A SunCam online continuing education course

Motor Control Part 3
AC Variable Speed Drives

by

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Learning Objectives

This continuing education course is intended to provide training and education about the following topics:

1. Benefits of using AC adjustable speed drives
2. How an adjustable speed drive controls motor speed
3. The components included in an adjustable speed drive
4. How the motor load type affects drive selection, overload capabilities and energy savings
5. Options for sources of control
6. System installation considerations

Introduction

In many industrial and commercial systems, electric motors are used to transform electrical energy into mechanical energy. The speed of the system depends on the mechanical design and the mechanical loading. With a single speed motor operating at full voltage, the system will operate at one speed with some variation based on the mechanical loading. In some applications there are benefits to having the ability to dynamically change the speed of the motor.

The speed of an AC induction motor can be changed through the application of an adjustable speed drive (ASD). An ASD is an electronic package that changes the voltage and frequency applied to the motor which changes the motor speed to achieve specific system performance. An ASD may also be referred to as variable frequency drive (VFD), inverter or simply as a drive. These terms refer to the same type of equipment and are used interchangeably.

Application of VFDs can achieve one or more of the following benefits:

1. Reduced mechanical stresses
2. Improved process control
3. Energy savings

Motor & Drives - Principles of Operation

An AC induction motor produces torque and power by creating a rotating magnetic field within the motor frame. The rated synchronous base speed of the motor (N_s) is based on the number of magnetic poles designed into the motor and the system voltage frequency (f).

$$N_s = \frac{120*f}{\#\ of\ poles} \tag{1}$$

In the case of a 4-pole motor on a 60 hertz system, the base speed will be 1800 RPM. The actual speed of the motor will be approximately 3-5% lower than the synchronous speed due to slip, however this course will use synchronous speeds for simplicity.

$$N_s = \frac{120*60}{4} = 1800 \tag{2}$$

Equation (1) shows that the speed of the motor can be changed by changing the voltage frequency.

The torque (T) produced by the motor is proportional to the strength of the magnetic field (Φ) which is proportional to the ratio of voltage (V) to frequency applied to the motor.

$$T \sim \Phi \sim \frac{voltage}{frequency} \tag{3}$$

By maintaining a constant ratio of V/f, the motor will produce 100% of the motor's rated torque as the frequency is changed. This holds true for speed ranges from 10-100% of the base speed.

The power produced by an AC motor is related to torque and speed by equation (4).

$$Power\ (hp) = \frac{T\ (ft-lbs)*N\ (rpm)}{5250} \tag{4}$$

This equation can be rearranged to solve for the torque produced by the motor.

$$T\ (ft-lbs) = \frac{Power\ (hp)*5250}{N\ (rpm)} \tag{5}$$

In the case of a 100 HP, 4-pole motor on a 60 hertz system with a base speed of 1800 RPM, the torque produced will be 291.7 ft-lbs.

To maintain constant torque as the motor speed is changed, the voltage needs to be changed in proportion to the change in frequency. For this reason, AC drives are designed to control the motor with a constant ratio of voltage to frequency. This produces a linear relationship between the motor speed and the applied voltage and frequency. This relationship is called the volts per hertz ratio. For a motor rated at 460 VAC and 60 hertz, the ratio is 7.67. Other ratios are shown in Table 1.

Table 1: Voltage - Frequency Ratios

Voltage	Frequency	V/Hz Ratio
460	60	7.67
230	60	3.83
380	50	7.60
415	50	8.30

Controlling the output of the VFD using a constant V/Hz ratio is a simple method of control, however it does not provide tight speed regulation of the motor. This type of control does not account for changes in motor loading which will impact the actual speed of the motor. The linear relationship between voltage and frequency is shown in Figure 1. If the V/Hz ratio is held constant from zero to the rated speed of the motor, the motor output torque will remain constant.

This holds true for frequencies below the motor's rated frequency. When the output frequency is increased above the 60 hertz, the voltage will remain constant and equal to the system voltage since the drive cannot create more voltage than is available from the system.

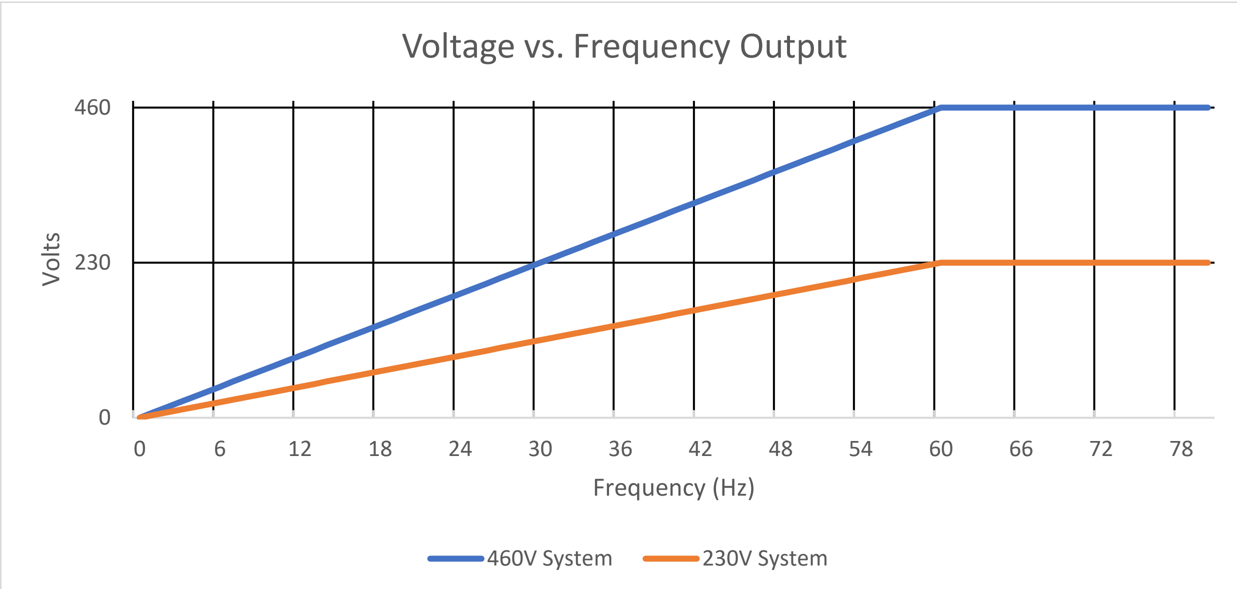

Figure 1: Voltage vs Frequency output for a VFD

As the frequency increases above the base frequency the voltage is held constant. When the voltage increases above the base frequency, (3) shows that the torque produced will decrease. In this condition, the power output will remain constant above the base speed. This relationship is shown in Figure 2. Operating above the base frequency is called the constant-horsepower range.

