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Methods of Commutating 3-Phase Motor Drivers

Since the invention of the variable frequency drive, 3-phase Motor Control has become more advanced, versatile, and efficient. With that advancement comes complexity. No longer can a 3-phase motor simply be plugged into the power grid with a mechanical gearbox for speed control. Instead, motors find themselves in applications that require DC-bus power, continuously variable speed, and tight closed-loop control to maximize torque and efficiency.

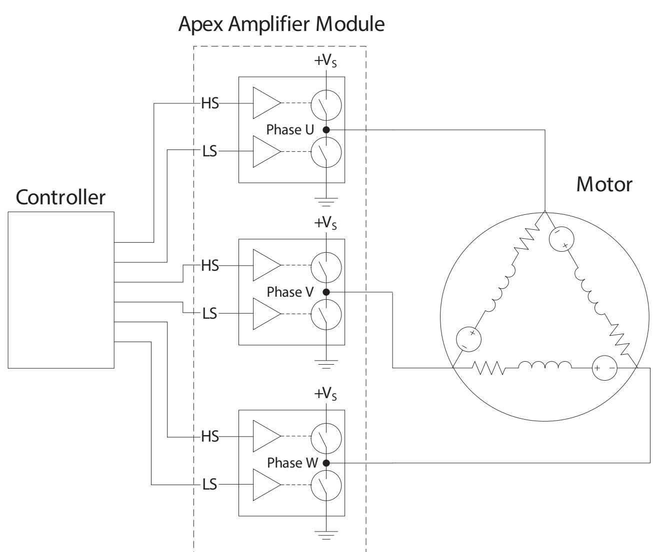
The typical 3-phase motor drive will need 2 things: a controller and an amplifier. Apex offers numerous products designed specifically to fulfill the amplifier (also known as inverter) portion. As for the controller, this application note details the different methods that the controller can interface with an Apex amplifier to commutate the motor properly and take full advantage of the motor's versatility.

This note discusses commutation methods that a controller would use to translate a desired drive state into signals that the Apex amplifier can use. Specifically, these methods are known in the industry as Sinusoidal, Trapezoidal, and Six-Step Commutation.

CONTROLLING THE AMPLIFIER

Most Apex 3-phase driver amplifiers offer the user full control of each "switch" in the inverter circuit of figure 1. Each phase consists of a high-side switch and a low-side switch. The input drivers require a low-voltage logic signal to make the switches close or open. By coordinating all 6 signals, the outputs of each phase can be controlled, and the motor can be turned.

Figure 1: General block diagram for a 3-phase inverter driving a motor

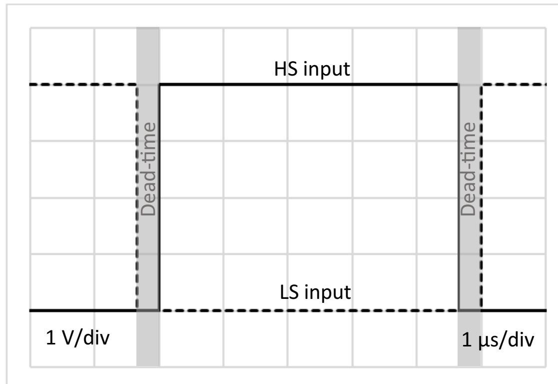


Typically, each phase output will be in one of three states: high-voltage (1), ground (0), or high-impedance (HZ). The truth table in figure 2 shows how each state can be achieved. High-voltage and ground are most commonly used, which require that the 2 input signals of a phase are inverses of each other. However, many amplifiers require that a short "dead-time" be inserted between any transition from high-voltage to ground or vise-versa. See figure 3 for an example of dead-time. Dead-time ensures that both switches are not closed simultaneously, which would cause a catastrophic condition known as “shoot-through”.

