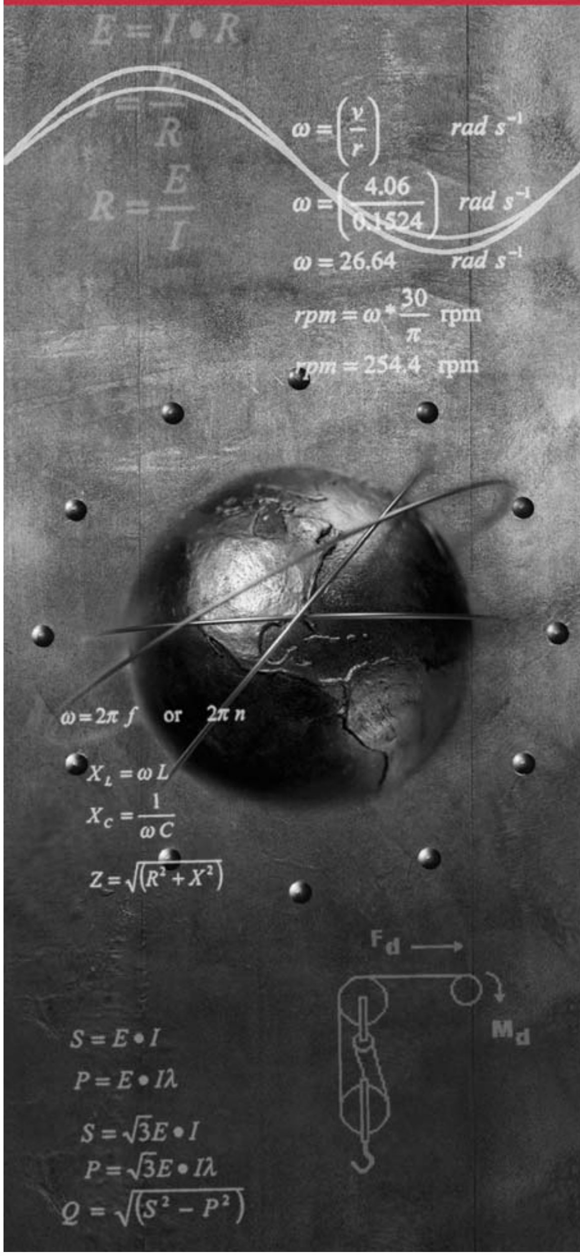

Allen-Bradley

Drives Engineering Handbook

Another Quality Solution
by Application Engineering

Rockwell Automation

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Section 1 – Motor and Load Basics

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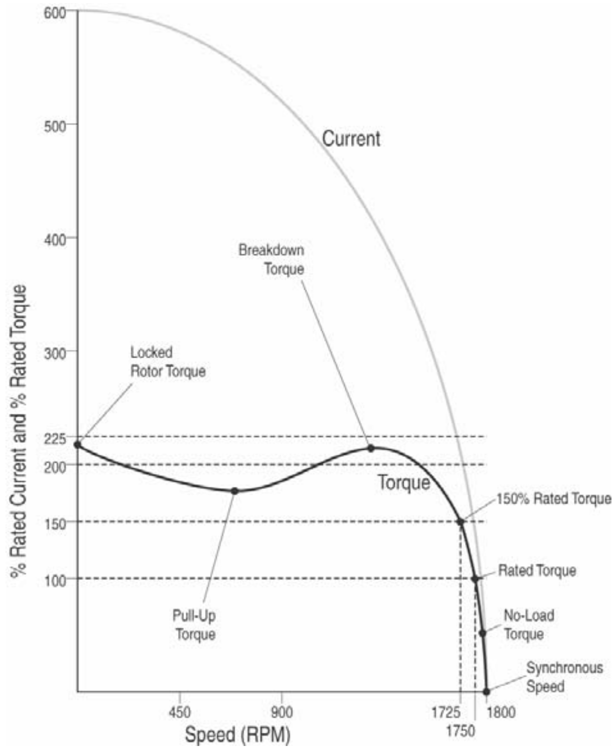
AC Motors

Generally speaking the following can be said about a speed torque curve when starting across the line. Starting torque is usually around 200% even though current is at 600%. This is when slip is the greatest. (Starting torque is also called Blocked Rotor Torque, Locked Rotor Torque or Breakaway Torque.) Such a large inrush of current may cause the supply voltage to dip momentarily, affecting other equipment connected to the same lines. Extra protective devices are also required to remove the motor from the supply lines if an excessive load causes a stalled condition.



The locked rotor torque and current, breakdown torque, pull-up torque and the percent slip, determine the classifications for NEMA design motors. The speed-torque curve and characteristics of each design are as follows:

NEMA Design Types

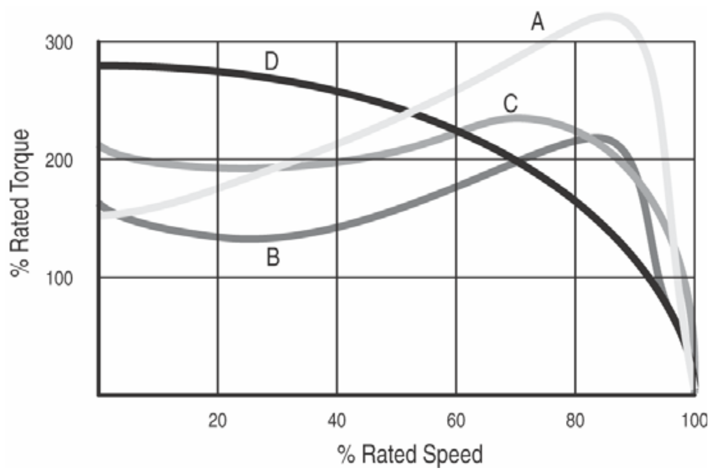
Design A — motors have a low resistance, low inductance rotor producing low starting torque and high breakdown torque. The low resistance characteristic causes starting current to be high. It is a high efficiency design; therefore the slip is usually 3% or less.

Design B — motors have a higher impedance rotor producing a slightly higher starting torque and lower current draw. For this reason, design B motors are a general-purpose type motor and account for the largest share of induction motors sold. The slip of a Design B motor is approximately 3-5% or less.

Design C — motors use a two-cage rotor design, high resistance for starting low resistance for running. This creates a high starting torque with a normal starting current and low slip. During starting, most of the current flows in the low inductance outer bars. As the rotor slip decreases, current flows more in the inner low resistance bars.

The Design C motor is usually used where breakaway loads are high at starting, but are normally run at rated full load, and are not subject to high overload demands after running speed has been reached. The slip of the Design C motor is 5% or less.

Design D — motors have the highest resistance rotor creating high slip, high starting torque and low starting current. Because of the high amount of slip, the speed varies dramatically with load. The slip of this type motor is approximately 5 to 8%. This high slip characteristic relates to a low efficiency design and a motor that runs hot.



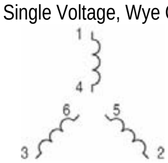
Motor Synchronous Speed

$$N = \frac{120f}{P}$$

where: N = RPM, f = Applied Frequency, P = Number of Poles

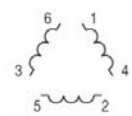
3-Phase Motor Connections - NEMA

6 Leads, Single Voltage, Wye Connection



T1	T2	T3	JOIN
1	2	3	4&5&6

6 Leads, Single Voltage, Delta Connection

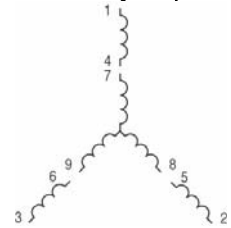


T1	T2	T3
1&6	2&4	3&5

6 Leads, Dual Voltage (1.732:1 Ratio), Wye or Delta Connection

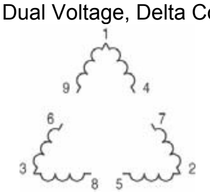
VOLTAGE	CONN	T1	T2	T3	JOIN
HIGH (1.732:1)	WYE	1	2	3	4&5&6
LOW (1:1)	DELTA	1&6	2&4	3&5	—

9 Leads, Dual Voltage, Wye Connection



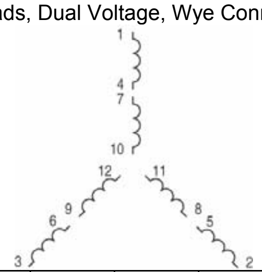
VOLTAGE	T1	T2	T3	JOIN
HIGH (2:1)	1	2	3	4&7, 5&8, 6&9
LOW (1:1)	1&7	2&8	3&9	4&5&6

9 Leads, Dual Voltage, Delta Connection



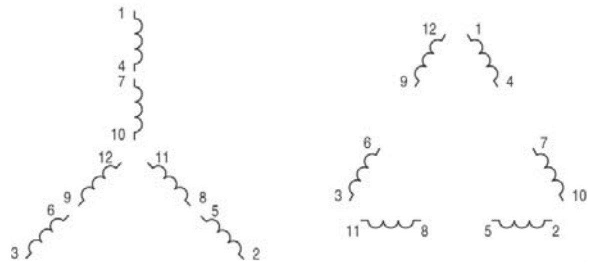
VOLTAGE	T1	T2	T3	JOIN
HIGH (2:1)	1	2	3	4&7, 5&8, 6&9
LOW (1:1)	1&6&7	2&4&8	3&5&9	—

12 Leads, Dual Voltage, Wye Connection



VOLTAGE	T1	T2	T3	JOIN
HIGH (2:1)	1	2	3	4&7, 5&8, 6&9, 10&11&12
LOW (1:1)	1&7	2&8	3&9	4&5&6, 10&11&12

12 Leads, Dual Voltage, Wye or Delta Connection



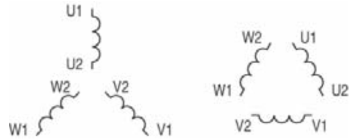
VOLTAGE	CONN.	T1	T2	T3	JOIN
HIGH (3.464:1)	WYE	1	2	3	4&7, 5&8, 6&9, 10&11&12
HIGH (2:1)	DELTA	1&12	2&10	3&11	4&7, 5&8, 6&9
LOW (1.732:1)	WYE	1&7	2&8	3&9	4&5&6, 10&11&12
LOW (1:1)	DELTA	1&6&7&12	2&4&8&10	3&5&9&11	—

Rotor Inertia – NEMA

	TEFC				OPD			
	2-Pole	4-Pole	6-Pole	8-Pole	2-Pole	4-Pole	6-Pole	8-Pole
HP	$Lbft^2$	$Lbft^2$	$Lbft^2$	$Lbft^2$	$Lbft^2$	$Lbft^2$	$Lbft^2$	$Lbft^2$
.5	0.015	0.017	0.017	0.04	0.018	0.17	0.18	0.18
.75	0.03	0.05	0.04	0.06	0.035	0.21	0.21	0.21
1	0.05	0.05	0.19	0.13	0.15	0.21	0.21	0.55
1.5	0.06	0.07	0.22	0.18	0.21	0.23	0.55	0.62
2	0.08	0.1	0.52	0.37	0.21	0.25	0.6	0.76
3	0.1	0.47	0.65	0.51	0.23	0.62	0.76	0.91
5	0.16	0.57	0.76	1.3	0.25	0.7	0.91	1.8
7.5	0.41	0.68	2.3	1.6	0.62	0.84	1.8	2.1
10	0.46	2.2	2.8	2.6	0.7	0.99	2.1	3.6
15	0.93	2.2	3.9	3.8	0.84	1.9	3.6	4.4
20	1.2	3	4.5	5	0.99	2.3	4.4	7.3
25	2	4	11	6.4	1.9	3.6	7.3	9
30	2.3	4.5	12.5	11	2.3	4.4	9	17
40	3.3	9	20	14	3.6	6.3	13	20
50	4.2	10	23.5	24	4.4	7.6	15	22
60	4.9	14.5	35	28	6.3	11	24	25
75	6.1	17	40.5	39	7.6	13	27	28
100	12	27	61.5	51	11	16	45	47
125	20	33	57.5	62	13	20	56	59
150	24	44.5	85	68	16	33	56	68
200	31	56	111	85	20	39	68	85
250	40	74.5	136	82	33	43	85	106
300	40	86	136	86	39	54	98	129
350	44.5	95		92	43	60	112	158
400	56	109		101	54	82	130	181
500	74.5	114		101	60	122	149	200

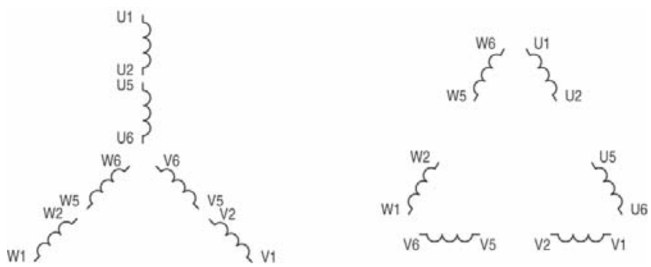
3-Phase Motor Connections – IEC Nomenclature

6 Leads, Dual Voltage (1.732:1 Ratio), Wye or Delta Connection



VOLTAGE	CONN.	T1	T2	T3	JOIN
HIGH (1.732:1)	WYE	U1	V1	W1	U2&V2&W2
LOW (1:1)	DELTA	U1&W2	V1&U2	W1&V2	—

12 Leads, Dual Voltage, Wye or Delta Connection



VOLTAGE	CONN.	T1	T2	T3	JOIN
HIGH (3.464:1)	WYE	U1	V1	W1	U2&U5, V2&V5, W2&W5, U6&V6&W6
HIGH (2:1)	DELTA	U1&W6	V1&U6	W1&V6	U2&U5, V2&V5, W2&W5
LOW (1.732:1)	WYE	U1&U5	V1&V5	W1&W5	U2&V2&W2, U6&V6&W6
LOW (1:1)	DELTA	U1&U5& W2&W6	V1&V5& U2&U6	W1&W5&V2 &V6	—

