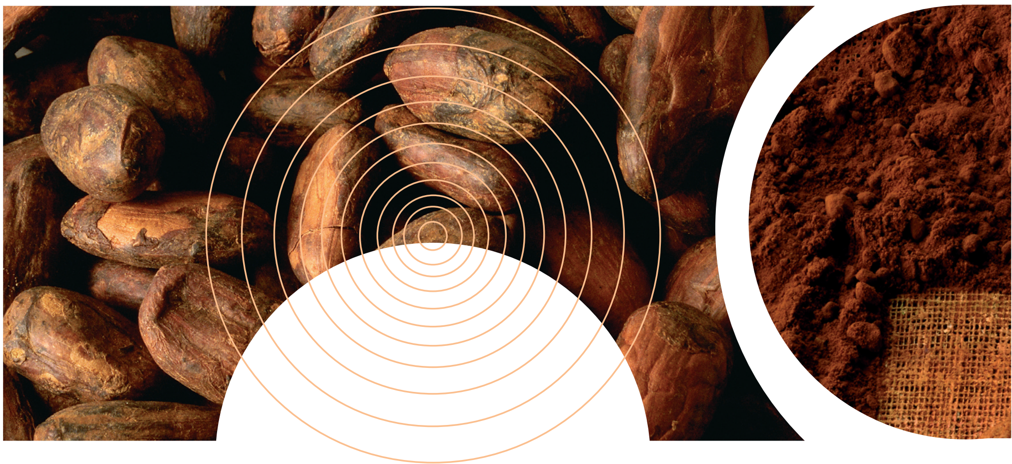
Save energy and control with



In today's climate of rising energy costs and carbon trading schemes, any technology which helps plants use energy more efficiently should be adopted. Variable speed drives offer the ability to control the speed and torque of motors in many applications while providing significant energy savings — but only if implemented correctly in the right application.

The most common type of variable speed drive (VSD) is the variable frequency drive (VFD), which is used to control the rotational speed of an AC motor by controlling the frequency of the electric power supplied to the motor. The type of motor controlled is usually a three-phase induction motor, generally designed for fixed-speed mains voltage operation. Some types of single-phase motors can be used, but generally three-phase motors are preferred.

Controlling speed and torque

Speed control

The synchronous speed of an AC motor is not dependent on voltage, but is determined by the frequency of the AC supply and the number of poles in the stator winding, according to the formula:
where:

$$RPM = \frac{120f}{p}$$

RPM = *revolutions per minute*
f = *AC supply frequency (Hz)*
p = *number of poles (an even number)*

The constant 120 is 60 seconds multiplied by two poles per pair. By varying the frequency f, the speed can be changed. For example, a 4-pole motor connected to a 50 Hz supply will have a speed of 1500 rpm. If the motor is connected to a VFD that is supplying a frequency of 30 Hz, then the speed will be 900 rpm.

Synchronous motors, which have a rotor connected to the supply via slip rings or similar technology, follow this formula exactly. Induction motors, which use a passive rotor, have a slightly lower speed, since the rotor is being propelled by a rotating magnetic field generated by the three phases and there is an inherent 'slip' due to the nature of the electromagnetic interaction between the rotor and the rotating field. Induction motors are usually favoured because of their lower complexity and safer operation in hazardous environments (lower chance of sparking).

Torque

A good way to discuss the control of torque is via an example of a variable torque load. Centrifugal pumps and fans are good examples, where the torque required to drive the load increases in proportion to the square of the speed (see Figure 1).

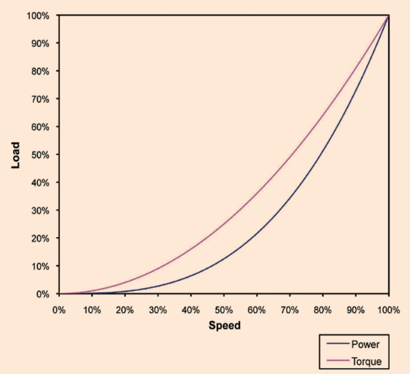


Figure 1: *Power and torque for a variable torque load.*

achieve greater variable speed drives

Glenn Johnson

The load decreases non-linearly from 100% torque at maximum speed. The torque is only 25% at half speed. Because power is proportional to torque multiplied by speed, the power is proportional to the speed cubed, so at half speed and 25% torque, the power required is only 12.5%. Operating a variable torque load at reduced speed substantially reduces energy requirements.

Without a variable speed drive, speed control of gases and liquids is performed by vanes, dampers or valves, while the motor runs at full speed. These methods restrict the flow without changing the pump speed and therefore have a lower impact on energy savings (see Figure 2).

