The Engineer's Guide to Driving 3-Phase AC Induction Motors with Inverters

For many years, adjustable-speed motion control relied on DC motors — first brush-type, then later brushless. That began to change in the late 1980s and early 1990s, when advances in power electronics and microprocessors made inverters more compact, reliable and affordable. With lower maintenance requirements than brush-type DC motors, three-phase AC motors began to take hold in applications where variable speed was needed.

Today, the adoption of three-phase AC motors paired with inverters continues to grow. As part of the broader shift toward IIoT and Industry 4.0, industrial systems are becoming more connected — and modern VFDs support enhanced communication protocols that make it easier to monitor motor parameters in real time.

Inverter-rated motors, gearmotors and an inverter from Bodine Electric. (Image: Bodine Electric Company.)

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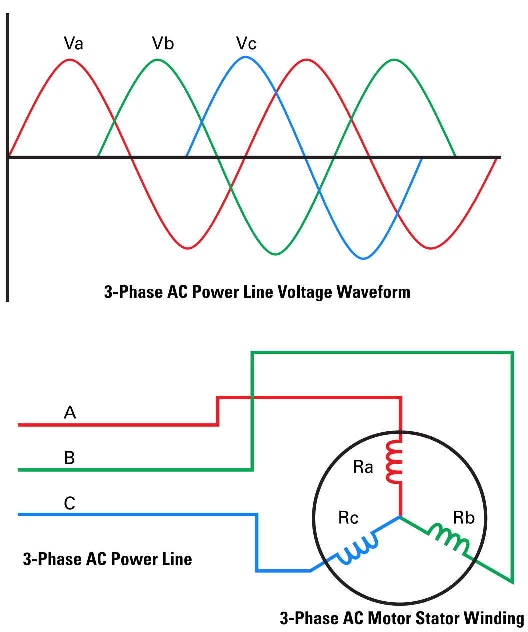
This whitepaper provides background on three-phase AC motors and inverters, and what to consider when specifying a motor and inverter pair for optimal performance.

The Basics of Three-Phase AC Induction Motors and Inverters

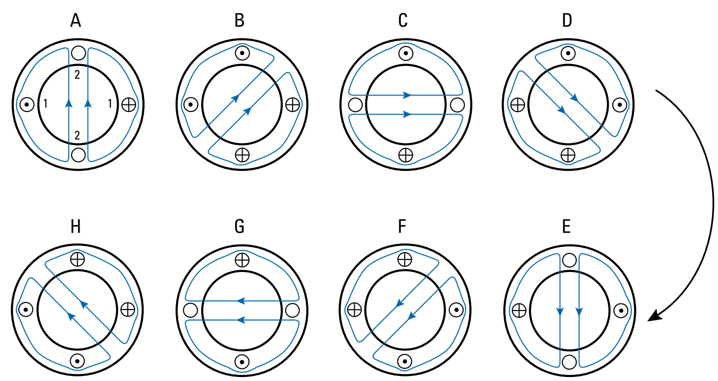
A three-phase AC induction motor is designed to operate on three-phase power (Figure 1). When alternating current is applied to the motor's stator winding, a rotating magnetic field is created (Figure 2). As that rotating magnetic field cuts across the conducting bars in the rotor, current is induced in those bars, and another magnetic field is created. That field interacts with the rotating field in the stator and causes the rotor to turn with it. The rotary speed of the rotor is proportional to the frequency of the alternating current.

If the frequency of the alternating current is changed, then the motor's rotational speed changes as well.