Rotor Inertia – IEC

Rated	2-Pole	4-Pole	6-Pole	8-Pole
kW	Kgm^2	Kgm^2	Kgm^2	Kgm^2
0.37	0.00035	0.0008	0.0015	0.0025
0.55	0.00045	0.0015	0.0018	0.0035
0.75	0.00085	0.0018	0.0028	0.0053
1.1	0.0011	0.0028	0.0035	0.007
1.5	0.0015	0.0035	0.0063	0.013
2.2	0.002	0.0048	0.011	0.025
3	0.0038	0.0058	0.02	0.033
4	0.0055	0.011	0.028	0.05
5.5	0.014	0.023	0.035	0.065
7.5	0.019	0.028	0.055	0.088
11	0.033	0.05	0.08	0.21
15	0.04	0.07	0.2	0.37
18.5	0.05	0.13	0.29	0.58
22	0.077	0.15	0.33	0.66
30	0.14	0.24	0.57	1.1
37	0.16	0.44	0.89	1.4
45	0.24	0.52	1.3	1.6
55	0.45	0.79	1.5	2.3
75	0.79	1.4	2.4	3
90	0.92	1.6	2.9	3.6
110	1.3	2.2	3.5	4.4
132	1.5	2.7	4.3	6.2
150	1.65	3.09	5.2	6.4
160	1.8	3.2	6	7.5
200	2.3	4.2	7.5	9.3
225	2.8	5.2	7.9	13.9
250	3.3	6	9.1	16
280	3.9	6.8	12.4	20
315	4	7.4	17	24
355	6.2	12	24	30
373	7.5	12.44	30	36

AC Motor Operation above Base Speed

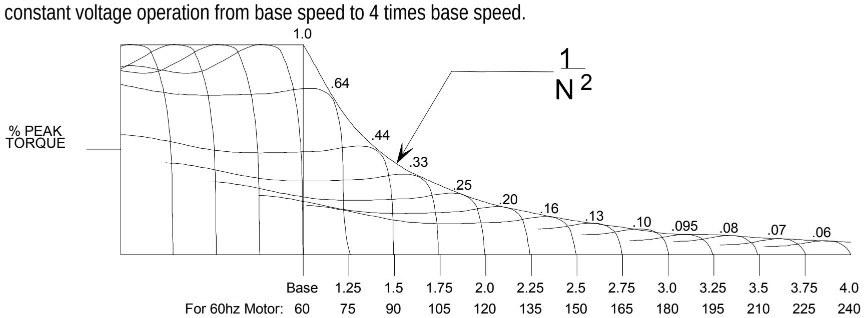
Constant Voltage Operation
The motor is operated in a "reduced flux" region. Below base speed, the volts-per-hertz ratio (460v/60hz) is 7.67, which satisfies the motor nameplate. By doubling the frequency to 120hz, the v/hz ratio is 3.83 (460/120). The same Volts per Hertz ratio results when a line started motor is operated at 60hz with only 50% voltage applied (for reduced voltage starting). As might be expected the effect on torque is the same. Recall that torque varies as the square of the applied voltage:

$$M = K \times E^2$$

where: K = motor torque constant
E = applied voltage

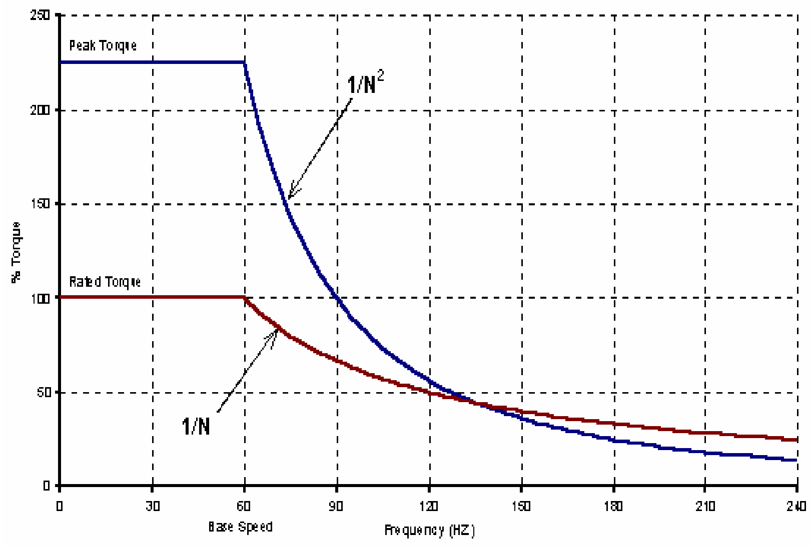
As such, maximum torque at 120hz is only 25% of the maximum torque at 60hz.

If AC drive output frequency is reduced from 120hz to 90hz at a constant voltage, the volts-per-hertz ratio improves from 3.83 to 5.1 V/Hz. This is the same as providing 66% voltage at 60hz to a line-started motor. Torque will be 0.66^2 or 44% of the full voltage torque at 60hz. Below illustrates the peak torque curve for constant voltage operation from base speed to 4 times base speed.



Since the voltage, in reality, is not changing above base speed, it is more appropriate to define torque in terms of frequency change instead of voltage change. It can be stated then that torque above base speed drops as the square of the frequency – doubling the frequency, quarters the available torque. Applied frequency and synchronous speed are equivalent, so going one step further; torque may be defined in terms of speed. In the constant voltage range then, motor torque drops off as the inverse of synchronous speed squared, or $1/N^2$. This is shown in the curves above.

Many machine applications are constant horsepower in their load characteristics. As speed increases, the torque drops off as the inverse of speed, or 1/N. The torque drop-off is not as severe as the motor's peak torque, $1/N^2$.



Synchronous Motors

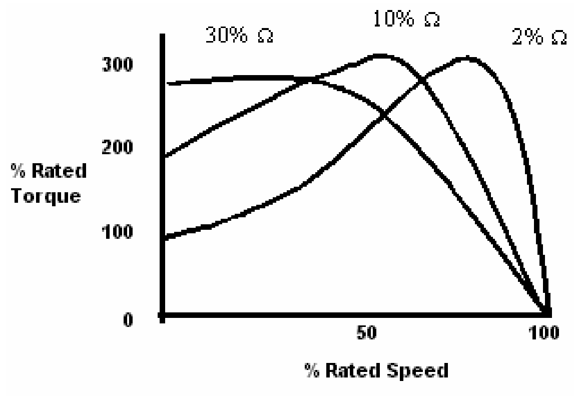
Synchronous motors operate at synchronism with the line frequency and maintain a constant speed regardless of load without sophisticated electronic control. The two most common types of synchronous motors are reluctance and permanent magnet. The synchronous motor typically provides up to a maximum of 140% of rated torque. These designs start like an induction motor but quickly accelerate from approximately 90% sync speed to synchronous speed. When operated from an ac drive they require boost voltage to produce the required torque to synchronize quickly after power application.

Wound Rotor

Some large motors may have a "Wound Rotor". This allows the motor characteristics to be altered by adding resistors in series with the rotor. This can effectively let the user define the motor torque curve as Nema A, B, C, or D. More resistance means higher slip and higher starting torque across the line while using a low value of series resistance results in lower slip and greater efficiency. Often the resistors will be present for start up then jumpered out while running.

In a case where a wound rotor motor is fed by an ac drive, the wound rotor connections should be permanently jumpered (no series resistance added).

In a case where replacing a wound rotor motor with a squirrel cage induction motor and an ac drive it is important to note that the wound rotor motor typically has high starting torque (300-400%). Therefore, in some applications it may be necessary to oversize the squirrel cage motor and ac drive to achieve the same level of starting torque.

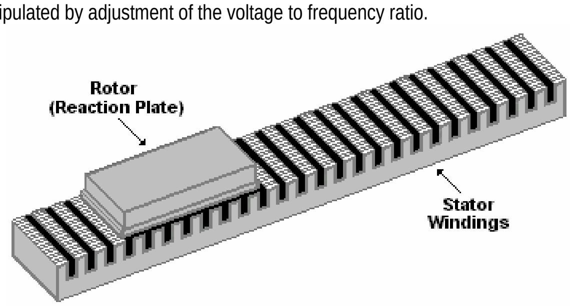


Linear Induction Motors

A linear motor operates on the same principal as a rotary, squirrel cage, induction motor. The difference being that the linear motor is laid out flat in a straight line. The primary or the static element is the equivalent of the stator, which has windings connected to the supply in one or three phase form. By applying a voltage across the winding, a linear traveling magnetic field is formed. The secondary is the equivalent of the rotor. The primary has two effects on the secondary. First, it induces currents into conductive windings of the secondary. Once that is complete, the magnetic field produces forces on the current carrying conductors of the secondary, which results in a thrust force being applied to the secondary.

Like the AC induction motor, the linear induction motor has an inherent function called slip. Slip quantifies the slower speed of the secondary in comparison with the magnetic field. The secondary is not locked into any position and therefore will continue to slip throughout the motion. The amount of slip increases proportionally with increases in load.

The secondary usually is some common combination of metal layers. With the use of an inverter, one can control the speed of the motor. Linear induction motors are great for extended or unlimited travel applications, such as baggage handling, people movers, gantries, or amusement rides. When applying an AC drive to this type of motor, the drive should be configured to operate in volts-per-hertz mode. With this configuration, the force can be manipulated by adjustment of the voltage to frequency ratio.

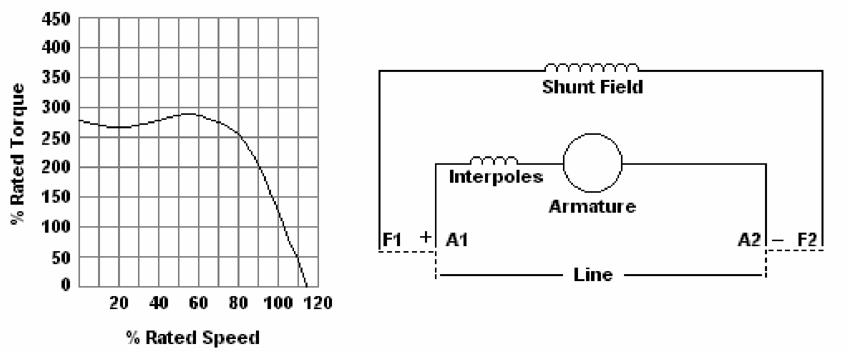


DC Motors

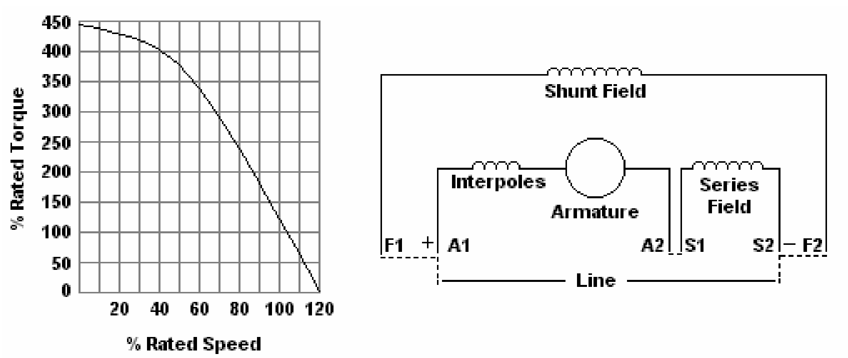
The DC motor converts the adjustable voltage DC from the drive controller to a rotating mechanical energy. Motor shaft rotation and direction are proportional to the magnitude and polarity of adjustable voltage applied to the motor. The following characteristic curves are shown with a fixed supply start of the motor.

Design Types (typical characteristics)

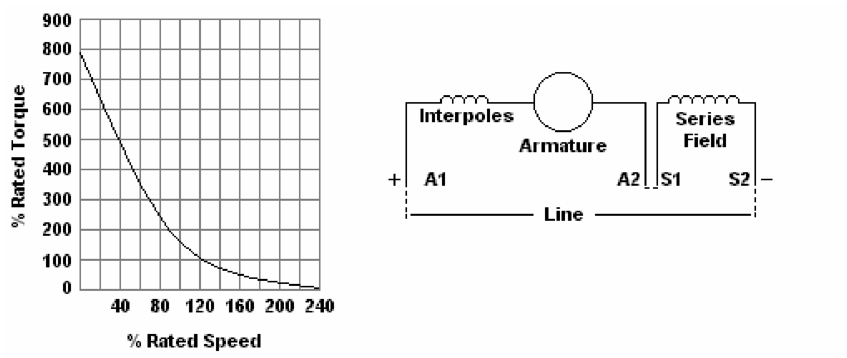
Shunt wound motors with the armature shunted across the field, offer relatively flat speed-torque characteristics. Combined with inherently controlled no-load speed, this provides good speed regulation over wide load ranges. While the starting torque is comparatively lower than other DC winding types, shunt wound motors offer simplified control for reversing service.



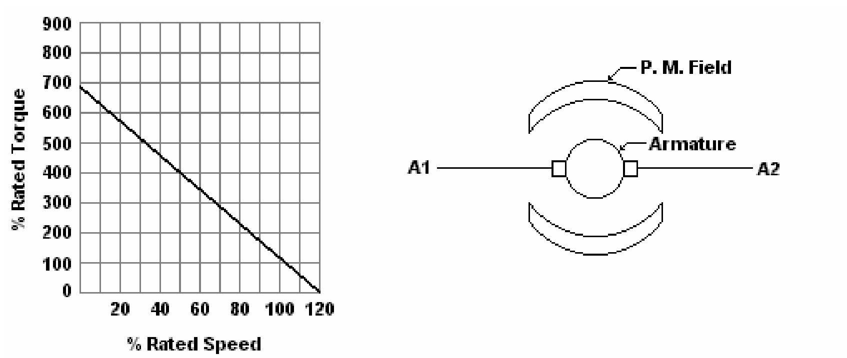
Compound wound motors utilize a field winding in series with the armature in addition to the shunt field to obtain a compromise in performance between a series and shunt type motor. This type offers a combination of good starting torque and speed stability. Standard compounding is about 12%. Heavier compounding of up to 40 to 50% can be supplied for special high starting torque applications, such as hoists and cranes.



