Drive Operations

Reference Manual

AC Drives & Motors

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Reference Manual:

The illustrations, charts and examples given in this manual are intended solely to illustrate the theory and application of drive technology. Because of the many variables and requirements of applications, ABB Drive Operations cannot assume responsibility or liability for actual use based on the content of this manual.

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Terms and Definitions

AC Contactor

This contactor is designed for the specific purpose of establish or interrupting AC power circuit.

AC Drive

An electronic device that converts a fixed frequency and voltage to an adjustable frequency and AC voltage source. It controls the speed, torque, horsepower and direction of an AC motor.

A / D Converter

A device that converts an analog signal (continuous values of voltage or current, i.e. sinewave) to a digital number.

ANSI (American National Standards Institute)

An association formed by industry and the U.S. Government to produce and disseminate drafting and manufacturing standards that are acceptable to and used by a majority of companies and the government.

ASCII

Acronym for American Standards Code for Information Interchange. Basically, it is a 7-bit code with an optional parity bit used to represent alphanumerics, punctuation marks and control code characters.

Adjustable Speed

Varying the speed of a motor, either manually or automatically. The desired operating speed (set speed) is relatively constant regardless of load.

Adjustable Speed Drive (Electrical)

An adjustable speed drive is comprised of the motor, drive controller and operator's controls (either manual or automatic).

Ambient Temperature

The temperature of air, water or a surrounding medium where equipment is operated or stored.

Analog Communications

Transfer of information by means of a continuously variable quantity, such as the voltage produced by a strain gauge or air pressure in a pneumatic line.

Analog Device

Apparatus that measures continuous information (e.g., voltage, temperature). The measured analog signal can take an infinite number of possible values. The only limitation on resolution is the accuracy of the device.

Analog Input (AI)

An analog input is an input for the user-supplied DC signal. The signal may be a speed reference or a process feedback. This signal can be from:

Manual speed pot

DC voltage (0 to 10 VDC)

DC current (0 to 20 mADC)

For most ABB AC drives, analog inputs on the Keypad Display are abbreviated AI.

Analog Input Module

An I/O module which converts an analog signal from an analog measuring device which may be processed by the processor.

Analog Output Module

An I/O module which converts a digital signal from the processor into an analog output signal for use by a user analog device.

Analog-To-Digital Convertor (A/D)

A hardware device that senses an analog signal and converts it to a representation in digital form.

Bandwidth

The frequency range of a system input over which the system will respond satisfactorily to a command.

Base Speed

The point where the motor will develop rated horsepower (HP) at rated load and voltage. With AC drive systems, it is commonly the point where 60 Hz, rated voltage, and rated load is applied to the induction motor.

Baud

A unit of signalling speed equal to the number of discrete conditions or signal events per second.

BCD (Binary Coded Decimal)

A numbering system that is used to express individual decimal digits (i.e. 0 through 9) in a four-bit binary rotation.

Bearing (Ball)

A "ball" shaped component that is used to reduce friction and wear while supporting rotating elements. For a motor, this type of bearing provides a relatively rigid support for the output shaft.

Bearing (Roller)

A special bearing system with cylindrical roller capable of handling belted load applications, too large for standard ball bearings.

Binary Coded Decimal (BCD)

A decimal notation in which the individual decimal digits are represented by a pattern of ones and zeros. This code is one of the most common variations of the binary system. It employs only the first four binary positions with respective values of 1, 2, 4, and 8. Any decimal digit from 0 to 9 can be represented by a combination of these four values. In this system a separate binary equivalent is required for each digit of the decimal number being expressed.

Binary Digit (Bit)

In the binary system, a bit can represent either 0 or 1; to a computer a bit will indicate an off or on signal. Bits are the units of information that, when combined in certain configurations, will signal to the computer what it is to do. Bits are organized into larger units called words for access by computer instructions. Computers are often categorized by word size in bits, i.e., the maximum word size that can be processed as a unit during an instruction cycle (i.e. 16-bit or 32-bit computers). The number of bits in a word is an indication of the processing power of the system, especially for calculations or for high-precision data.

Bit Rate

The speed at which bits are transmitted, usually expressed in bits per second (sometimes referred to as "baud rate").

Block

A group of electronic words transmitted as a one unit.

Block Transfer

A programming technique used to transfer up to 64 electronic words of data to or from an intelligent I/O module.

Braking

Provides a means of stopping an AC motor and can be accomplished in several ways:

_*Braking (Dynamic, AC Drives).* AC motors do not have separate field excitation. Dynamic braking is accomplished by continuing to excite the motor from the drive. This causes a regenerative current to the drive's DC Bus to dissipate the power returned. The brake resistor is usually switched by a transistor or other power switch controlled by the drive.

__*Braking (Regenerative).* This is essentially *electronic braking*. The generated power is returned to the line through the power converter. It may also be dissipated as losses in the converter (within its limitations).

_*Braking (Mechanical)* This is a positive action friction device. In a normal configuration the brake is set when power is removed. This can be used as a holding brake. (Note: A *separately-mounted brake* is one which is located on some part of the mechanical drive train other than the motor.)

Breakaway Torque

The torque required to start a machine from a stopped position. It is always greater than the torque needed to maintain motion.

Breakdown Torque

The maximum torque which an AC motor will develop with rated voltage applied at rated frequency.

Bridge Rectifier

A full-wave rectifier that conducts current in only one direction of the input current. AC applied to the input results in approximate DC at the output.

A *diode* bridge rectifier is a non-controlled full-wave rectifier that produces a constant DC voltage. An SCR bridge rectifier is a full-wave rectifier with an output that can be controlled by switching ON the gate control element.

Burn-In

The process of operating a unit (i.e. drive) at elevated temperatures. This operation, prior to its une in an application, tends to stabalize the unit characteristics and detects early failures.

Byte

This is equal to 8 consecutive bits.

"C" Face (Motor Mounting)

This type of motor mounting is used to close couple pumps and similar applications where the mounting holes in the face are threaded to receive bolts from the pump. Normally the "C" face is used where a pump or similar item is to be overhung on the motor. This type of mounting is a NEMA standard design and available with or without feet.

CEMF

Counter electromotive force, is the product of a motor armature rotating in a magnetic field. This generating action takes place whenever a motor is rotating. Under stable motoring conditions, the generated voltage (CEMF) is equal to the voltage supplied to the motor minus small losses. The polarity of the CEMF is opposite to that of the power being supplied to the armature.

Cable Termination Filters

Filters installed at the motor, designed to match the terminating impedance at the motor to the characteristic impedance of the power cable between the drive and motors.

CE Marking

CE marking is a label attached by the manufacturer to a product certifying that the product complies with certain European directives (e.g. EMC) and safety standards.

Closed Loop

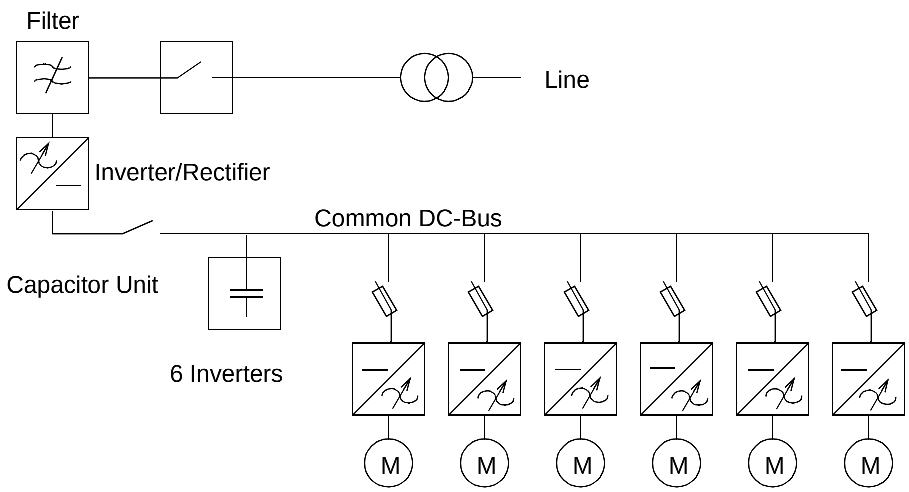
A regulator circuit in which the actual value of the controlled variable (e.g., speed) is sensed. A signal proportional to this value (feedback signal) is compared with a signal proportional to the desired value (reference signal). The difference between these signals (error signal) causes the actual value to change in the direction that will reduce the difference in signals to zero.

Cogging

A motor condition where the shaft does not rotate smoothly but "steps" or "jerks" from one position to another. Cogging is most evident at low motor speeds and can cause objectionable vibrations in the driven machine.

Common DC Bus

A drive system where several inverters are connected to a common DC bus. The advantages are: Space reduction, reduced cabling costs (only one incoming section is used) and, in some instances, energy saving. For example: In a sugar mill, a battery of centrifuges can be driven by a common DC bus system such that energy generated from a decelerating machine may be utilized, via the DC bus, by an accelerating machine.



Commutation (Inverter)

This is a process where forward current is interrupted or transferred from one switching device to the other. In most AC circuits, turn-on-control is adequate and turn-off occurs naturally when the AC cycle causes the polarity across a given device to reverse.

Complementary Metal-Oxide Semiconductor (CMOS)

An integrated circuit logic family characterized by very low power dissipation, moderate circuit density per chip, at moderate speed of operation.

Comparator

A device that compares one signal to another, usually the process signal compared to the set point or command signal.

Concentric Windings

Motorwindings that are wound so that each turn of the coil is next to the previous turn, and the coil is built up in successive layers. This ensures that each turn of the coil is in contact only with immediately preceding and successive turns.

Constant Horsepower Load

A load characterized by torque relative to the inverse of speed, abbreviated "CHP". This type of load occurs above base speed. Horsepower stays constant because torque decreases as speed increases. The load requires low torque at high speeds. Some typical applications would be drilling, shaping, milling, turning metal. In AC applications, the CHP range is sometimes referred to as the "constant voltage range".

Constant Horsepower Range

A range of motor operation where motor speed is controlled by field weakening. In this range, motor torque decreases as speed increases. Since horsepower is speed times torque (divided by a constant), the value of horsepower developed by the motor in this range is constant.

Constant Torque Load

A load characterized by torque proportional to a constant at any speed. Torque stays constant because horsepower increases as speed increases up to base speed. The load requires the same amount of torque from zero to base speed. Some typical applications would be hoists, conveyors, and printing presses.

Constant Torque Range

A speed range in which the motor is capable of delivering a constant torque, subject to cooling limitations of the motor.

Constant Voltage Range

This term is related to AC drives. It is the range of motor operation where the drive's output voltage is held constant as output frequency is varied. This speed range produces motor performance similar to a DC drive's constant horsepower range.

Constant Volts per Hertz (v/Hz)

The relationship that exists in AC drives where the output voltage is varied in direct proportion to frequency. This type of operation is required to allow the motor to produce constant rated torque as speed is varied.

Continuous Duty

A motor that can continue to operate within the insulation temperature limits after it has reached normal operating temperature.

Control Logic Section

Low voltage and current circuits that tell the Power Conversion sub-section devices when to switch ON or OFF.

Converter

The process of changing AC to DC. This is accomplished through use of a diode rectifier or thyristor rectifier circuit. The term *converter* may also refer to the process of changing AC to DC to AC (e.g., adjustable frequency drive). A *frequency converter*, such as that found in an adjustable frequency drive, consists of a *rectifier*, a *DC intermediate circuit*, an *inverter* and a *control unit*.

A variable frequency drive (VFD) uses a three-phase diode bridge to convert the applied AC line voltage to rectified DC.

The DC Bus is comprised of the:

_DC potential source (internal rectifier bridge or external source),

_DC link inductor (connecting the DC Bus capacitors to the DC potential source), and

_DC Bus capacitors that, together with the DC link inductor, provide filtration of the DC source potential and provide some buffering between the DC source and the power inverter section.

The DC Bus voltage is 1.35 x Supply Voltage (V_{IN}).

Critical Frequency

The frequency at which continuous operation will cause mechanical vibration of the machine being controlled.

Current Limiting

An electronic method of limiting the maximum current available to the motor. This is adjustable so that the motor's maximum current can be controlled. It can also be preset as a protective device to protect both the motor and control from extended overloads.

Current Regulation

This is the drive's ability to control the amount of current output. If the motor current exceeds the current limit setting, the drive output will stop. The output frequency will decrease until the motor current is reduced below the current limit level. The drive will then accelerate at the rate determined by the accel time.

Cycle

One complete cycle is the variation of an AC signal from zero to a maximum and back to zero in a positive direction, and then in a negative direction.

"D" Flange (Motor Mounting)

This type of motor mounting is used when the motor is to be built as a part of the machine. The mounting holes of the flange are not threaded. The bolts protrude through the flange from the motor side. Normally "D" flange motors are supplied without feet since the motor is mounted directly to the driven machine.

D / A Converter

A device that converts a digital number into an analog voltage or current level (continuous values of voltage or current, i.e. sinewave).

Damping

The reduction in amplitude of an oscillation in the system.

DC Braking

This is sometimes referred to as “DC Injection Braking.” This process provides quicker stopping times compared to a standard ramp-to-stop. The drive actually applies a DC voltage to the stator windings thereby quickly dissipating any energy within the drive system.

DC Bus

Circuitry that filters the DC voltage entering the Power Output sub-section from the rectifier.

DC Contactor

A contactor specifically designed to establish or interrupt a direct-current power circuit.

DC Line Reactor

Sometimes called a “DC Link Inductor,” this component adds impedance to the DC Bus. Because of this, the inductor actually slows the rate of rise of current spikes therefore smoothing the effects of DC ripple on the Bus voltage output. The results are improvement in the displacement power factor and lower harmonic distortion sent back to the AC line.

Dead Band

The range of values through which a system input can be changed without causing a corresponding change in system output.

Default

A default is a preprogrammed value for a parameter. During start-up of an AC drive, all application macro parameter values appearing on the Keypad Display are default settings. These default settings may be changed during the process of customizing your drive for your particular application.

Definite-Purpose Motor

A definite-purpose motor is any motor design, listed and offered in standard ratings with standard operating characteristics from a mechanical construction for use under service conditions other than usual or for use on a particular type of application (NEMA).

Definite-Purpose Inverter-Fed Motor

Motors that are specifically designed for use with adjustable frequency drives, also called “inverter duty motors.” NEMA MG1-1993, Part 31 defines performance requirements for “Definite-purpose Inverter-fed Motors.”

Deviation

Difference between an instantaneous value of a controlled variable and the desired value of the controlled variable corresponding to the set point. Also called error.

di/dt

The rate of change in current versus a rate of change in time. Line reactors and isolation transformers can be used to provide the impedance necessary to reduce the effects of unlimited current on phase-controlled rectifiers (SCRs).

Digital Communications

Transfer of information by means of a sequence of signals called bits (for binary digits), each of which can have one of two different values. The signals may, for example, take the form of two different voltage levels on a wire or the presence of absence of light in a fiber-optic light guide. It can be made arbitrarily insensitive to external disturbances by means of error control procedures.

Digital Input (DI)

The digital inputs (DI) receive bistable (two-state On-Off) control signals from the outside world. An example of such would be a two-position Start-Stop selector switch. Digital inputs on some ABB AC Drive Keypad Displays are abbreviated DI.

Diode

A device that allows current to flow one direction, but doesn't allow current in the reverse direction.