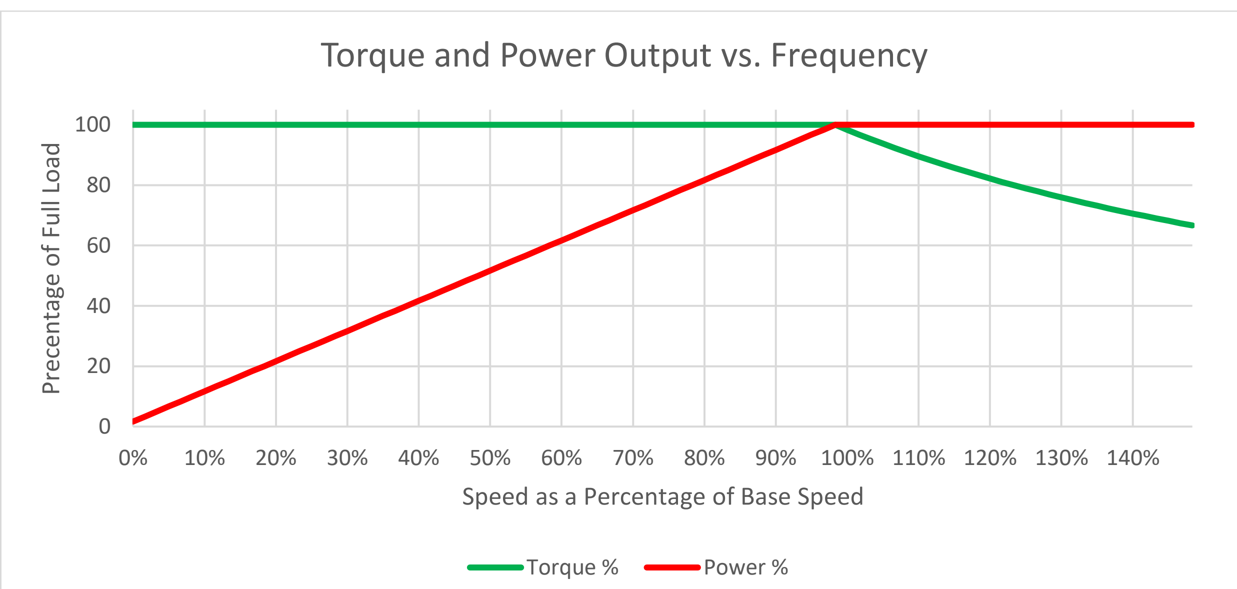

Figure 2: Torque and power produced vs speed for a motor using a VFD

Types of Loads

Motor loads can be categorized as constant horsepower, constant torque, and variable torque.

Constant Horsepower Load

Constant horsepower loads are applications where the amount of work to be done does not vary throughout the speed range. This is typical of applications that require tension control such as winders on a paper machine. In a winding application, when the diameter of the roll is small, high speed is required to maintain proper tension. As the roll is wound, the diameter and weight increase. The larger diameter requires a slower speed to maintain proper tension, while the larger roll weight requires more torque. This is shown graphically in Figure 3.

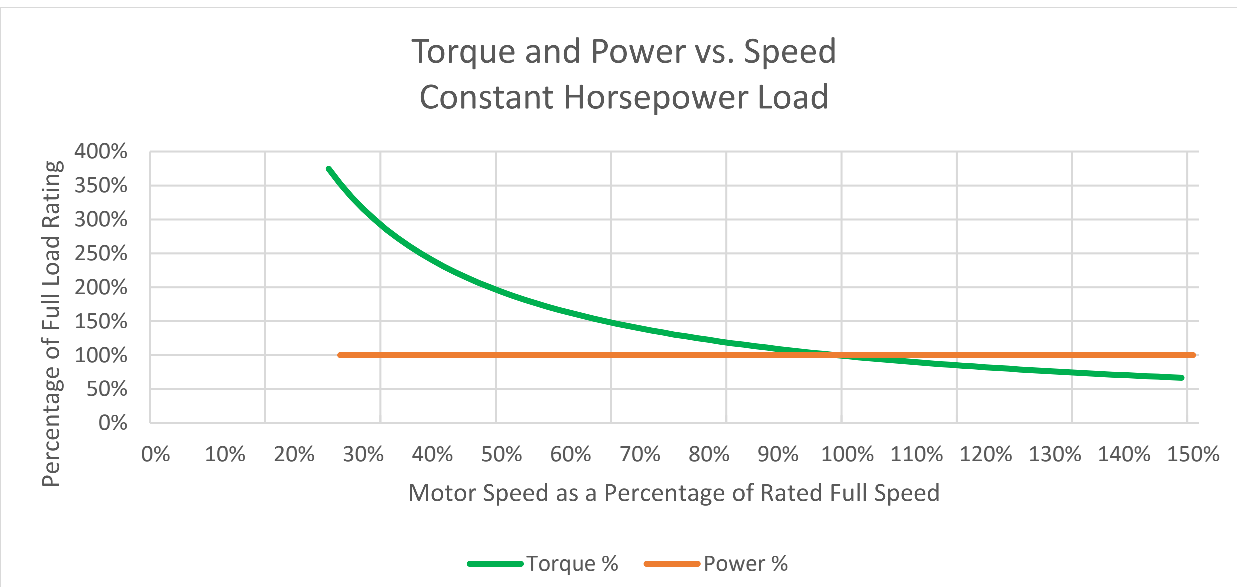

Figure 3: Torque and power vs speed required by a constant horsepower load

Constant Torque Load

Constant torque loads are characterized by a load requiring a constant amount of force throughout the speed range. This is typical for industrial loads such as conveyors. The torque and power vs speed profiles are shown in Figure 4.

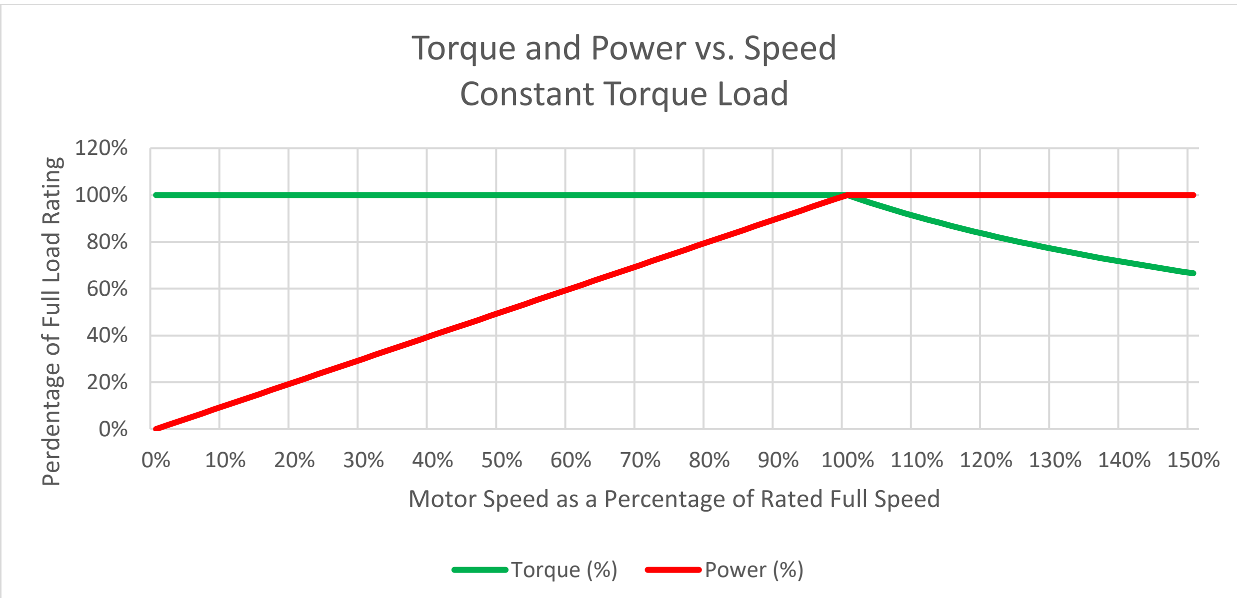

Figure 4: Torque and power vs speed required by a constant torque load

Variable Torque Load

A variable torque load is characterized by a load that requires an increasing amount of torque as the speed increases. This is typical of fans and many types of pumps. For these applications, the torque and power vs speed profiles are shown in Figure 5.

