

The truth about five common VFD myths

Knowing the truth about VFD operation can simplify the selection process.

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No matter how commonplace variable frequency drives (VFDs) have become to you, somewhere someone is using one or considering using one for the first time (see Figure 1). Think back to when you first thought about applying one of today's pulse-width modulation (PWM)-based VFDs to an ac motor. Chances are you probably had a few misconceptions about their abilities and designs. This article addresses five common VFD myths and corrects misconceptions about their proper usage.

Myth No. 1: The output of a VFD is sinusoidal

People tend to be more familiar with running their ac induction motors using motor starters. With a starter, starting the motor involves connecting the 3-phase leads of the motor to 3-phase power. Each phase is a sine wave with a frequency of 60 Hz and usually has a voltage amplitude of 230 V, 460 V, or 575 V in the U.S. This applied voltage creates a sine wave current waveform with the same frequency if checked at the motor leads. So far, running a motor is quite simple.

What happens at the output of a VFD is an entirely different story. A VFD typically rectifies the 3-phase input to a fixed dc voltage, which is filtered and stored using large dc bus capacitors. The dc bus voltage is then inverted to yield a variable voltage, variable frequency output. The inversion process is carried out using three insulated gate bipolar transistor (IGBT) pairs—one pair per output phase (see Figure 2a).



Figure 1: Users select variable frequency drives (VFDs) to control motor speed and reduce energy consumption. All graphics courtesy: Yaskawa America Inc.

Because the dc voltage is inverted into ac, the output stage is also called “the inverter.” The duration for which each IGBT switch in a given pair is turned ON or held OFF can be controlled, which determines the RMS value of the output voltage. The ratio of the output RMS voltage to output frequency determines the flux developed in the ac motor. In general, there is a fixed relationship between the two. When the output frequency increases, the output voltage should also increase at the same rate to keep the ratio constant and thus the motor flux constant. Normally, the relationship between voltage and frequency is kept linear so that a constant torque can be produced. The resulting voltage waveform applied to the motor winding is not sinusoidal (see Figure 2b). Note that sometimes the voltage by frequency (V/f) ratio can be quite nonlinear, which is typical for fans,

pumps, or centrifugal loads that do not require constant torque but instead favor energy savings.

What makes this work is that, as the name implies, an induction motor is a big inductor of sorts. A characteristic of induction is its resistance to current changes. Whether a current is increasing or decreasing, an inductor will oppose the change. What does this have to do with the PWM voltage waveform in Figure 2b? Instead of letting the current pulse rise on the same order as the applied voltage pulse, the current will start to rise slowly. When the voltage pulse has ended, the current doesn't disappear immediately, it slowly starts to ebb. In general terms, before the current has fallen back to

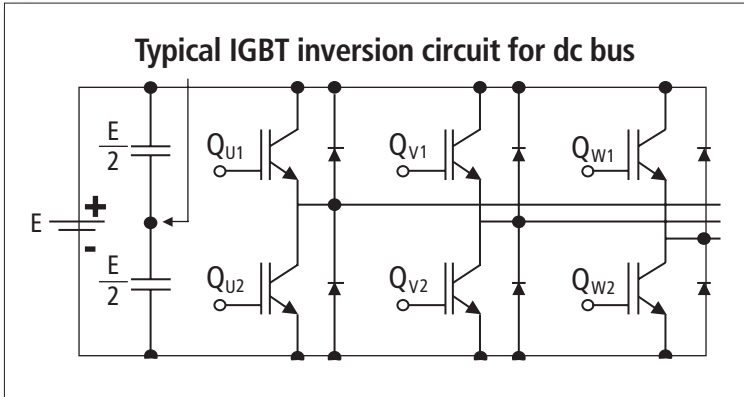


Figure 2: In a basic VFD, the inversion process is carried out using three IGBT pairs—one pair per output phase (a). The resulting voltage waveform applied to the motor winding is not sinusoidal (b).