Direct Torque Control (DTC)

Direct Torque Control (DTC) is an optimized AC drives control principle where inverter switching directly controls the motor variables (i.e. flux and torque). The measured motor current and voltage are inputs to an adaptive motor model which produces an exact actual value of flux and torque every 25 microseconds. Motor torque and flux two-level comparators compare the actual values produced by torque and flux reference controllers. Depending on the outputs from the two-level controllers, the optimum pulse selector directly determines the optimum inverter switch positions. The inverter switch positions again determine the motor voltage and current, which in turn influence the motor torque and flux and the control loop is closed.

Drift

Deviation from the initial set speed with no load change over a specific time period. Normally the drive must be operated for a specific warm-up time at a specified ambient temperature before drift specifications apply. Drift is normally caused by random changes in operating characteristics of various control components.

Drive Controller

An electronic device that can control the speed, torque, horsepower and direction of an AC or DC motor. This device is also called a variable speed drive.

Drive End of a Motor

The end (D.E.) that carries the coupling or driving pulley (NEMA).

Driver

A circuit that adjusts the reference signal to the correct level.

DSP

A Digital Signal Processor (DSP) is a fast-acting component for mathematical calculations. It operates at 40 MHz and is able to multiply two numbers (less than 8 Million) in the time it takes for light to travel 20 m.

Duty Cycle

The relationship between the operating and rest times or repeatable operation at the different loads.

dv/dt

The term dv/dt comes from differential calculus and means the derivative of v (voltage) with respect to t (time) or the instantaneous rate of change in voltage with respect to time. To conform to the mathematical definition, the dv/dt of a voltage pulse should be defined as a function that describes the rate of change in voltage at any time during the duration of the pulse. In most discussions of motor insulation voltage stress, the term dv/dt is applied to the average rate of voltage change as voltage rises from 10% to 90% of the peak voltage or:

$$dv/dt = \frac{\text{Peak Voltage x 0.8}}{\text{Rise Time}}$$

The rate of change in voltage versus a rate of change in time. Specially designed resistor-capacitor networks can help protect the SCRs from excessive dv/dt which can result from line voltage spikes, line disturbances and circuit configurations with extreme forward conducting or reverse blocking requirements.

Dwell

The time spent in one state before moving to the next. In motion control applications for example, a dwell time may be programmed to allow time for a tool change or part clamping operation.

Dynamic Braking

See Braking

Eddy Current

Currents induced in motor components from the movement of magnetic fields. Eddy currents produce heat and are minimized by lamination of the motor poles and armature.

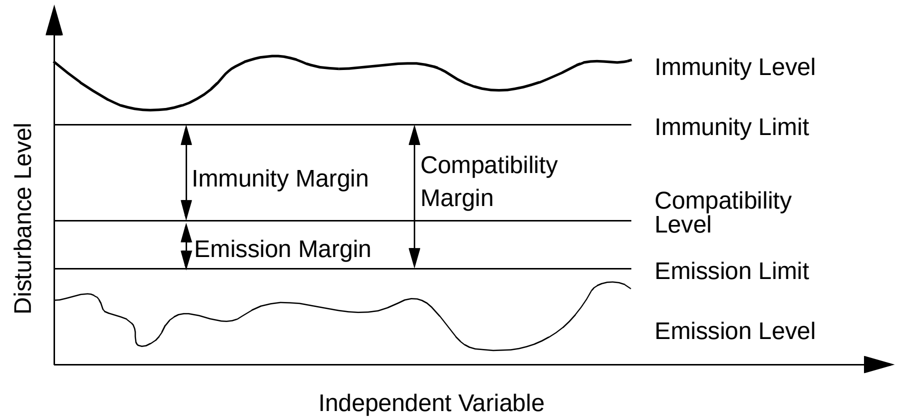
In transformers, it is the current that circulates in the metallic core material. This current is a result of electromotive forces induced by a variation of magnetic flux. Magnetic flux is a condition produced by the movement of voltage induced in an electical conductor.

EEPROM

EEPROM is an acronym for *electrically erasable programmable read only memory.* The EEPROM is the non-volatile memory that stores all parameters, even when power is removed. (Sometimes referred to as E^2 PROM.)

EMC (Electromagnetic Compatibility)

EMC is described as the ability of a device or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in the same environment. To achieve the EMC, the immunity of all equipment in the environment must be higher than the emissions from any source in the environment.



EMF

Electromotive force. EMF is a way of expressing voltage or potential difference.

This is an abbreviation for "electro-magnetic interference." This characteristic occurs during the switching of electronic power supplies and is similar to a radio wave. If the EMI signal is strong enough, it will cause unwanted refernce signals or "noise" in other electronic equipment, such as drives.

EPROM

An acronym for erasable programmable read only memory. The EPROM is a circuit that can be erased with ultraviolet light, then reprogrammed with electrical pulses. It is essentially where the drive software exists - the section that controls semiconductor firing signals, etc.

Efficiency

Ratio of mechanical output to electrical input indicated by a percent. In motors, it is the effectiveness with which a motor converts electrical energy into mechanical energy.

Enable

To allow an action or acceptance of data by applying an appropriate signal to the appropriate input (e.g., to allow the drive to start).

Enclosure

The housing in which the control is mounted. Enclosures are available in designs for various environmental conditions.

Encoder

A device that produces a serial or parallel digital indication of mechanical angle or displacement. Essentially, an encoder provides high resolution feedback data related to shaft position and is used with other circuitry to indicate velocity and direction. The encoder produces discrete electrical pulses during each increment of shaft rotation.

There are two types of encoders available: *absolute* and *incremental*.

The *absolute encoder* provides multiple channel coding of shaft position, with the output in a unique binary code. This type of encoder is higher in cost than an incremental one due to the complexity of circuitry.

The *incremental encoder* consists of magnetic or optically coupled electronic devices inside a case. These devices give out a number of pulses that correspond to speed and direction. This type of encoder has a disadvantage when used in positioning. When power is lost, this device also loses its starting point.

Error

Difference between the set point signal and the feedback signal. An error is necessary before a correction can be made in a controlled system.

ESD

ESD is an acronym for *Electrostatic Discharge*. ESD cautions indicate situations in which static electricity can damage circuit boards without any visible signs of damage. Precautions listed in the AC Drive Installation Start-Up Manual must be followed when installing or removing circuit boards.

FCC (CFR47)

Defines the limits of radiated energy (RFI - Radio Frequency Interference) from computing devices. These limits indicate protection from interference when receiver located at least 10 meters from the RFI source.

Feedback

This part of a system provides an actual operation signal for comparison with the set point to establish an error signal used by the regulator circuit.

Feedback Loop

The *feedback loop* provides the self-corrective signal necessary to tell the drive to adjust output to the motor. The motor performs the required adjustment in speed or direction.

The *feedback loop* is critical to the automatic accurate operation of the system. Because the "feedback loop" is directly connected to the motor or machine, it provides an exact representation of speed because the feedback device is directly connected to the motor.

Fieldbus

The word field indicates that we are dealing with the field level, the lowest layer of automation hierarchy, where the field devices like sensors and actuators are used. The word bus tells us that these devices are connected to a common communication bus instead of point-to-point connections.

Field Range

The range of motor speed from base speed to the maximum rated speed. With AC drives this is also referred to as the “Above Base Speed” range or “Constant Horsepower” range.

Field Weakening Point

On AC drive systems, this is the point at which the output voltage no longer increases even though the output frequency is increased. Operation above this point results in reduced motor torque capability while the output kVA remains constant. Refer to *Parameter 20.4.4 (Field Weak Point) in the ACS 501 Programming Manual.*

Filter

A device that passes a signal or a range of signals and eliminates all others.

Flash Prom

This is a memory chip imbedded on a circuit board similar to an E^2PROM. This memory can contain drive parameters and values and can be upgraded to a new software version through fiber optic communications.

Flux Vector

Flux vector drives use a method of controlling torque similar to that of DC drive systems, including wide speed control range with quick response. Flux vector drives have the same power section as all PWM drives, but use a sophisticated *closed loop control* from the motor to the drive’s microprocessor. The motor’s rotor position and speed is monitored in real time via a resolver or digital encoder to determine and control the motor’s actual speed, torque, and power produced.

Firmware

This is a series of instructions in an EPROM. The instructions are used for internal processor functions only and are transparent to the drive operator.

Floating Ground

An electrical common point that is not at earth ground potential or the same ground potential as circuitry it is associated with. A voltage difference can exist between the floating ground and earth ground.

Flying Start

The inverter (AC drive) searches for the frequency that corresponds to the motor speed and synchronizes with it smoothly. Some modern inverters will even find a motor rotating in the opposite direction.

Form Factor

A figure of merit which indicates how much rectified current deviates from pure (non-pulsating) DC. A large departure from unity form factor (pure DC) increases the heating effect of the motor. It is expressed as I_{RMS}/I_{AV} (motor heating current/torque producing current).

Four-Quadrant Operation

The four combinations of forward and reverse rotation and forward and reverse torque of which a regenerative drive is capable. The four combinations are:

_Forward rotation/forward torque (motoring)

_Forward rotation/reverse torque (regeneration)

_Reverse rotation/reverse torque (motoring)

_Reverse rotation/forward torque (regeneration)

Frame Size

The physical size of a motor, usually consisting of NEMA defined "D" and "F" dimensions at a minimum. The "D" dimension is the distance in quarter inches from the center of the motor shaft to the bottom of the mounting feet. The "F" dimension relates to the distance between the centers of the mounting feet holes.

Frequency

The number of cycles generated each second. The unit of measurement isHertz (Hz). *(1 Hertz = 1 cycle per second)*

Frequency Converter (AC Drive)

Equipment to convert single- or three-phase alternating voltage into alternating into alternating voltage with another frequency or phase number. The frequency converter consists typically of a rectifier and an inverter. Main types: direct converter and indirect converter.

Frequency Resolution (analog)

This is the minimum step in motor frequency the drive can deliver in realtion to the analog input. The smaller the step, the finer the control. This becomes important for fine speed control in conveying systems. Frequency can also be set with the panel, but as the process is usually controlled by the analog input, panel frequency setting is not as important.

Full Load Torque

The torque necessary to produce rated horsepower at full-load speed.

Gate

The control element of an SCR (silicon-controlled rectifier). When a small positive voltage is applied to the gate momentarily, the SCR will conduct current (when the anode is positive with respect to the cathode of the SCR). Current conduction will continue even after the gate signal is removed.

Gateway ®

An electronic device that is used to translate one form of data to another form of data. It could also be considered an electronic “interpreter.” It interprets the protocol of a device such as a PLC.

General-Purpose Motor

This motor has a continuous Class "B" rating and design, listed and offered in standard ratings with standard operating characteristics and mechanical construction for use under usual service conditions without restriction to a particular application or type of application (NEMA). These types of motors are not recommended for use with Variable Frequency Drives.

Group

In ABB drives, a Group is a category of parameters. Groups identify parameters by their functionality.

GTO

Gate turn-off or gate turn-on power semiconductor device.

Hall Effect Sensor

A transducer that produces a voltage feedback proportional to the magnetic field generated in a conductor. The magnetic field is proportional to the current flow in the conductor and is used in drives in the current limit circuit. The benefit of this type of sensor is the high accuracy to measure AC current at low frequency output.

Harmonic

The component frequency that is an integral of the fundamental frequency (i.e. 60Hz). For example, the 3rd harmonic is 60 X 3 or 180 Hz.

Harmonic Distortion

A condition that exists in a power distribution system due to the switching of equipment power supplies (computers, etc.) This “distorting” of the AC sinewave occurs wherever an electronic device (computer, drive, etc) draws current in short pulses. Drives, for example, draw current only during a controlled part of the incoming voltage waveform. This process improves the efficiency, but causes harmonic distortion (currents) which could cause overheating in transformer neutrals. The harmonic currents would show up as an AC waveform that no longer looks like a pure sinewave. The voltage and current waveforms are no longer related. Thery are therefore called “non-linear.”

Head

A measurement of pressure, usually in feet of water. A 20 foot head is the pressure equivalent to the pressure found at the base of a column of water 20 feet high.

Horsepower

A measure of the amount of work that a motor can perform in a given period of time (see the “Formulas and Conversions” section).

Hunting

Fluctuations in motor speed that can occur after a step change in speed reference (either acceleration or deceleration) or load.

Hysteresis Loss

Laminated iron materials offer some resistance to becoming magnetized. This resistance results in energy being expended and corresponding loss. Hysteresis loss in a magnetic circuit is the energy expended to magnetize and demagnetize the core.

IEEE Standard 519

A standard that indicates the guidelines for harmonic control and inductive reactance of static power converters. This guide recommends limits of disturbances to the AC power distribution system which affects other equipment and communications.

Impedance

The total opposition to AC that occurs in a circuit. This opposition (indicated by Z) is sometimes referred to as an "AC resistance." It is actually the combined product of resistance, inductance and capacitance. Because of the inductor and capacitor part of the circuit, impedance is very frequency sensitive.

I_N

This notation abbreviates the current which the drive trips and on which settings are based.

Induction Motor

An AC motor, that has the primary winding on one member (usually the stator), is connected to the power source. A secondary winding on the other member (usually the rotor) carries the induced current. There is no physical electrical connection to the secondary winding.

Inertia

A measure of body's resistance to changes in velocity, whether the body is at rest or moving at a constant velocity. The velocity can be either linear or rotational. The moment of inertia (WK^2) is the product of the weight (W) of an object and the square of the radius of gyration (K^2). The radius of gyration is a measure of how the mass of the object is distributed axis of rotation. WK^2 is usually express in units of lb-ft^2.

Instability

Characteristics of a system where there is an output but no corresponding input.

Insulated Gate Bipolar Transistor (IGBT)

A current-operated power device which incurs lower losses than standard bipolar transistors. This results in increased switching frequencies and requirements for smaller heat sinks. Smaller gate currents can control large motor currents. Higher switching frequencies reduce the amount of audible motor noise and allow for smoother motor control (compared to low switching rates of 1KHz and below).

These devices allow a drive to operate at near "tripless" control. They also allow the motor to develop high starting torque with 100% load capability.

Integral Horsepower Motor

A motor built in a frame having a continuous rating of 1 HP or more.

Intelligent Power Module (IPM)

This module includes the drive and protection circuits in a compact unit that is attached to the heat sink. IPM's offer increased reliability and lower losses because the IGBT's within the module have lower power losses.

Intermittent Duty Motor

A motor that never reaches maximum temperature, but is permitted to cool down between operations.

Inverter

A term commonly used for an AC adjustable frequency drive (AFD). An inverter is also a term used to describe a particular section of an AC drive. The section uses the DC voltage from a previous circuit stage (DC Bus) to produce an AC current or voltage having the desired frequency.

Inverter Duty Motor

This type of motor is designed to be operated on variable frequency drives (VFDs). An inverter duty motor design includes phase insulation paper between the first few turns of stator wndings. In addition, the stator windings are "form wound" (windings are laid exactly parallel next to eachother). This increases inductance in each length of winding. An inverter duty motor also has winding insulation of a high voltage class (i.e. 1600 V).

Inverter Spike Resistant (ISR) Wire

A trademark of the Phelps-Dodge company aplied to a new magnet wire insulation that provides an increased level of protection from voltage peaks. This type of wire is found in some motors powered by adjustable frequency drives.

IP-Classes

Protection of equipment against ingress of water or solid bodies such as dust.
IP = Ingress Protection
Example: IP00: No water protection, no guards.
IP54: Protection against damaging dust accumulation and against splashing water from any direction

I_R

This notation abbreviates the constant torque rated output current, in amperes, of an AC Drive.

IR Compensation

This term was used in DC drive systems, and related to the voltage drop across the armature (E = I X R). A way to compensate for the loss in speed due to additional load on the motor. This compensation provides a way to improve the speed regulation characteristics of the motor, especially at low speeds. Drives that use a tachometer-generator for speed feedback generally do not require an IR Compensation circuit because the tachometer will inherently compensate for the loss in speed.

