveforms. The advantage of DCM Y-configured drive is that the open terminal can be used to sense the phase of the open phase-winding with no current in it to drop voltage across its winding impedance, and with the neutral node either available or "synthesized," v_ω phase can be sensed directly.

When determining phase-winding polarities with an oscilloscope (with OS ground connected to the neutral N node of the motor), the V phase-winding polarity will result in a phase sequencing of either 60° el or 120° el phase separation from the other two phase-windings. If the three winding-phases have 60° el separation, swap the terminals of one of them for 120° el phase separation so that the winding phases are symmetrical. The drive step sequence aligns with the phase of the induced voltage so that current drive is applied to maximum v_ω for maximum power transfer.

The six-step phase sequencing scheme has been introduced because it is used in motor-drives of consumer products such as heat pumps and blower motors in vehicles. For higher-performance drives such as those in multi-motor motion controllers of robotics and automation, the 60° el resolution of six-step drives might be inadequate. However, it is both a practical and conceptual place to start in understanding phase control.

Winding Inductance Effects

One of the complications addressed in a later article and also in the portion of this series on motor-drive design is the effect of the winding inductance L_W. As motor speed ω_{me} increases and electrical drive frequency $\omega_{el} = p \cdot \omega_{me}$ (p = pole-pairs) increases along with it, inductive reactance increases, dropping increasing voltage and adding to the voltage drop across winding R_W. The series impedance of motor windings,

$$Z_w = R_w + j \cdot \omega_{el} \cdot L_w = R_w + j \cdot X_L$$

determines stator current i_S, and as X_L increases, i_S decreases as does torque. This can be compensated by increasing drive voltage V_g as a function of speed, as $V_g(\omega_{el})$, or advancing the phase of i_S to be in-phase with v_ω.

A related effect of L_W is that it forms a time-constant with R_W that causes delay in the rise of current waveforms when drive voltage is applied. This *electrical time-constant* $\tau_{el} = L_W / R_W$ can be corrected by phase-lead compensation to advance phase steps, but it also affects motion-control loop dynamics. These and other interesting or annoying nuances of motor-drive design and motion control appear later in this motor control mini-course. Happily, all of them have an engineering solution of some kind.

References

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About The Author

Dennis Feucht has been involved in power electronics for 40 years, designing motor-drives and power converters. He has an instrument background from Tektronix, where he designed test and measurement equipment and did research in Tek Labs. He has lately been working on projects in theoretical magnetics and power converter research.

For further reading on motors and motor drives, see "A Practical Primer On Motor Drives".