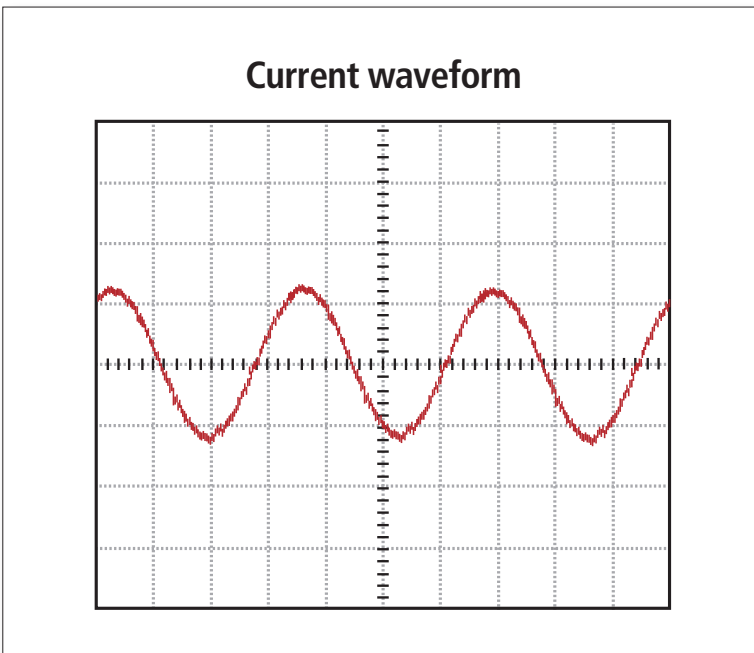
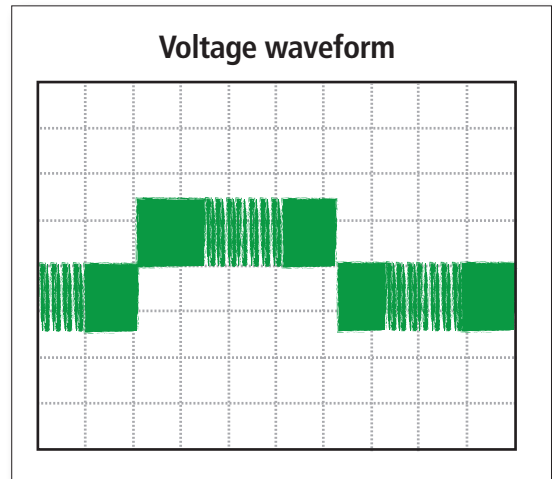


Figure 3: Because a motor's induction characteristics resist changes in current, the resulting current waveform approaches a sine wave with jagged transitions that correspond with the rise and fall of the voltage pulses.

Myth No. 2: All VFDs are the same

The common ac VFD of today is a fairly mature product. Most commercially available drives contain the same basic components: a bridge rectifier, a soft-charging circuit, a dc bus capacitor bank, and an output inverter section. Granted, there are differences in how the inverter section does its switching, the reliability of the components, and the efficiency of the thermal dissipation scheme. But the basic components remain the same.

There are exceptions to this “all-the-same” thinking. For example, some VFDs offer a three-level-output section. This output section allows the output pulses to vary from half-bus, voltage-level pulses and full-bus level pulses (see Figure 4).

To achieve the three-level output, the output section must have twice the number of output switches, plus clamping diodes (see Figure 5). The benefit gained by using a three-level output is reduction in voltage amplification at the motor due to reflected wave, lower common-mode voltage, shaft voltage, and bearing current.

The matrix-style inverter is an even more atypical type of VFD. VFDs with matrix-style inverters do not have a dc bus or a bridge

rectifier. Instead, they use bidirectional switches that can connect any of the incoming phase voltages to any of the three output phases (see Figure 6). The benefit of this arrangement is that power is allowed to flow freely from line-to-motor or motor-to-line for fully regenerative four-quadrant operation. The drawback is that filtering is required on the input to the drive because extra inductance is necessary to filter the PWM waveform so that it does not affect the input ac lines.

zero, the next voltage pulse comes along, and the current starts to slowly rise again—even higher than before because the pulses are getting wider. Eventually, the current waveform becomes sinusoidal, albeit with some jagged up-and-down transitions as the voltage pulses start and end (see Figure 3).

However, don't think that you can power your solenoid from a single-phase output of a PWM VFD. It's not that kind of ac voltage.