In AC drives, IR Compensation is a parameter that allows the motor to develop extra torque at motor speeds between 0.1 Hz and the set Field Weakening Point.

I_{RSQ}

This notation abbreviates the rated variable drive output current, in amperes, of an AC drive.

Isolation Transformer

A transformer that electrically separates the drive from the AC power line. An isolation transformer provides several advantages:

_Enhances protection of semiconductors from line voltage transients.

_Reduces disturbances from other solid state control equipment such as drives without isolation transformers, time clock systems, electronic counters, etc.
_Allows voltage matching of line power and drive input power (either step-up or step-down transformer).

I^2T (Thermal Protection)

The ability of an AC drive to calculate the motor heating from the operation history.

Jogging

Momentary motor movement by repeated contact closures (e.g., using a single pushbutton).

Joystick Control

Joystick control allows you to use a joystick for external speed and direction drive control through an analog input. Typically, the center joystick position is zero speed and movement of the control causes forward or reverse direction.

Local Area Network (LAN)

A privately owned network communication channel which is used for connecting communication equipment (i.e. data processing, drives, PLC's, etc.) This system is usually in a limited geographical area.

LED (Light Emitting Diode)

A solid-state device used for signal indication on the manual control and the I/O module.

LED Display

An alphanumeric display consisting of an array of LED's.

Limit Switch

An electrical switch positioned to be actuated when a certain motion limit occurs. The switch then opens a contact which may then be used as a Digital Input to an AC drive.

Line Reactor

Reduces the amount of electrical noise fed back to the AC power line. It reduces the line notching (absence of power) caused by switching of power conversion devices (phase controlled rectifiers such as SCRs). Line reactors also serve to limit the current surge seen by the DC Bus capacitors.

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This surge happens when a voltage surge occurs to the input of the drive. When a voltage surge occurs, a large current surge will occur as the Bus capacitors charge to the peak voltage of the surge. The higher the surge level, the quicker the capacitor will charge (The surge may be 5 to 10 times higher than normal operating current.). When the capacitors reach an overvoltage level, the drive shuts down.

Line reactors, connected in series with the drive input, limit the magnitude of the current surge. The capacitor charges at a slower rate, thereby not allowing the capacitor to reach the voltage trip level.

Line Voltage

The input voltage that provides power to the drive. Line voltage is connected to the Terminals L_1, L_2, and L_3 (U_1, V_1, and W_1). Also refer to *Supply Voltage* in this glossary.

Linear Acceleration / Deceleration

This drive circuit controls the rate at which the motor is allowed to accelerate to a set speed or decelerate to zero speed. On most drives, this circuit is adjustable and can be set to a particular application.

Linearity

A measure of how closely a characteristic follows a straight line function.

Linear Load

Any type of electrical equipment that does not change the voltage or current waveform. This load does not distort the AC sine wave. Examples of this type of load include: standard incandescent lights

Living Zero

The Living Zero function allows an AC drive to detect a loss of reference signal. This function operates when Parameter “Minimum AI1” is set to a value greater than 0.3 V/ 0.6 mA. You can then supervise the presence of a control signal by setting an “AI < Min Function” to WARNING or FAULT. A Warning or Fault message will then display if the analog input falls below the set minimum.

Load Sharing

This is an application where the shafts of several motors are mechanically connected together through the load. If the load is shared unevenly, one or more motors may be overloaded while the others operate lightly loaded. With DC motors, load sharing can be adjusted by adjusting the field currents of the individual motors. With AC motors, there is no comparable means of adjusting the load sharing. Load sharing with AC motors is determined by the mechanical design of the driven equipment, the placement of the motors and the motor torque-speed curves.

Since the AC motor torque-speed curve dictates that the motor speed must decrease when the torque speed increases, motors will share the load evenly if the mechanical connection among the motors prevents them from operating at different speeds.

Locked-Rotor Current

Current taken from the line with the rotor at standstill (at rated voltage and frequency). This is the starting current when the motor is connected to the load.

Locked-Rotor Torque

Torque that a motor will develop for all positions of the rotor (with rated voltage applied at rated frequency).

Logic Control

Controlling the power switching devices to obtain adjustable frequency. It also controls the firing sequence to maintain phase coordination, and the output voltage to produce the required V/Hz ratio. The *driver* sub-section adjusts the reference signals to the correct level. The *power output control* subsection automatically adjusts the switching of the power output sub-section. Monitoring devices for Overcurrent and Bus Voltage level report to the control logic.

Macro

A macro is a pre-programmed set of defaults for all of the parameters, which are typical for the specified application. You typically select the macro that most closely defines the drive functions necessary for your particular application. After selecting the macro, you can modify or customize the macro to specifically conform to your application.

Mean-Time-Between-Failures (MTBF)

The average time that a device will operate before failure.

Meggar Test

A measurement an insulation system's resistance. This is usually in megohms and tested by passing a high voltage at low current through the motor windings and measuring the resistance of the various insulation systems.

Metal Oxide Varistor (MOV)

A surge protection device that has low resistance to a voltage spike above operating level. The spike is routed back to the AC line.

Motor Model

A motor model is an electronic circuit or software modeling of the internal circuits of the asynchronous motor. Examples of inputs to the model are: Motor current, DC-bus voltage, and switching positions of the inverter. Examples of outputs are calculated flux, and calculated torque. Examples of internal parameters in the model are: stator resistance, mutual inductance and saturation coefficients. These parameters can be tuned during an identification run as part of the drive commissioning.

Multimeter

Measures electric component functions and values such as voltage (volts) resistance (ohms), and current (amperes). Some multimeters also test the condition of diodes.

Multispeed Motor

An induction motor that can obtain two, three, or four fixed speeds by the selection of various stator winding configurations.

NEC (National Electric Code)

Recommendations of the National Fire Protection Association. It is revised every three years. City or state regulations may differ from code regulations and take precedence over NEC rules.

NEMA

The National Electrical Manufactures Associates is a non-profit organization organized and supported by manufacturers of electrical equipment and supplies. Some of the standards NEMA specifies are: HP ratings, speeds, frame sizes and dimensions, torques and enclosures.

Nonlinear Load

Any type of electrical equipment that changes or modifies the voltage or current waveform to one that is somewhat distorted. Prime examples of this type of load include: personal computers, magnetic ballasts, electronic ballasts and variable speed DC and AC drives. Basically, a nonlinear load is one that uses a “switch mode power supply” (A circuit that changes AC to DC).

OEM

Original Equipment Manufacturer or Machine manufacturer

Offset

Deviation of a controlled variable from a fixed setpoint.

Open Loop

A control system that does not use a feedback element.

ODP or Open Dripproof

Open dripproof motors have ventilation openings that allow an exchange of cooling air to flow through the interior of the motor from teh surroundings. The air is forced through the motor by fins on the end of the motor’s rotor. Since outside air comes into contact with the stator windings, rotor and air gap, ODP motors are suitable only for installation in clean, dry environments.

Open Machine (Open Motor)

A machine having openings that allow external cooling air over and around the windings of the machine.

_*Dripproof Machine* is an open type machine in which the ventilating openings are so constructed that successful operation is not interfered with when drops of liquid or solid particles strike or enter the enclosure at any angle from 0 to 15 degrees downward from vertical.

_*Splashproof* is an open machine in which the ventilating openings are so constructed that successful operation is not interfered with when drops of liquid or solid particles strike or enter the enclosure at any angle not greater than 100 degrees downward from the vertical.

_*Semiguarded* is an open machine in which part of the ventilating openings in the machine, normally in the top half, are guarded as in the case of a "guarded machine" but the others are left open.

_*Guarded Machine (NEMA Standard)* is an open machine in which all openings giving direct access to live metal or rotating parts (except smooth rotating surfaces) are limited in size by the structural parts or by the screens, baffles, grills, expanded metal or other means to prevent accidental contact with hazardous parts. Openings giving direct access to such live or rotating parts shall not permit the passage of a cylindrical rod 0.75 inch in diameter.

_*Dripproof Guarded Machine* is dripproof machine whose ventilating openings are guarded in accordance with the definition of a guarded machine.

_*Open Externally Ventilated Machine* is one which is ventilated by means of a separate motor driven blower-mounted on the machine enclosure. This machine is sometimes known as a blower-ventilated or a force-ventilated machine.

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_*Open Pipe Ventilated Machine* is an open machine except that allows ventilating air inlet ducts or pipes connected to them. Air may be circulated by means integral with the machine or by means external to the machine (separately or forced ventilated).

_*Weather-Protected Machine* is an open enclosure divided into two types:

1.*Type 1* enclosures have ventilating passages constructed to minimize the entrance of rain, snow, airborne particles and prevent passage of a 0.75 in. diameter cylindrical rod.

2.*Type 2* enclosures provide additional protection through the design of their intake and exhaust ventilating passages. The passages are so arranged that wind and airborne particles blown into the machine can be discharged without entering directly into the electrical parts of the machine. Additional baffling is provided to minimize the possibility of moisture or dirt being carried inside the machine.

Operating/Service Deviation

A means of specifying the speed regulating performance of a drive controller generally in percent of base speed.

Operating Deviation defines speed change due to load change and typically assumes:

_A change from one steady state load value to another (not transient),

_A 95% maximum load change.

Service Deviation defines speed change due to changes in ambient conditions greater than these typical variations:

Condition	Change	
AC Line Voltage	+10%	-5%
AC Line Frequency	+ 3%	-3%

Ambient Temperature 15•C

Output Reactors

Inductors, also called reactors or chokes, placed in series with the output terminals of an adjustable frequency drive. Inverter output reactors are usually located near the AF drive.

Overcurrent

This circuit shuts down the drive when a safe current level is exceeded (e.g., 375% instantaneous or 265% x-nominal RMS).

Overload Capacity

The ability of the drive to withstand currents beyond the systems continuous rating. It is normally specified as a percentage of full load current for a specific time period. Overload capacity is defined by NEMA as 150% of rated full load current for one minute for *Standard Industrial* DC Motors.

Overshoot

The amount that a controlled variable exceeds desired value after a change of input.

Overvoltage

This circuit shuts down the drive when a safe voltage level is exceeded.

Parallel Communications

A digital commucication method that transmits the bits of a message several at a time (usually 8 to 17 bits at a time); usually only used over distances of a few feet with electrical cables as the transmission medium.

Parallel interface

A type of digital interface using multiple data lines, each line transmitting one bit of data at a time.

Parallel Operation

The type of electronic information transfer that occurs when all bits, bytes or words are handled simultaneously.

Parity Bit

An additional bit added to a memory word to make the sum of the number of 1's in a word always even parity or odd parity.

PC

(Programmable Controller) Solid-state control logic for machines and processes where a sequence of operations can be changed easily with software.

PI Control

PI is an acronym for "proportional integral" control. In this type of motor control, two signals are sent to the drive. One signal acts as a process reference and the other acts as an actual signal (feedback) brought back from the process. The drive compares the two signals and adjusts the output frequency up or down to reduce the difference between the signals (zero error).

This type of control maximizes the efficiency of the process. PI control is very useful in maintaining a process variable - such as speed, flow, fluid level, pressure of a system, etc.

Plugging

Motor braking provided by reversing either line voltage polarity or phase sequence so that the motor develops a counter-torque which exerts a retarding force to brake the motor.

Position Transducer

An electronic device (e.g., encoder or resolver) that measures actual position and converts this measurement into a feedback signal convenient for transmission. This signal may then be used as an input to a programmable controller that controls the positioning system.

Power

Work done per unit of time. Measured in horsepower or watts: 1 HP = 33,000 ft-lb/min. = 746 watts.

Power Conversion Section

Electronic power devices that convert a fixed AC voltage into DC voltage (i.e., AC drive converter).

Power Factor (Displacement)

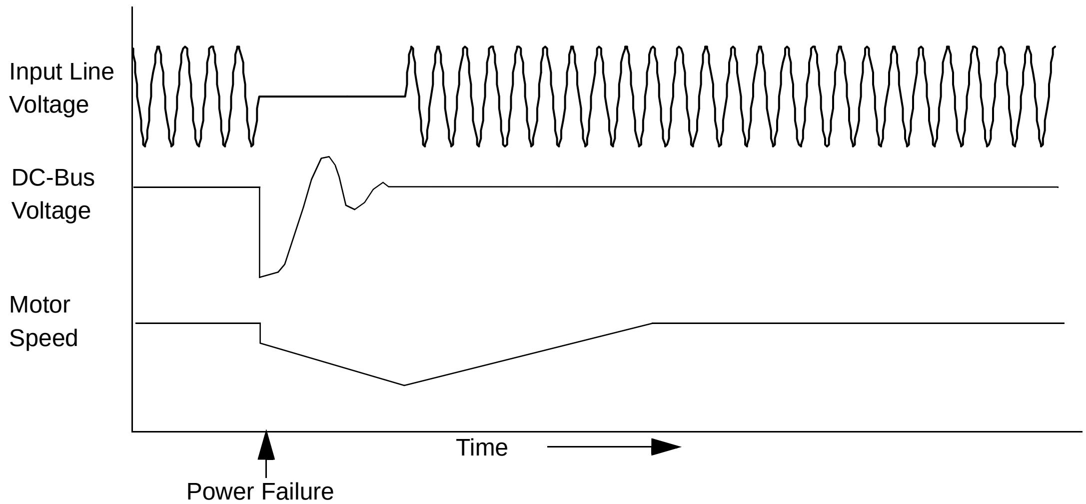
A measurement of the time phase difference between the fundamental voltage and fundamental current in an AC circuit. It represents the cosine of the angle of the phase difference.

Power Factor (Distortion)

A measurement of the ratio of the real power (kW) to the apparent power (kVA). Distortion power factor takes into account harmonic voltage and current distortion as well as voltage to current displacement.

Power Loss Ride-Through

If the supply to a freqency converter is lost, the drive may continue to run without external power supply utilizing the kinetic energy of the rotating motor and driven equipment. The power loss ride-through time depends on the relationship between the load and the inertia of the rotating masses.



Power Output

The section of the drive that delivers adjustable voltage/frequency to the motor (AC drives). The output terminals are typically referred to as U_2, V_2, and W_2.

Power Output Control

The circuit that automatically adjusts the switching of the Power Output sub-section.

Precharge

A circuit within the drive that supplies a limited amount of current to the DC Bus capacitors. This allows the capacitors to gain an small initial charge prior to receiving a full charge during a "drive enable" function. This process reduces the amount of inrush current to the Bus capacitors.

Preset Speed

Preset speed refers to one or more fixed speeds at which the drive will operate.

Programmable Logic Controller (PLC)

A stored program device intended to replace relay logic used in sequencing, timing, and counting of discrete events. Instead of physical wiring relay, pushbuttons, limit switches, etc., a PLC is programmed to test the state of input lines, to set output lines in accordance with input state, or to branch to another set of tests. The instruction sets of these machines generally exclude all arithmetic and Boolean operators, but do include vital decision instructions such as skip, transfer unconditional, transfer conditional, and even transfer and link.

Protection Devices

The sub-section of the drive that works to reduce the electrical hazard within the drive.

Protocol

A set of standards governing the format and timing of data between different types of communicating devices. Essentially, a protocol is a communication language (i.e. Modbus, Profibus, DeviceNet, etc.).

P_{RSQ}

This notation abbreviates the rated variable torque output power rating of an AC Drive.

Pull-In Torque

The maximum constant torque which a synchronous motor will accelerate into synchronism at rated voltage and frequency.

Pull-Out Torque

The maximum running torque of a synchronous motor.