Figure 2: Truth table for each input/output

HS input	LS input	Output State
0	0	**High-Impedance (HZ)**
0	1	**Ground (0)**
1	0	**High-Voltage (1)**
1	1	**Do not use**

Figure 3: Dead Time inserted between transitions

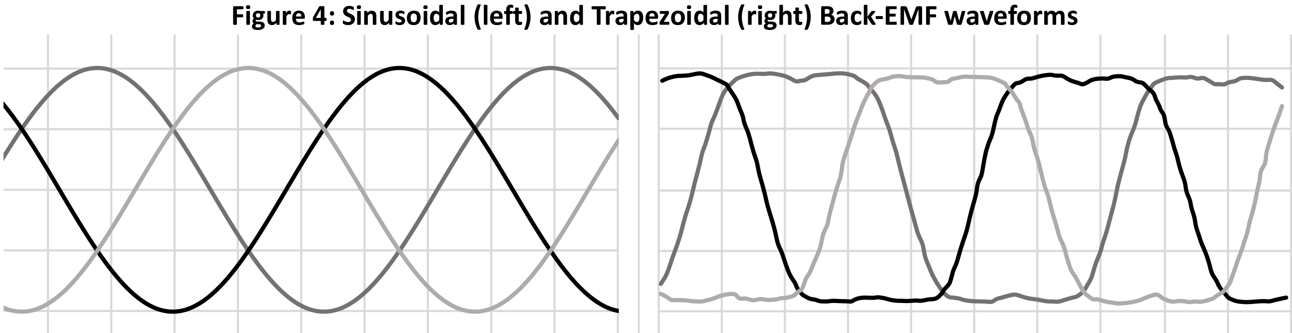


SINUSOIDAL COMMUTATION

Sinusoidal commutation is exactly what it sounds like: it attempts to vary the duty cycle of each phase to produce a sinusoidal current in each phase. The phase currents would be equal in magnitude and separated by phase differences of 120°. This technique mimics the 3-phase voltage produced by the power plant, with the added benefit that frequency and amplitude can be independently adjusted, as in a Variable Frequency Drive (VFD).

This method of commutation is typically used for Permanent Magnet Synchronous Motors (PMSM) or motors with windings that are deliberately wound to produce sinusoidal Back-EMF. One way to tell if a motor is wound sinusoidally is to connect the three power leads of the motor to 3 oscilloscope channels, then spin the rotor with a drill or other rotating tool. This will generate the Back-EMF of the 3 phases and display each one on the oscilloscope. If the oscilloscope shows 3 equally-spaced sine waves, then the motor is likely a good candidate for sinusoidal commutation. Note: The amplitude of Back-EMF will increase with RPM at a roughly linear rate. Record the amplitude and RPM of the motor, as this relationship will be helpful when calculating the power dissipation.

Figure 4: Sinusoidal (left) and Trapezoidal (right) Back-EMF waveforms



Another requirement for sinusoidal commutation is a position sensor with good resolution, such as an encoder. Hall-effect sensors do not provide enough resolution to get the most benefit out of sinusoidal commutation.

This type of commutation is the most difficult to set up from a software standpoint. Most implementations of sine commutation will take advantage of a micro-controller with 3 or more output compare modules connected to a single timer running in “Phase-Correct PWM” Mode. The timer will increment up and decrement down with a repetition frequency that matches the desired switching frequency (typically 20kHz). Each output compare register (trigger level) must be filled with a value that corresponds to a desired duty cycle, and these trigger values are updated to “ride” on the 3 desired sine waves. Conceptually, the timers, compare registers, and outputs would look something like figure 5:

Figure 5: Conceptual Diagram of Sinusoidal PWM Signal Generation.