Three-level output waveform

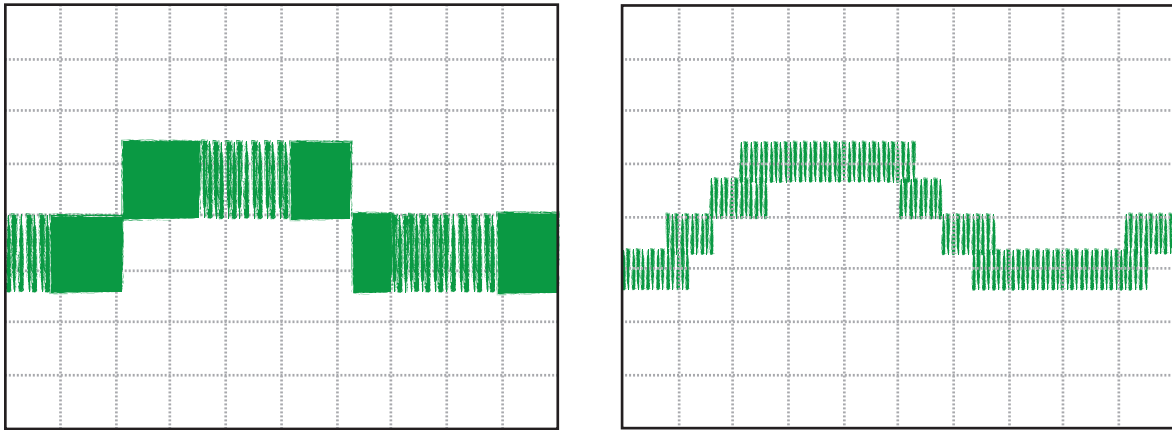


Figure 4: Compare the two-level output pulses on the left with the three-level output pulses on the right.

In addition to VFDs with three-level outputs and matrix-style inverters, there are more examples that prove not all ac VFDs are the same.

Myth No. 3: VFDs cure power factor (PF) issues

It is not uncommon to see VFD manufacturers quote PF statistics like “0.98 displacement PF” or “near-unity PF.” And it is true that input displacement PF improves after a VFD is installed ahead of an induction motor. The VFD uses its internal capacitor bus to supply any reactive current the motor requires, thereby protecting the ac line

from being the source of the reactive current and lowering the displacement PF. However, displacement PF is not the full story.

The full story of the PF calculation is that it must include the reactive power demanded by harmonics that are created when ac voltage is rectified to dc. The diode bridge conducts the current from the ac line to the dc bus in a discontinuous way. It is important to remember that a diode conducts only when the voltage on the anode side is higher than the voltage on the cathode side (forward biased). This means that the diodes are only ON at the peak of each phase during both the positive and negative portions of the sine wave. This leads to a ripple-like voltage waveform. It also causes the input current to be distorted and discontinuous (see Figure 7).

Much can be said about how to calculate harmonics and how to mitigate them. Regardless, to calculate true PF, the effects of harmonics must be included. The following equation indicates how harmonics influence true PF:

$$\text{True PF} \approx \text{Displacement PF}_1 + \text{THD}^2$$

Where THD = total harmonic distortion

For the discontinuous input current in the equation, THD would be in the neighborhood of 100% or more. Substituting that into the equation yields a true PF closer to 0.71, compared to a displacement PF of 0.98, which disregards harmonics.

Not to panic though, there are currently many ways to reduce THD. These techniques make use of passive and active methods of

Typical three-level output circuit

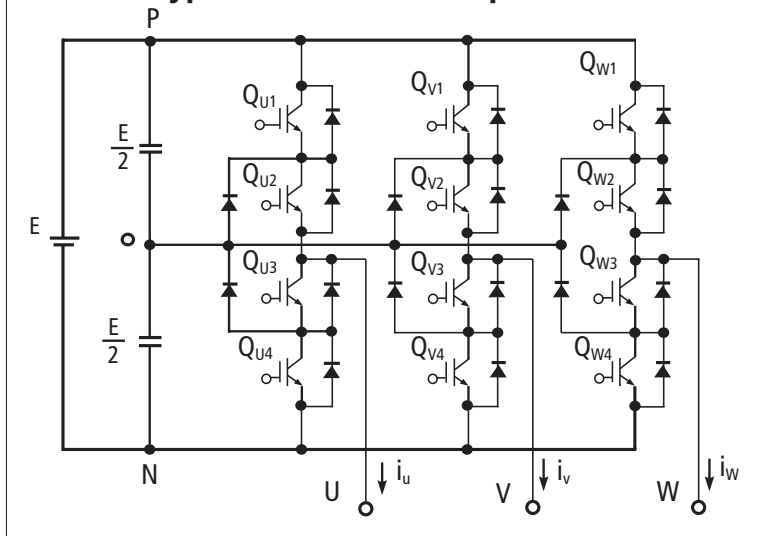


Figure 5: A three-level output section must have twice the number of IGBT output switches, plus clamping diodes.