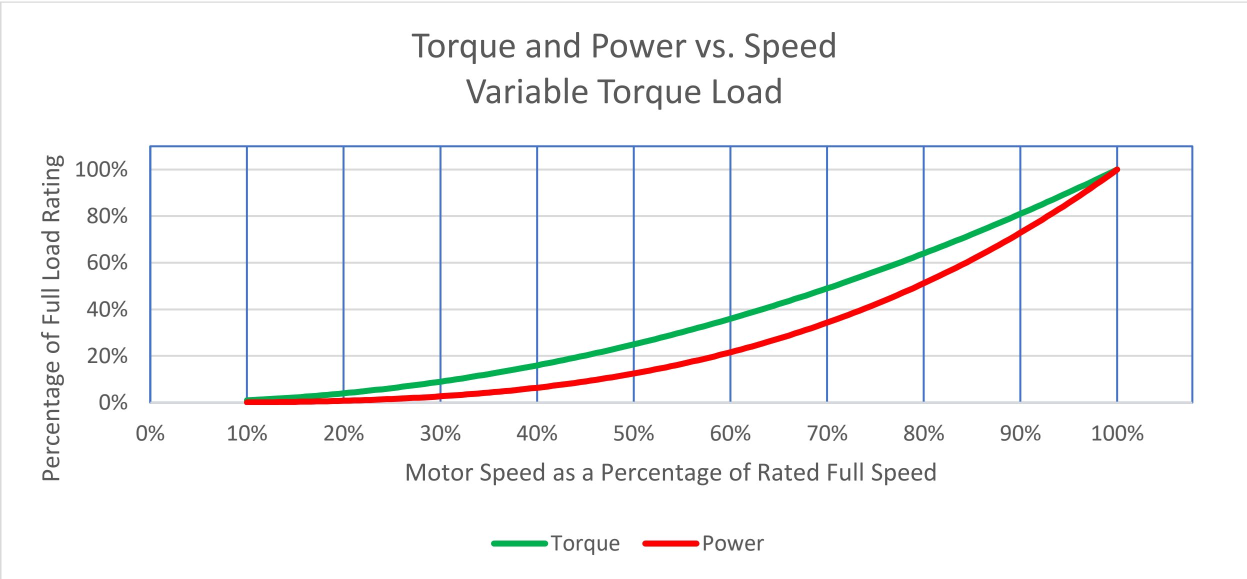

Figure 5: Torque and power vs speed required by a variable torque load

Benefits of Using AC drives

There are three primary benefits when using AC drives:

1. Reduced mechanical stresses
2. Improved process control
3. Energy savings

Mechanical stress is reduced by using the speed control of a drive to slowly increase torque, thus reducing the shock loading on the driven equipment.

Process control can be improved by matching the speed of the driven equipment with the requirement of the process. An example of this is in a chemical process when a motor is used to pump cooling water through a vessel jacket to maintain a chemical process reaction at an optimal temperature.

Controlling the cooling water can be accomplished by using a pump with a motor at full voltage and full speed and mechanical valves to reduce the flow or provide a by-pass loop. When the process temperature is below the set point the valves can reduce the flow of cooling water allowing the process temperature to increase to the required set point. When the process temperature is higher than the set point, the valve can open wider to allow more cooling water into the vessel jacket.

Applying an AC VFD in this application can provide similar process control, while providing benefits such as decreased energy usage and eliminating valves and by-pass loops that increase the installed cost and increase the operating maintenance costs. Increasing the motor speed with the VFD will increase the volume of cooling water to the process which increases the cooling capacity and lowers the temperature. Decreasing the motor speed will have the opposite effect. This can be accomplished with a temperature sensor in the process tank to provide feedback to the drive. When the process temperature feedback increases, the drive will increase the speed of the motor providing more cooling water to the jacket. By using a VFD in this application there will be energy savings when the motor is operating at less than full speed.

Energy savings can be a main driver in justifying the use of a VFD, especially in variable torque applications.

The amount of energy consumed by the motor is the amount of power produced over time.

$$\text{Energy} = \text{power} * \text{time} \tag{6}$$

$$\text{Energy} = 100\text{HP} * 0.746\ \text{kw/hp} * 1\ \text{hour} = 74.6\ \text{kwh} \tag{7}$$

When a drive is used in a constant torque application, if a 100HP motor operates at 50% speed, the power produced can be calculated using (4). Since the drive will operate with a constant volts/frequency ratio, the torque produced will be the motor's rated torque as calculated earlier.

$$Power = \frac{291.7\ ft{-}lb * 900\ rpm}{5250} = 50HP \tag{8}$$

In a constant torque application, the energy consumed by the motor is proportional to the speed of the motor. This was shown by the power curve in Figure 4.

There is a greater energy savings benefit when applying a drive on a variable torque load because of the affinity laws. The affinity laws describe the relationship of values for pump and fan performance. These laws state that the torque required by this load is proportional to the square of the speed (T ~ N^2) and that the power required is proportional to the cube of the speed (Power ~ N^3). This is shown graphically in Figure 6.