Pull-Up Torque

The torque required to accelerate the load from standstill to full speed (where breakdown torque occurs), expressed in percent of running torque. It is the torque required not only to overcome friction, windage and product loading but also to overcome the inertia of the machine. The torque required by a machine may not be constant after the machine has started to turn. This load type is characteristic of fans, centrifugal pumps and certain machine tools.

PWM

Abbreviation for Pulse Width Modulation. An adjustable frequency AC drive that accomplishes frequency and voltage control at the output section (inverter) of the drive. The drive’s output voltage is always a constant amplitude and by "chopping" (pulse width modulating) the average voltage is controlled.

Random Winding

A method of winding wire n a motor in which the wire is inserted into the stator slots randomly without controlling the positions of the individual turns. With random winding, it is possible for the first turn of a coil to be in contact with the last turn.

Reactance

Measurement of the opposition of a circuit or component to an alternating current, expressed in ohms.

Rectifier

A device that permits current flow in one direction and blocks the flow of current in the other direction. In today’s technology, rectifiers are of the silicon diode type. A 6-Pulse AC drive uses six rectifiers, configured into a three-phase bridge configuration, as the power converter section of the drive.

Regeneration

This occurs when a motor acts as a generator. Regeneration also occurs when the CEMF is larger than the drive's applied voltage (DC drives) or when the rotor synchronous frequency is greater than the applied frequency (AC drives).

Regenerative Braking

The motor becomes a generator by taking the mechanical power of the motor and converting it into electrical power. The generated power is dissipated in the power source through a regenerative bridge circuit in the drive. The power may also be dissipated as losses in the power conversion section of the drive (within its limitations). Also see *Braking*.

Regenerative Control

A drive that has capability to control the flow of power to and from the motor.

Regulation

The ability of a control system to hold a set speed. Regulation is given in percentages of either base speed or set speed. Regulation is rated upon two separate sets of conditions.

_*Load Regulation (speed regulation)* is the percentage of speed change with a defined change in load, assuming all other parameters to be constant. Speed regulation values of 2% are possible in drive utilizing armature voltage feedback, while regulation of 0.01% is possible using digital regulator schemes.

_*Line Regulation* is the percentage of speed change with a given line voltage change, assuming all other parameters to be constant.

Resolution

The smallest distinguishable increment into which a quantity can be divided (e.g., position or shaft speed). It is also the degree to which nearly equal values of a quantity can be discriminated. For encoders, it is the number of unique electrically identified positions occurring in 360 degrees of input shaft rotation.

Resolution - 10 & 12 Bit

A circuit that has 10 Bit resolution means has an accuracy of 1.7 RPM or 0.06 Hz. This number is generated by the fact that a speed range of 0 to 60 Hz is divided in even increments that equal 1024. In other words, $(2)^{10}$=1024.

A circuit that has 12 Bit resolution would have an accuracy of 0.4 RPM or 0.015 Hz. 2^{12}=4096.

Resolvers

Resolvers are inherently an analog device, as opposed to a digital encoder. A resolver accepts an AC signal, then modifies the signal relative to the rotor/stator position inside the case.

A disadvantage of resolvers is the need to convert sinewave signals to digital pulses. This is required for the newer digital drive technology in existence.

Reversing

Changing direction of the motor shaft. An AC motor is reversed by reversing the connections of one leg on the three phase power line. The reversing function can be performed in one of the following ways:

_*AC Static Reversing* is the act of reversing the phase rotation of an AC motor with no mechanical switching. This is accomplished electronically with solid state devices.

Rise Time

The time required for a voltage pulse to rise from 10% to 90% of the peak voltage.

RFI

This is an abbreviation for “radio frequency interference.” This is also referred to as an electromagnetic noise which can operating problems in other electronic equipment. RFI is caused by switching circuits in electonic equipment. The effects are noticed more with equipment that is not properly grounded or in inductive devices like solenoids that do not have noise suppressors.

RS-232

An electrical connection standard that is used as an interface between data terminal equipment and communications equipment. One disadvantage of this type is usually a maximum cable length of about 15 feet and communication only between two devices at separate locations (point to point communication).

RS-422

An electrical connection standard that is used as an interface between data terminal equipment and communications equipment. Unlike the RS-232 connection, the RS-422 allows data transmission to be received by multiple locations.

RS-485

An electrical connection standard that is used as an interface between data terminal equipment and communications equipment. This type of connection allows faster data transmission rates (100 ms, 9600 baud) as compared with an RS-232 connection. In addition, longer cable lengths may be used (up to 1,200 feet) with very little additional amplification required. RS-485 also allows multiple point transmission and receiving of data on the same communication link.

RTD Module

This optional monitor circuit, accepts temperature inputs from an RTD mounted on a motor. (RTD is an abbreviation for resistive temperature device. This device changes resistance with changes in temperature and is an accurate indicator of heat generated within the motor.) A monitor circuit can provide actual temperature monitoring during motor operation as opposed to a thermistor (bi-metallic switch) that opens only when a dangerous condition exists.

Scalar

A type of drive (inverter) control that regulates the frequency to the motor to achieve a set speed without use of a tachometer. This is the simplest form of control and is considered “open loop” (no feedback device). The SAMI STAR is available in scalar control as standard with optional Vector control (closed loop using a feedback device such as a digital encoder).

Scalar Control

Scalar control adjusts the motor speed by varying the output frequency of a drive. The motor speed is then defined by the frequency and loading torque. The speed accuracy can be improved by speed feedback (tacho generator) and this system calls for Closed-loop scalar control.

Separately Ventilated

Separately ventilated motors have provisions for connecting an air duct that supplies cooling air from an external source. Since the cooling air comes into contact with the stator windings, rotor and air gap, a clean, dry air source is required.

Serial Communications

A method of digital communication where transmission occurs one electronic bit at a time. This is the most common long-distance communcation method such as from PLC in the control room to drive on the assembly floor.

Serial Interface

A method of data transmission that permits transmitting a single bit at a time through a single line. Used where high speed input is not necessary. Requires only one wire.

Serial Port

A connection point on a piece of electronic equipment that allows communication to another device. This port has fewer signal lines than a parallel port and passes information as a series of binary “on’s” and “off’s” (0’s and 1’s). An I/O configuration of only 3 lines will allow two-way communication (send and receive). This simple design is suitable for long-distance transfer of information but is at a slower rate compared to parallel communication.

Service Deviation

See Operating/Service Deviation

Service Factor

A number which indicates how much above the nameplate rating a motor can be loaded without causing series degradation (e.g., a motor with 1.15 S-F can produce 15% greater torque than one with 1.0 S-F)

When used in applying motors or gearmotors, it is a figure of merit which is used to adjust measured loads in an attempt to compensate for conditions which are difficult to measure or define.

Set Speed

The desired operating speed.

Silicon Controlled Rectifier (SCR)

A solid-state switch, sometimes referred to as a thyristor. The SCR has an anode, cathode and control element called the gate. The device provides controlled rectification since it can be turned on at will. The SCR can rapidly switch large currents at high voltages. They are small in size and low in weight.

Shield

A wire barrier, sometimes a wire mesh braid, that reduces the effect of electrical and/or maganetic fields. If shield braid is used, it completely surrounds the wires inside the outer casing.

Shock Load

The load seen by a clutch, brake or motor in a system which transmits high peak loads. This type of load is present in crushers, grinders, conveyors, winches and cranes.

Skew

The slight angular pattern of laminations on a rotor or armature with respect to the shaft axis. This pattern helps to eliminate low speed cogging in an armature and minimize induced vibration in a rotor as well as reduce associated noise.

Skewing

Refers to time delay or offset between any two signals in relation to each other.

Slip

The difference between rotating magnetic field speed (synchronous speed) and rotor speed of AC induction motors. Usually expressed as a percentage of synchronous speed.

Slip Compensation

Slip compensation is a technique for reducing the speed drop caused by the application of load in the asynchronous motor. The speed drop can be reduced to about 10% of the nominal slip. If very high speed control accuracy is required, a speed controller with a tachogenorator is required.

Special-Purpose Motor

A motor with special operating characteristics or special mechanical construction or both, designed for a particular application and not falling within the definition of a general purpose motor (NEMA).

Speed Range

Minimum and maximum speed at which a motor must operate under constant or variable torque load conditions. A 10:1 speed range for a motor with top speed of 1800 RPM means the motor must operate as low as 180 RPM and still remain within regulation specifications. Controllers are capable of wider controllable speed ranges than motors because there is no thermal limitation, only electrical. Controllable speed range of a motor is limited by the ability to deliver 100% torque below base speed without additional cooling.

Speed Regulation

A measurement, in percent, of how accurately the motor speed can bemaintained. It is the percentage of change in speed between full load and no load.

Stability

Ability of a drive to operate a motor at constant speed (under varying load), without "hunting" (alternately speeding up and slowing down). It is related to both the characteristics of the load being driven and electrical time constants in the drive regulator circuits.

Start-up Data

Start-up Data parameters allow an operator to set certain parameter values prior to starting the AC drive. These parameters are set according to the language you want the drive to display (such as German, Spanish, or English), the supply voltage providing power to the drive, and so on. In most cases, these parameters are one-time settings made only during the drive installation process.

Start-up Data parameters are not accessed through the same display levels as Operating Data parameters.

Stiffness

The ability of a device to resist deviation due to load change.

Supply Voltage

Supply voltage normally refers to the input voltage that provides power to the drive. Supply voltage is connected to Terminals L_1, L_2, and L_3 (U_1, V_1, and W_1).

Surge Protection

Absorbing and clipping voltage transients on an incoming AC line or control circuit. MOVs (Metal Oxide Varistors) and specially designed R-C networks are usually used to accomplish this.

Switching Frequency

Switching frequency is the internal operating frequency of and inverter. Typical values are from 1 kHz to 20 kHz. Increase of switching frequency reduces the motor noise but also reduces the efficiency of the drive.

Switching Frequency Range

This is the frequency of the PWM waveform for driving the output switches. The motor will make a noise that has its fundamental at twice the switching frequency. Most drives that use IGBT switches can go to 16 kHz switching frequency. When setting up a drive system, adjust the switching frequency for the lowest value that gives an acceptable noise level. As the switching frequency goes up, the drive efficiency goes down and losses increase. It is best to set the switching frequency as low as possible.

Synchronous Motors

A synchronous motor is a motor that operates at its synchronous speed without any slip. As long as the load does not exceed the limit for synchronous operation, the average operating speed is maintained exactly at the synchronous speed. There are several types of synchronous motors. The types that are sometimes used in AF applications are permanent magnet motors, wound rotor synchronous motors and synchronous reluctance motors. Synchronous reluctance motors are also called synchronous induction motors. Wound rotor synchronous motors require special AF controllers that are specifically designed for use only with synchronous motors. Permanent magnet and synchronous reluctance motors are sometimes used with AF controllers that are designed for use with induction motors, but special modifications are usually required.

Synchronous Speed

The speed of an AC induction motor's rotating magnetic field. It is determined by the frequency applied to the stator and the number of magnetic poles present in each phase of the stator windings. Mathematically, it is expressed as: Sync Speed (RPM) = 120 x Applied Freq. (Hz)/Number of poles per phase.

Tachometer - Generator (Tach)

There are two main types: AC and DC. The speed accuracy and motor type will dictate which type is required (e.g., PY, AN, C42, C46, etc.). The cost of these devices is related to the accuracy provided.

An AC tachometer has lower maintenance and is generally less expensive than a DC tach. The DC tach, however, operates over a higher speed range and has a higher accuracy than an AC tachometer. Also, no rectification is needed of a DC tachometer signal as compared with an AC tachometer.

A tach is basically a small generator normally used as a rotational speed sensing device. Tachometers are typically, coupled to the shaft of DC or AC motors requiring close speed regulation. The tach feeds a signal to a controller which then adjusts the output voltage or frequency to the motor.

TEFC (Totally Enclosed Fan Cooled)

TEFC motors are completely enclosed to prevent the entry of air or moisture into the interior of the motor. They are cooled by a small fan that is mounted on the motor shaft at one end of the motor. The fan forces air to flow over the outside surface of the motor. The motor surface may have fins or ribs to increase the outside surface area.

TENV (Totally Enclosed Nonventilated)

TENV motors are completely enclosed to prevent the entry of air or moisture into the interior of the motor. They are cooled only by the convection flow of air over the outside surface of the motor. The motor surface may have fins or ribs to increase the surface area. TENV motors are available in sizes of about 10 Hp and smaller.

TEBC (Totally Eclosed Blower Cooled) or TEAO (Totally Enclosed Air Over)

TEBC and TEAO motors are completely enclosed to prevent the entry of air or moisture into the interior of the motor. They are cooled by a separately powered fan or blower that is mounted on one end of the motor. The fan or blower forces air to flow over the outside surface of the motor. The motor surface may have fins or ribs to increase the surface area.

Termination Resistor

This resistor (located on many AC drive boards) provides an ending point for data transmission when connected to a PLC. The transmission and receiving devices therefore see the network as a complete electrical circuit.

Thread Speed

An adjustable, low fixed speed that provides a convenient method for loading and threading machines. May also be called a preset speed.

Thyristor

A controllable silicon rectifier is a contactless switching element (also known as an SCR).

100 V to 4500 V
0.4 A to 1500 A

Torque

A turning force applied to a shaft, tending to cause rotation. Torque is normally measured in ounce-inches or pound-feet and is equal to the force applied, times the radius through which it acts.

Torque Boost

The automatic increase of starting current for loads with high starting torque. It is possible for a short time to have a starting current higher than the normal current limit for the drive in the frequency range up to 20 Hz. Operates simutaneously with IR-compensation.

Torque Constant

This motor characteristic provides a relationship between input current and output torque. For each ampere of current applied to the rotor, a fixed amount of torque will result. This constant is listed in ft-lbs or in-lbs.

Torque Control

With torque control, the motor torque is always controlled by the torque reference. The motor speed operating point is defined by the intersection of motor torque and load torque curves. Direct Torque Control (DTC) is used when a very fast or accurate torque control is required.

Torque Loop

Basically, the same as a *Current Loop*. Because current is in direct relation to torque, the terms are sometimes used interchangeably. Current sensors within the drive monitor the current output. These sensors tell the drive Control Logic if the current output is within power device limitations.

Total Harmonic Distortion (THD)

A condition that exists when one or more harmonic current or voltage waveforms are added to the fundamental waveform (i.e. 60 Hz). This harmonic alters the fundamental waveform. The value is expressed in a percentage.

Totally Enclosed Machine (Enclosed Motor)

A totally enclosed machine is one so enclosed as to prevent the free exchange of air between the inside and the outside of the case but not sufficiently enclosed to be termed air-tight.

_*Totally Enclosed Fan-Cooled* is a totally enclosed machine equipped for exterior cooling by means of a fan or fans integral with the machine but external to the enclosing parts.

_*Explosionproof Machine* is a totally enclosed machine whose enclosure is designed and constructed to withstand an explosion of a specified gas or vapor which may occur within and to prevent the ignition of the specified gas or vapor surrounding the machine by sparks, flashes or explosions of the specified gas or vapor which may occur within the machine casing.

_*Dust-Ignition-Proof Machine* is a totally enclosed machine whose enclosure is designed and constructed in a manner which will exclude ignitable amounts of dust or amounts which might affect performance or rating, and which will not permit arcs, sparks or heat otherwise generated or liberated inside of the enclosure of cause ignition of exterior accumulations or atmospheric suspensions of a specific dust on or in the vicinity of the enclosure.

_*Waterproof Machine* is a totally enclosed machine so constructed that it will exclude water applied in the form of a stream from a hose, except that leakage may occur around the shaft provided it is prevented from entering the oil reservoir and provision is made for automatically draining the machine. The means for automatic draining may be a check value or a tapped hole at the lowest part of the frame which will serve for application of a drain pipe.