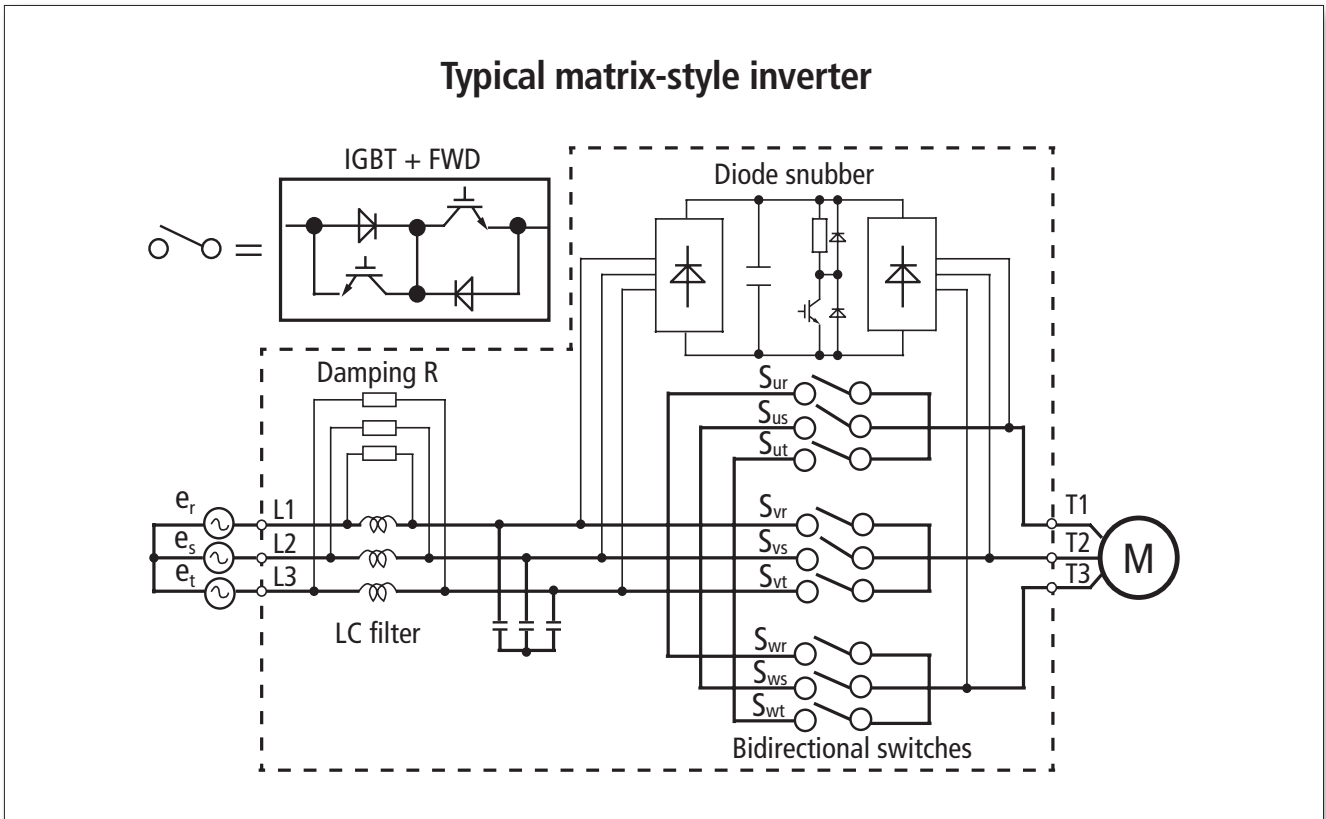


Figure 6: Instead of having a dc bus and bridge rectifier, a VFD with matrix-style inverters use bidirectional switches that can connect any of the incoming phase voltages to any of the three output phases.

making the input current waveform much less distorted and the THD much lower. The aforementioned matrix-style inverter VFD is an example of an active method of THD reduction.