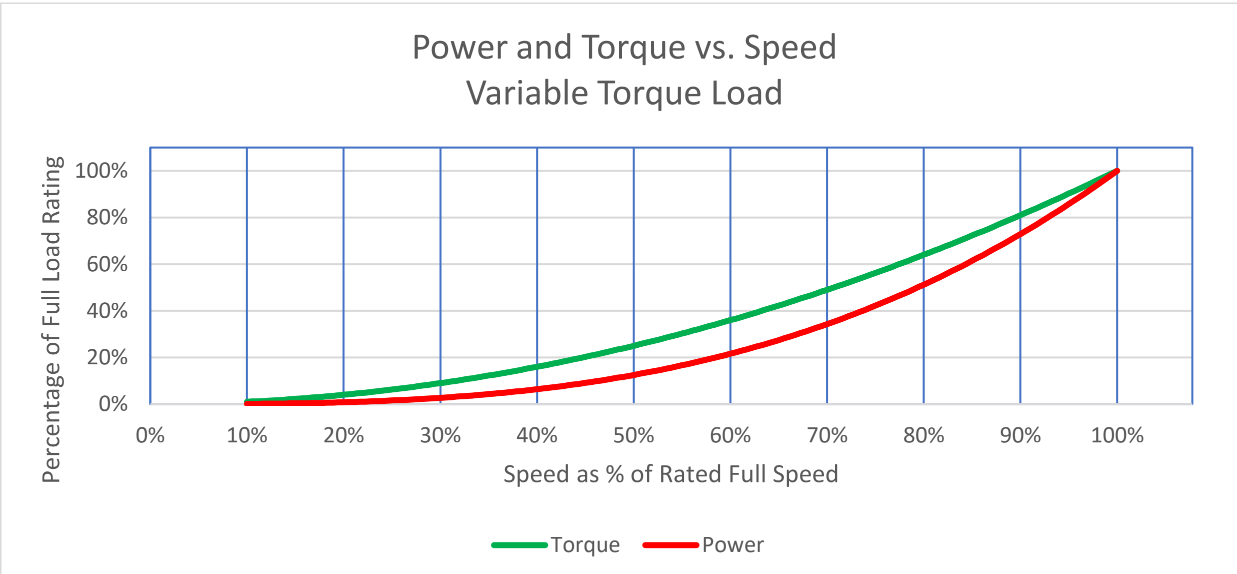

Figure 6: Torque and power vs speed for a variable torque load

Make note of the distinction between the torque and power that can be produced by the motor, and the torque and power required by the load. The motor can produce 100% of the rated torque from 10-100% of the base speed. The load requires less torque as the speed is reduced from 100% of rated speed. By application of a drive, the output of the motor can match the lower torque required by the load which reduces the power and energy consumed.

From the earlier calculation for a 100hp, 4-pole motor on a 60 hertz system, the rated full load torque is 291.7 ft-lbs. When a drive is applied to a variable torque load and the speed is set at 50%, the torque required by the load is 73 ft-lbs., which is 25% of the full load torque.

$$T_{load} = T_{full\ load} * \left(\frac{N}{N_s}\right)^2 \qquad (9)$$

$$T_{load} = 292 * \left(\frac{900}{1800}\right)^2 = 73\ ft\ lbs \qquad (10)$$

The power required by the load at the 50% speed setting is 12.5% of the full load rated power.

$$P_{load} = P_{full\ load} * (\frac{N}{N_s})^3 \quad (11)$$

$$P_{50\%} = 100 * (\frac{900}{1800})^3 = 12.5\ hp \quad (12)$$

When applying a drive, the energy savings can be calculated by estimating the expected load profile of the application and calculating the load power requirements for each time frame. This energy consumption can then be compared to the energy consumed if the motor is running at full speed 100% of the time. Figure 7 shows the load profile for a cooling water pump through the course of one day.

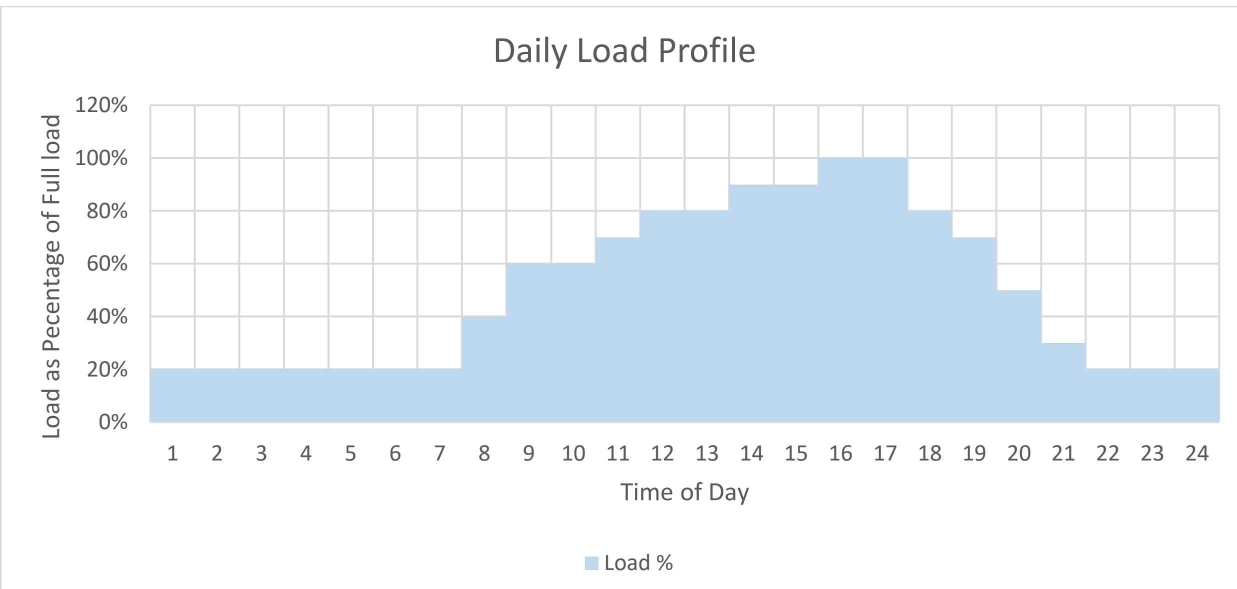

Figure 7: Load profile for a cooling water pump

The power required by the load at various speeds is calculated for a variable torque load using (11) and a constant torque load using (8) and is shown in Table 2. The energy consumed per hour is calculated using (13), assuming 1hp = 0.746kw of energy consumed.

$$Energy\ consumed\ per\ hour\ (kw/h) = Power\ (hp) * 0.746\ (\frac{kw}{hp}) \quad (13)$$

Table 2: Power and Energy Consumption for Variable and Constant Toque Loads

Speed	VT Load Power (hp)	VT Load Energy Per Hour (kwh)	CT Load Power (hp)	CT Load Energy Per Hour (kwh)
0%	0	0.0	0	0.0
10%	0	0.0	10	7.5
20%	1	0.8	20	15.0
30%	3	2.3	30	22.4
40%	6	4.5	40	29.9
50%	13	9.7	50	37.3
60%	22	16.5	60	44.8
70%	34	25.4	70	52.3
80%	51	38.1	80	59.7
90%	73	54.5	90	67.2
100%	100	74.6	100	74.6

The energy consumed during each hour of the day based on the load profile in figure 7 is shown in Table 3. The energy consumed by the variable torque load for one day is 480.8 kwh and 896.5 kwh for a constant torque load. If the motor were running 24 hours per day, the motor would consume 1,790 kwh. This demonstrates that there is greater energy savings when applying a drive on a variable torque load compared to a constant torque load for the same load profile.

Table 3: Energy Consumption for load profile in Figure 7

Time	VT Energy (kwh)	CT Energy (kwh)
1	0.8	15
2	0.8	15
3	0.8	15
4	0.8	15
5	0.8	15
6	0.8	15
7	0.8	15
8	4.5	29.9
9	16.5	44.8
10	16.5	44.8
11	25.4	52.3
12	38.1	59.7
13	38.1	59.7
14	54.5	67.2
15	54.5	67.2
16	74.6	74.6
17	74.6	74.6
18	38.1	59.7
19	25.4	52.3
20	9.7	37.3
21	2.3	22.4
22	0.8	15
23	0.8	15
24	0.8	15
Total	480.8 kwh	896.5 kwh

Variable Speed Drive Technology

The most common drive technology for low voltage drive application is a voltage source inverter using pulse width modulation. The main parts of this type of drive are the converter, DC link and inverter section shown in Figure 8. Input line power is connected to L1, L2 and L3. The motor is connected to the VFD output on U, V and W.