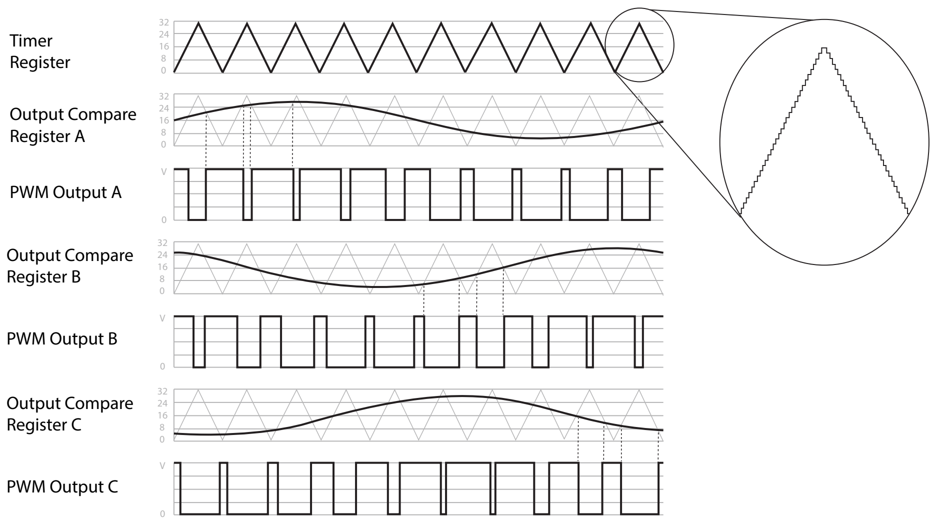


Figure 5 shows a timer ramping up and down while comparing against 3 output compare registers. A 5-bit timer is used here for visibility, but larger maximum timer values may be used for better duty cycle resolution. X-axis is an arbitrary time scale. Y-axis scales for Registers are integer values; Y-axis scales for PWM outputs are relative to the micro-controller’s logic voltage V.

These compare registers must be updated by the program frequently to provide the proper sine wave values. The corresponding PWM output pins should be configured to change state on output compare match, as demonstrated by the dashed vertical lines. These PWM Outputs will correspond to a specific pin on the micro-controller; check the micro-controller datasheet to determine which pins these are.

The above PWM Outputs A, B, and C can often be connected directly to the inverter’s high-side input pins (the pins that control the high-side switches). The low-side signals should be inversions of the high-side signals, with a programmed dead-time. Many micro-controllers, such as the STMicro STM32F030 series (and several others), have this functionality built-in. At least 3 more pins will be designated as “Output Compare Inverse Outputs” that can be configured with a dead time as a multiple of clock cycles. If this functionality is not available, dead time and inverse outputs can be easily programmed using a timer that has at least 6 output compare modules.

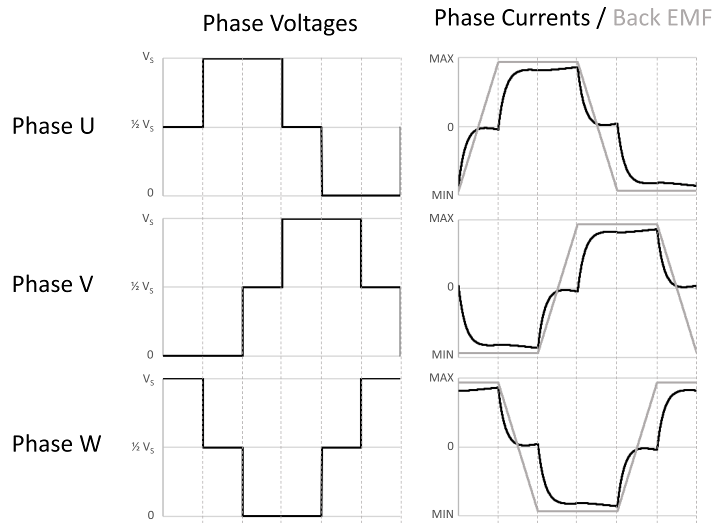
Sinusoidal commutation is difficult because it requires the control hardware to operate at least 2 clocks: one for the 20 kHz ramp, and another to manage the adjustable sine wave frequency. Additionally, to populate the trigger values, a sine function is required in the programming. In many cases, sine functions take up too many computational resources, so a lookup matrix with integer values corresponding to a sine wave is an excellent alternative.

TRAPEZOIDAL COMMUTATION

Trapezoidal commutation is typically used for motors that are wound deliberately to produce trapezoid-shaped Back-EMF waveforms. In many cases, manufacturing tolerances cause the Back-EMF to appear distorted from a perfect trapezoid. See figure 4 for an example. For the purposes of commutation and modeling, we can assume that this is close enough to a perfect trapezoidal waveform. Trapezoidal Back-EMF shape is very common for Brushless-DC (BLDC) motors, as it makes the commutation control scheme easier to understand and implement.