_*Totally Enclosed Water-Cooled Machine* is a totally enclosed machine which is cooled by circulating water, the water or water conductors coming in direct contact with the machine parts.

_*Totally Enclosed Water-Air-Cooled Machine* is a totally enclosed machine which is cooled by circulating air which, in turn, is cooled by circulating water. It is provided with a water-cooled heat exchanger for cooling the internal air and a fan or fans, integral with the rotor shaft or separate, for circulating the internal air.

_*Totally Enclosed Air to Air Cooled Machine* is a totally enclosed machine which is cooled by circulating the internal air through a heat exchanger which, in turn, is cooled by circulating external air. It is provided with an air to air heat exchanger for cooling the internal air and a fan or fans, integral with the rotor shaft or separate, for circulating the internal air and a separate fan for circulating the external air.

_*Totally Enclosed Fan-Cooled Guarded Machine* is a totally enclosed fan-cooled machine in which all openings giving direct access to the fan are limited. They are limited in size, the design of the structural parts, or by screens, grills, expanded metal, etc. These parts prevent accidental contact with the fan. Such openings shall not permit the passage of a cylindrical rod 0.75 inch in diameter, and a probe shall not contact the blades, spokes or other irregular surfaces of the fan.

_*Totally Enclosed Air-Over Machine* is a totally enclosed machine intended for exterior cooling by a ventilating means external to the machine.

T_R

This notation abbreviates the rated output torque of the motor.

Transducer

A device that converts one form of energy (e.g., mechanical to electrical) to another. For example, a tach or encoder converts mechanical rotation or position into electrical signals. These signals are understood by the drive Control Logic circuits. A pressure transducer (PT) converts air pressure to an analog electric signal.

Transient

A momentary deviation in an electrical or mechanical system (i.e., voltage spikes imposed on the AC supply line).

Transistor

A solid-state three-terminal device that allows amplification of signals and can be used for switching and control. The three terminals are called the *emitter, base* and *collector.*

Variable Frequency Drive (VFD)

A drive system including the electric machine with its mechanical and electrical control equipment where the speed of the driven equipment is varied electrically. The output of this drive is variable frequency (Hz) which changes the speed of an AC motor. A VFD could indicate an AC or a DC Drive.

Variable Torque Load

A load where torque varies directly to the square of speed and horsepower varies directly to the cube of speed. The load requires much lower torque at low speeds than at high speeds. Typical applications include centrifugal pumps, fans and some mixers.

Vector

A quantity that has magnitude, direction and sense. This quantity is commonly represented by a directed line segment whose length represents the magnitude and whose orientation in space represents the direction.

Vector Control

The technique of controlling a standard AC induction motor by electronically modeling the motor within the logic of the AC drive. The AC drive logic simulates what actually happens in a DC motor. This process allows the AC motor to operate much like a DC motor, with high speed response and without speed oscillations. The result is a fast, controlled torque response, which was previously only obtained by DC systems.

In vector control, a feedback device (i.e. digital encoder) sends back a signal to the drive indicating actual rotor / stator position or relationship. The drive then calculates the voltage and current "vectors." This permits the accurate control of speed and motor torque at all speeds, even zero.

V_{IN}

This notation abbreviates the input voltage of the drive. Refer to *Supply Voltage* in this "Terms and Definitions" section.

V_N

This notation abbreviates the voltage for which the drive is programmed (i.e. Nominal).

Voltage Reflection

A phenomenon in which a voltage wave or pulse is transmitted through a cable to a motor and is reflected or transmitted back to the AC drive.

V / Hz (Volts per Hertz)

This is the fixed relationship between voltage and frequency that exists in a motor. The motor will develop rated torque if this relationship is kept constant (linear). The drive can vary this relationship in order to minimize audible noise, motor losses and maximize efficiency.

If a "squared" V / Hz pattern is programmed, the voltage of the motor varies as the square of the frequency applied by the drive. This is useful in applications where the load torque is proportional to the square of speed (i.e. centrifugal pumps and fans). These loads are called variable torque loads.

An "automatic" V / Hz pattern automatically controls the voltage to the motor, thereby controlling the torque. This is considered an energy saving feature of the drive and is useful in lightly loaded applications.

V_R

In an AC drive, this notation abbreviates the rated input voltage setting, in volts.

VVI

This type of AC drive controls the voltage and frequency to the motor to produce variable speed operation. A VVI type drive controls the voltage in a section other than the output section where frequency generation takes place. Frequency control is accomplished by an output bridge circuit which switches the variable voltage to the motor at the desired frequency.

Wound Rotor Motors

Wound rotor motors are sometimes used with variable frequency drives by shorting their slip rings and operating them like regular induction motors.

General Information

When selecting an adjustable speed AC or DC drive, the load type is a very important consideration. During the selection process, it is important to understand the speed and torque characteristics. It is also important to understand the horsepower requirements of the type of load to be considered.

AC drive characteristics are somewhat different than DC drives. The requirements of a particular application need to be matched to the drive capabilities. Once the application requirements are understood, a decision regarding the type of adjustable speed drive can be made.

The following load characteristics need to be considered when evaluating applications:

_Type of load involved?

_Is a shock factor involved with the load?

_Size of the load?

_Are heavy inertial loads involved?

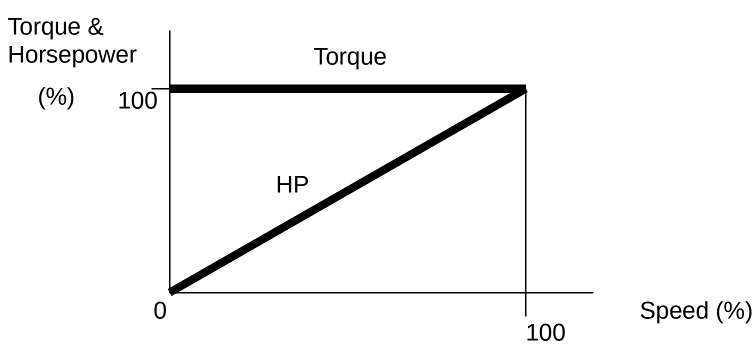
_What special motor considerations are involved?

_What speed range is involved with the load?

Loads are classified into three main categories depending on torque and horsepower relationships. The following reviews various DC and AC motor load types usually found in typical applications.

Constant Torque Load

This type of load is the one most frequently encountered. In this group, the torque demanded by the load is constant throughout the speed range. The load requires the same amount of torque at low speeds as at high speeds. Loads of this type are essentially friction loads (e.g. the torque characteristic needed to overcome friction). the following figure shows the constant torque and variable horsepower demanded by the load.



As shown in the figure, torque remains constant while horsepower is directly proportional to speed. A look at the basic horsepower equation also verifies this fact.

$$HP = \frac{Torque X Speed}{5252}$$

Where:

Torque = lb-ft.

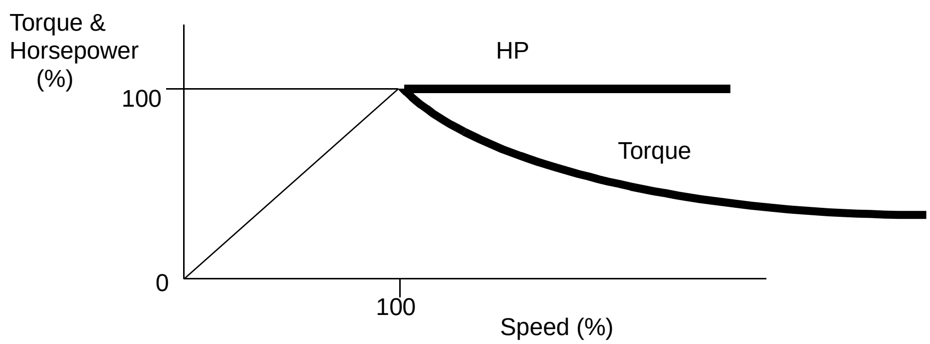
Speed = RPM

5252 = a proportionally constant

Examples of this type of load are conveyors, extruders and surface winders. Constant torque is also used when shock loads, overloads or high inertia loads are encountered.

Constant Horsepower Load

In this type of load, the horsepower demanded by the load is constant within the speed range. The load requires high torque at low speeds. From the equation above, you can see that with the horsepower held constant, the torque will decrease as the speed increases. The speed and torque are inversely proportional to each other. The following figure shows the constant horsepower and decreasing torque demanded by the load.



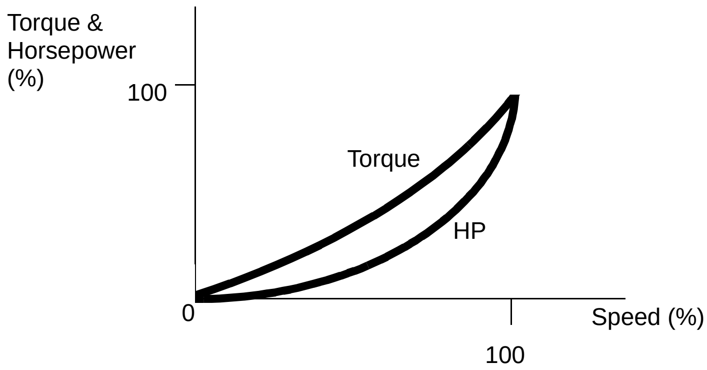
Examples of this type of load are center-driven winders and machine tool spindles. A specific example of this application would be a lathe that requires slow speeds for rough cuts and high speeds for fine cuts (e.g. little material is removed). Usually very high starting torques are required for quick acceleration.

Variable Torque Load (Centrifugal Load)

With this type of load, the torque is directly proportional to a mathematical power of speed, usually speed squared ($Speed^2$). Mathematically it can be expressed as:

Torque Constant X $Speed^2$

In a Variable Torque Load, horsepower is typically proportional to speed cubed ($Speed^3$). The following figure shows the variable torque and horsepower demanded by the load.

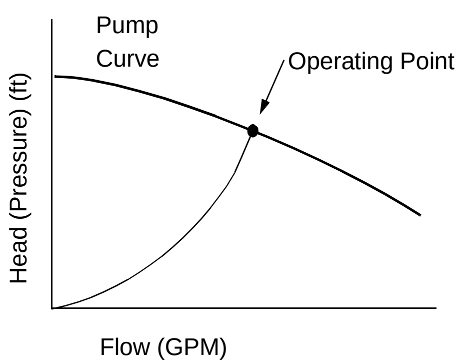


Examples of this type of load are centrifugal fans, pumps and blowers. This type of load requires much lower torque at low speeds than at high speeds.

Pump Energy Savings

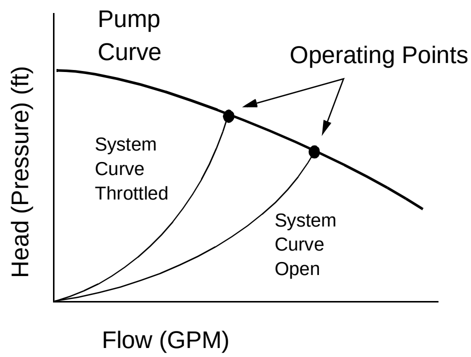
Pumps are generally grouped into two broad categores: positive displacement pumps and dynamic (centrifugal) pumps. The vast majority of pumps used today are the dynamic or centrifugal type, and will be discussed in the following paragraphs.

The graph below shows two independent curves. The pump curve is solely a function of the pump characteristics. The other is the system curve. This curve depends on the size of pipe, the length of pipe, the number and location of elbows, etc. The intersection of these two curves is called the operating point, because the pump pressure matches the system losses.



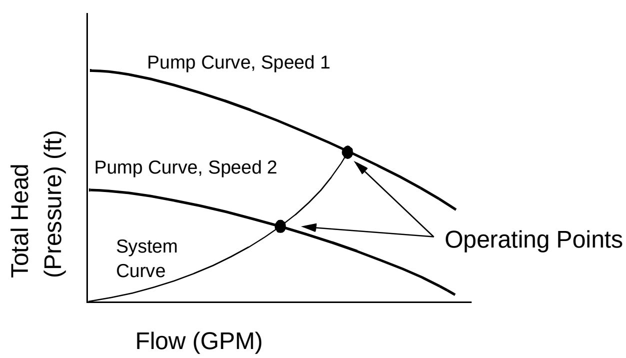
If the system is part of a process that requires adjustable flow rates, then some method is needed to continuously alter the pump characteristics or the system parameters. Methods include valves for throttling, which change the system curve, or variable speed control of the pump, which modifies the pump curve.

The figure below shows a throttling system with two operating conditions: one with the valve open and the other with the valve throttled or partially closed. Closing the valve effectively increases the system head and decreases the flow.

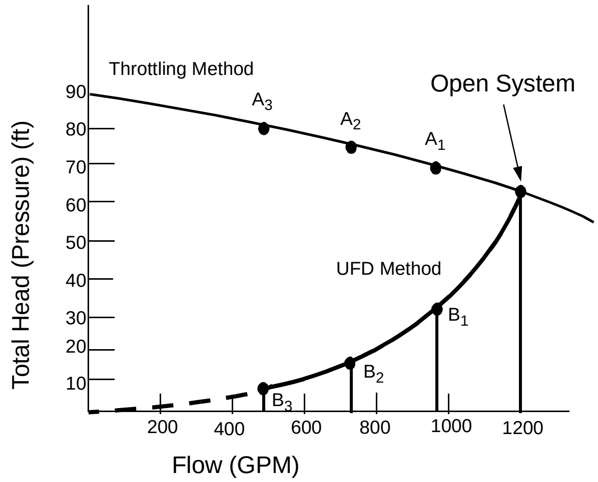


By comparison, the variable speed method changes the pump characteristics when the pump impeller speed is changed (see figure below).

Of these two, only the adjustable speed method uses considerably less energy with reduced flow, thus offering significant energy savings. As an example, let’s look at a particular pump with a 14 in. impeller, operating at a base speed of 1150 rpm in a system with a 63 ft head (no static head). The pump delivers 1200 gpm when teh system is not throttled (see figure below). The process requires flow rates of 1200, 960, 720, and 480 gpm.



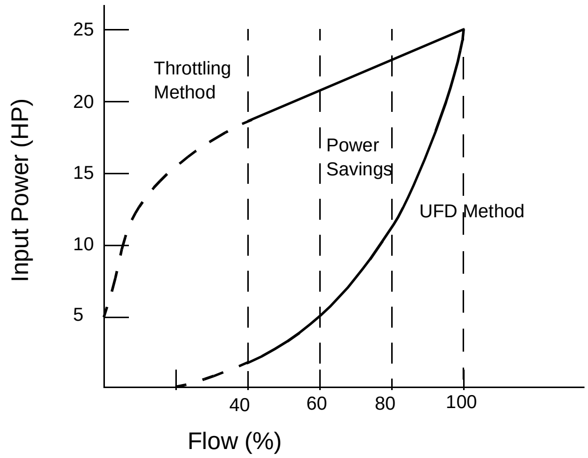
For a specific flow rate, the difference between points A and B gives a visual indication of possible energy savings (see figure below). In addition, changes in pump efficency should be included in the calculation to determine brake horsepower.