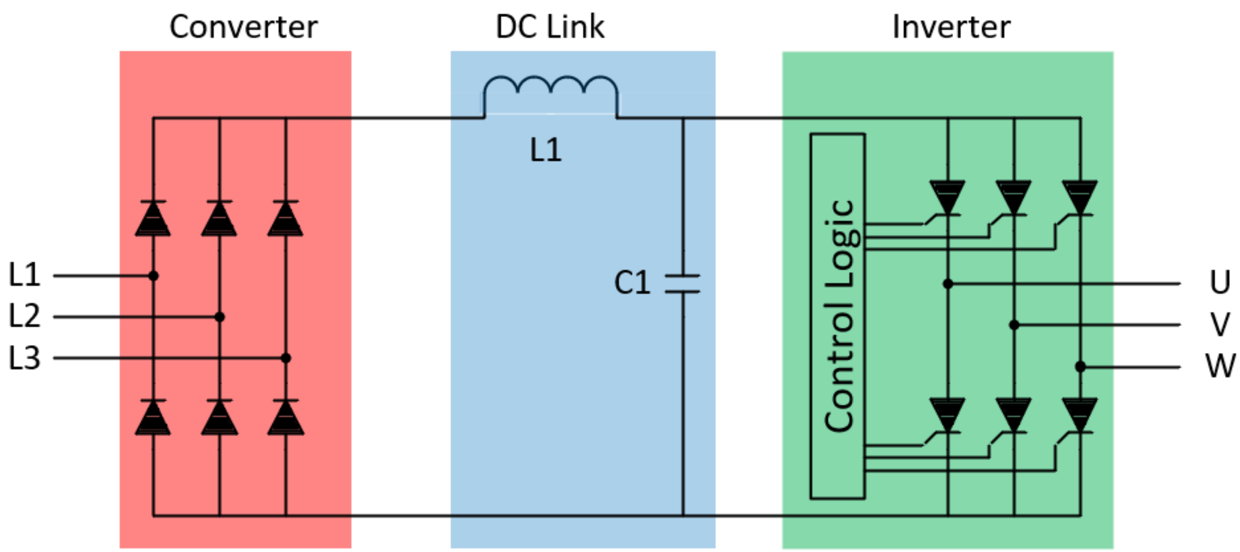

Figure 8: Components of a voltage source inverter

Converter Section

The converter section is also referred to as the “front end” of the drive. The basic converter section is a 3-phase diode bridge rectifier that converts the AC input voltage to a DC bus voltage. The DC voltage will be 1.35 times the incoming system voltage. For a 480VAC system, this will be 648VDC. This type of rectifier is called a 6-pulse rectifier because it uses six diodes, 2 in each of the three phases. This type of rectifier creates some harmonic distortion on the input system. Distortion is created in the voltage and current waveforms which has detrimental effects on the system.

There are ways to reduce harmonics. One way is to add a passive or active filter at the input to the drive. There are also optional rectifier designs that reduce the level of harmonics produced on the system.

Multiple 6-pulse rectifiers can be used which will reduce the total harmonics in the system. Harmonics are reduced because using multiple 6-pulse rectifiers shift the input phases, resulting in harmonics that cancel each other out. If two 6-pusle rectifiers are used, it is called a 12-pulse rectifier. Similarly, there are 18-pulse and 24-pulse rectifiers used in drives. Adding rectifiers to the converter section increases the physical size and cost of the drive.

Another option to reduce harmonics is to use transistors in place of the diodes in the rectifiers. Because transistors can be turned on and off to control the flow of current, this design is called an active front end (AFE). Circuitry is used to control the current waveform to reduce the harmonic distortion. The AFE manages the lower order harmonics. The fast switching of these input transistors creates some higher order harmonics which are addressed by adding an LCL filter. An AFE front end provides two other benefits: higher power factor and the ability to handle regenerative power.

Regenerative power is power created by a load that has inertia which drives the motor faster than the intended output of the VFD. When this happens, the motor acts as a generator which causes power to flow back into the VFD. This power flow raises the DC bus voltage. If this high DC voltage is not controlled, it will cause the drive to shut down with a "high DC bus" fault. The AFE can be used to allow power flow from the DC bus back into the electrical distribution system. This will reduce the DC bus voltage avoiding this type of fault and reducing the total energy consumed from the utility at the site.

DC Link Section

The DC link section includes an inductive choke and capacitance to manage the charging of the DC bus and to smooth the DC voltage. The DC link section has circuitry to derive low voltage values to be used for control within the drive and to interface to outside control signals.

Inverter Section

The inverter section consists of six power switching devices. While thyristors and bipolar transistors have been used for this function, currently the most commonly used switching device is an insulated gate bipolar transistor (IGBT). IGBTs are used because of their high efficiency and fast switching capabilities. The rate at which the IGBTs switch is called the carrier frequency or pulse frequency.

The microprocessor in the drive switches the IGBTs on and off to create a variable voltage and frequency output to the motor. This control methodology is called pulse width modulation (PWM).

PWM Output

When the inverter output section turns on and off, it creates a square wave output with a magnitude equal to the DC voltage of the DC link section of the drive. Because the motor coils are inductors, the current in the motor does not rise instantaneously but rises more slowly. A simplified profile of the output pulses and motor waveform are in Figure 9. This example shows the PWM pulse output with a square wave magnitude of 632V and a resulting AC waveform with an RMS value of 100% of the system voltage and a frequency of 60 Hz.

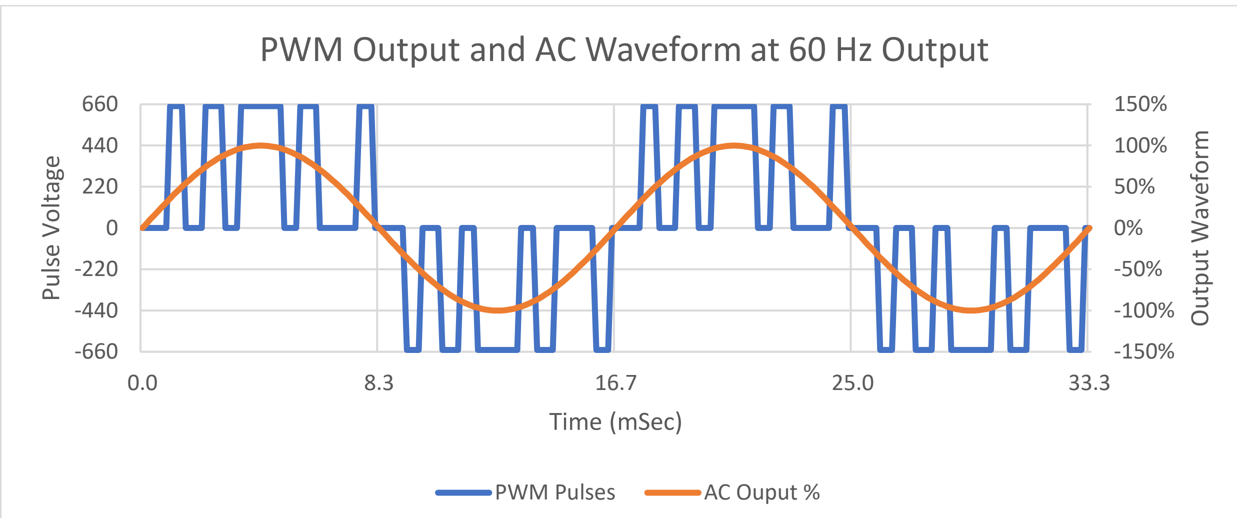

Figure 9: AC VFD pulse output and AC waveform

Reducing the width of the pulse will reduce the rate of rise of the AC waveform. By modulating the width of the pulses, the AC waveform can be controlled in term of its peak value and its frequency. Controlling the drive output to be 50% of the full rating will use more narrow pulses and will use positive pulses over a longer period of time to have an AC frequency that is 50% of the system frequency as shown in Figure 10.