In trapezoidal commutation, there is always at least one leg in high-impedance mode. The other two inverter outputs are controlling the direction of current, with one output going to high-voltage and one output going to ground. A typical sequence of trapezoid commutation is shown in figure 6:

Figure 6: Trapezoidal Commutation Sequencing. X-axes are arbitrary time scales.



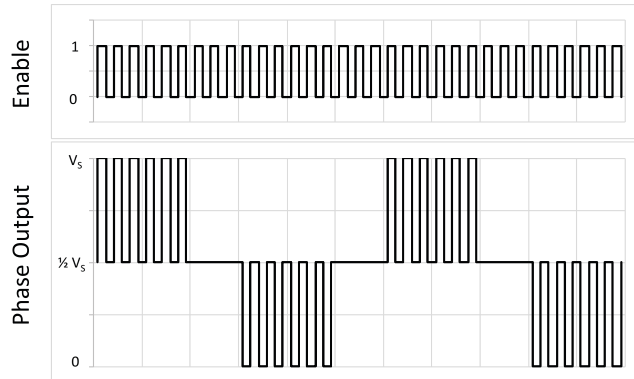
Phase U	HZ	1	1	HZ	0	0
Phase V	0	0	HZ	1	1	HZ
Phase W	1	HZ	0	0	HZ	1

HZ	1	1	HZ	0	0
0	0	HZ	1	1	HZ
1	HZ	0	0	HZ	1

Figure 6 shows a typical sequencing for a trapezoidal commutation. The charts at the bottom of the figure represent the commanded output state during each sequence: HZ (High-Impedance; both switches open), 1 (High-side switch closed, Low-side switch open), and 0 (High-side switch open, Low-side switch closed). Dead-time is not required for trapezoidal commutation, as there are no direct transitions from high-voltage to ground nor from ground to high-voltage. Reversing the order shown in figure 6 will turn the motor in the opposite direction.

Amplitude control (throttling) can be achieved by super-imposing a PWM enable signal. The duty cycle of this enable signal will correspond to the amplitude, with 0% duty cycle giving no current, and 100% duty cycle giving maximum current. Most amplifiers, like Apex's SA306 and SA110, will have an enable input to easily control this function. If not, enable/disable can be easily implemented by commanding all 6 switches to an "open" condition (high-impedance). An amplitude-controlled application might look like figure 7:

Figure 7: Trapezoidal Commutation with amplitude control

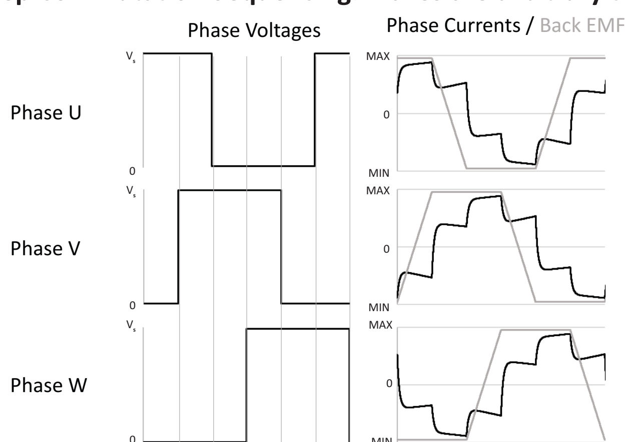


Trapezoidal commutation pairs well with motors that employ hall-effect sensors as the position feedback component. If hall sensors are not desired, similar position feedback can be achieved by sensing the Back-EMF voltage of the floating leg during its high-impedance period.

SIX-STEP COMMUTATION

In contrast to trapezoidal commutation, six-step commutation closes 3 switches at once, rather than just 2. See figure 8 below:

Figure 8: Six-Step Commutation Sequencing. X-axes are arbitrary time scales.