Series motors have the armature connected in series with the field. While it offers very high starting torque and good torque per ampere, the series motor has poor speed regulation. Speed of DC series motors is generally limited to 5000 rpm and below. Series motors should be avoided in applications where they are likely to lose their load because of their tendency to “run away” under no-load conditions.



Permanent magnet motors have a conventional wound armature with commutator and brushes and a permanent magnet field. This motor has excellent starting torque, with speed regulation not as good as compound wound motors. The speed regulation can be improved with various designs, with corresponding lower rated torques for a given frame. Because of the permanent magnet field, motor losses are less with better efficiencies. These motors can be dynamically braked and reversed at some low armature voltage (10%) but should not be plug reversed with full armature voltage. Reversing current can be no higher than the locked armature current.



Operation above Base Speed

The field current must be reduced to allow motor operation above base speed. This is referred to as “field weakening”. A regulated field supply is required to operate in this region.

DC Motor Control Basics

Commonly used methods of controlling the speed of a direct current motor are armature-voltage control, shunt-field control and a combination of armature-voltage and shunt-field control.

Output torque of a d-c motor is proportional to the product of the main pole flux, armature current, and a machine constant which is a function of the armature winding.

$$M = K\phi I_a$$

Where:

- M = torque
- K = machine constant
- ϕ = main pole flux in air gap
- Ia = armature current

Armature-Voltage Control

As the name implies, the armature voltage is varied while maintaining constant shunt-field excitation. Therefore, with armature-voltage speed control and constant shunt-field excitation, the torque is dependent upon armature current only. At rated armature current the torque is constant.

Shunt-Field Control

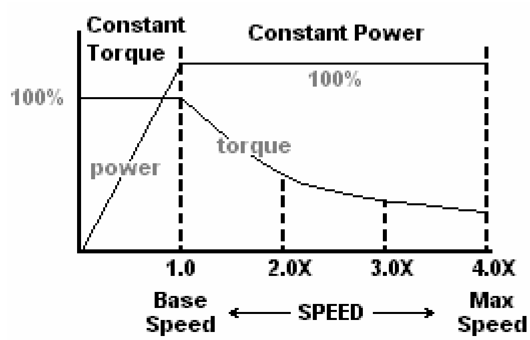
Adjusting the voltage applied to the shunt-field controls the speed. Reducing the shunt field voltage decreases main pole flux and motor speed is increased.

Combination Control

Utilizes both armature-voltage and shunt-field control to achieve a very wide speed range. Armature-voltage control is used for speed below base speed, resulting in constant torque capacity and shunt-field control is used to obtain speed above base speed resulting in a constant power capacity.

Operation with Variable Speed Drive

The shunt wound motor is used in conjunction with a dc drive to provide speed and or torque regulation to a given machine. The drive operates the motor in constant torque or constant power by regulating both the armature and the field as shown in the diagram below (armature current constant).

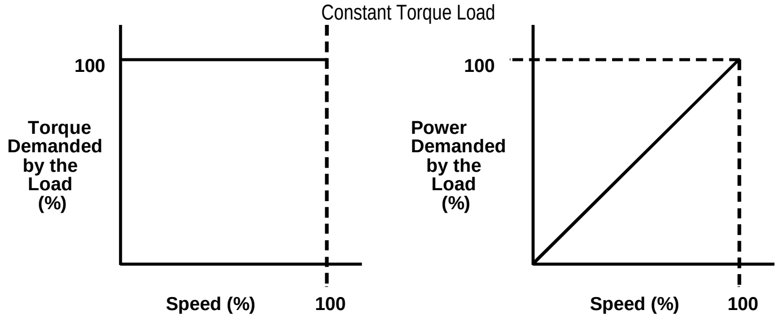


Load Types

Constant Torque Load

The torque demanded by the load is constant throughout the speed range. Loads of these types are essentially friction loads. The figure below shows the constant torque and its effect on horsepower demanded by the load.

Constant Torque Load



Since HP is a product of Torque times speed, and torque remains constant in this type of load, horsepower is a function of speed.

$$HP = \frac{Torque \times Speed}{5252} \quad \text{OR} \quad watts = \frac{Torque \times Speed}{9.55}$$

Where:

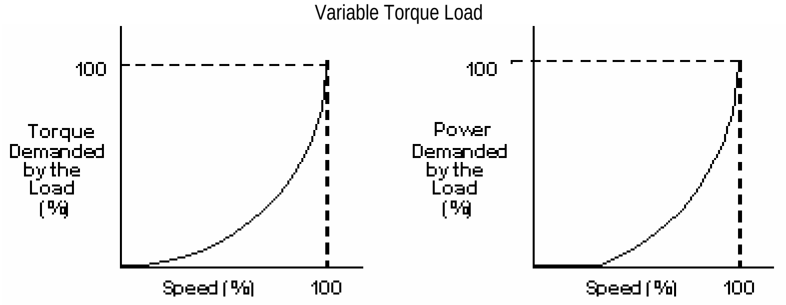
Torque = lb-ft.	Torque = Nm
Speed = RPM	Speed = RPM
5252 = a proportionality constant	9.55 = a proportionality constant

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

Variable Torque Load

With this type of load, the torque demand increases with speed, usually speed squared ($Speed^2$). Horsepower is typically proportional to speed cubed ($Speed^3$).

Variable Torque Load

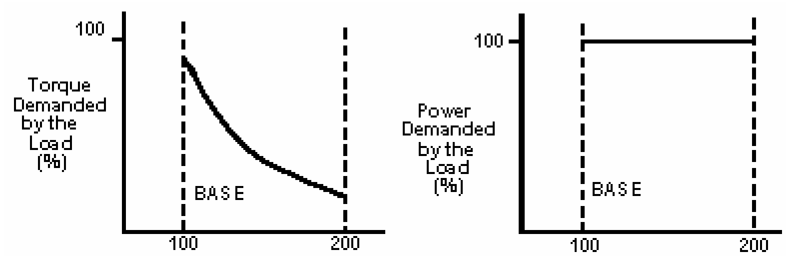


Examples of loads that exhibit variable load torque characteristics are centrifugal fans, pumps and blowers. This type of load requires much lower torque at low speeds than at high speeds.

Constant Horsepower Operation

This is a function of the motor being operated above base motor speed. The horsepower demanded by the load is constant within the speed range. The speed and torque are inversely proportional to each other.

Constant Horsepower Load



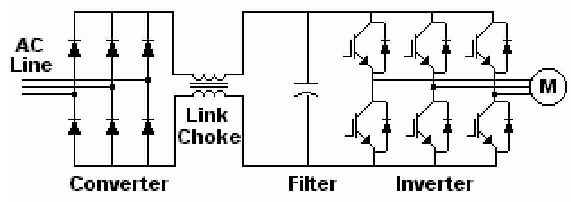
Overload Operation

Many constant torque applications require intermittent operation in overload. Acceleration and deceleration torque requirements may be severe to meet a machine “cycle time”.

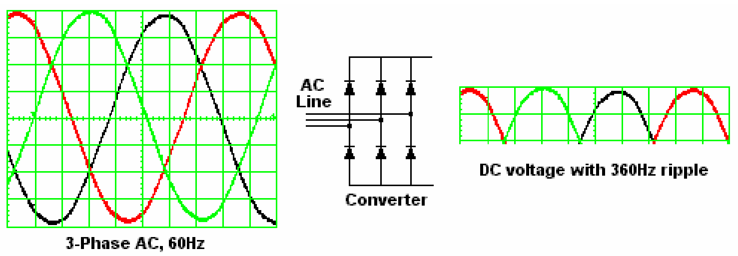
Overload protection for both the motor and drive must be considered when the machinery has a severe duty cycle. Though the drive and motor may be able to perform the application for short periods, the I^2t of continuous operation may require a larger drive and/or motor.

AC Drive Power Structure

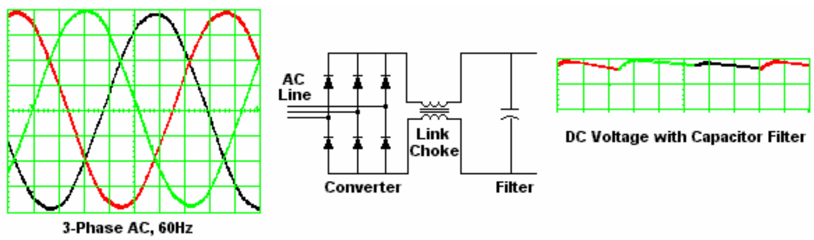
The most common type of drive on the market today is the Pulse Width Modulated (PWM) AC drive. The power structure of the drive can be broken into three distinct sections.



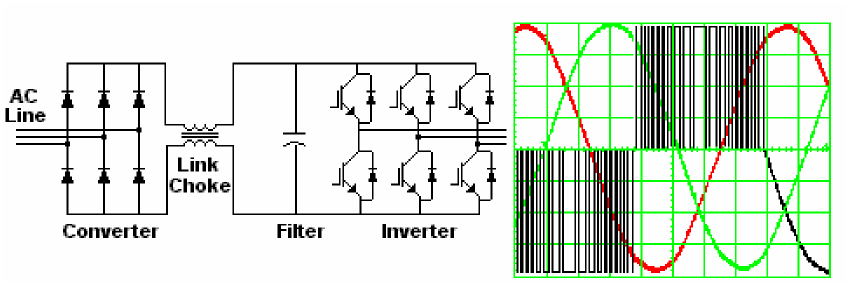
The figure above is a diagram of a typical "voltage source" PWM AC drive power structure. The inverter section requires a stable DC source to operate. The first stage is the converter. In most cases this stage consists of a three-phase, full wave, diode-bridge, though SCR's are sometimes used in place of diodes. Diodes conduct only when they are forward biased and are used in this stage to convert AC to DC. If this stage were isolated from the rest of the power structure we would see a pulsating 360 HZ DC voltage at the DC bus connection when 3 phase power is applied to the input.



Though we now have DC voltage, it is not smooth. A filter is required to create the smooth stable DC power needed to run the IGBT inverter. Therefore a second "filter" stage is required. Primarily this consists of a large capacitor bank. Often an inductor or "link choke" may be added. The choke when used helps buffer the AC line from the capacitor bank and serves to improve power factor and reduce harmonics. While the capacitor bank is always present, the inductor is sometimes an option. In both cases the 360 HZ pulsating DC voltage is filtered smooth by the Capacitor bank.



The third stage is the inverter section. This section uses high-speed transistors as switches to apply a “Pulse Width Modulated” or PWM waveform to the motor. Taking advantage of the fact that a motor is basically a large inductor, and that current does not change very fast in an inductor, the DC bus voltage can be applied in pulses of varying width in order to achieve current in the motor that approximates a sine wave.



Only one-phase of the PWM waveform is shown to indicate how the modulated pulse width emulates an AC voltage when applied to an inductive load.

Varying the width of the pulses in proportion to the frequency creates a volts-per-hertz ratio that satisfies the motor design and allows the motor to produce rated torque at base speed and below without excessive current.

The output power is equal to the input power plus any efficiency losses within the drive.

$$kW = \frac{1.732 \times I \times E \times pf}{1000}$$

Example: 5HP, 460V, 60Hz, 4-pole, 6.25 FLA motor, 5Hz drive output. To produce rated torque, rated current is required, but only ~38V (ratio of 460V/60Hz). Assuming a motor pf of .85 solve for power.

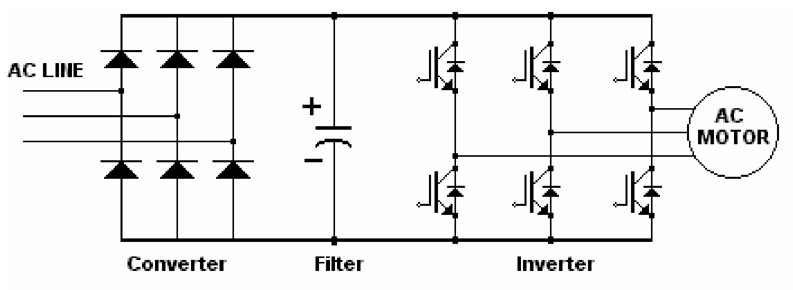
$$kW = \frac{1.732 \times 6.25 \times 38 \times .85}{1000} = 0.35kW$$

The power consumed from the AC line is ~ 10% of the rated power (5HP = 3.7kW).

Regeneration

When the rotor of an induction motor turns slower than the speed set by the applied frequency, the motor is transforming electrical energy into mechanical energy at the motor shaft. This process is referred to as 'motoring'. When the rotor turns faster than the synchronous speed set by a drive output, the motor is transforming mechanical energy from the motor shaft into electrical energy. It may be a ramp to stop, a reduction in commanded speed or an overhauling load that causes the shaft speed to be greater than the synchronous speed. In any case this, condition is referred to as 'regeneration". Essentially, mechanical energy is converted to electrical energy.

For an AC drive and motor in a regenerative condition, the AC power from the motor flows backward through the inverter bridge diodes shown below.



On most AC drives, utility power is first converted into DC by a diode or SCR rectifier bridge These bridges are very cost effective, but only handle power in the "motoring" direction. Since the laws of physics state that energy is never lost or gained, this energy needs a place to go.

Stored Energy

Rotational

In the case of a large rotating mass such as a Centrifuge, the stored energy is:

$$\frac{1}{2} \cdot J\omega^2$$

Where *J* is the moment of inertia in Kg Meters squared and *w* is the angular velocity (rotational speed) in radians/second. From this equation we can see that the energy is proportional to the square of the speed. This means that if we cut the speed in half we will have only ¼ the kinetic energy. For this reason, a uniform "linear" ramp to stop from a given speed results in a linear reduction in the transfer of energy from motor to drive as the load slows.