The PWM control allows the drive to maintain the constant V/Hz ratio that was described earlier to provide constant torque below the base speed of the motor.

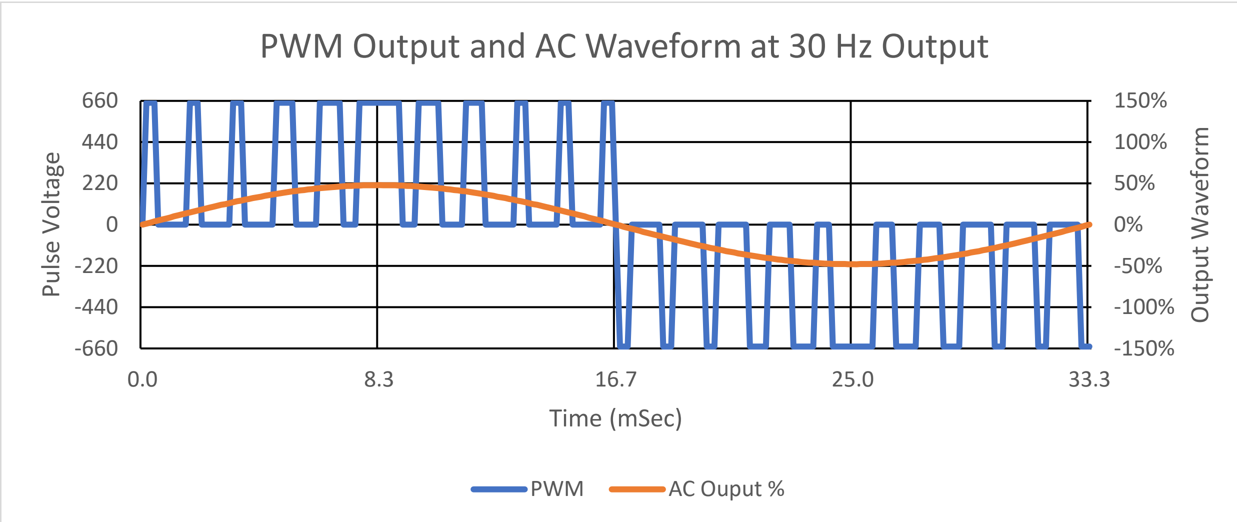

Figure 10: AC VFD pulse outputs and AC waveform

Vector Control

As stated earlier, using constant V/Hz output does not provide the tightest speed regulation. It also does not provide full torque at low speed because at low speeds a higher proportion of the current is creating the magnetic field rather than creating torque.

Vector control is a different control algorithm that provides tighter speed regulation, higher starting torque and increased torque at low speed compared to constant V/Hz control. Vector control is also referred to as flux vector control or field-oriented control. These are different terms used to describe the same control algorithm.

The motor current can be divided into two components, the magnetizing current and the torque producing current. The magnetizing current creates the magnetizing flux and lags the voltage by 90-degrees. The torque producing current is in-phase with the voltage. The vector control strategy controls these two currents independently. This allows vector control to provide torque at low speed. The drive measures the current output and uses a mathematical model of the motor operating parameters to change its output to provide tighter speed and torque control.

The type of control described here is also referred to as sensorless vector control or open-loop vector control. This refers to the fact that there is no external feedback device such as an encoder providing feedback to the drive. Open-loop vector control provides good speed and torque control from 6 – 60 Hz.

If an encoder is used to provide feedback, the system is referred to as closed-loop vector control. Types of encoders include analog or digital and incremental or absolute. For speed control, an analog or digital incremental encoder can be used. An absolute encoder will provide the exact rotational position of the motor shaft which is useful in a positioning application. Using an encoder will allow a vector control drive to produce 100% of rated torque from 0 – 60 Hz.

Drive Selection

Selection of a VFD is based on the motor horsepower rating, full-load current rating and the type of load the motor is driving.

Application Type and Overload

Understanding the type of load that the motor will be driving impacts the VFD overload rating selection. It is common for a manufacturer to list two ratings for each drive based on the VFD overload capacity.

For a variable torque application, the motor horsepower rating is typically selected so that the normal load on the motor is below the full power rating, and any anticipated overload conditions are at or below the full power rating of the motor. The reason for these design parameters is that the load profile increases quadratically. This increases the power requirement on the motor and drive system exponentially above the base rating. Manufacturers typically provide rating tables labeled for variable torque loads, normal duty or light overload for this type of load, which refers to drives that have an overload rating of 110% of the base rating for 60 seconds.

Constant torque applications exhibit a linear relationship when in an overload condition. Manufacturers typically provide rating tables labeled for constant torque loads, heavy duty or high overload for this type of load, which refers to drives that have an overload rating of 150% of the base rating for 60 seconds.

The specific terminology used by each manufacturer should be clear enough to differentiate between the two tables. It will also provide the percentage overload capabilities of ratings shown in each table.

Drives as a Current Rated Device

As stated above, it is common for a single drive part number to have ratings for both variable torque application and constant torque application. An example of the multiple ratings for a drive are shown in Table 4. This dual labeling is best understood when you consider the drive as a current rated device.

Table 4: VFD overload ratings for variable torque and constant torque loads

Application	Variable Torque (VT)	Constant Torque (CT)
Description	Normal Duty	Heavy Duty
HP	100	75
KW	75	55
Continuous output current (A)	145	106
Overload for 60 seconds	110%	150%

Calculating the overload current capability, the variable torque rating is 145A * 110% = 159.5A. The constant torque overload rating is 106A * 150% = 159A. This demonstrates that the drive is capable of 159A of output current for 60 seconds. The difference in the base HP rating depends on the percentage overload rating to be applied.

Another reason to consider drives as a current rated device is because the manufacturer's catalog data provides horsepower ratings based on a motor full load current that is "typical" for the 4-pole NEMA design B motor. Table 5 shows the full load current rating for various motor horsepower ratings and speeds.

Table 5: Full Load Current for 75HP and 100HP Motors

HP	Speed	Full load Current (A)
75	3600	80.7
75	1800	84.9
75	900	89.3
100	3600	110
100	1800	112
100	900	125

For the 100HP, 1800RPM motor, a 110% overload condition in a variable torque application will require 112A * 110% = 123A. The drive in the previous example is capable of 159.5A for 1 minute in the variable torque application. When applying this drive-motor combination there is additional margin between the current required by the motor under a 110% overload and the maximum overload rating of the drive.