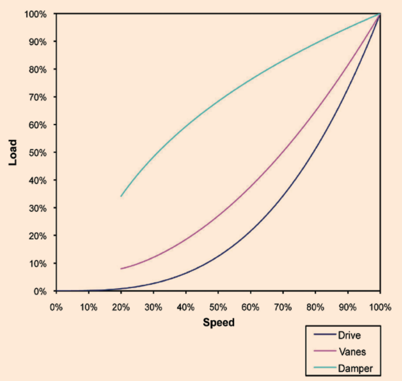


***Figure 2:** Other forms of flow control are less energy efficient.*

AC motor characteristics require that the applied voltage must be proportionally adjusted whenever frequency is changed in order to deliver the rated torque. If a motor is designed to operate at 415 V at 50 Hz, then if the frequency is reduced to 30 Hz, the voltage must be reduced to 249 V, maintaining the volts per hertz ratio at 8.3. This ratio can be changed by a VFD to change the torque delivered by the motor. The VFD therefore provides control options other than simple speed control.

Running at higher speed

Because the VFD controls the frequency of the applied voltage, it is possible to increase the speed above the synchronous speed of the motor. This can only be done where the full power of the motor is not required, because the voltage would need to be limited to the rated voltage, and the torque will be reduced. For example, a 415 V, 50 Hz, 1500 rpm motor (8.3 V/Hz) supplied with 415 V, 60 Hz, (6.917 V/Hz) would run at 1800 rpm (120% speed) with 83.33% torque.

Starting and stopping

When a motor is simply started by a switch or contactor, there is a large inrush current. Typically this can result in drawing 300% of rated current but only delivering 50% of the rated torque. As the load accelerates, the available torque drops a little further and then rises to a peak, while the current remains high, until the motor approaches full speed.

When a VFD starts a motor, it initially applies a low frequency (typically 2 Hz or less) and low voltage to the motor, and ramps up to the required speed, which avoids the drawing of excess current. It is possible to configure a VFD to maintain a steady 150% torque from standstill right up to full speed while still drawing only 150% of rated current. More torque is available to get the load moving more quickly, while consuming less energy at the same time.

The stopping sequence with a VFD is the reverse of the starting sequence, where the frequency and voltage are ramped down at a controlled rate. A small amount of braking torque allows the motor to slow quicker, and additional braking torque can be obtained by including a braking circuit to return the braking energy to the source or simply dissipate it.

Power factor correction not required

Being inductive loads, motors normally result in a non-unity power factor on the supply (usually about 0.8), with the current and voltage out of phase. The reactive component of the load the motor presents to the supply results in energy consumption that is not associated with useful work. With VFDs, because the motor supply is being completely regenerated and the VFD presents a non-reactive load to the mains supply, the power factor is unity.

How they work

The usual design of VFD controllers converts the AC mains power to DC using a rectifier bridge. The DC is then converted to a quasi-sinusoidal AC power using an inverter switching circuit (Figure 3) using insulated-gate bipolar transistors (IGBTs). The switching of the IGBTs is controlled by a microprocessor using a technique known as pulse width modulation (PWM). The output waveform is actually a series of narrow pulses with varying on/off times. A control signal varies the amplitude of the pulses and the ratio of off-time to on-time. The result is an output current that varies as a function of the pulse width, magnitude and polarity.

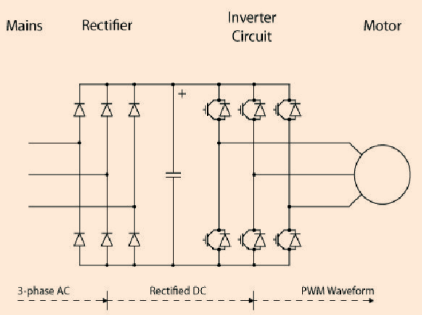


Figure 3: *VFD functional schematic.*

The speed at which the power devices pulse on and off is known as the carrier frequency, or switch frequency. Typical switch frequencies are 3 to 4 kHz, and the higher the switch frequency, the finer the resolution each PWM pulse represents. Higher switch frequencies reduce the efficiency of the drive, however, because of increased heat dissipated in the IGBTs.