Linear

This type of load can generally be characterized by a large mass such as a conveyer belt or transfer car being driven by a motor through a gearbox. Though the dominant component of stored energy may be in the large mass traveling in a linear motion, calculating the stored energy is much the same. Kinetic energy for this case is:

$$\frac{1}{2} \cdot MV^2$$

Where M is the mass in Kg and V is the velocity in meters per second.
In the case of the linear and rotational load, ramping to a stop from a given speed will result in a linear decline in power being absorbed by the brake over the given deceleration time.

Overhauling Load

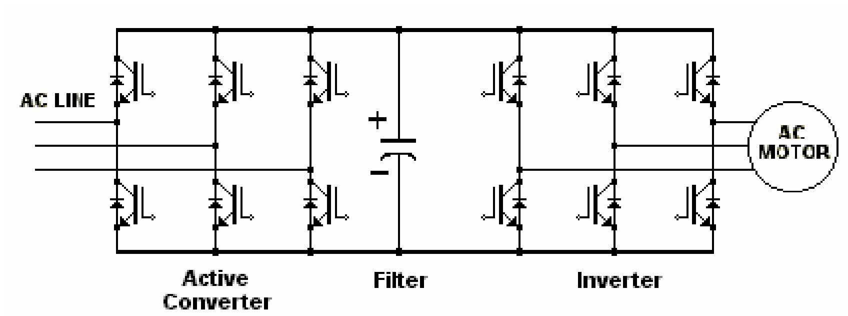
An overhauling load, on the other hand, usually acts a bit different. The big difference here is that the condition that causes the overhauling can be sustained for extended periods of time. An example would be a decline conveyer where material is being moved from the top to the bottom of the conveyer. The weight of the material constantly being loaded on the belt provides a continuous regenerative energy source.

Braking

See Chapter on “Braking”

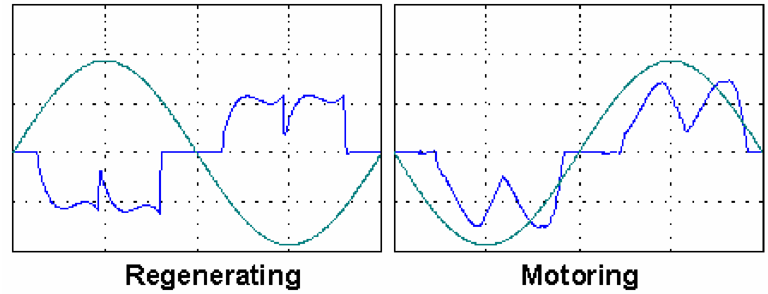
Line Regeneration

An “active” converter bridge is required to regenerate power from the drive dc bus to the ac line. The typical VFD uses passive devices (diodes) to convert ac to dc. An active bridge uses IGBT's that allow current to flow from the ac line when the ac line voltage is higher than the dc bus voltage, and the opposite direction when the dc bus voltage is greater than the ac line.



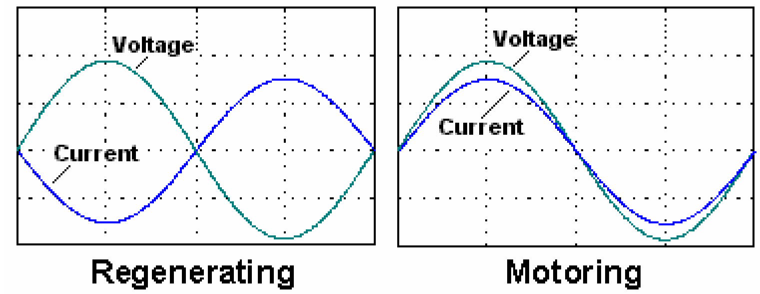
Regenerative Brake

Like a dynamic brake or chopper, a line regenerative brake connects to the dc bus and prevents an over-voltage condition by providing a place for motor and load energy to go when a motor is acting as a generator. This however is where the similarity ends. Unlike the dynamic brake and chopper, the regenerative brake has no voltage regulator or power resistor. It does not attempt to regulate the drive bus voltage. Rather, it uses a set of IGBT switches synchronized to the line to provide a path for current flow should the DC bus voltage become higher than the line. The regenerative brake does not provide motoring power for the load. The motoring power is supplied by the AC drive.

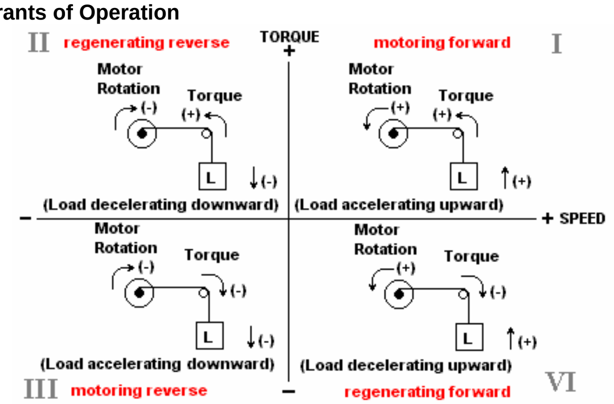


Active Converter

In this configuration, the IGBT bridge connected to the AC line is regulating dc bus voltage by switching at a fast rate. This allows power to flow in and out of the drive with very little harmonic content. The active converter supplies motoring power and a path for load power to be returned to the AC line.



Four Quadrants of Operation



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Section 2 – Basic Physics

SI Units (International System of Units)

Mechanical Quantities

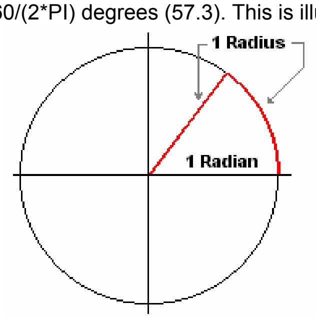
Symbol	Quantity	SI Unit
a	Acceleration	m s^2
d	Diameter	M
F	Force	N, kg m s^2
g	Acceleration due to gravity	m s^2
J	Moment of Inertia	kg m^2
l	Length	m
M	Torque	Nm
n	Speed, rotational ($\omega/2\pi$)	rev s^1
p	Pressure	Nm^2, Pa
P	Power	W, Js^1, Nms^{-1}
Q	Flow rate	m^3 s^1
r	Radius	m
s	Distance	m
t	Time	s
T	Temperature	K
v	Speed (velocity), linear	m s^1
w	Force	N
W	Energy	Kg m^2s^2, J, Ws, Nm
α	Acceleration, angular	rad s^2
Δ	Change in value (delta)	
γ	Angle (plane)	rad
η	Efficiency	
μ	Coefficient of friction	
ρ	Density	kg m^3
ω	Velocity, angular (2π n)	rad s^1
m	Mass	g

The SI unit of force is the newton.
One newton-meter = one watt-second = one joule.
Therefore one newton produces unit acceleration of unit mass.
Acceleration due to gravity 9.81m s^2

Electrical Quantities

Symbol	Quantity	SI Unit
C	Capacitance	F
f	Frequency	Hz
g	Fundamental frequency content	
G	Conductance	S
I	Current	A
k	Distortion factor	
L	Inductance	H
n	Rotational speed	rad s^1
p	Number of poles	
P	Real (active) power	W
Q	Reactive power	var
R	Resistance	Ω
S	Total (apparent) power	VA
W	Energy	J, Ws
U or *E*	Potential difference (voltage)	V
X_c	Capacitive reactance	Ω
X_l	Inductive reactance	Ω
Z	Impedance	Ω
α	Delay angle	deg
Δ	Change in value (delta)	
pf	Power factor	
cos ϕ	Displacement factor, phase angle between voltage and current	
ω		rad s^1

A radian is an angle whose length equals one radius. Since the circumference of a circle is 2* PI *radius and a radian spans an arc of one radius, there are 2*PI radians in a complete circle. So 1 radian equals 360/(2*PI) degrees (57.3). This is illustrated below.



Formulas

Mechanical

Linear Motion
Distance after time *t* at a constant velocity.

$$s = vt \qquad \text{m}$$

Linear acceleration

$$a = \frac{v}{t} \qquad \frac{\text{m}}{\text{s}^2}$$

Velocity after time *t* when under constant acceleration. (v_0 = initial velocity)

$$v = v_0 + at \qquad \frac{\text{m}}{\text{s}}$$

Distance after time t when under constant acceleration.

$$s = v_0 t + \left(\frac{1}{2} a t^2\right) \qquad \text{m}$$

Derived velocity-acceleration-distance equation.

$$v^2 - {v_0}^2 = 2as \qquad \frac{\text{m}}{\text{s}}$$

Accelerating force

$$F = ma \quad \text{or} \quad mg \qquad \text{N, kg m}^2$$

$$F = m \bullet \frac{v}{t} \qquad \text{N, kg m}^2$$

Kinetic energy at constant velocity

$$W = \frac{1}{2} m v^2 \qquad \text{Nm, Ws}$$

Work done by acceleration force

$$W = Fs \qquad \text{Nm, Ws}$$

or change of kinetic energy at constant acceleration

$$W = \frac{1}{2} m\left(v^2 - {v_0}^2\right) \qquad \text{Nm, Ws}$$

Rotational Motion

Angular velocity (angle measured in radians)

$$\omega = 2\pi\, n \qquad (n \text{ in rev/s}) \qquad \frac{\text{rad}}{\text{s}}$$

$$\text{or} \quad \frac{\pi\, n}{30} \qquad (n \text{ in rev/min}) \qquad \frac{\text{rad}}{\text{s}}$$

Angular acceleration

$$\alpha = \frac{\omega}{t} = \frac{2\pi n}{t} \quad (n \text{ in rev/s}) \qquad \frac{\text{rad}}{\text{s}^2}$$

$$\text{or} \quad \frac{\pi n}{30t} \quad (n \text{ in rev/min}) \qquad \frac{\text{rad}}{\text{s}^2}$$

Angular displacement after time *t* under acceleration

$$\gamma = \omega_o t + \left(\frac{1}{2}\alpha\, t^2\right) \qquad \text{rad}$$

Angular velocity after time *t* under constant acceleration

$$\omega = \omega_o + \alpha\, t \qquad \frac{\text{rad}}{\text{s}}$$

Derived velocity-acceleration-angle equation

$$\omega^2 - \omega_o{}^2 = 2\alpha\, \gamma \qquad \frac{\text{rad}}{\text{s}^2}$$

Acceleration – (linear accelerating force)

Torque

$$M = \frac{J\omega}{t} \qquad (\text{where } \omega = 2\pi \text{ radians}) \qquad \frac{\text{kgm}^2}{\text{s}^2}$$

Time

$$t = \frac{J\omega}{M} \qquad \text{s}$$

Acceleration torque -(revolutions)

Where *d* in meters, *t* in seconds, Δ is difference between initial and final values.

Rotational speed, *n* is in rev / s

$$M = \frac{\pi}{4} m\, d^2 \frac{\Delta n}{\Delta t} \qquad \frac{\text{kg m}^2}{\text{s}^2}$$

Rotational speed, *n* is in rev / min

$$M = \frac{\pi}{240} m\, d^2 \frac{\Delta n}{\Delta t} \qquad \frac{\text{kg m}^2}{\text{s}^2}$$

Acceleration time -(revolutions)

Rotational speed, *n* is in rev / s

$$t = \frac{\pi}{4} m\, d^2 \frac{\Delta n}{M} \qquad \text{s}$$

or

$$t = \frac{2\pi\ J\Delta n}{M} \qquad \text{s}$$

Rotational speed, *n* is in rev / min

$$t = \frac{\pi}{240} m\, d^2 \frac{\Delta n}{M} \qquad \text{s}$$

or

$$t = \frac{2\pi\ J\Delta n}{60M} \qquad \text{s}$$

Kinetic energy for Rotational Motion

At a constant velocity

$$W = \frac{1}{2} J\, \omega^2 \qquad \text{Nm, Ws}$$

Rotational speed, *n* is in rev / s

$$W = 2\pi^2\ J\ n^2 \qquad \text{Nm, Ws}$$

Rotational speed, *n* is in rev / min

$$W = \frac{\pi^2\ J\ n^2}{1800} \qquad \text{Nm, Ws}$$

Work done by acceleration force

$$W = M\gamma\ r \qquad \text{Nm, Ws}$$

or change of kinetic energy

$$W = \frac{1}{2} J\left(\omega_2{}^2 - \omega_1{}^2\right) \qquad \text{Nm, Ws}$$

Moment of Inertia

Rotational

Rotational speed, n is in rev / min

$$J = \frac{60Mt}{2\pi\Delta n} \qquad \text{kgm}^2$$

$$J = \frac{60Mt}{2\pi\Delta n} = Wk^2 \qquad \text{kgm}^2$$

Where W (not as SI unit) is the total mass in kg, K is radius of gyration, 9.5493 is the constant for converting Rev/min. to Radians /sec. and Rotational speed, *n* is in rev / min.

$$J = Wk^2 = \frac{9.543Mt}{\Delta n} \qquad \text{kgm}^2$$

Refer to Appendix IV for Moment of Inertia for a given Body Type description and formulas.

Equivalent moment of inertia referred to the motor shaft through reducer or gearbox.

$$\text{Equivalent} = J_{motor} = J\left[\frac{n}{n_{motor}}\right]^2 \qquad \text{kgm}^2$$

Linear

Equivalent moment of inertia J or WK^2 of linearly moving parts can be directly referred to the motor shaft as follows, based on the principle of conservation of energy Kinetic Energy linear = Kinetic Energy rotary:

Where m is the mass in kg of the total load including equipment, v is linear velocity in m/s and n is in rev / min.

$$J = \frac{mv^2}{\omega^2} \qquad \text{kgm}^2$$

OR

$$J = \frac{mv^2}{\left(\frac{2\pi n_{motor}}{60\,\text{sec/min}}\right)} \qquad \text{kgm}^2$$

OR

Where **V** is linear velocity in m/min and n is in rev / min

$$J = \frac{mv^2}{39.48\left(n_{motor}\right)^2} \qquad \text{kgm}^2$$

Caution:
This linear to rotation equivalent inertia formula does not take into account the influence of coefficient of friction nor windage. This formula is useful and accurate for applications with relatively free moving bodies of mass or for isolating only the moment of inertia. Care must be taken when calculating acceleration and/or deceleration torque requirements, to use appropriate formulas that compensate for the additive and subtractive respective effects of friction and windage.