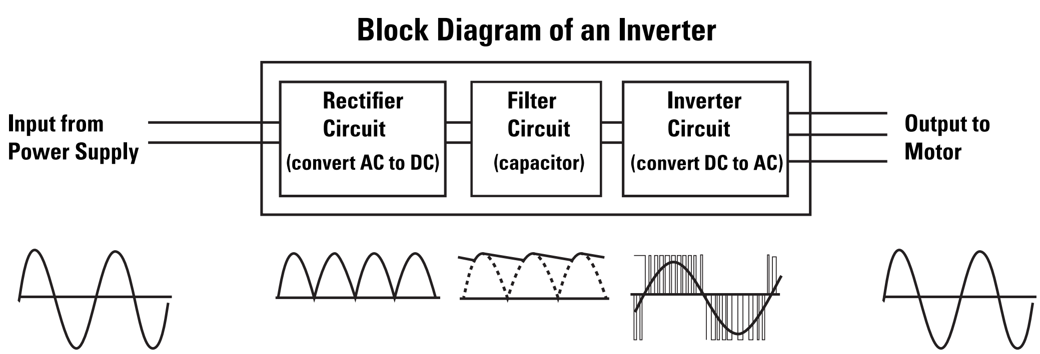
One means of changing the frequency of the alternating current applied to a motor is the inverter. The inverter, also referred to as a variable frequency drive (VFD), starts by converting an AC input, whether single phase or three phase, to DC. That DC is then filtered and chopped using insulated-gate bipolar transistors (IGBTs) and pulse-width modulation (PWM) to generate a three-phase AC output to the motor. That synthesized AC output can be manipulated by the microprocessor to adjust its frequency, and therefore the motor's speed (Figure 3).



(Figure 1.)



(Figure 2.)



(Figure 3.)

Adapting Motor Design for Inverter-Driven Operation

Despite the numerous benefits for the user, using a three-phase AC motor with an inverter does introduce important considerations for the motor designer. "The three most important considerations are designing for higher temperatures and higher running speeds, and designing to withstand the potential for high voltage spikes associated with inverter operation," says Joe Norris, director of electrical and electronics engineering at Bodine Electric.

While standard motors are intended to operate at a fixed speed and frequency, motors operating with a VFD may potentially run at lower speeds. Since many AC motors use a fan for cooling, slower speeds mean less airflow, putting greater strain on the motor's power dissipation requirements. To address this, inverter-duty motors use Class F insulation rated to 155°C, compared to the 130°C rating of Class B insulation commonly used in standard motors.

Conversely, motors operating with a VFD may run at higher speeds than standard motors.

"A standard 4-pole motor rated to run at 1,700 rpm at 60 Hz would run at twice the speed, or 3,400 rpm, if the inverter is set for an output frequency of 120 Hz," says Terry Auchstetter, director of marketing and product development at Bodine Electric. "That generally isn't an issue mechanically, if the motor has good bearings and the rotor is well-balanced. But in a gearmotor, the higher input speed to the gear reducer can reduce the life of the gearing if run continuously at the higher speed. The gearmotor designer may opt for a different steel or hardening or gear geometry to maintain the life expectancy with the higher input speed."

As for the voltage spikes, motors designed for inverter duty include several layers of electrical insulation. Inverter-grade magnet wire is used, which includes film insulation better suited to withstand voltage stress. Phase insulators are added, and sleeving is applied to both ends of splice points.

A motor and inverter attached to a conveyor. (Image: Bodine Electric Company.)

Key Considerations When Pairing Motors with Inverters

When using a three-phase AC motor with a VFD, the first step is to confirm that the motor is designed for inverter use. The easiest way to confirm that is to check the motor nameplate and look for the phrase "inverter-duty" or something similar. After doing that, the next important consideration is how the inverter is sized.