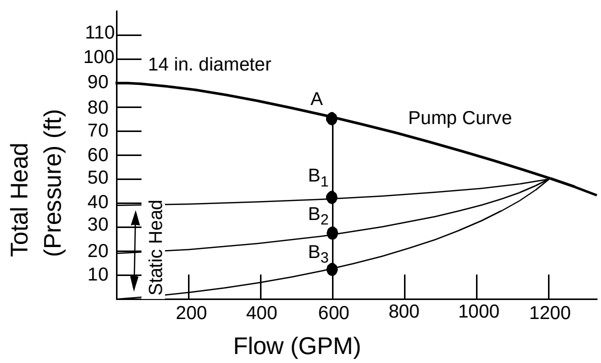
The following table lists the comparative brake horsepower values required by throttling and adjustable speed methods for the four operating points.

Throttling Method				VFD Method		
Flow (gpm)	**Head (ft)**	**Pump Efficiency (%)**	**Bhp**	**Head (ft)**	**Pump Efficiency (%)**	**Bhp**
1200 (100%)	63	76.3	25	63	76.3	25
960 (80%)	69	73	23	40	75	13
720 (60%)	75	65	21	23	75	5.6
480 (40%)	81	54	18	10	75	1.6

The following figure shows the power requirements and savings for the various flow rates.



This example does not include a static head (pressure required to overcome a change in elevation). The magnitude of the static head will affect the possible power savings. The less the static head is in relation to the total head, the greater the power savings will be achieved by using VFDs--one with no static head, and two with different amounts of static heads.

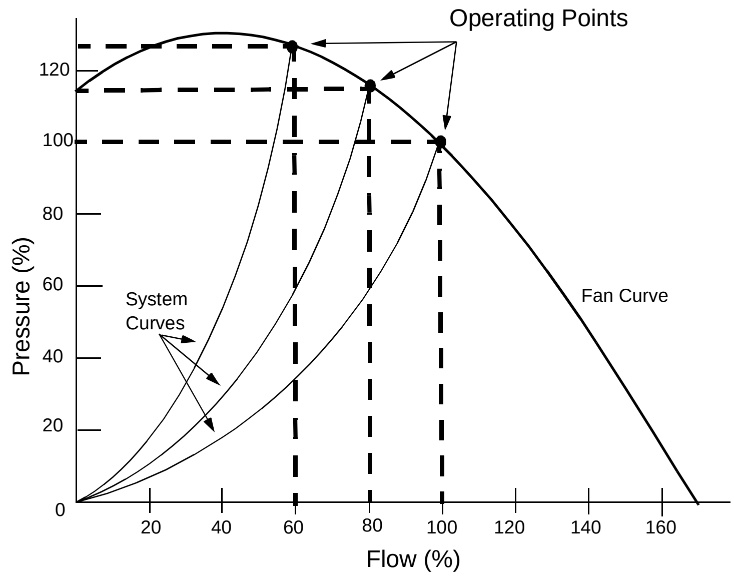


For a given flow rate, the difference between operating points A and B indicate possible power savings with VFDs. The difference between points A and B_3 (no static head) is greater -- and offers greater power savings -- than between a and B_1, which has a 40 ft static head.

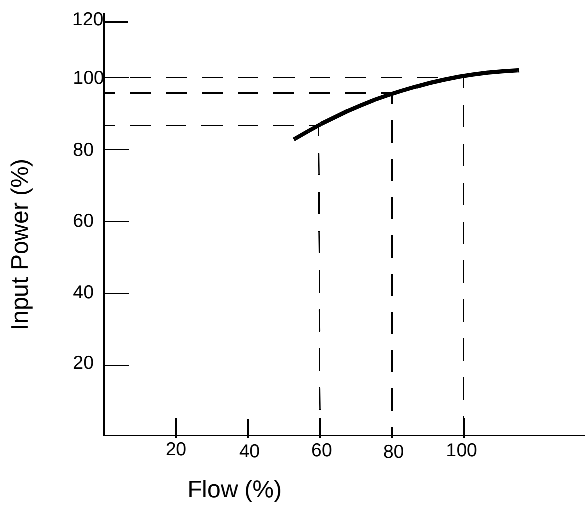
Fan Energy Savings

The basic operation of centrifugal fans is similar to pumps. Similar energy savings are achieved. However, the common units are slightly different. Outlet pressure (static inches of water) is used in place of head (feet of water) and flow is usually expressed in cubic feet per meter (cfm)

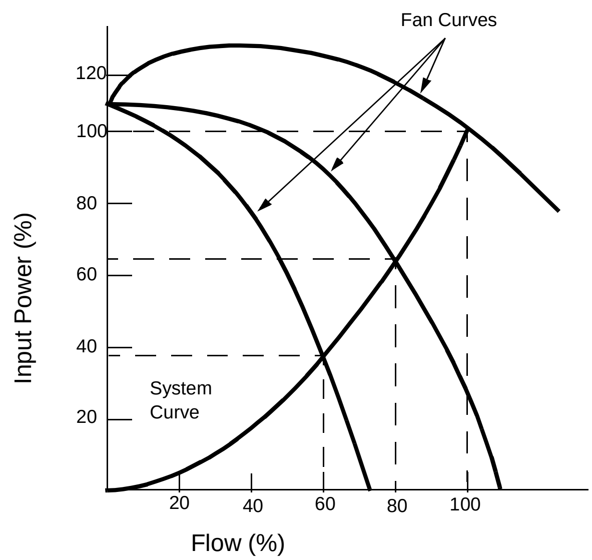
Several different methods are used to throttle or regulate fan outputs. The most common include outlet dampers and variable inlet vanes. Outlet dampers affect the system curve by increasing the resistance to air flow, much the same as a valve throttles a pump output (see the next figure).



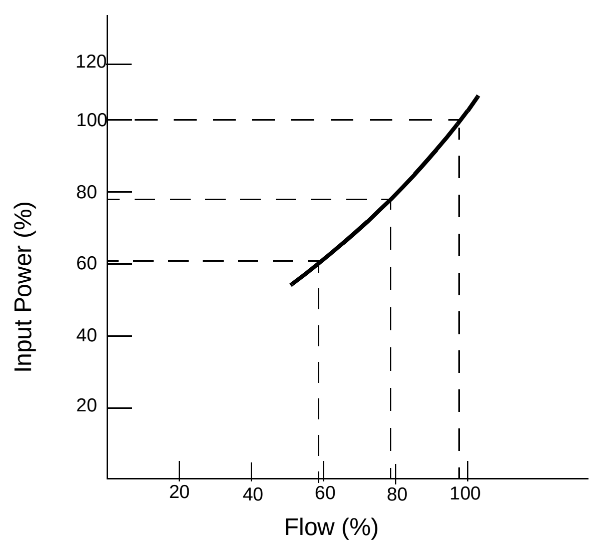
The following figure shows that as the flow is decreased, the power requirement is reduced only slightly.



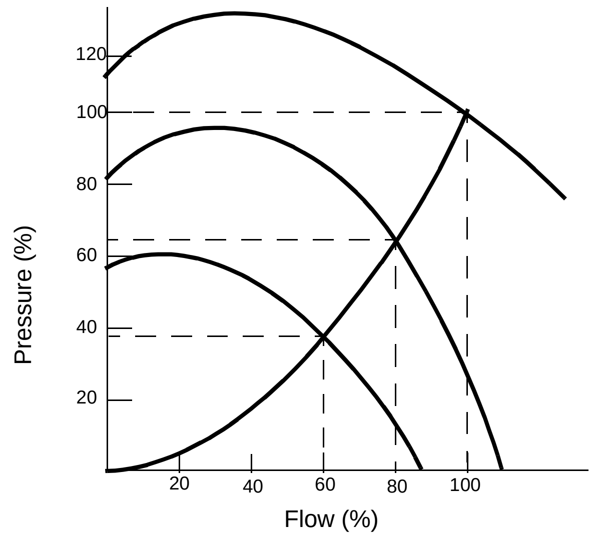
Inlet guide vanes direct the air flow as the air enters the fan, and, actually modify the fan curve (see the next figure).



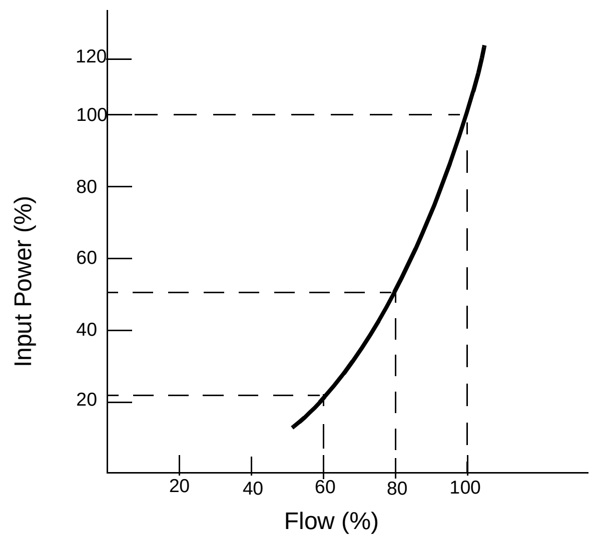
With these vanes, power requirements are significantly reduced as flow is decreased (see figure below).



As with pumps, VFDs offer the greatest energy savings for fans. This adjustable flow method changes the fan curve (see the next figure).



Using VFDs greatly reduces the power requirements, even more than for inlet guide vanes.(see figure below)



Application Examples

Below is a listing of the common load types and application examples of each type.

Load Type	Example:
Constant Torque	General Machinery, hoists, cranes, conveyors printing presses (about 90% of applications)
Constant Horsepower	Metal cutting (operating over a high speed range) extruders, machines where operation at speed may be continuous, mixers

Variable Torque	Centrifugal pumps and fans (Fan power may vary as Speed^2

Special Considerations

High Inertia Loads

These loads are usually associated with machines using flywheels that supply most of the operating energy. Typical examples of this type include punch presses and centrifuges. When applying an AC drive, Torque Boost and IR Compensation settings will assist in overcoming high starting torque requirements.

Shock Loads

These types of loads include: crushers, separators, grinders, conveyors, winches, cranes and vehicular systems. Drives applied to these loads must manage loads ranging from a small fraction to several hundred percent of the rated load.

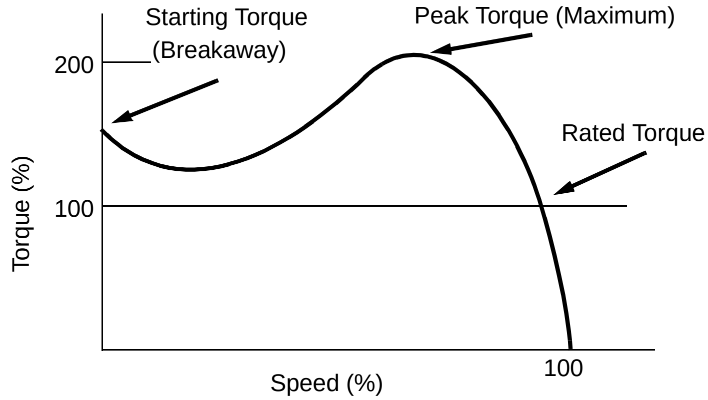
Under these considerations, a drive has two tasks: move the load and protect the prime mover and driven equipment. If the prime mover is an electric motor, shock loads can damage components such as bearings, brushes and commutators. This load can also damage components of the drive control circuitry, by inducing signal irregularities and electrical overloads in the power converter.

Size of Load

The size of the load determines the type of drive to be applied. Adjustable speed drives (AC, DC, fluid, traction, etc.) range from fractional to multithousand horsepower. However, not all types of drives can be manufactured in full the range. Generally, power converter rectifier technology is the limiting factor in what is practical or economical to manufacture for any given type of electrical drive.

AC Motor Torque

In an AC induction motor, torque results from the magnetic attraction between the rotor and stator. In essence, the stator (stationary case) has a rotating magnetic field at a frequency delivered by the VFD (variable frequency drive). The rotor (rotating piece) is attracted to the stator producing a twisting motion called torque. The following figure shows an AC induction motor curve.



As seen in the figure, the torque produced at locked rotor (breakaway torque) is higher than rated torque, but less than the peak torque point.

As the motor begins to accelerate, torque drops off, reaching a minimum value. This is between 25-40% of synchronous speed.

As acceleration continues, rotor frequency and inductive reactance decrease. The rotor flux moves more in-phase with stator flux and consequently, torque increases.

Maximum torque is developed where inductive reactance becomes equal to the rotor resistance. Beyond the maximum torque point, the inductive reactance continues to drop off along with the current through the rotor. The slip also decreases. The torque capabilities of the motor therefore also decreases.

For a NEMA Design B motor, typical operating slip is between 3 to 5% (operating at the Rated Torque point).

General Information

AC adjustable frequency drives are also sometimes referred to as VFD's (Variable Frequency Drives) or ASD's (Adjustable Speed Drives). These drives are gaining in popularity due to the energy savings that can be obtained related to the AC technology. In addition, AC motors are simpler than DC and are usually an "off-the-shelf" item compared to DC motors. Advances in technology have made the size, cost, reliability and performance of AC drives (controllers) very appealing in industrial variable speed applications.

Basic Operation

AC drives convert a fixed, 3 phase voltage and 60 Hz frequency source into a variable voltage and frequency source. In order to control the speed of the motor, the frequency applied to the motor must also be controlled. This can be seen by the following formula:

$$N = \frac{120 \text{ X } F}{P}$$

Where:
N = Speed in RPM
F = Frequency in Hz
P = Number of pole pairs

Since the number of poles is relatively constant, the only convenient factor to vary is the frequency. Frequency determines the motor speed. However, the motor needs to supply rated torque, no matter what the speed is.

In order for rated torque to occur, it is necessary to keep the voltage and frequency in a constant relationship. This is called the Volts per Hertz relationship and is shown in the following proportions:

For 230 VAC Input

$$\frac{230 \text{ V}}{60 \text{ Hz}} = \frac{3.83 \text{ V}}{1 \text{ Hz}}$$

For 460 VAC Input

$$\frac{460 \text{ V}}{60 \text{ Hz}} = \frac{7.67 \text{ V}}{1 \text{ Hz}}$$

As seen in the proportions, there is a specific voltage to frequency relationship that exists in an AC motor. With this relationship supplied to the motor, the motor will be able to develop rated torque at all speeds. There is one exception however - low speed operation.

At low speeds, the stator losses tend to rob the motor of its full torque producing capability. In order for the motor to compensate for this problem, additional voltage must be supplied by the drive. In the case of ABB drives, Torque Boost (an additional DC voltage) is supplied to the motor when operating from 0 to 20 Hz. In most cases, it is possible to select how much boost and when it will occur in the speed range.

There are three major categories of AC drives that we will consider for the remainder of this discussion: VVI (Variable Voltage Input), CSI (Current Source Inverter) and PWM (Pulse Width Modulation).

Variable Voltage Input (VVI)

This design takes the supply voltage (i.e. 230 V or 460V), rectifies it and sends the variable voltage to the DC Bus and then to an inverter section. The Inverter section then "inverts" (changes DC to AC) the variable voltage DC to a variable voltage and frequency AC. The Inverter section contains power semiconductors such as transistors or thyristors (SCR's).