Total equivalent moment of inertia referred to the motor shaft can be a combination of rotary and linear

$$J_T = J_A + J_B\left[\frac{n_B}{n_{motor}}\right]^2 + J_C\left[\frac{n_C}{n_{motor}}\right]^2 + \frac{mv^2}{39.48\left(n_{motor}\right)^2} \qquad \text{kgm}^2$$

Where J_A is for all rotating parts on the same direct drive shaft of the motor,
J_B is for all rotating parts on an intermediate shaft,
J_C is for all rotating parts on the final shaft
mv^2 / 39.48 n^2_{motor} is for linearly moving load and parts.

Power

Efficiency

$$\eta = \frac{\text{Power delivered}}{\text{Power consumed}} \qquad \text{per unit}$$

$$P = F_v \qquad \frac{\text{Nm}}{\text{s}}, \text{W}, \frac{\text{J}}{\text{s}}$$

Power for Linear Motion

$$P = \frac{m\,v^2}{t} \qquad \frac{\text{Nm}}{\text{s}}, \text{W}, \frac{\text{J}}{\text{s}}$$

Power for Rotational Motion

$$P = M\omega \qquad \frac{\text{Nm}}{\text{s}}, \text{W}, \frac{\text{J}}{\text{s}}$$

$$P = \frac{J\omega^2}{t} \qquad \frac{\text{Nm}}{\text{s}}, \text{W}, \frac{\text{J}}{\text{s}}$$

$$P = 2\pi\, M\, n \qquad \frac{\text{Nm}}{\text{s}}, \text{W}, \frac{\text{J}}{\text{s}}$$

Where rotational speed, *n* is in rev / s

$$P = \frac{\pi\, M\, n}{30} \qquad \frac{\text{Nm}}{\text{s}}, \text{W}, \frac{\text{J}}{\text{s}}$$

Where rotational speed, *n* is in rev / min

$$P = \frac{M\, n}{9550} \qquad \text{kW}$$

Power due to Acceleration of Gravity

$$P = \frac{m \bullet \text{g} \bullet \text{h}}{t} \qquad \frac{\text{Nm}}{\text{s}}, \text{W}, \frac{\text{J}}{\text{s}}$$

Where g = 9.8 m/s^2, h = height in meters

Time for Motor to Reach Operating Speed

$$t = \frac{J \bullet \Delta\omega}{M_{ave}} \qquad s$$

Where $\Delta\omega$ is the change in speed (rad/s) and M_{ave} is the average accelerating torque

Electrical

Ohms Law

$E = I \bullet R$	V
$I = \dfrac{E}{R}$	A
$R = \dfrac{E}{I}$	Ω

Angular frequency

$\omega = 2\pi\ f \quad \text{or} \quad 2\pi\ n$	$\dfrac{\text{rad}}{\text{s}}$

Impedance

$X_L = \omega L$	Ω
$X_C = \dfrac{1}{\omega C}$	Ω
$Z = \sqrt{\left(R^2 + X^2\right)}$	Ω

Where $X = X_L + X_C$ for series circuits

Power

DC

$P = E \bullet I$	W

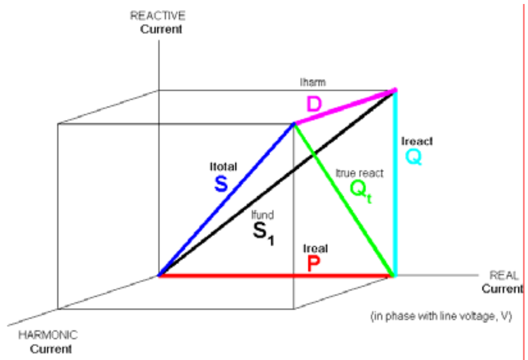
AC Single-Phase

$S = E \bullet I$	VA
$P = E \bullet I \bullet pf$	W

AC Three-Phase

$S = \sqrt{3}E \bullet I$	VA
$P = \sqrt{3}E \bullet I \bullet pf$	W
$Q = \sqrt{\left(S^2 - P^2\right)}$	var

Power Factor



For 3-Phase, Non-Sinusoidal, Balanced Systems (where V(THD) <or=5%)

True Apparent Power = S = V x I_{total} (kVA)
Apparent Power = S_1 = V x I_{fund} (kVA)
Real Power = P = V x I_{real} (kW)
True Reactive Power = Q_t = V x sqrt(I_{react}^2 x I_{harm}^2)
Reactive Power = Q = V x I_{react} (kVAR)
Harmonic Power = D = V x I_{harm} (kVAR)
S = sqrt($P^2 + Q^2 + D^2$) = sqrt($P^2 + Q_t^2$)
pf total = true pf = pf disp x pf dist = I_{real} / I_{total} = P/S
pf disp = cosϕ = I_{real} / I_{fund} = P/S_1
pf dist = cosϕ = I_{fund} / I_{total} = S_1/S
(ϕ is the phase angle between the sinusoidal voltage and the fundamental current waveforms)

3-Phase relationships

Voltage and current in RMS quantities

Wye or Star connection

$$\text{Line voltage}\, U_L = \sqrt{3} \times \text{phase voltage}\, U_P$$

$$\text{Line current}\ I_L = \text{phase current}\ I_P$$

Delta connection

$$\text{Line voltage}\, U_L = \text{phase voltage}\, U_P$$

$$\text{Line current}\ I_L = \sqrt{3} \times \text{phase current}\ I_P$$

Power (sinusoidal voltage)

$$S = \sqrt{3}\, U_L\ I_L \qquad \text{VA}$$

Imperial Units

1 HP = [33,000 ft lbs] x [1 rad/min]

$Pwr_{(HP)}$ = $[Trq_{(ft\ lbs)}]$ $[Spd_{(rad/min)}]$ / [33,000 ft lbs/min]

$Pwr_{(HP)}$ = $[Trq_{(ft\ lbs)}]$ $[Spd_{(RPM)}]$ [2π rd/rev]/[33,000 ft lbs/min)]

$Pwr_{(HP)}$ = $[Trq_{(ft\ lbs)}]$ $[Spd_{(RPM)}]$ [0.0001904]

or

$Pwr_{(HP)}$ = $[Trq_{(ft\ lbs)}]$ $[Spd_{(RPM)}]$ / [5252]

Note: 5252 = [33,000 ft lbs/min / 2πrad/rev]

Mechanical

Linear Motion

Distance after time *t* at a constant velocity.

$$s = vt \qquad \text{ft, in}$$

Linear acceleration

$$a = \frac{v}{t} \qquad \frac{\text{ft}}{\text{s}^2}, \frac{\text{in}}{\text{s}^2}$$

Velocity after time *t* when under constant acceleration. (v_0 = initial velocity)

$$v = v_0 + at \qquad \frac{\text{ft}}{\text{s}}, \frac{\text{in}}{\text{s}}$$

Distance after time *t* when under constant acceleration.

$$s = v_0 t + \left(\frac{1}{2} at^2\right) \qquad \text{ft, in}$$

Accelerating force

$$F = ma \quad \text{or} \quad mg \qquad \text{Poundal, lb}$$

$$F = m \bullet \frac{v}{t} \qquad \text{Poundal, lb}$$

Kinetic energy at constant velocity

$$W = \frac{1}{2} mv^2 \qquad \text{ft lb}$$

Work done by acceleration force

$$W = Fs \qquad \text{ft lb}$$

or change of kinetic energy at constant acceleration

$$W = \frac{1}{2} m\left(v^2 - {v_0}^2\right) \qquad \text{ft lb}$$

Rotational Motion

Angular velocity (angle measured in radians)

$$\omega = 2\pi n \quad (n \text{ in rev/s}) \qquad \frac{\text{rad}}{\text{s}}$$

OR

$$\omega = \frac{2\pi n}{60} \quad (n \text{ in rev/min}) \qquad \frac{\text{rad}}{\text{s}}$$

Angular acceleration

$$\alpha = \frac{\omega}{t} = \frac{2\pi n}{t} \quad (n \text{ in rev/s}) \qquad \frac{\text{rad}}{\text{s}^2}$$

OR

$$\alpha = \frac{2\pi n}{60t} \qquad \frac{\text{rad}}{\text{s}^2}$$

Angular displacement after time *t* under acceleration

$$\gamma = \omega_0 t + \left(\frac{1}{2}\alpha t^2\right) \qquad \text{rad}$$

Angular velocity after time *t* under constant acceleration

$$\omega = \omega_0 + \alpha t \qquad \frac{\text{rad}}{\text{s}}$$

Derived velocity-acceleration-angle equation

$$\omega^2 - {\omega_0}^2 = 2\alpha\gamma \qquad \frac{\text{rad}}{\text{s}^2}$$

Acceleration – (linear accelerating force)

Torque

$$M = \frac{WK^2\omega}{t} \quad (\text{where } \omega = 2\pi \text{ radians}) \qquad \frac{\text{lbft}^2}{s^2}$$

Time

$$t = \frac{WK^2\omega}{M} \qquad \text{s}$$

Acceleration torque – (revolutions)

Where *d* in feet, *t* in seconds, Δ is difference between initial and final values.

Rotational speed, *n* is in rev/s

$$M = \frac{\pi}{4} md^2 \frac{\Delta n}{\Delta t} \qquad \frac{\text{lbft}^2}{\text{s}^2}$$

Rotational speed, *n* is in rev/min

$$M = \frac{\pi}{240} md^2 \frac{\Delta n}{\Delta t} \qquad \frac{\text{lbft}^2}{\text{s}^2}$$

Acceleration time – (revolutions)

Rotational speed, *n* is in rev/s

$$t = \frac{\pi}{4} md^2 \frac{\Delta n}{M} \qquad \text{s}$$

OR

$$t = \frac{2\pi J \Delta n}{M} \qquad \text{s}$$

Rotational speed, *n* is in rev/min

$$t = \frac{\pi}{240} md^2 \frac{\Delta n}{M} \qquad \text{s}$$

OR

$$t = \frac{2\pi J \Delta n}{60M} \qquad \text{s}$$

Kinetic Energy

At a constant velocity

$$W = \frac{1}{2} WK^2 \omega^2 \qquad \text{ft lb}$$

Rotational speed, *n* is in rev/s

$$W = 2\pi^2 WK^2 n^2 \qquad \text{ft lb}$$

Rotational speed, *n* is in rev/min

$$W = \frac{\pi^2 WK^2 n^2}{1800} \qquad \text{ft lb}$$

Work done by acceleration force

$$W = M\gamma r \qquad \text{ft lb}$$

Or change of kinetic energy

$$W = \frac{1}{2} WK^2 \left(\omega_2{}^2 - \omega_1{}^2\right) \qquad \text{ft lb}$$

Moment of Inertia

Rotational

Rotational speed, *n* is in rev/min

$$WK^2 = \frac{308 \bullet Mt}{\Delta n} \qquad \text{lbft}^2$$

Where *W* is the total weight in lb, *K* is radius of gyration in ft, 308 is the constant for converting Weight to mass and Rev/min to Radians/sec when Rotational speed, *n* is in rev/min.

Refer to Appendix IV for Moment of Inertia for a given Body Type description and formulas.

Equivalent moment of inertia referred to the motor shaft through reducer or gearbox.

$$\text{Equivalent}\, WK^2 = WK^2 \left[\frac{n}{n_{motor}}\right]^2 \qquad \text{lbft}^2$$

Linear

Equivalent moment of inertia WK^2 of linearly moving parts can be directly referred to the motor shaft as follows, based on the principle of conservation of energy Kinetic Energy linear = Kinetic Energy rotary:

$$WK^2 = \frac{Wv^2}{\omega^2} = \frac{Wv^2}{2\pi n^2} \qquad \text{lbft}^2$$

Where *W* is the weight in kg (representing mass on earth's gravitational influence) of the total load including equipment, *K* is radius of gyration in ft, *v* is linear velocity in ft/s, and *n* is in rev/min.

Electrical

Power

	3-Phase	1-Phase	DC
Kva	$\frac{\sqrt{3} \bullet I \bullet E}{1000}$	$\frac{I \bullet E}{1000}$	
kW	$\frac{HP \bullet 746}{Eff \bullet 1000}$	$\frac{HP \bullet 746}{Eff \bullet 1000}$	$\frac{HP \bullet 746}{Eff \bullet 1000}$
kW	$\frac{\sqrt{3} \bullet I \bullet E \bullet pf}{1000}$	$\frac{I \bullet E \bullet pf}{1000}$	$\frac{I \bullet E}{1000}$
kW	$kva \bullet pf$	$kva \bullet pf$	kva
HP	$\frac{\sqrt{3} \bullet I \bullet E \bullet Eff \bullet pf}{746}$	$\frac{I \bullet E \bullet Eff \bullet pf}{746}$	$\frac{I \bullet E \bullet Eff}{746}$
I	$\frac{HP \bullet 746}{\sqrt{3} \bullet E \bullet Eff \bullet pf}$	$\frac{HP \bullet 746}{E \bullet Eff \bullet pf}$	$\frac{HP \bullet 746}{E \bullet Eff}$
I	$\frac{kW \bullet 1000}{\sqrt{3} \bullet E \bullet pf}$	$\frac{kW \bullet 1000}{E \bullet pf}$	$\frac{kW \bullet 1000}{E}$
I	$\frac{kva \bullet 1000}{\sqrt{3} \bullet E}$	$\frac{kva \bullet 1000}{E}$	

Newton's laws of motion

1. A body continues in its state of rest or uniform motion in a straight line unless an external force acts upon it.
2. The rate of change of momentum produced by an impressed force is proportional to that force, and the change of momentum occurs in the direction of the action of the force.
3. Action and reaction are equal and opposite.