Myth No. 4: You can run a motor at any speed with a VFD

The beauty of using VFDs is that they can vary both their output voltage and output frequency. Their ability to run the motor slower and faster than its nameplate-rated speed is part of why they are specified so often. Take the motor out of the equation, and this myth is actually true. Without the limitations of the motor, the VFD can easily run any frequency within its speed range without limitation. But in reality, the motor is necessary to do real work, and its cooling and power needs start to limit the actual speed range of the motor/drive combination.

Limit No. 1: From a motor cooling perspective, turning some motors too slowly is not a good idea. In particular, totally enclosed fan cooled (TEFC) motors have limitations because the fan that blows air over the motor shell is attached to the motor shaft. The slower the motor is operated, the less cooling air that goes to the motor.

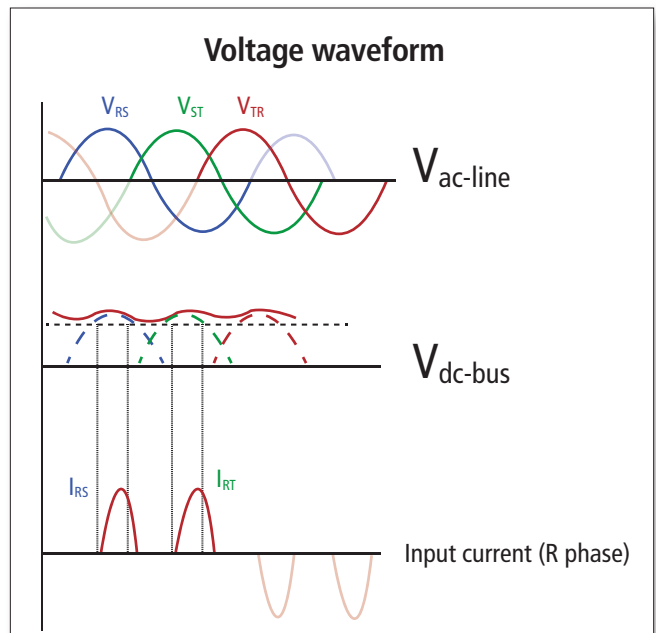


Figure 7: The diode bridge of a typical VFD produces a ripple-like voltage waveform on the dc bus. It also causes the input current to be distorted and discontinuous.

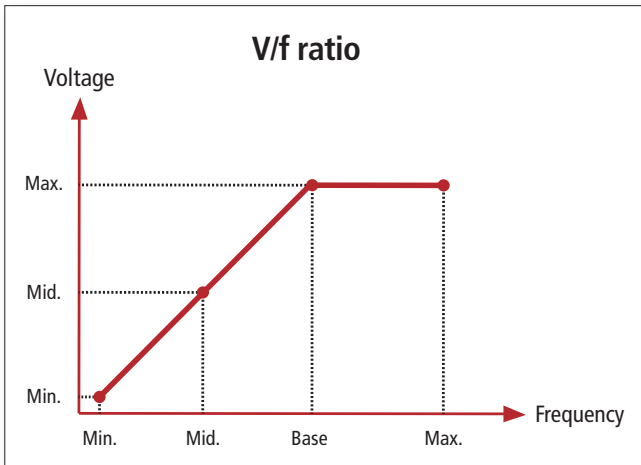


Figure 8: This graph shows the relationship between voltage and frequency and how the V/f ratio can produce constant torque within a motor.

Most motor manufacturers specify speed ranges for their motor designs that reflect how slow the motor can be run—especially while loaded. TEFC motors typically are not recommended for operation at full load below 15 Hz (a 4:1 speed range).

Limit No. 2: It is not always stated on the motor nameplate, but mechanically, motors have a speed range limitation. Commonly referred to as the maximum safe operating speed, this speed is tied to mechanical limitations, such as bearings and balance. Some motor data sheets specify the maximum speed.

Limit No. 3: Before the motor reaches its maximum operating speed, it could run out of torque. This speed limitation is not due to cooling or mechanics, but is due to power limitation, which is a product of speed and torque. To be exact, the VFD runs out of voltage. Note that the rotation of the motor also generates a voltage of its own, referred to as back-electromotive force (EMF), which increases with speed. The back-EMF is produced by the motor to oppose the supplied voltage from the VFD. At higher speeds, the VFD must supply more voltage to overcome the back-EMF so that current can still flow into the motor as current is instrumental in producing torque. After a certain point, the VFD cannot push any more current into the motor because the output voltage has reached maximum, and thus the motor torque reduces, which, in turn, reduces speed. This reduction in speed results in lower back-EMF, which, in turn, allows more current to flow into the motor again. There is an equilibrium point where the motor reaches the maximum speed for a given torque condition so that the product of torque and speed equals its power capability.