In order to deliver variable voltage to the inverter, the input rectifier section or front-end consists of a controllable rectifier - SCR's. The control logic fires the SCR's at the appropriate time during the sine wave, thereby providing the variable voltage to the DC Bus. Figure AC-1 shows a block diagram of a VVI drive.:

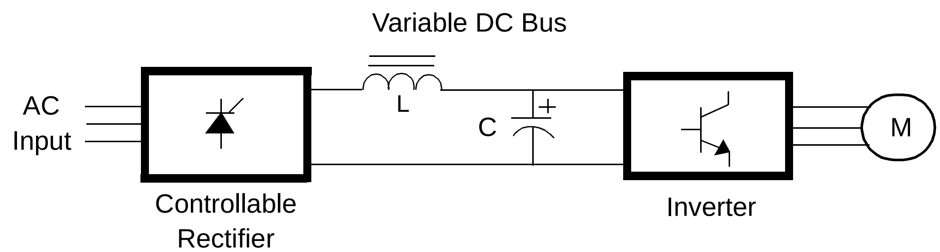


Figure AC-1. VVI Block Diagram

Some of the advantages of a VVI drive include:

- Good speed range
- Able to connect multiple motors to the drive (within drive current limitations)
- Simple control regulator

There are some limitations, however:

- Input power factor decreases as the speed of the drive / motor decreases
- The ability for the drive to "ride through" a low input voltage situation
- The generation of additional output harmonics
- The characteristic of low speed motor cogging (shaft pulsations / jerky motion)
- Requirement of an input isolation transformer due to the control technology (line spike generation)

The last limitation, low speed cogging, is best illustrated in Figure AC-2

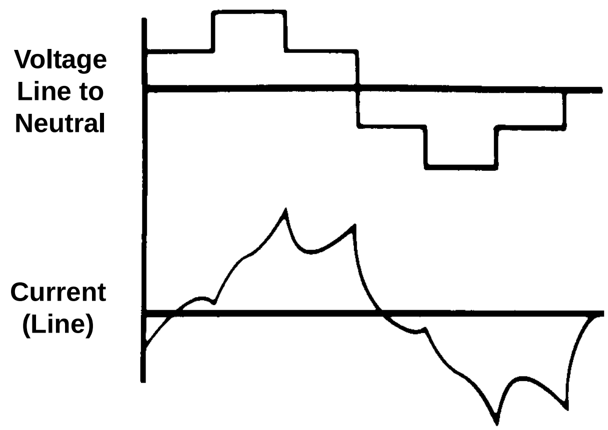


Figure AC-2. VVI Voltage and Current Waveforms

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As seen in the figure, the voltage waveform approximates a series of steps. Because of this characteristic, this drive is sometimes called a "six step" drive.

During low speed operation (under 15-20 Hz), the rotor actually searches for the next available magnetic field in the stator. The result is jerky rotation of the motor shaft. Because of this, gears or gear reducers connected to the motor shaft will suffer additional friction and wear. At high speeds, the inertia of the motor will provide continuous movement of the motor shaft. Therefore, cogging is not a problem.

As shown in the current waveform, there are several spikes that occur at regular intervals. These spikes or transients are caused by the SCR’s gating "on" or triggering. The DC Bus filter circuit (shown by an L and C) does reduce the effects of these spikes, but they are not eliminated. These spikes translate into additional motor heating and inefficiency.

The VVI drive was one of the first AC drives to gain acceptance into the industrial drives market. It may be considered one of the most economical drives in the 25 to 150 HP range if a 6:1 speed range is acceptable (operation from 10 to 60 Hz). This type of drive is also widely used in high-speed drive applications - 400 Hz to 3,000 Hz.

Another type of AC drive to gain acceptance is the CSI drive.

Current Source Inverter (CSI)

This type of AC drive (sometimes referred to as Current Source Input) has basically the same components as a VVI drive. The major difference is that it is more of a current sensitive drive as opposed to a VVI which is more of a voltage sensitive drive.

This design also takes the supply voltage (i.e. 230 V or 460V), rectifies it and sends the variable voltage to the DC Bus and then to the inverter section. As with the VVI, the CSI drive inverter section "inverts" (changes DC to AC) the variable voltage DC to a variable voltage and frequency AC. The inverter section is made up of power semiconductors such as transistors or thyristors (SCR’s).

In order to deliver variable voltage to the inverter, the input rectifier section also consists of a controllable rectifier - SCR's. The control logic fires the SCR's at the appropriate time during the sine wave, thereby providing the variable voltage to the DC Bus. Figure AC-3 shows a block diagram of a CSI drive.

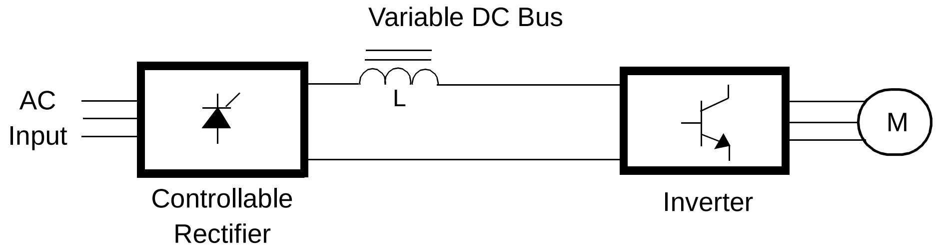

Figure AC-3. CSI Block Diagram

Some of the advantages of a CSI drive include:

- High efficiency
- Capability of optional regeneration
- Inherent short circuit protection (due to the current regulator within the drive)
- Inherent regenerative capability back to the AC line during overhauling load situations
- Capability of synchronous transfer (bringing other motors on-line during full voltage output)

There are also some limitations, however:

- Input power factor decreases as the speed of the drive / motor decreases
- Limited speed range due to low speed motor cogging (shaft pulsations / jerky motion)
- Inability to operate more than one motor at a time on the drive
- Inability for the drive to "ride through" a low input voltage situation
- Requirement to match the motor characteristics to the drive (usually the motor and drive are sold as a complete package)
- Motor normally requires a feedback device (i.e. tachometer) to provide information to the drive current regulator
- Inability to test the drive without the motor connected
- Requirement of an input isolation transformer due to the control technology (line spike generation)
- Physical size is usually larger than other drive types due to internal power components

As mentioned earlier, the VVI and CSI drives produce low speed cogging . This is illustrated in Figure AC-4.

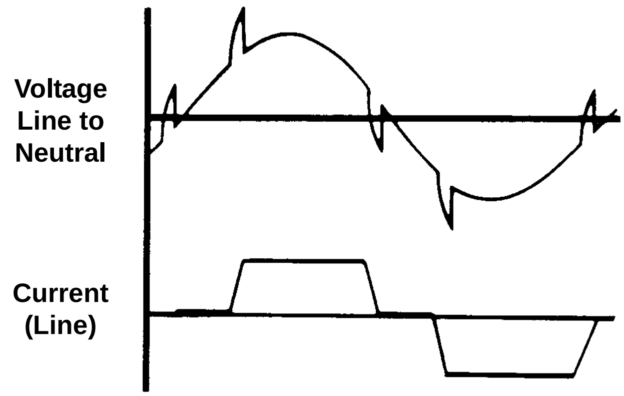

Figure AC-4. CSI Voltage and Current Waveforms

As seen in the figure, there is also line notching or spikes developed due to the gating of SCR's in the drive front-end. The voltage waveform is, however, somewhat closer to the sinewave voltage required by the motor.

The current waveform appears to simulate a trapezoid. In addition, there are times when no current flows. These "gaps" in current cause the rotor to search for the next available magnetic field in the stator. This characteristic, like that of the VVI, results in jerky rotation of the motor shaft at low speeds (under 15-20 Hz).

As with the VVI drive, the DC Bus filter circuit (shown by an L) does reduce the effects of these spikes, but they are not eliminated. Here again, these spikes translate into additional motor heating and inefficiency.

CSI drives are the latest addition of the line-up of AC Variable Frequency Drives. They are usually used in applications requiring 50 HP or larger. These VFD's are well suited for powering pumps and fans due to the inherent synchronous transfer capability. The cost of a CSI drive may be less than either a VVI or PWM in powering pumps, fans or similar applications. However, the efficiency of the CSI drive matches that of the DC drive and may not provide a total energy saving package compared to the PWM drive (discussed next).

Pulse Width Modulation (PWM)

The power conversion principle of this drive is different from that of VVI and CSI. One of the major differences is that of a fixed diode front-end, not a controllable SCR front-end. This fixed diode bridge provides a constant DC bus voltage. The DC Bus voltage is then filtered, and sent to the Inverter section. Another difference between PWM and the other types is the operation of the Inverter section.

The Inverter in the PWM drive has a dual purpose: changes fixed voltage DC to variable voltage AC, changes fixed frequency to variable frequency. In the other types, the Inverter's primary purpose is to change the fixed frequency to a variable frequency output.

PWM drives use several types of power transistors. IGBT's (Insulated Gate Bipolar Transistors) and GTO's (Gate Turn-Off - SCR's) are several examples. These semiconductors offer the advantages of PWM technology without the expense of commutation circuits. (Commutation circuits are required to turn-off the SCR's once they start conducting. They are found in early VVI or CSI units.)

Another major difference is the actual voltage output of the Inverter itself. The DC Bus voltage is fixed, and approximately equal to the RMS value of the drive input voltage (i.e. 460V X 1.414 = 650V). By chopping or modulating the DC Bus voltage, the average voltage (output voltage) is increased or decreased.

The output voltage value is controlled by the length of time the power semiconductors actually conduct. The longer the "on" time for the semiconductors, the higher the output voltage. The longer the "off" times occur in the process, the lower the frequency output. Thus the Inverter accomplishes both variable voltage and frequency. Figure AC-5 shows a block diagram of a PWM drive.

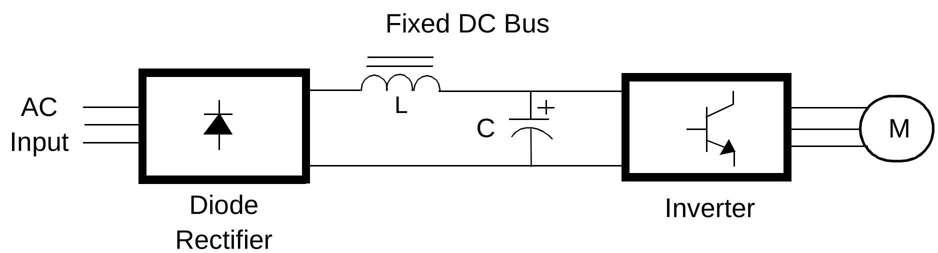

Figure AC-5. PWM Block Diagram

Some of the advantages of a PWM drive include:

- High efficiency
- The capability of optional common bus regeneration (operating several inverter sections off of one DC Bus)
- Wide controllable speed range (in some cases up to 200:1, with no low speed cogging under 20 Hz operation)
- Ride through capability (inherent in many AC Drives)
- Open circuit protection
- Constant input power factor (This is due to the fixed diode front end and DC Bus inductor. Constant power factor is not seen by CSI, VVI or DC drives.)
- Multimotor operation (within the current limitations of the drive)

There are also some limitations, however:

- Extra hardware is required for line regenerative capability
- Complexity of the regulator is higher compared to VVI (Note: Microprocessor control has nearly eliminated significant economic differences.)

As mentioned, low speed cogging is not an issue with PWM drives. This fact can be illustrated in Figure AC-6.

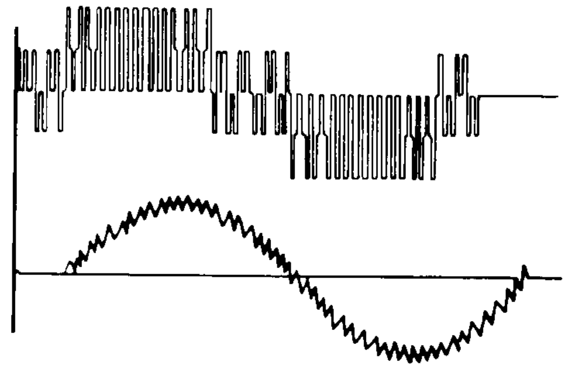

Figure AC-6. PWM Voltage and Current Waveforms

As seen in the figure, there is no line notching or spikes developed due to the diode front-end. The voltage waveform, that could be superimposed on the modulations, very closely approximates the sinewave voltage required by the motor. If the carrier frequency is high (8-12KHz), the quality of low speed operation is improved. The higher the carrier frequency, the smoother the motor operation. (Carrier frequency is the speed at which the power semiconductors are switched on and off.)

Another benefit of high carrier frequencies is that of reduced audible noise. The higher the frequency, the less motor noise is generated. Audible motor noise can be an issue with low switching rates (i.e. 1 to 3 KHz).

The current waveform, though it contains some ripple, is the smoothest of the 3 types of drives. It closely approximates the AC sinewave. The efficiency is therefore very high with little motor heating.

Continued improvements in drive technology have enabled PWM drives to deliver a response almost equal to that of DC Servo's. High response applications such as machine tools and robots require very precise control of motor speed and torque. PWM vector drives provide this type of capability and are covered in separate technical articles.

Note

The following information is an overview of NEMA enclosures available for drives. For detailed descriptions consult the *National Electrical Manufacturers Association (NEMA) Standards Publication No. 250.* Refer to the sales manual for specific ABB enclosures available as standard or as an option.

Enclosures normally do not protect devices against internal conditions such as condensation, corrosion or contamination. The user is responsible for protecting equipment from these conditions.

Enclosures normally do not protect internal devices against conditions such as: condensation, icing, corrosion or contamination. These conditions may occur inside the enclosure or may enter by way of the conduit or unsealed openings. Ultimately, protection is in the hands of the user who must take adequate precautions to protect the equipment inside the enclosure.

NEMA Type 1 (Surface Mounting) (IP 21)

These enclosures provide a degree of protection against contact with the enclosed equipment. These enclosures are intended for indoor use and in typical service conditions. The enclosure is sheet steel, treated to resist corrosion.

NEMA Type 1 (Flush Mounting)

These enclosures are for installation in machine frames and plaster walls. These enclosures are for similar applications and are designed to meet the same tests as NEMA Type 1 surface mounting.

NEMA Type 3

These enclosures are intended for outdoor use primarily to provide a degree of protection against windblown dust, rain, sleet and external ice formation. They are designed to meet rain[1], external icing,[2] dust and rust-resistance design tests. They are not intended to provide protection against conditions such as internal condensation or internal icing.

NEMA Type 3R

These enclosures are intended for outdoor use primarily to provide a degree of protection against falling rain, sleet, and external ice formation. They are designed to meet rod entry, external icing,[2] rain,[3]and rust-resistance design tests. They are not intended to provide protection against conditions such as dust, internal condensation or internal icing.

NEMA Type 4 (IP 55)

These enclosures provide protection against windblown dust and rain, splashing water, and hose-directed water. They can be used in both indoor and outdoor installations. They are designed to meet hosedown, dust, external icing [1], and rust-resistance design tests. These enclosures do not provide protection against conditions such as internal condensation or internal icing. Enclosures are made up of heavy gauge stainless steel, cast aluminum or heavy gauge sheet steel, depending on the type and size of unit. Cover has a synthetic rubber gasket.

NEMA Type 4X (IP 45)

These enclosures are intended for indoor or outdoor use primarily to provide a degree of protection against corrosion, windblown dust and rain, splashing water and hose-directed water, undamaged by the formation of ice on the enclosure.

NEMA Type 6

These enclosures are intended for use indoors or outdoors where occasional submersion is encountered.

NEMA Type 6P

These enclosures are intended for indoor or outdoor use primarily to provide a degree of protection against the entry of water during prolonged submersion at a limited depth. They are designed to meet air pressure, external icing,[2] and corrosion-resistance design tests. They are not intended to provide protection against conditions such as internal condensation or internal icing.

NEMA Type 7

(For hazardous gas locations with bolted enclosure) These enclosures are for indoor use in locations classified as Class 1, Groups C or D, defined in the National Electrical Code. Enclosures of this type are designed to be capable of withstanding the pressures resulting from an internal explosion os specified gases, and contain such an explosion sufficiently that an explosive gas-air mixture existing in the atmosphere surrounding the enclosure will not be ignited. Enclosed heat generating devices are designed not to cause external surfaces to reach temperatures capable of igniting explosive gas-air mixtures in the surrounding atmosphere. Enclosures are designed to meet explosion, hydrostatic, and temperature design tests. The exterior finish of this enclosure is a special corrosion-resistant enamel.