A force *F* acting on a mass *m* produces acceleration *a*. $F = m * a$

Where: *m* is measured in kilograms
And *a* is measured in meters per second per second

Mass and weight

Mass is the property of an object, which determines its resistance to changes in velocity. Weight is the vertical force exerted by the mass acted upon by the gravitational pull.

Lifting

The mass to be lifted must be accelerated from rest to the desired speed and must overcome the gravitational effect. Example, to accelerate a mass from rest to *v* m s^{-1} in *t* seconds requires an average acceleration of *v/t* m s^{-2}, and therefore a force of

$$F = m \bullet \frac{v}{t} \qquad \text{N}$$

But the acceleration due to gravity must be overcome too. Therefore the total lifting force is

$$F = m\frac{v}{t} + mg$$
$$= m\left(\frac{v}{t} + g\right) \qquad \text{N}$$

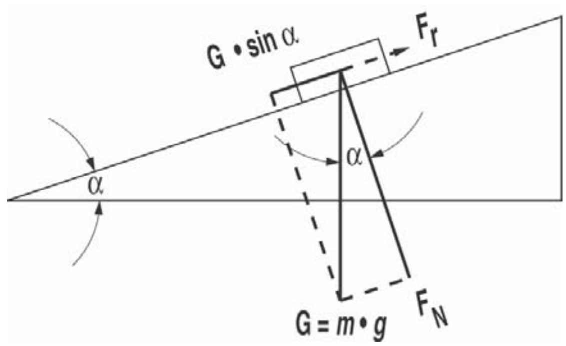
Friction

The horizontal force required to overcome friction is found by applying the coefficient of friction, *u*, to the *weight*, which is the force pressing the two surfaces together. The formula for frictional resistance is:

$$F_r = m \bullet g \bullet \mu \qquad \text{N}$$

The frictional resistance on an incline plane must take into account the angle of ascent.

$$F_r = \mu \bullet F_N \quad \text{OR} \quad F_r = m \bullet g \bullet \mu \bullet \cos\alpha \qquad \text{N}$$

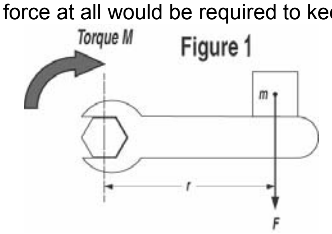


Torque

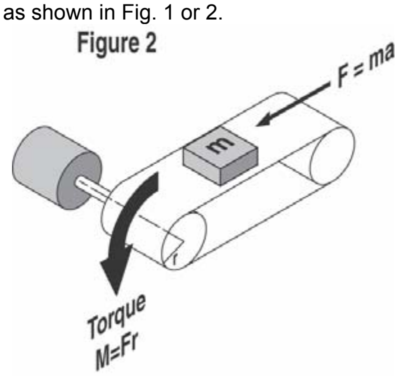
A rotational force acting through a lever arm or radius is called a torque or moment, *M*, unit Nm. Torque is the product of a force *F* and the radius *r* of the lever through which it acts, expressed as:

$$M = F \bullet r \qquad \text{Nm}$$

A torque is required to operate a typical conveyor installation, Fig. 2. Calculation of the torque value begins with the horizontal force *F* required to accelerate the mass *m*. It is important to understand the fact that, if frictional and other resistance were absent, once the mass *m* is in motion no force at all would be required to keep it moving.



A force *F* is required to accelerate the mass from rest. If the mass is known, as it will be, the only variable in $F = m * a$ is the acceleration *a*. In practice, the value of *a* will be decided by operational constraints of velocity and time. When F is known, the required torque input is obtained as shown in Fig. 1 or 2.



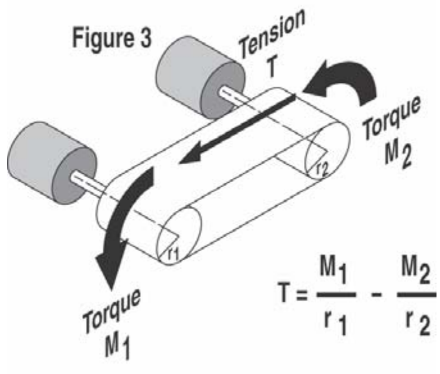
The torque, Fig. 2, to be applied by the motor at the driving pulley (neglecting friction) is the accelerating force multiplied by the radius of the pulley

$$M = F \bullet r \qquad \text{Nm}$$

$$= m \bullet a \bullet r \qquad \text{Nm}$$

Torque and Tension

The diagram Fig. 3 shows how tension is directly related to torque. The torque of each pulley is equal to the force at its rim multiplied by the pulley radius. The tension *T* is the difference between the torques, M_1 and M_2, exerted by each pulley. If the sense of torque M_2 is in the same as M_1, *T* will be reduced; if the torques are in the opposite sense (that is, if M_2 is a braking torque and therefore negative), *T* will be increased.



Moment of Inertia

A mass, which is constrained to rotate about an axis, is *independent of gravity* – unless it is not symmetrical about the axis of rotation. Rotational acceleration of a symmetrical mass is directly analogous to horizontal linear acceleration of mass. The acceleration force may act tangentially upon the mass or may be a shaft torque (as it is in VSD applications).

In linear motion the acceleration force is F = ma. Correspondingly, in rotational motion the accelerating torque is

$$M = J\alpha \qquad \text{Nm}$$

Where *J* is the moment of inertia and α is the angular acceleration in radians per second.

Calculation of moments of inertia is only valid for a few simple shapes. For rotating machinery the moment of inertia is measured by test procedures. Manufacturers' data for moment of inertia may be given in the SI-derived quantity GD^2 (or imperial quantity WK^2 measured in lb-ft^2). The conversions are:

$$GD^2 = 4\text{J} \qquad \text{kg m}^2$$

$$GD^2 = 4.21\,\text{WK}^2 \bullet 10^{-2} \qquad \text{kg m}^2$$

To calculate the moment of inertia for a given shape, refer to Appendix IV.

Gearing

The mechanical transmission system between the motor and the driven load frequently incorporates gearing of one kind or another, usually to enable the final output shaft to turn slower than the motor shaft.

The speed ratio of gearing is the difference between motor and load rotational speed, typically stated as:

$$\frac{\text{Input Shaft RPM}}{\text{Output Shaft RPM}} \qquad \text{example}: \frac{1750}{70} = 25:1 \text{ gear ratio}$$

If there are two or more gearing devices in the transmission system, the overall ratio is the product of:

$$\text{Ratio}_1 \times \text{Ratio}_2 \times \text{Ratio}_3 \times ....$$

The relationships on either side of a transmission ratio are as follows:

$$\frac{\omega_1}{\omega_2} = \frac{n_1}{n_2} \qquad \text{where } \omega \text{ is in } \frac{\text{rad}}{\text{s}} \text{ and } n \text{ is in rpm or } \frac{\text{rev}}{\text{s}}$$

$$\frac{\omega_1}{\omega_2} = \frac{M_2}{M_1} \qquad \text{Torque ratio is the } \textit{inverse} \text{ of the speed ratio.}$$

$$\frac{\omega_1}{\omega_2} = \left(\frac{J_2}{J_1}\right)^{\frac{1}{2}} \qquad \text{Moment of inertia ratio is the } \textit{inverse square} \text{ of the speed ratio.}$$

As shown above, transmission systems that reduce the speed at the output are torque amplifiers. The transmission of the torque is reduced by the losses of the gearing.

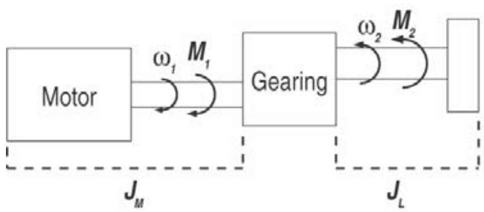
The measurement of velocity is more conveniently measured in rev-per-minute or rev-per-sec. There are 2π radians (rad) in 360^0, so that:

$$(n \text{ in revs per second}) \qquad \omega = 2\pi\, n \qquad \frac{\text{rad}}{\text{s}}$$

$$(n \text{ in revs per minute}) \qquad \omega = 2\pi \frac{n}{60} = \frac{\pi}{30} n \qquad \frac{\text{rad}}{\text{s}}$$

Moment of Inertia Reflected to Motor Shaft

As shown by the earlier formula, the load moment of inertia reflected to the motor shaft, is the inverse square of the speed ratio. The efficiency, η, must also be taken into consideration.



$$Ratio = \frac{n_1}{n_2} = \frac{\omega_1}{\omega_2} = \frac{M_2}{M_1} = \sqrt{\frac{J_L}{J_M}}$$

Load inertia reflected to motor shaft calculation

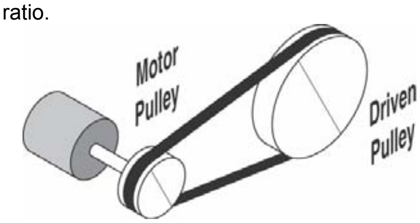
$$J_{LOAD} = \frac{J_L \, \omega_2^{\,2}}{\omega_1^{\,2}} \times \frac{1}{\eta} \qquad \text{kg m}^2$$

Total inertia reflected to motor shaft calculation

$$J_T = J_M + \left(\frac{J_L \, \omega_2^{\,2}}{\omega_1^{\,2}} \times \frac{1}{\eta} \right) \qquad \text{kg m}^2$$

Belts and Sheaves

The ratio of the pulley diameters when a belt/sheave transmission system is used determines the speed ratio.



$$\text{Driven RPM} = \frac{\text{Motor Pulley Dia.}}{\text{Driven Pulley Dia}} \bullet \text{Motor RPM}$$

Acceleration Torque

Accelerating torque is the difference between the torque applied to the input shaft and the sum of all the torques demanded by the load. Another way of stating this is: to accelerate the motor and connected load, the load, gearing and motor resistances must first be overcome, then additional torque must be applied that allows acceleration to occur.

Acceleration torque at any moment is -

$$M_{Accel} = M_{Motor} - M_{Resistance} \quad \text{where}: M_{Resistance} = M_{Load} + M_{Losses} \qquad N$$

The acceleration torque at the motor is

$$M = J_T \alpha_1 \qquad \text{Nm}$$

Where α_1 is the angular acceleration of the motor shaft. This is derived from

$$\alpha_1 = \frac{\omega_1 \alpha_2}{\omega_2} \qquad rad\ s^2$$

Where α_2 is the desired angular acceleration of the input shaft of the driven load.

Torque and Power

Torque is a measurement of the mass and acceleration, where power is a measure of the torque and the velocity.

$$\text{Power } P = \text{Torque} \times \text{Speed}$$

$$= M\omega \qquad \text{W}$$

Section 3 – Application Examples

Application Matrix

	Load Characteristics				Speed / Torque Characteristics				
Application	Friction	Gravity	Fluid	Inertia	CT	VT	Speed Range	Regen/ Braking	Reg Type
Agitators	x				x		30:1		S
Braider				x	x		10:1		S
Can Making	x				x		15:1	x	S
Centrifugal Fans			x			x	4:1	x	S
Centrifugal Fans (I D)			x			x	10:1	x	S
Centrifugal Pumps			x			x	3:1		S
Centrifuge				x	x		30:1	x	S
Coaters	x				x		4:1	x	S/T
Coilers				x	x		60:1	x	S/T
Compressors / Reciprocating	x				x		10:1		S
Compressors / Screw Type	x				x		10:1		S
Conveyors (Auger)	x				x		20:1		S
Conveyors (Belt)	x				x		30:1	x	S
Conveyors (Chain Type/Load Share)	x				x		40:1	x	S/T
Conveyors (Vibratory)				x	x		10:1		S
Cut to Length	x				x		100:1	x	S/P
De- Barkers				x	x		20:1	x	S
Diverters				x	x		40:1		S
Dryers			x			x	10:1		S
Edge Trimmer	x				x		15:1	x	S
Elevators		x			x		100:1	x	S/T
Extruders	x				x		60:1		S/T
Feeders	x				x		4:1		S
Floculators	x				x		10:1		S
Flying Cut Off	x				x		100:1	x	S/P
Gantry type Cranes and Hoists	x	x		x	x		100:1	x	S/T
Grinders				x	x		10:1	x	S
Hoists		x			x		100:1	x	S/T
HVAC			x			x	3:1		S
Indexers	x				x		20:1		S/P
Injection Molding	x				x		40:1		S/T
Kiln Drives				x	x		10:1	x	S
Lift applications		x			x		100:1	x	S/T
Line Shaft	x				x		10:1	x	S/T
Mill / Ball Type				x	x		10:1	x	S
Mill / Machining Type	x				x		100:1	x	S/P
Regulation types: S=Speed, T=Torque, P=Position									