For the 75HP, 1800RPM motor, a 150% overload in a constant torque application will require 84.9A * 150% = 127A. This condition also has additional margin between the 150% overload on the motor and the maximum overload rating of the drive.

Control sources – Inputs and outputs

When designing systems with AC drives, there are several options for the source of the control signals. There are three main potential sources of control:

1. Digital and analog inputs and outputs
2. Operator panel
3. Serial communication

Figure 11 shows a typical layout of the terminals of a VFD. The digital input terminals are designated as “DI x” along with the internally generated 24V power for these inputs. The digital outputs are designated as DO. These are shown as form-C contacts with one normally open and one normally closed contact. The analog input is as “AI 1” along with the terminals for +10V and ground. The serial input connection is shown as the RS-485 block with P+ and N-, although the physical connection on the drive may be a D-shell connector or RJ-45 connector.

This figure also shows the power terminals as L1, L2 and L3 for the incoming power and U, V, W for the connections to the motor.

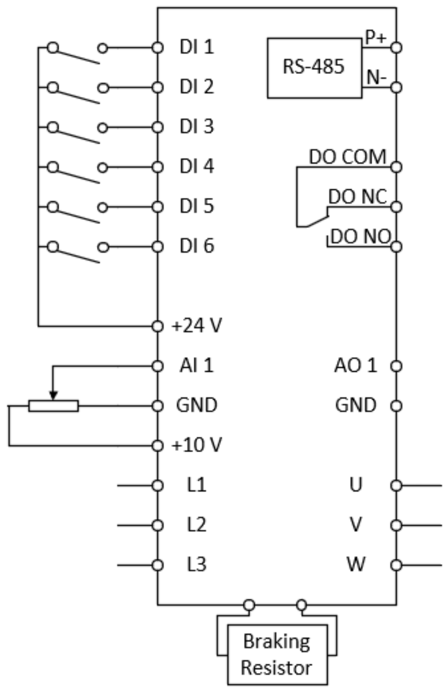

Figure 11: AC Variable Frequency drive input and output terminals

Digital and Analog Inputs & Outputs for Control

Drives have a series of terminals for digital and analog inputs. The drive will have an internal 24VDC power supply that will be used to provide the signal power for these inputs. Each input terminal can be wired to a separate control element, such as a pushbutton or process sensor. The digital inputs can be used for START, STOP, FORWARD/REVERSE, JOG, preset speed, or other possible functions that the manufacturer allows. Consult the manufacturer's documentation for more details regarding programming of each input to a specific function.

The analog input can be used as the speed reference / set point. This circuit is powered by the drive's internal power supply and can typically be configured as a DC voltage signal or a milli-ampere (mA) signal. Typical options for the voltage input range are listed in Table 6.

Table 6: Analog input signal value ranges

Signal	Min	Max
VDC	-10VDC	10VDC
VDC	0VDC	10VDC
mA	0mA	20mA
mA	4mA	20mA

The analog input speed refence will be scaled in the drive by programming parameters for the minimum and maximum speed setpoint. The min and max parameters will be associated with the minimum and maximum input signal. The drive will calculate the scale factor to apply to the input signal across the full range of the input values.

Operator Panel Control for Control

Most drives can be supplied with an operator control panel mounted on the front of the drive or mounted on the outside of an enclosure. They will typically have the following buttons and display:

LCD or LED display - This may be a single or multi-line display that is used to display drive parameters during programming or to show status of the drive during operation.

START button - This button may be identified as green, the word ON, START, RUN, or “1”.

STOP button - This button may be identified as red, the word OFF, STOP or “0”.

Forward/Reverse button - This button may be identified by the words FWD/REV or arrows pointing to the right and left.

Jog button - This button may be identified by the word JOG.

Parameter button - This button may be identified by PARAM, “P” or some other variant of the word “parameter”.

Up and down arrow buttons – These buttons may be used to scroll through a parameter list, change parameters during set up or change setpoints during operation.

During the setup of the drive, the parameter for the source of control will be set to get the control sources from the operator panel. In this case the drive will ignore any signals wired to the digital and analog terminal inputs.

When the START button on the operator panel is pressed, the drive will start at a predetermined speed that was programmed during set up. The output of the drive will follow the programmed Ramp Up Rate until the initial speed set point is reached.

Once the drive reaches the initial speed set point, the operator panel can be used to change the speed setpoint by using the UP and DOWN arrows. This function is commonly referred to as a simulated motor operated potentiometer (MOP). An MOP is a mechanical device that uses a motor to rotate a potentiometer. The motor rotates the potentiometer in either direction using pushbutton inputs. This functionality is simulated using the internal circuits of the drive to change the speed reference.

Communications for Control

Digital communications can be used to send commands to a drive from an automation system and for the drive to send status information back to the automation system. Drives may have the capability of using more than one type of communication that can be selected for control. When selecting a communications protocol, you should be aware of the differences between the selection of the physical connection and the communication protocol.

The physical connection describes physical attributes of the connection between the automation system (master) and the drive (slave). There are industry standards established to enhance interoperability of communication network devices.

RS-232 is a serial communication standard developed in the 1960's. This standard defines the electrical characteristics of the cabling, how signals are transmitted, and the physical characteristics of device connectors. RS-232 is a point-to-point communication standard between one master and one slave device, such as a PC and a printer. The point-to-point characteristic does not allow for multiple drives on a single RS-232 communication network and therefore is not used for drive control.

RS-485 is a serial communication standard that can be used to connect multiple slave devices to one master device in a multi-drop daisy-chain network. This network topology makes it more useful in industrial networks for control of drives. The physical specification for RS-485 defines a 2-wire system for half-duplex communication and a 4-wire system for full-duplex communications. Refer to the manufacturer's manual for the specific RS-485 standard that has been implemented.

Ethernet is a communication network standard that is defined by the Institute of Electrical and Electronic Engineers (IEEE) in standard IEEE 802.3 for a wired communication network using packets. The physical connection is typically an RJ-45 connector. This is a higher speed network compared to RS-485.

Installation Considerations

When planning and designing systems using AC variable speed drives there are several criteria that deserve attention.

Harmonics

Drives create harmonics on the electrical system they are connected to because of the nonlinear nature of the electronics in the converter section. Of the converter section designs described earlier, the 6-pulse design causes the most harmonics. The 12-pulse, 18-pulse and active front-end have lower harmonics. The harmonic content causes distortion of the voltage and current waveform which can cause problems.

Problems caused by the waveform distortion are:

- Efficiency loss in transmission and distribution
- Failures in VAR compensation systems
- Overheating in electrical motors and transformers
- Failures in sensitive electronic devices
- Electrical stress or failure of insulation systems
- Increased losses in the system that reduce electrical efficiency
- Nuisance tripping of protective devices

Whether the amount of harmonics caused by a drive applied in a system will cause problems depends on several factors including the size and quantity of drives relative to the rest of the system, what other non-linear loads are on the system and size of the utility service transformer. IEEE 519 is a standard proving recommendations regarding acceptable levels of voltage and current harmonic content in an electrical distribution system. The level of harmonic distortion is measured at the point of common coupling (PCC), which is the closest point on the utility side of the customer's service where another utility customer could be supplied.