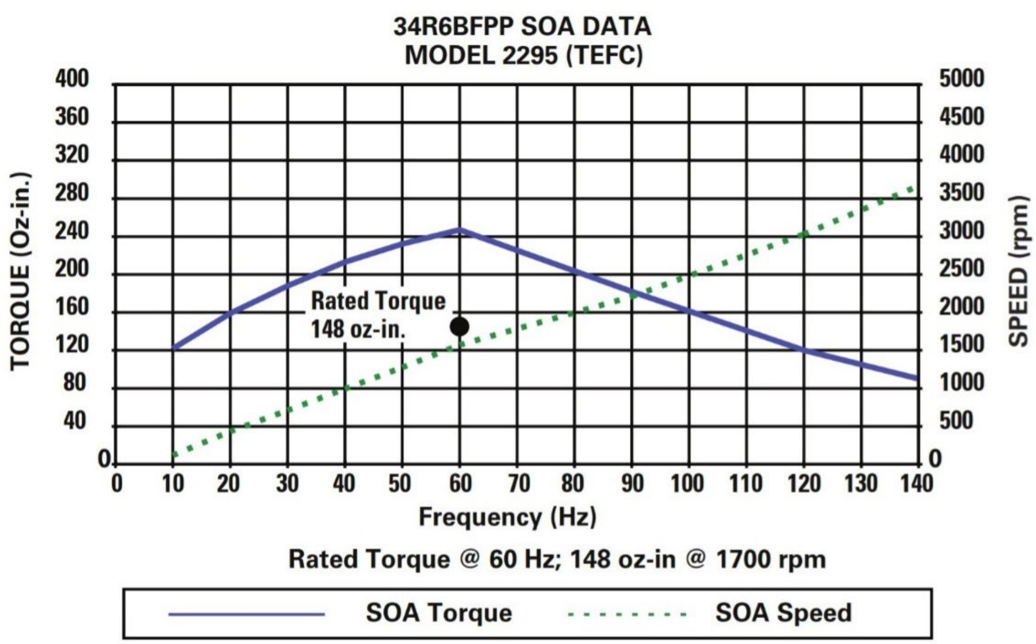
"Sizing by horsepower is not the recommended way to size an inverter for a motor," says Frank Caputo, sales engineer at Bodine Electric. "It is best to size the inverter based on the full-load amps on the motor nameplate."

In addition to current, engineers should also confirm that the inverter is compatible with the motor's input voltage. The output voltage of the inverter must match the nameplate voltage of the motor.

Application type plays a role as well. In constant-torque applications — such as conveyors, hoists, elevators or positive displacement pumps — the torque remains steady across the motor speed range. With variable-torque loads, like centrifugal pumps and fans, the torque increases with motor speed. Selecting an inverter that is configurable to match the load type ensures that both the motor and the drive stay within their operating range.

Another key factor is the motor's Safe Operating Area (SOA). "SOA is a graph of the allowable torque to keep the motor within the thermal limit of its insulation class at each frequency when the motor is operated with a variable frequency drive," explains Norris (Figure 4). "The highest SOA torque is at the motor's nameplate frequency. You're not going to be able to operate at as high a torque at lower frequencies. As frequency increases above the motor's rated frequency, the torque capability also goes down, just as it does at lower frequencies."

Auchstetter explains why the SOA torque is lower at both lower and higher frequencies. "There is an optimal volts/hertz ratio that keeps the motor from overheating. That means the inverter reduces the output voltage at lower frequencies. Because torque is proportional to voltage in an AC motor, that's why the torque goes down at lower frequencies. On the other hand, at frequencies above the motor's rated frequency, it is not possible for the inverter to maintain the volts/hertz ratio because it cannot raise the



(Figure 4.)

output voltage higher than what's available from the input power supply. Because the motor doesn't get the voltage it wants at higher frequencies, the torque goes down. Because, again, torque is proportional to voltage in an AC motor."

What that means for the user is that they may safely operate the motor above its rated torque, depending on other conditions. But, Caputo cautions, "if the motor is driven above its rated current, then make sure the inverter used with it is rated for the higher SOA current, and not just for the motor's rated current."

"When you're first setting up an inverter, it's recommended to make sure the motor parameters are correct for your motor and application," says Caputo. "Acceleration and deceleration times are another factor. Braking methods can also affect the life and performance of the motor. If you're trying to hit your torque rating in five milliseconds, that's going to stress the motor or overcurrent the drive."

Another setting to be aware of is the switching frequency of the IGBTs, or carrier frequency. "It is common for inverters to have a high carrier frequency, like 16 kHz or higher," says Caputo. "Some inverters have the option of halving the carrier frequency to 8 kHz, for example." There are trade-offs for each setting.

"The trade-off is that higher carrier frequencies are acoustically quieter and less annoying to most people's ears than the lower carrier frequencies, but they also have the potential to cause fretting damage to the motor bearings," says Auchstetter. "The high-speed switching of current in the motor winding can induce stray currents in the rotor that seek a path to ground. The only path is through the motor bearings."

It is worth noting that the effects of voltage spikes worsen with longer cable lengths between the motor and the inverter.