	Load Characteristics				Speed / Torque Characteristics				
Application	Friction	Gravity	Fluid	Inertia	CT	VT	Speed Range	Regen/ Braking	Reg Type
Mill / Plate Type				x	x		10:1	x	S/T
Mill / Rod Type				x	x		10:1	x	S/T
Mixers (Rotating Beater)	x				x		4:1		S
Mixers / Banbury	x				x		10:1		S/T
Monorails	x				x		10:1	x	S
Packaging Equipment	x				x		20:1	x	S/P
Palletizers	x	x			x		10:1	x	S/P
Positioning	x			x	x		100:1	x	P
Positive Displacement Blowers / Pumps	x				x		10:1		S
Press / Blanking Type				x	x		30:1	x	S
Press / Punch Type				x	x		30:1	x	S
Press / Reciprocating				x	x		10:1	x	S
Press Feeders	x				x		60:1	x	S
Rolling Mills	x				x		10:1	x	S
Rotary Tables				x	x		100:1	x	S/P
Shakers				x	x		10:1		S
Slitter	x				x		100:1	x	S/T
Sorter	x				x		40:1		S
Spindles				x	x		100:1	x	S
Spray Painting	x	x			x		40:1	x	S
Stackers / Storage & Retrieval		x			x		10:1	x	S/P
Tension Reels				x	x		100:1	x	S/T
Tentoring	x				x		100:1	x	
Test Stands / Chassis (Dynamometer)				x	x		100:1	x	S/T
Test Stands / Engine				x	x		100:1	x	T
Test Stands / Generic	x			x	x		100:1	x	T
Test Stands / Transmission				x	x		100:1	x	T
Tower type Cranes and Hoists		x			x		100:1	x	S/T
Transfer Line	x				x		10:1	x	S
Unwinder (for web / wire)				x	x		100:1	x	S/T
Web Calendaring				x	x		100:1	x	S/T
Web Coating				x	x		100:1	x	S/T
Web Pickling				x	x		20:1	x	S/T
Wind Tunnels			x			x	4:1		S
Winder (for web / wire)				x	x		100:1	x	S/T
Wire Drawing	x				x		40:1	x	S/T
Regulation types: S=Speed, T=Torque, P=Position									

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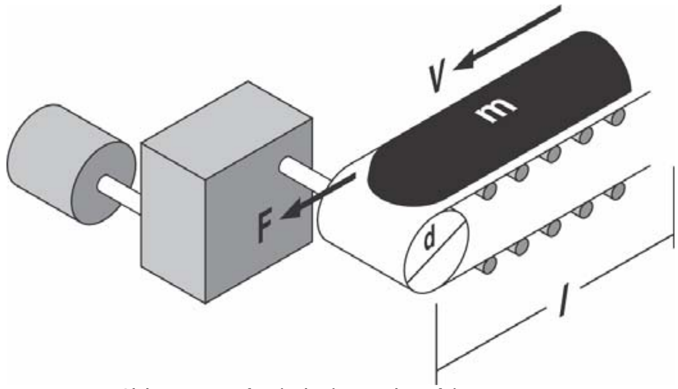
Conveyor



Sizing a motor for desired operation of the conveyor.

Application data	Data Given	Converted to SI Units
Material delivery rate:	1000 tons per hour	(252 kg/s)
Density of material:	2 kg dm^{-3}	(2000 kg/m^3)
Width of belt:	750 mm	(0.75m)
Length of conveyor:	325ft	(99.06m)
Depth of load:	100mm	(0.1m)
Weight of belt:	15 kg per meter	
Diameter of belt pulley	400mm	(0.4m)
Coefficient of friction, static	0.09	
Coefficient of friction, moving	0.07	
Breakaway torque, fully loaded	5800 lb-ft	(4280Nm)
Desired acceleration	4 seconds	

The example application is required to start when fully loaded. Find the rating of a standard 3-phase, 460V AC induction motor to drive the conveyor, assuming typical 4-pole, 60Hz, 1750RPM at full load.

Procedure

1. Convert all value to SI units, if not already done.
2. Determine the linear and rotational speeds and gear ratio.
3. Determine the loading and acceleration, and from them the forces to accelerate and to run.
4. Calculate power ratings of the motor and the drive.

Calculations

1. Data not in SI units converted, values shown in parenthesis

2. Velocity and Gearing

2.1 Volume of required delivery rate.

Required delivery rate per hour = volume x density

$$\text{Volume delivered} = \frac{\text{mass delivered}}{\text{density}} \qquad m^3/hr$$

$$\text{Volume per second} = \frac{252}{2000} \qquad m^3/s$$

$$= 0.126 \qquad m^3/s$$

2.2 Linear velocity

$$v = \frac{\text{volume per second}}{\text{cross-section area}}$$

$$= \frac{0.126}{(0.75 x 0.1)} \qquad m/s$$

$$= 1.575 \qquad m/s$$

2.3 Rotational speed of driven pulley.

$$\omega = \frac{\text{linear speed}}{\text{radius}} \qquad rad/s$$

$$= \frac{1.575}{0.2} \qquad rad/s$$

$$= 7.875 \qquad rad/s$$

$$RPM = \omega \text{ x } \frac{30}{\pi} = 75.2 \qquad rpm$$

2.4 Gearbox ratio will be 1750 / 75.2 = 23 to 1 approximately.

Notes

- This is the ratio appropriate for a standard 4-pole motor as stated earlier.
- Output speeds are determined by the application but input speeds can be varied. If the gearbox calculated for a particular application is unacceptably high, a motor with more pole pairs may be a better solution.
- The rotational speed *n* of a motor, where *p* is the number of poles and *f* is the rated frequency, is

$$n = \frac{f \text{ x } 120}{p} \qquad rpm$$

3. Calculating Load, Force and Torque

Note

- A factor of 2 is applied to account for the return run of the conveyor belt.

3.1 Load calculations

$$\begin{aligned} \text{Load} &= \text{mass of material plus mass of belt} \\ &= (\text{volume of material x density}) + 2(\text{conveyor length x mass of belt per meter}) \\ &= [(99.06 \text{ x } 0.75 \text{ x } 0.1)(2000)] + 2(99.06 \text{ x } 15) \\ &= 17{,}830.8 \qquad \text{kg} \end{aligned}$$

3.2 Breakaway torque to start the conveyor from rest in a fully loaded state is given in the data as.

$$4280 \qquad Nm$$

3.3 Horizontal *force* required to accelerate the loaded conveyor against rolling friction after breakaway is.

$$\begin{aligned} \text{F}_a &= (\text{load mass x acceleration}) + (\text{load mass x g x coeff. of rolling friction}) \\ &= ma + mg\mu \quad \text{or} \quad m(a + g\mu) \qquad N \end{aligned}$$

and, torque to accelerate conveyor against rolling friction is *force* multiplied by the *radius of pulley*,

3.4 Determine the linear acceleration, all other factors being known.

Linear velocity = 1.575 (from step 2.2)
Required acceleration time is 4sec (given in data)

$$\text{Linear acceleration} = \frac{1.575}{4} = 0.39 \qquad \frac{m}{s^2}$$

3.5 From step 3.3

$$M_a = F_a r \qquad Nm$$
$$= [m(a + g\mu)]r \qquad Nm$$

$$M_a = 17{,}830\,[0.39 + (9.81x0.07)]0.2 = 3839 \qquad Nm$$

3.6 Horizontal *force* required to run the fully loaded conveyor at full speed against rolling friction.
(Assuming wind resistance to be negligible)

$$F_s = (\text{load mass } x \text{ g } x \text{ coeff. of rolling friction}) = mg\mu \qquad Nm$$

and, torque to run the conveyor against rolling friction is force multiplied by the radius of pulley.

$$M_s = F_s r$$
$$= mg\mu r$$
$$= 17.83x10^3 x9.81x0.07x0.2$$
$$= 2448 \qquad Nm$$

4. Power ratings, motor and drive

4.2 Summarize the known torque demands.
Breakaway torque = 4280 Nm
Accelerating torque (Ma) = 3839 Nm
Running torque (Ms) = 2448 Nm

Torque and acceleration do not need to be referred to the motor since power is equal on both sides of a gearing mechanism. The power demand at the belt pulley is the power demand at the motor.

$$P = M\omega \qquad W$$

Since power is proportional to speed, this appears to present a problem. At the instant of starting, the motor speed is zero, therefore power is also zero.

During acceleration, the speed increases from zero to the running speed and therefore the power demand appears to have no particular value. The accelerating torque at full speed can be used as the accelerating power demand.

Per the data given, the starting and acceleration period is 4 seconds. Since this is well within the intermittent overload time of a typical motor, the overload capability may be used for acceleration power.

4.3 Motor power to accelerate the conveyor is the accelerating torque at the conveyor pulley multiplied by the rotational speed of the pulley at full speed, taking into account the efficiency (η) of the gearing. For this example, η is 95%, but in practice it must be verified for the gearbox installed.

$$P_a = M_a \omega \eta$$

$$= 3839 \text{ (from 3.5) x } 7.875 \text{(from 2.3) x } \frac{1}{0.95}$$

$$= 31823 \text{ x } 10^{-3}$$

$$= 31.8 \qquad kW$$

4.3 This would be the rating of a motor able to deliver accelerating torque continuously. In order to make full use of the 150% overload rating of the motor, the actual rating is:

$$31.8\, x \frac{100}{150} = 21.2 \qquad kW$$

A standard 22kW rated motor will work.

4.4 This rating must now be verified with the drive required to operate the motor. The drive must be able to deliver the current required for breakaway torque. Since current is proportional to torque, the current demand is in the ratio of required acceleration current.

$$\text{(from 3.2 and 3.4)} \quad \frac{4280}{3839}$$

Note that the current demand during acceleration must be based on the 31.8kW overload rating for acceleration, not the selected 22kW rating.

4.5 Calculate the currents involved, and having found the starting current demand, find the rating of the drive. The starting current is based on the motor rating of 31.8 kW and is calculated from.

$$P = \sqrt{3}\; x\, V_L \;x\; I_L \;x\; p.f. \qquad kW$$

Where the working power factor (p.f.) is assumed to be the full load, full speed, full voltage rated power factor of the motor, 0.85 (from data).

$$\text{Total} \quad I_L = \frac{P}{\sqrt{3} \text{ x } V_L \text{ x p.f.}} = \frac{31800}{\sqrt{3} \times 460} \, x \, \frac{1}{0.85}$$

$$= 47$$

$$\text{Starting current} = 47 \text{ x } \frac{4280}{3839}$$

$$= 52.4 \qquad \text{A}$$

4.6 Like the motor, the drive will have a short duration overload. For this example, 150% for 60 seconds is assumed. The drive efficiency must be taken into account (98% assumed). The full load rated current of the drive is

$$52.4 \text{ x } \frac{100}{150} \text{ x } \frac{1}{0.98} = 35.6 \qquad A$$

Note

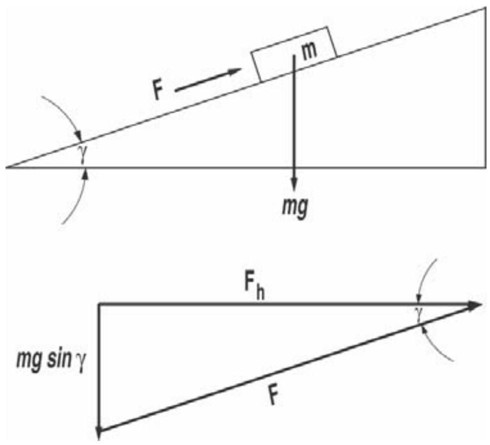
- The overload performance of a given drive may vary in magnitude and time rating.

Inclined Conveyor

From the same conveyor data, find the motor power if the conveyor raises the load through a height of 14 meters.

An inclined plane adds a component of force to the forces required to start, accelerate and run the conveyor. This component is the force required to raise the load.

The total force is the hypotenuse of the vector diagram of which the horizontal component is the force required to start, accelerate or drive the load at constant speed. These have already been calculated in the "conveyor" application. The additional vertical component is *m g* multiplied by the *sine* of the angle of the slope, γ (in this case, 14 ÷ 99).



The total force, *F* is calculated from. (Note - calculator must be in radians mode)

$$F = \left[F_h^{\ 2} + (mg \sin\gamma)^2\right]^{\frac{1}{2}} \qquad N$$

Using the torque values from step 4.1 of the previous "conveyor" example, we can calculate the forces required to start, accelerate and run the incline conveyor at constant speed.

These torque values were either given in the data or calculated by multiplying the force x the radius of the pulley. The pulley radius is 0.2 meters.

1.1 Calculate the Force required to start the conveyor. Starting torque is 4280 Nm.

$$F = \frac{M}{r} \qquad N$$

$$= \frac{4280}{0.2} = 21.4 \times 10^3 \qquad N$$

1.2 Calculate the force required to accelerate the conveyor. Accel torque is 3839 Nm.

$$\frac{3839}{0.2} = 19.195 \times 10^3 \qquad N$$

1.3 Calculate the force required to run the conveyor. Running torque is 2448 Nm.

$$\frac{2448}{0.2} = 12.24 \times 10^3 \qquad N$$

We can calculate the angle of the slope. This is determined by taking the incline height (given at 14 meters) and dividing by the length (given at 99 meters).

$$\gamma = \sin^{-1}\left(\frac{14}{99}\right) = 0.1418 \qquad rad$$

3. The mass, *m* of the load is 17.83 x 10^3 kg (from conveyor example step 3.1).

4. Now, using these force values (step 1.1-1.3), we can calculate the force required to raise (incline) the conveyor 14 meters in a distance of 99 meters.