Phase U	1	1	0	0	0	1
Phase V	0	1	1	1	0	0
Phase W	0	0	0	1	1	1

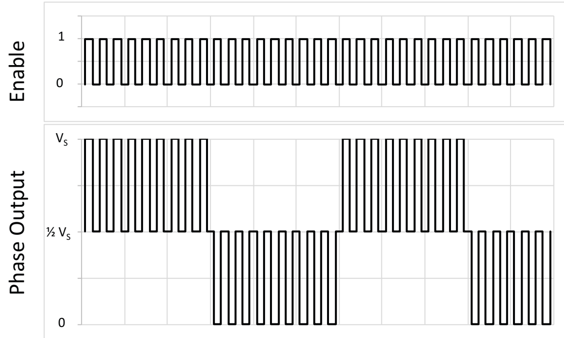
1	1	0	0	0	1
0	1	1	1	0	0
0	0	0	1	1	1

Similar to figure 6, figure 8 shows the six-step sequencing charts at the bottom for commanded output states on each phase. A "1" indicates that the output is programmed to high-voltage (high-side switch closed, low-side switch open), and a "0" indicates that the output is programmed to ground (high-side switch open, low-side switch closed). A particular "step" can be named with these symbols; for example, the left-most step would be named "100". Since this commutation method includes transitions from high-voltage to ground and vice-versa, dead-time must be considered. Reversing the above sequence reverses the motor direction.

In this commutation method, current can flow in the inverter in 1 of 2 ways: out of 1 high-side switch and into 2 low-side switches (sequences 100, 010, and 001), *or* out of 2 high-side switches and into 1 low-side switch (sequences 110, 011, and 101). When current is shared between 2 high-side switches or 2 low-side switches, they each carry roughly half the peak current magnitude. There are then 4 “levels” that the phase currents can be: full negative, half negative, half positive, or full positive.

Once again, amplitude control can be achieved in six-step commutation by applying a PWM enable signal similar to figure 9. All three phases should be in a high-impedance state (all switches open) during the PWM “low” times, and the phases would resume their normal sequencing during the PWM “high” times. The enable signal must be synchronous on all 3 channels for proper operation.

Figure 9: Six-step commutation with amplitude control



Six-step commutation can be used for the same types of motors that Trapezoidal commutation would be used on, with some advantages and disadvantages. The advantage would be that of better torque distribution. In delta-connected motors, six-step commutation energizes 2 of the 3 legs at any one time, while trapezoidal commutation would only energize 1 leg of a delta-connected motor. This offers more area for the magnetic flux to take effect, improving the torque ripple.

The disadvantage of six-step commutation is that it does not have a floating leg for Back-EMF measurement. Position feedback must be supplied by some other form of rotor measurement, like hall-effect sensors or an encoder. Sensing phase current in six-step can be a good substitute for position feedback; Apex products SA306 and SA310 are particularly well-suited for this method because they provide an easy way to sense phase current.

HYBRID COMMUTATION METHODS

In many cases, the motor is more versatile than the commutation method. Many 3-phase motors are designed for a wide stable region and a very flat torque capability over a long range of RPMs. However, these commutation methods above have limited usability over the entire speed range.

While sinusoidal commutation approaches the ideal waveform for driving a 3-phase motor, its maximum speed is severely limited by the hardware capabilities. Sinusoidal commutation needs real-time position feedback in order to match the current space vector with the magnetic space vector. The faster the motor turns, the harder it is for the encoder and micro-controller to keep up due to phase lag. For this reason, sinusoidal commutation is normally limited to a motor speed of around 0-1000 RPM.

In contrast, trapezoidal and six-step commutation are limited in their low-end torque driving capabilities. These methods have only 6 “states” of position resolution per each electrical cycle, while sinusoidal can have theoretically infinite states. Therefore, there are many positions where the magnetic flux vector is not orthogonal to the current vector, and maximum torque cannot be achieved until the rotor turns another 30° or so. This makes trapezoidal and six-step poor choices for starting up motors that are driving a heavy torque load. But once the motor is up to a reasonable speed, these methods allow the motor to be much more efficient than with sinusoidal commutation.

The solution to both problems is to include 2 forms of commutation in the controller module and select which one to use based on the rotor speed. Having the program automatically use sinusoidal for low speeds and trapezoidal for high speeds can drastically improve the motor's efficiency.