One more inverter setting that shouldn't be overlooked is the motor base frequency. "I remember a case with a customer in Europe where the line frequency was 50 Hz, so they set the motor base frequency setting of the inverter to 50 Hz. But really, that setting should be based on the motor's nameplate rating. So, if they're using a 60 Hz motor in Europe, they should set the inverter's motor base frequency for 60 Hz, even though the line frequency is 50 Hz. Setting it wrong can result in overheating of the motor."

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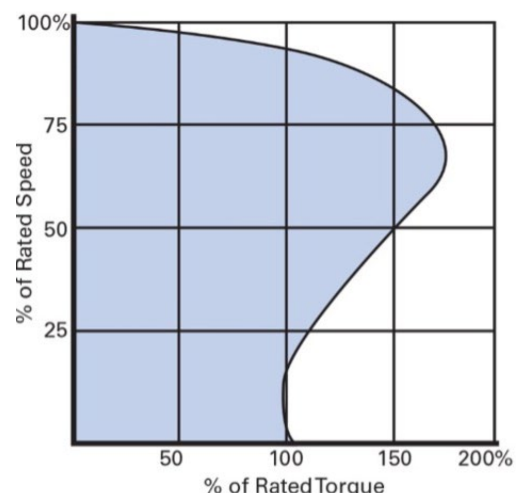
Real-World Examples of Inverter-Driven Motors

In applications where temperature control or airflow management is crucial, inverter-driven motors offer advantages over fixed-speed systems. One example is commercial pizza ovens, where some manufacturers are transitioning from simple on/off single-phase blower motors to three-phase AC motors driven by inverters. Instead of running fully on or fully off, the blower can adjust speed to deliver just the right amount of hot air, helping to maintain consistent baking temperatures.

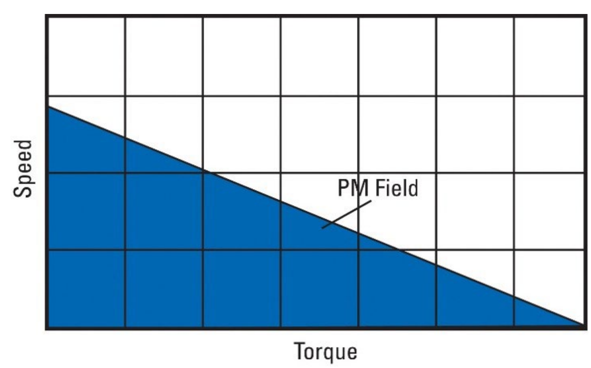
HVAC systems in commercial buildings follow a similar approach. Rather than cycling motors at full speed, VFDs enable operation at reduced speeds during lower demand. "That's one of the benefits of inverters: efficiency," says Caputo. "During peak times, you don't have to run at 100%; it adjusts to where the air needs to go."

Auchstetter recalled another application where a manufacturer of packaging machinery needed to drive two gearmotors at the same speed from a single inverter. "The customer wanted to achieve that without the complexity of a leader-follower control system. They wanted to simply output a frequency and have both gearmotors respond accordingly." A benefit of inverter-driven motors is the ability to run multiple motors in open-loop control. That is because normal slip AC motors have a relatively constant speed from no load to full load without the need for feedback (Figure 5). DC motors, on the other hand, have a linear speed/torque curve and so they rely on a feedback loop to maintain constant speed from no load to full load (Figure 6). Because a controller would need separate feedback from each DC motor, that complicates driving two DC motors from a single control. Electronically commutated DC motors (brushless DC) are even more complicated.

An inverter-duty gearmotor drives a conveyor that carries hanging flower baskets under a water sprinkler in a greenhouse. By adjusting the gearmotor speed slower or faster, the flowers receive more or less water. (Image: Control Dekk)



(Figure 5.)



(Figure 6.)

Conclusion

Driving three-phase AC motors with Inverters introduces specific thermal, electrical and control considerations that call for close attention during specification. When those variables are addressed up front, they enable reliable variable-speed operation in today's increasingly connected environments.

To learn more, explore the library of technical resources at *Bodine Electric's Motor University.*