Let's take a step back. VFDs can produce constant torque from a motor by keeping the V/f constant (see Figure 8).

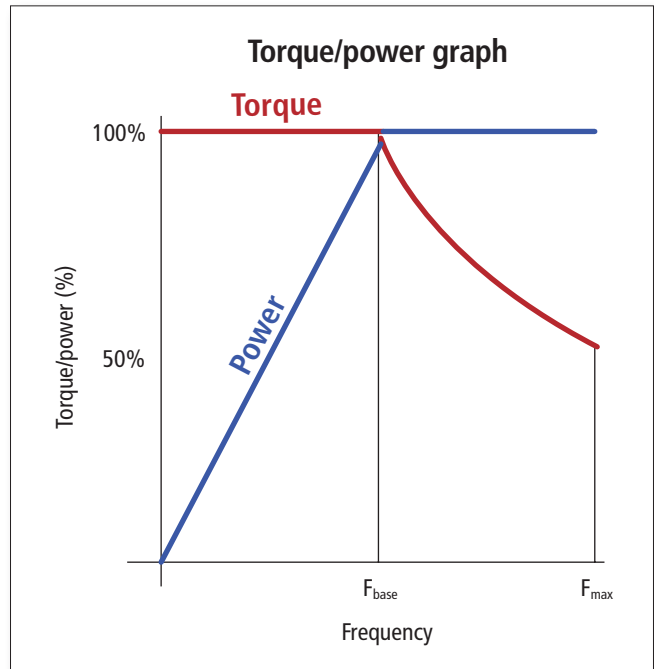


Figure 9: The ability of a motor to produce rated torque at higher than base speed declines at a rate of 1/frequency. The region of operation above base speed is called the constant power range, while operation at speeds below the base speed is called the constant torque range.

When the output frequency is increased, the voltage increases linearly. The problem arises when the frequency is raised beyond the base frequency of the motor, most commonly 60 Hz in the U.S. Beyond the base frequency, the output voltage cannot increase, which causes the V/f ratio to reduce. The V/f ratio is a measure of the magnetic field strength in the motor and reducing it reduces the torque capability of the motor. Hence, the ability to have the motor produce rated torque at higher-than-base speed must decline at a rate of 1/frequency, so that the product of torque and speed, which equals power, is constant. The region of operation above base speed is called the constant power range, while operation at speeds below the base speed is called the constant torque range (see Figure 9).

Myth No. 5: A VFD's input current should be higher than its output current

Perhaps this is not a myth but a misunderstanding. Some VFD users check their output and input currents with a current clamp meter or by using VFD display monitors and find that the input current is much lower than the output current. It doesn't seem to align with the idea that the VFD should have some losses due to its own thermal component losses, so input should always be slightly

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higher than output. The concept is correct, but it is power, not current that should be considered:

$$\frac{P_{in}}{V_{in} \times I_{in}} = \frac{P_{out}}{V_{out} \times I_{out}}$$

The voltage portion of the preceding power equation is straightforward. The input voltage is always at the ac line voltage. The output voltage varies with the speed per the V/f pattern. The current components of the equation are a bit more complex. The key to understanding current components is knowing that a typical induction motor has two current components: One is responsible for producing the magnetic field in the motor, which is necessary to rotate the motor; while the second component is the torque-producing current, which, as the name suggests, is responsible for producing torque.

The drive consumes input current proportional to the motor's active torque demand, or load. The current needed for producing the magnetic field typically does not vary with speed and is provided by the drive's main

dc bus capacitors, which are charged during power up of the VFD. Under low torque conditions, the output current may seem to be much higher than the input current because the input current mirrors only the torque-producing current plus some harmonics but does not include the magnetizing current. The magnetizing current circulates between the dc bus capacitors and the motor. Even at full load conditions, the input current will typically be lower than the motor current because the input still does not have any magnetizing current component in it.

Remember, we are balancing input and output power. For example, consider a fully loaded motor at low speed. The input voltage is at the rated line while the output voltage will be low due to the low speed. Because of the full load on the motor, output current will be high. To balance the power equation, the input current must be lower than the output current.

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