NEMA Type 9

(For hazardous dust locations) These enclosures are intended for indoor use in locations classified as Class II, Groups E, F, or G, as defined in the National Electrical Code. Type 9 enclosures are designed to be capable of preventing the entrance of dust. Enclosed heat generating devices are designed not to cause external surfaces to reach temperatures capable of igniting or discoloring dust on the enclosure or igniting dust-air mixtures in the surrounding atmosphere. Enclosures are designed to meet dust penetration and temperature design tests, and aging of gaskets. The outside finish is of a special corrosion-resistant enamel.

NEMA Type 12 (IP 54)

Type 12 enclosures are intended for indoor use primarily to provide a degree of protection against dust, falling dirt, and dripping noncorrosive liquids. They are designed to meet drip [2], dust, and rust-resistance tests. They are not intended to provide protection against conditions such as internal condensation.

NEMA Type 13

These enclosures are intended for indoor use primarily to provide a degree of protection against dust, spraying of water, oil and noncorrosive coolant. They are designed to meet oil exclusion and rust-resistance design tests. They are not intended to provide protection against conditions such as internal condensation.

[1] Evaluation criteria: Undamaged after ice which built up during specified test has melted (Note: **NOT** required to be operable while ice-laden).

[2] Evaluation criteria: No water shall rise as high as the lowest electrical part after the specified test.

[3] Evaluation criteria: No water shall rise as high as the lowest electrical part after the specified test.

General Information

The following information is a summary of typical formulas and conversion factors used in the rotating machinery industry. This information can be used as a basis for sizing drives and evaluating application types and factors.

However, these formulas are to be used for estimating purposes only. These formulas do not include allowance for machine friction, windage or other machine factors. When sizing a drive, always consider all machine factors (i.e. electrical, mechanical and environmental) and motor factors (i.e. full load amperes, speed range, etc.)

Horsepower Formulas

General Formula

$$HP = \frac{Torque \times Speed}{5252}$$

Where:
Torque = lb-ft.
Speed = RPM
5252 = a proportionally constant

Conveyors

$$HP(Vertical) = \frac{Force \times Velocity}{33,000}$$

Where:
Force = Force or Weight (lbs.)
Velocity = FPM

$$HP(Horizontal) = \frac{Force \times Velocity \times CoefofFriction}{33,000}$$

Where:
Force = Force or Weight (lbs.)
Velocity = FPM

Fans and Blowers

$$BHP = \frac{CFM \times Pressure}{33,000 \times EffofFan}$$

Where:
CFM = Cubic Feet per Minute
EffofFan = Efficiency of fan (%/100)
Pressure = lbs/ft.^{2}

$$BHP = \frac{CFM \times Pressure}{229 \times EffofFan}$$

Where:
CFM = Cubic Feet per Minute
EffofFan = Efficiency of fan (%/100)
Pressure = lbs/In.^{2}

$$HP = \frac{CFM \times PSI}{6356 \times EffofFan}$$

Where:
CFM = Cubic Feet per Minute
EffofFan = Efficiency of fan (%/100)
PSI = Pressure in inches of water

Pumps

$$BHP = \frac{GPM \times Head \times SpecificGravity}{3960 \times EffofPump}$$

Where:
GPM = Gallons per Minute
Head = Measurement of pressure in ft.
Eff of Pump = Efficiency of pump (%/100)
Specific Gravity = 1.0 (water)
Efficiency of Pump (Positive displacement) = May vary between 50 and 80% depending on size
Efficiency of Pump (Centrifugal) = 500 to 100 GPM = 70 to 75%
1000 to 1500 GPM = 75 to 80%
Over 1500 GPM = 80 to 85%

$$BHP = \frac{GPM \times PSI \times SpecificGravity}{1713 \times EffofPump}$$

Affinity Laws For Centrifugal Applications:

$$\frac{Flow_1}{Flow_2} = \frac{RPM_1}{RPM_2}$$

$$\frac{Pres_1}{Pres_2} = \frac{(RPM_1)^2}{(RPM_2)^2}$$

$$\frac{BHP_1}{BHP_2} = \frac{(RPM_1)^2}{(RPM_2)^2}$$

Torque Formulas

General Formulas

$$T = \frac{HP \times 5252}{Speed}$$

Where:
T = Torque in lb-ft.
HP = Horsepower
Speed = Speed in RPM

$$Torque = Force \times Radius$$

Where:
Torque = Torque in lb-ft.
Force = Force in lbs.
Radius = Radius in ft.

$$Torque = \frac{WK^2 \times \Delta RPM}{308 \times t}$$

Where:
Torque = Torque in lb-ft.
WK^2 = Inertia reflected to the motor shaft (lb-ft.^{2})
Delta RPM = Change in speed (RPM)
t = Time to accelerate (seconds)

AC Motor Formulas

$$Speed = \frac{120 \times Frequency}{NumberofPoles}$$

Where:
Speed = Synchronous speed in RPM
Frequency = Applied frequency in Hz
Number of Poles = Number of Poles per phase

$$Slip = \frac{(SyncSpeed - FLSpeed) \times 100}{SyncSpeed}$$

Where:
Slip = Slip in %
Sync Speed = Synchronous speed in RPM
FL Speed = Full load speed in RPM

Electrical Formulas

Power (DC Circuits)

$$HP = \frac{I \times E}{746}$$

Where:
I = Intensity of current (amperes)
E = EMF or Voltage (volts)

Power (AC Circuits)

$$kVA = \frac{I \times E}{1000}$$

Where:
kVA = Kilovolt amperes (1 phase)
I = Intensity of current (amperes)
E = EMF or Voltage (volts)

$$kVA = \frac{I \times E \times 1.73}{1000}$$

Where:
kVA = Kilovolt amperes (3 phase)
I = Intensity of current (amperes)
E = EMF or Voltage (volts)

$$kW = \frac{I \times E \times PF}{1000}$$

Where:
kW = Kilowatts (1 phase)
I = Intensity of current (amperes)
E = EMF or Voltage (volts)
PF = Power Factor

$$kW = \frac{I \times E \times PF \times 1.73}{1000}$$

Where:
kW = Kilowatts (3 phase)
I = Intensity of current (amperes)
E = EMF or Voltage (volts)
PF = Power Factor

$$PF = \frac{W}{E \times I} = \frac{kW}{kVA}$$

$$PF = \frac{InputWatts}{V \times A \times 1.732}$$

Where:
PF = Power Factor
W = Watts
I = Intensity of current (amperes)
E = EMF or Voltage (volts)
kW = Kilowatts
kVA = Kilovolt amperes

Motor Amperes (calculating)

$$MotorAmperes = \frac{HP \times 746}{E \times 1.73 \times EFF \times PF}$$

$$MotorAmperes = \frac{kVA \times 1000}{1.73 \times E}$$

$$MotorAmperes = \frac{kW \times 1000}{1.73 \times E \times PF}$$

Where:
HP = Horsepower
E = EMF or Voltage (volts)
EFF = Efficiency of the motor (in %/100)
kVA = Kilovolt amperes
kW = Kilowatts
PF = Power Factor

Constants

Weight

16 oz =	1 lb
2.204 lb =	1 kg
2.309 ft. of water at 62°F =	1 PSI
28.35 gm =	1 oz.
62.35 lbs =	Weight of 1 cu. ft. of water at 62° F
1 gal. of water at 62°F =	8.326 lbs.

Power

1 kW =	1.34 HP
1 HP =	2.54 BTU / hour
1 HP =	33,000 ft-lb per minute
1 HP =	746 Watts

Pressure

14.22 PSI =	1 kg per sq. cm (1 metric atmosphere)
1 PSI =	2.035 inches of Mercury at 32° F
1 PSI =	2.041 inches of Mercury at 62° F

1 PSI =	27.71 inches of water at 62 ° F
Atmospheric pressure =	29.92 inches of Mercury at 32 ° F
Atmospheric pressure =	30 inches of Mercury at 62 ° F (approx.)

Length

1 inch =	2.54 centimeters (cm)
1 yard =	3 feet
1 yard =	1.094 meters
1 meter (m) =	3.28 feet
1 meter (m) =	39.37 inches

Temperature

$$°C = \frac{(°F - 32)}{1.8}$$

$$°F = (°C \times 1.8) + 32$$

Locate known temperature in either degrees Celsius (°C) or degrees Fahrenheit (°F) in boldface **°F/°C** column. For conversion, read desired temperature in respective column.

Example: To convert 110 °C to Fahrenheit, find **110** in the boldface column. Then look to the right for the desired conversion value, 230 °F.
To convert 75 °F to Celsius, find **75** in the °F/°C column. Then look to the left for the desired conversion value, 23.9 °F.

°C	**°F/°C**	°F		°C	**°F/°C**	°F		°C	**°F/°C**	°F
-45.6	**-50**	-58		15.6	**60**	140		76.7	**170**	338
-42.8	**-45**	-49		18.3	**65**	149		79.4	**175**	347
-40.0	**-40**	-40		21.1	**70**	158		82.2	**180**	356
-37.2	**-35**	-31		23.9	**75**	167		85.0	**185**	365
-34.4	**-30**	-22		26.7	**80**	176		87.8	**190**	374
-31.7	**-25**	-13		29.4	**85**	185		90.6	**195**	383
-28.9	**-20**	-4		32.2	**90**	194		93.3	**200**	392
-26.1	**-15**	5		35.0	**95**	203		96.1	**205**	401
-23.3	**-10**	14		37.8	**100**	212		98.9	**210**	410
-20.6	**-5**	23		40.6	**105**	221		101.7	**215**	419
-17.8	**0**	32		43.3	**110**	230		104.4	**220**	428
-15.0	**5**	41		46.1	**115**	239		107.2	**225**	437
-12.2	**10**	50		48.9	**120**	248		110.0	**230**	446
-9.4	**15**	59		51.7	**125**	257		112.8	**235**	455
-6.7	**20**	68		54.4	**130**	266		115.6	**240**	464
-3.9	**25**	77		57.2	**135**	275		118.3	**245**	473
-1.1	**30**	86		60.0	**140**	284		121.1	**250**	482
1.7	**35**	95		62.8	**145**	293		123.9	**255**	491
4.4	**40**	104		65.6	**150**	302		126.7	**260**	500
7.2	**45**	113		68.3	**155**	311		129.4	**265**	509
10.0	**50**	122		71.1	**160**	320		132.2	**270**	518
12.8	**55**	131		73.9	**165**	329		135.0	**275**	527

Torque

1 Newton-Meters (N-m) =	.0.737 lb-ft.
1 lb-ft. =	1.356 Newton-Meters (N-m)
1 lb-in. =	0.083 lb-ft.
1 lb-ft. =	12.0 lb-in.

Note: A 2-pole motor (3600 RPM) develops 1.5 lb-ft of torque per HP
A 4-pole motor (1800 RPM) develops 3.0 lb-ft of torque per HP
A 6-pole motor (1200 RPM) develops 4.5 lb-ft of torque per HP
An 8-pole motor (900 RPM) develops 6.0 lb-ft of torque per HP

Volume

1 cm^3 (ml)=	0.00001 m^3
1 fl-oz. =	29.57 cm^3
1 liter =	0.001 m^3
1 $yd.^3$ =	0.765 m^3
1 $ft.^3$ of water at 39.2°F =	28.32 kg or liters
1 cfm =	0.000472 m^3/s

Rotation & Rates

1 RPM =	6.00 degrees/s
1 degree/s =	0.167 RPM
1 in./s =	0.0254 m/s
1 km/hr. =	0.278 m/s
1 mph =	0.447 m/s
1 FPM =	0.00508 m/s
1 FPS =	0.305 m/s
1 gal./min. =	63.09 cm^3/s
1 $yd.^3$/min. =	0.0127 m^3/s

Inertia

1 oz-$in.^2$ =	0.000434 lb.-$ft.^2$
1 lb-$in.^2$ =	0.00694 lb.-$ft.^2$
1 oz-in-$sec.^2$ =	0.167 lb-$ft.^2$
1 in-lb-$sec.^2$ =	2.68 lb-$ft.^2$
1 N-m^2 =	2.42 lb-$ft.^2$

Conversion Factors

MULTIPLY		**BY**	**=**	**TO OBTAIN**
LENGTH				
Centimeters	X	0.3937	=	Inches
Fathoms	X	6.0	=	Feet
Feet	X	12	=	Inches
Feet	X	0.3048	=	Meters
Inches	X	2.54	=	Centimeters
Kilometers	X	0.6214	=	Miles
Meters	X	3.281	=	Feet
Meters	X	39.37	=	Inches
Meters	X	1.094	=	Yards

MULTIPLY		BY		TO OBTAIN
Miles	X	5280.0	=	Feet
Miles	X	1.609	=	Kilometers
Yards	X	0.9144	=	Meters
AREA				
Acres	X	43560.0	=	Square feet
Acres	X	4840.0	=	Square yards
Circular mils	X	0.7854	=	Square mils
Square centimeters	X	0.155	=	Square inches
Square feet	X	144.0	=	Square inches
Square feet	X	0.0929	=	Square meters
Square inches	X	6.452	=	Square centimeters
Square meters	X	1.196	=	Square yards
Square miles	X	640.0	=	Acres
Square yards	X	0.8361	=	Square meters
VOLUME				
Cubic feet	X	0.0283	=	Cubic meters
Cubic feet	X	7.481	=	Gallons
Cubic inches	X	0.5541	=	Ounces (fluid)
Cubic meters	X	35.31	=	Cubic feet
Cubic meters	X	1.308	=	Cubic yards
Cubic yards	X	0.7646	=	Cubic meters
Gallons	X	3.785	=	Liters
Gallons	X	0.1337	=	Cubic feet
Liters	X	0.2642	=	Gallons
Liters	X	1.057	=	Quarts (liquid)
Ounces (fluid)	X	1.805	=	Cubic inches
Quarts (liquid)	X	0.9463	=	Liters
FORCE AND WEIGHT				
Grams	X	0.0353	=	Ounces
Kilograms	X	2.205	=	Pounds
Newtons	X	0.2248	=	Pounds (force)
Ounces	X	28.35	=	Grams
Pounds	X	453.6	=	Grams
Pounds (force)	X	4.448	=	Newtons
Tons (short)	X	907.2	=	Kilograms
Tons (short)	X	2000.0	=	Pounds
TORQUE				
Gram-centimeters	X	0.0139	=	Ounce-inches
Newton-meters	X	0.7376	=	Pound-feet
Newton-meters	X	8.851	=	Pound-inches
Ounce-inches	X	72.0	=	Gram-centimeters
Pound-feet	X	1.3558	=	Newton-meters
Pound-inches	X	0.113	=	Newton-meters

MULTIPLY		BY		TO OBTAIN
ENERGY OR WORK				
Btu	X	778.2	=	Foot-pounds
POWER				
Btu per hour	X	0.293	=	Watts
Horsepower	X	33000	=	Foot-pounds per minute
Horsepower	X	550	=	Foot-pounds per second
Horsepower	X	746	=	Watts
Kilowatts	X	1.341	=	Horsepower
PLANE ANGLE				
Degrees	X	0.0175	=	Radians
Minutes	X	0.01667	=	Degrees
Minutes	X	$2.9X10^{-4}$	=	Radians
Quadrants	X	90.0	=	Degrees
Quadrants	X	1.5708	=	Radians
Radians	X	57.3	=	Degrees

Notes:

ST-10 (10/23/98) REV 4
Supersedes 10/21/93

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