Many project specifications will include a section requiring compliance with IEEE 519 recommendations and include requirements to provide testing to verify compliance.

Load cable distances

Long motor cables, greater than 300 feet from the output of the drive to the motor terminal, have the potential to cause problems. The potential problems are caused by the different impedance of the long cable. The output of a PWM drive is a series of square pulse outputs, but these are not perfectly square pulses. The rise time of the leading edge has the potential to create a reflected voltage wave which can be added to the initial voltage. This can create a voltage spike that is higher than the system voltage and higher than the motor’s insulation rating.

The problems can be described by the rate of change of the voltage (dv/dt) and the peak of the initial voltage plus the added reflected wave. Typical limits for a nominal 480VAC system are a maximum voltage of 1000VAC and dv/dt limit of 500V/µ second.

If an installation will have cables greater than 300 feet, the drive manufacturer should be consulted about their recommendation regarding whether this is a problem and how to address the issue. One common solution is to add inductors or reactors at the output of the drive. The added inductance will reduce the voltage rise time (dv/dt) which can reduce the reflected wave. A second solution is to add a filter at the output of the drive. The filter will add inductance, resistance, and capacitance. They may be referred to as LRC filters, dv/dt filers or sinusoidal filters. Drive manufacturers can provide guidance on proper installation based on the project specific requirements.

Motor selection / specification

Some standard motors may be used with drives depending on the specific installation, load, and performance requirements. The National Electrical Manufacturers' Association (NEMA) publishes standard MG-1, which is a standard to assist users in the proper selection and application of motors and generators. Part 31 of this standard applies to definite purpose inverter-fed AC motors.

NEMA MG1 Part 31 requires motor insulation systems for 460V rated motors to be capable of withstanding a peak voltage of 1,600 volts. This is required to handle the possible added reflected wave discussed above.

A motor's ability to operate within its defined temperature condition will vary depending on the type of load and the operating speed range.

For a constant torque load, as the speed is reduced the power requirements will be reduced in a linear relationship with the speed reduction. With this reduced power requirement, the motor will generate less heat than when the motor is running at rated speed and full power load. For a variable torque load, as the speed is reduced the power requirement will be reduced by the square of the speed reduction. For this reason, the motor with a variable torque load will generate less heat than with a constant torque load for the same speed reduction.

The other factor in maintaining proper operating temperatures is that for a total-enclosed fan cooled (TEFC) motor, the cooling fan is connected to the motor shaft. As the motor speed is reduced, the cooling fan speed will also be reduced creating less air flow across the motor for cooling. The lower volume of cooling air results in the commonly acceptable speed ranges for TEFC inverter rated motors in Table 7.

Table 7: Motor Speed Ranges for TEFC Motors

Load	Speed range
Variable Torque	10:1
Constant Torque	4:1

If an application requires a wider speed range than shown in Table 7, a motor can be specified with a separately powered fan. This type of motor will have a fan mounted on the non-drive end of the motor that will be powered by a separate power circuit. This fan will run at a constant speed and maintain full air flow across the motor regardless of the speed of the motor.

Audible sound

The carrier frequency of the output IGBTs is typically 2 – 4 kHz. In this range, drives may create an audible sound caused by the switching of the output IGBTs which may not be acceptable in some applications. Changing the carrier frequency will impact the audible noise, heat generation and drive efficiency. Drive current ratings are based on their default switching frequency in the 2-4 kHz range.

A solution to nuisance audible noise is to increase the switching frequency to a point that is inaudible or to a level lower than other ambient noises. Many drives can have the switching frequency changed up to 16 kHz. As the carrier frequency is increased the heat generated by the drive will increase and the internal losses will increase (reducing efficiency). A result of these effects is a reduction in the output capability of the drive. Typical derating of the drive due to increased carrier frequency is shown in Figure 12.

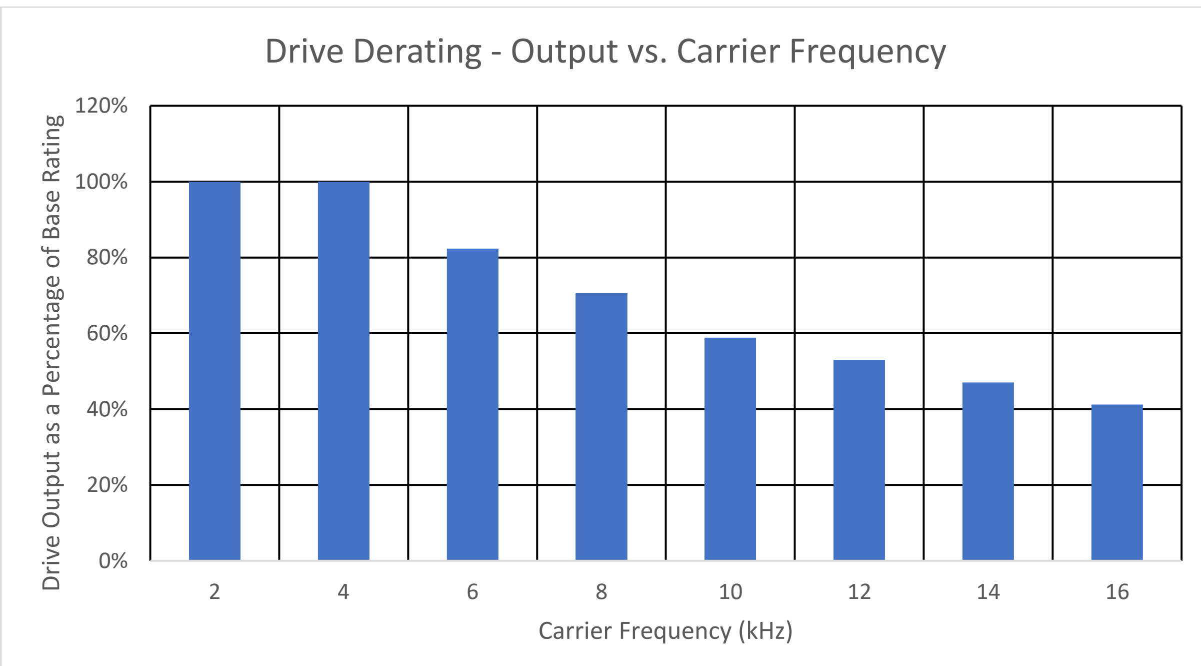

Figure 12: Drive output deratings vs carrier frequencies

Other Installation Considerations

Other installation considerations that may require derating are:

1. Ambient temperature – typical range with no derating -10°C to +40°C
2. Installation altitude – typical range with no derating 0 – 1000m above sea level

Consult manufacture's documentation for their specific normal operating ranges and derating tables. The derating table may vary between manufacturers and across their product ranges.

Bringing it all together

AC adjustable speed drives can provide several benefits. The ability to achieve the specific benefits depends on the type of load to which the drive and motor are connected.

Although all drives contain the same three main components (converter, DC link, inverter), drive selection depends on the system installation requirements. Additional components may be needed at the input or output of the drive to have a reliable, high-quality system. Installation considerations should include harmonic distortion, motor selection, motor cable length and ambient conditions. The methods to address these conditions may differ slightly between manufacturers, so their installation guide should be consulted to ensure a reliable system.