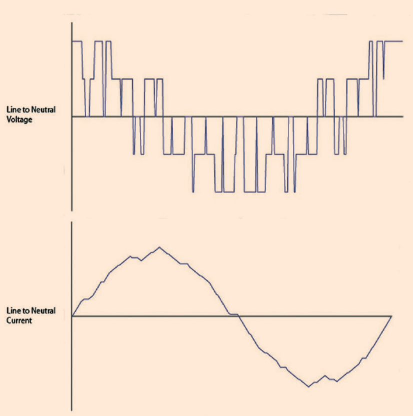


Figure 4: *Inverter output waveform.*

The benefit of this technology is that it is easy to digitally control output frequency and voltage (and therefore motor speed and torque), and the incremental steps available can be as small as the carrier frequency allows.

The downside of PWM

All is not perfect with the application of PWM inverters in drives, however, and there are a number of detrimental side effects that must be taken into account to ensure that the longevity of the motor is not severely compromised.

Bearing problems

Because the sinusoidal supply is severely distorted by the PWM switching, high frequency harmonics, high dV/dt switching transients and common mode voltages are generated. Any stray capacitance between the components of the motor become significant. They are charged up and result in an induced common mode current flowing through the motor shaft and bearings. In large motors, these currents and the associated heating are large enough to cause the breakdown of bearing lubricants and cause erosion effects resulting in bearing pits and flutes. These side effects can severely shorten the working life of a motor not designed for use with a PWM inverter drive.

Noise level

Due to the switching harmonics, motor noise level is increased when using a PWM inverter drive. It has been shown that the sound pressure level can increase by anything between 2 and 15 dbA.

Vibration

Inverter drives can cause torque ripples on the motor shaft. Even with the inverter programmed not to operate near the resonant frequency of the motor, the extra harmonics present can result in increased vibration levels, and further reduce the life of mechanical parts. Better motor rigidity and balancing is required to counteract these effects, once again making the choice of motor and drive combination important.

Insulation problems

The higher harmonics caused by inverters increase the copper and core losses in the motor windings, resulting in about 10% more current required to drive the motor at the same output than with a direct supply connection, and hence an increase in operating temperature. On average, inverter-driven motors operate about 15 °C hotter at rated speed and load. The life of a motor is approximately halved for every 10° increase above its rated insulation temperature limit.

The voltage peaks caused by fast switching can be as high as 1500 V at a rate of 5000 V/µs, occurring at a rate depending on the inverter carrier frequency. These repeated spikes can cause a gradual breakdown in the dielectric strength of the motor windings, depending on the type and thickness of insulation and the motor geometry.

Motors made with higher temperature materials, higher breakdown strength insulation and better thermal dissipation are required in order to avoid a drastic decrease in the lifespan of the motor.

Cable length

The harmonics can result in high voltage peaks on the cable between the drive and the motor due to transmission line effects. In practice, the cable length should be kept to a minimum, with 25 m being an upper limit in most cases.

What is a vector drive?

A standard VFD outputs a PWM pattern to maintain the required voltage and frequency under ideal conditions. How the motor reacts to that pattern is, however, dependent on load conditions. The standard VFD, therefore, knows nothing about the difference that may result. If the motor spins at a slightly lower speed than specified, the drive doesn't know, and therefore accurate speed and torque control may not be possible under some circumstances. This effect gets worse as the speed slows down, so if the motor is to operate at low frequencies like 10 Hz, the standard 'scalar' VFD may not do the job.

A vector drive uses feedback from the motor or its load to influence the PWM output to correct for any discrepancies. A closed loop vector drive uses a shaft encoder to measure the actual speed and feed it back directly to the microprocessor. This allows, for example, a drive to make an AC motor develop full torque at zero speed, making closed loop vector drives suitable for crane and hoist applications, where the motor must be able to hold the load when the brake is released, or else the load may drop and not be able to be stopped.

So-called open loop vector drives (also known as sensorless vector drives) use an internal mathematical model to compare with the output current of the drive. Differences in the actual current compared with the model result in corrections to maintain the expected motor behaviour. These drives can lose their ability to predict accurately what the motor is doing at low speeds and therefore are not suitable for all the same applications as closed loop vector drives.

Conclusion

Variable speed drives, particularly variable frequency drives, provide enormous opportunities to reduce energy consumption in a plant or factory and provide greater control over processes. They can also extend the range of available applications for AC induction motors, even into areas where DC motors are traditionally used, such as crane and hoist applications.

The application of VFDs in a particular application should be planned with an understanding of what is required in terms of the behaviour of the process and the type of motors to be controlled. For example, there is little point in applying a VFD where motors are required to mostly operate at rated speed or where the existing motor is not designed for operation with a VFD. Careful matching of the complete drive and motor combination to the required application is required, and in many cases existing motors may need to be replaced.