4.1 Starting force is (Note: calculator in radians mode)

$$F_{starting} = \left[F_h^{\ 2} + (mg \sin\gamma)^2\right]^{\frac{1}{2}} \qquad N$$

$$= \left[(21.4 \times 10^3)^2 + (17.83 \times 10^3 \cdot 9.81 \cdot \sin 0.1418)^2\right]^{\frac{1}{2}} \qquad N$$

$$= 32.707 \times 10^3 \qquad N$$

4.2 Accelerating force is (Note: calculator in radians mode)

$$F_{accel} = \left[F_h{}^2 + (mg\sin\gamma)^2\right]^{\frac{1}{2}} \qquad N$$

$$= \left[\left(19.195\times10^3\right)^2 + \left(17.83\times10^3\cdot 9.81\cdot\sin 0.1418\right)^2\right]^{\frac{1}{2}} \qquad N$$

$$= 31.309\times10^3 \qquad N$$

4.3 Running force is (Note: calculator in radians mode)

$$F_{run} = \left[F_h{}^2 + (mg\sin\gamma)^2\right]^{\frac{1}{2}} \qquad N$$

$$= \left[\left(12.24\times10^3\right)^2 + \left(17.83\times10^3\cdot 9.81\sin 0.1418\right)^2\right]^{\frac{1}{2}} \qquad N$$

$$= 27.597\times10^3 \qquad N$$

5. Torque required for the forces calculated.

$$M = F\,r \qquad Nm$$

5.1 Starting torque is

$$M = \left(32.707\times10^3\right)\cdot 0.2 \qquad Nm$$

$$= 6.54\times10^3 \qquad Nm$$

5.2 Accelerating torque is

$$M = \left(31.309\times10^3\right)\cdot 0.2 \qquad Nm$$

$$= 6.26\times10^3 \qquad Nm$$

5.3 Running torque is

$$M = \left(27.597\times10^3\right)\cdot 0.2 \qquad Nm$$

$$= 5.51\times10^3 \qquad Nm$$

6. Now that the torque values have been calculated, the next step is to determine the power required for acceleration. Calculate the power by multiplying the torque at the conveyor pulley by the rotational speed of the pulley at full speed. The efficiency of the gearing must also be considered. For this example, we will use 94%.

$$P = M_a \omega \eta \qquad W$$

$$= 6261 \times 7.875 \times \frac{1}{0.94} \qquad W$$

$$= 54798 \times 10^{-3} \qquad kW$$

$$= 54.79 \qquad kW$$

6.1 The power calculated is continuous, so we will make use of the overload capability of the motor (150%) so the actual rating required is:

$$54.79 \times \frac{100}{150} \qquad kW$$

$$= 36.5 \qquad kW$$

A standard 37kW rated motor will work.

6.2 This rating must now be verified with the drive required to operate the motor. The drive must be able to deliver the current required for breakaway torque. Current is proportional to torque, so the current required is in the ratio of breakaway to acceleration torque.

$$(\text{from } 5.1 \text{ and } 5.2) \quad \frac{6541}{6261}$$

Note that the current demand during acceleration must be based on the 54.8kW overload rating, not the selected 37kW rating.

6.3 Calculate the currents involved, having found the starting current demand, find the rating of the drive. Starting current is based on the motor rating of 82.3kW.

$$P = \sqrt{3} \times V_L \times I_L \times p.f. \qquad kW$$

The working power factor (p.f.) are assumed to be the full load, full speed, and full voltage rated power factor of the motor, 0.85.

$$\text{Total } I_L = \frac{P}{\sqrt{3} \cdot V_L \cdot p.f.} = \frac{54.79 \times 10^3}{\sqrt{3} \times 460} \times \frac{1}{0.85} \quad A$$

$$= 80.9 \quad A$$

$$\text{Starting current } = 80.9 \times \frac{6541}{6261} \quad A$$

$$= 84.5 \quad A$$

6.4 Like the motor, the drive will have a short duration overload. For this example, 150% for 60 seconds is assumed. The drive efficiency must be taken into account (98% assumed). The full load rated current of the drive is:

$$84.5 \times \frac{100}{150} \times \frac{1}{0.98} \quad A$$

$$= 57.5 \quad A$$

Note

- The overload performance of a given drive may vary in magnitude and time rating.

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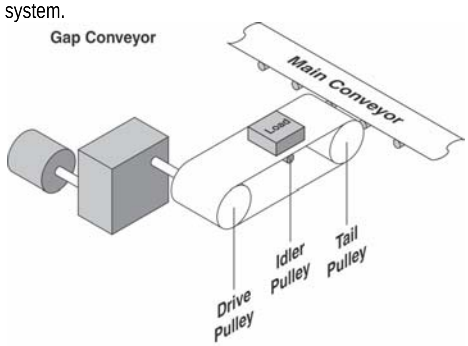
Gap Conveyor

A gap conveyor is a short conveyor with fast accel/decal times used to load the product onto the longer conveyor when there is an opening. Because of their fast accel and decel times it is necessary to take into account the inertia of the system.



Application Data	Data Given		Converted to SI Units	
Conveyor Speed:	325	fpm	(1.651	m/s)
Conveyor Length:	4	ft	(1.219	m)
Belt Mass:	5	lb/ft	(7.440	kg/m)
Load Mass:	100	lb	(45.36	kg)
Belt Pulley Radius:	0.25	ft	(0.0762	m)
Coefficient of Friction, Moving:	0.07	per unit		
Breakaway torque, fully loaded:	35.0	lb*ft	(47.46	Nm)
Desired Acceleration:	0.3	sec		
Desired Deceleration:	0.3	sec		
Run Time @ Top Speed:	0.4	sec		
Idle Time:	0.5	sec		
Desired Motor RPM	1750	RPM		
Inertia:				
Drive pulley:	15.1	lb*ft^2	(0.6363	kg*m^2)
Tail pulley	11.3	lb*ft^2	(0.4762	kg*m^2)
Idler roller:	0.5	lb*ft^2	(0.0211	kg*m^2)
Rotor Inertia:			0.0065	kg*m^2

Procedure
1. Convert all values to SI units, if not already done.
2. Determine the rotational speeds and gear ratio.
3. Determine the accelerating, running, and decelerating torque.
4. Calculate the power ratings of the motor, drive, and dynamic braking.

Calculations
1. Convert data not in SI units, SI values shown converted in parenthesis.
2. Determine the rotational speeds and gear ratio.

2.1 Angular velocity.

$$\omega = \frac{\text{linear speed}}{\text{radius}} \qquad \text{rad}/\text{s}$$
$$= \frac{1.651}{0.0762} \qquad \text{rad}/\text{s}$$
$$= 21.67 \qquad \text{rad}/\text{s}$$

Now the RPM at the load side of the gear box are calculated.

$$RPM = \omega \times \frac{30}{\pi} = 21.67 \times \frac{30}{\pi} = 206.9 \qquad \text{rpm}$$

2.2 Gearbox ratio will be

$$\text{Gearbox Ratio} = \frac{\text{Desired Motor RPM}}{206.9} = \frac{1750}{206.9} = 8.46 \text{ to } 1 \text{ approximately}$$

3. Load, Force, and Torque

3.1 Breakaway torque to start the conveyor from rest in a fully loaded state is given in the data as 47.46 Nm.

3.2 Load Calculations

$$m_{Load} = \text{mass of material} + \text{mass of belt} \qquad \text{kg}$$
$$= (\text{mass of material}) + 2(\text{conveyor length} \times \text{mass of belt}) \qquad \text{kg}$$
$$= (45.36) + 2(1.219 \times 7.440) \qquad \text{kg}$$
$$= 63.50 \qquad \text{kg}$$

3.3 Load Inertia

$$\text{Linear Acceleration} = \frac{v}{t} = \frac{1.651}{0.3} = 5.503 \qquad \text{m}/\text{s}^2$$

$$F = m_{Load} \times a + m_{Load} \times g\mu = m_{Load}(a + g\mu) \qquad \text{N}$$
$$= 63.50(5.503 + 9.81 * 0.07) \qquad \text{N}$$
$$= 393.0 \qquad \text{N}$$

$$M = Fr \qquad Nm$$
$$= 393.0 \times 0.0762 \qquad Nm$$
$$= 29.95 \qquad Nm$$

$$J_{Load} = \frac{M \times t}{\Delta\omega} \quad \text{kg m}^2$$

$$= \frac{29.95 \times 0.3}{21.67} \quad \text{kg m}^2$$

$$= 0.4146 \quad \text{kg m}^2$$

3.4 Total Inertia

$$J_{Total} = J_{Load} + J_{Drive\ Pulley} + J_{Tail\ Pulley} + J_{Idler\ Roller} + (J_{Rotor} \text{ x Gear Ratio}^2) \quad \text{kg m}^2$$

$$= 0.4146 + 0.6363 + 0.4762 + 0.0211 + (0.0065 \text{ x } 8.458^2) \quad \text{kg m}^2$$

$$= 2.013 \quad \text{kg m}^2$$

3.5 Accelerating Torque

$$M_{Accel} = \frac{J_{Total} \times \Delta\omega}{\text{Accel Time}} \quad \text{Nm}$$

$$= \frac{2.013 \times 21.67}{0.3} \quad \text{Nm}$$

$$= 145.4 \quad \text{Nm}$$

3.6 Running Torque

$$F_{Run} = \text{Load} \times 9.81 \times \text{coeff. of rolling friction} \quad \text{N}$$

$$= 63.50 \times 9.81 \times 0.07 \quad \text{N}$$

$$= 43.61 \quad \text{N}$$

$$M_{Run} = F_{Run} \times \text{Belt Pulley Radius} \quad \text{Nm}$$

$$= 43.61 \times 0.0762 \quad \text{Nm}$$

$$= 3.323 \quad \text{Nm}$$

3.7 Decelerating Torque

$$M_{Decel} = \frac{J_{Total} \times \Delta\omega}{\text{Decel Time}} \qquad \text{Nm}$$

$$= \frac{2.013 \times 21.67}{0.3} \qquad \text{Nm}$$

$$= 145.4 \qquad \text{Nm}$$

4. Power Ratings of the Motor, Drive and Dynamic Braking

4.1 From step 3, we will use accelerating torque to calculate the motor size, since it is the largest torque requirment out of the 4 torques calculated: breakaway torque, accelerating torque, running torque, and decelerating torque. Motor power to accelerate is the acceleration torque multiplied by the rotational speed, taking into account the efficiency of the gearbox η. In this example η is 95%, but in practice it must be verified with the gearbox installed.

$$P_{Accel} = M_{Accel} \times \omega \times \eta \qquad \text{W}$$

$$= 145.4 \times 21.67 \times \frac{1}{0.95} \qquad \text{W}$$

$$= 3317 \qquad \text{W}$$

4.2 Motor power to decelerate. Motor power to accelerate is the acceleration torque multiplied by the rotational speed. We will not take into account the losses in gearbox efficiency in order to give us some headroom for sizing dynamic braking.

$$P_{Decel} = M_{Decel} \times \omega \qquad \text{W}$$

$$= 145.4 \times 21.67 \qquad \text{W}$$

$$= 3151 \qquad \text{W}$$

4.3 Motor size. Because the motor is accelerating and decelerating 0.6 seconds out of a total cycle time of 1.5 second, we will not utilize 150% overload capability.

Therefore, a standard 3.7kW (5 HP) motor will work.

4.4 Drive size. We will calculate the required current rating of the drive using the largest of either the PAccel or P_{Decel} above and the formula for 3 phase power.

$$P = \sqrt{3} \times V_L \times I_L \times \text{p.f.} \qquad \text{W}$$

The motor power factor (p.f.) is assumed to be at full speed, full torque, and full voltage. In this example, the motor power factor is 0.85. Next we solve for current.

$$I_L = \frac{P}{\sqrt{3} \times V_L \times p.f.} \qquad A$$

$$= \frac{3317}{\sqrt{3} \times 460 \times 0.85} \qquad A$$

$$= 4.898 \qquad A$$

A 460V, 5A drive will be sufficient for this application.

4.5 Dynamic brake size. We calculate the peak power that must be dissipated in the dynamic brake based on power to decelerate, and taking into account motor efficiency. Motor efficiency for the motor is 0.84.

$$P_{Peak} = P_{Decel} \times \text{motor efficiency} \qquad W$$

$$= 3151 \times 0.84 \qquad W$$

$$= 2647 \qquad W$$

$$P_{Ave} = \frac{P_{Peak}}{2} \times \frac{\text{decel time}}{\text{cycle time}} \qquad W$$

$$= \frac{2647}{2} \times \frac{0.3}{1.5} \qquad W$$

$$= 264.7 \qquad W$$

The dynamic brake chosen, or other method of regeneration, must be able to dissipate 2647 W peak and have a continuous rating of at least 265 W.

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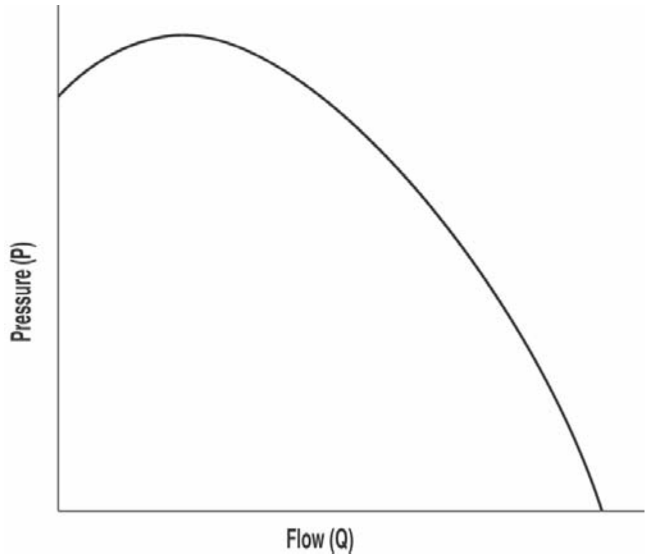
Centrifugal Fan

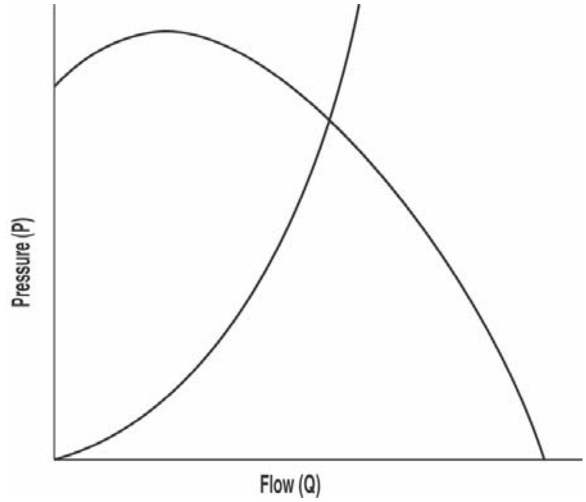
Fans are designed to be capable of meeting the maximum demand of the system in which they are installed. Quite often the actual demand varies and may be much less than the designed capacity.

The centrifugal fan imparts energy into air by centrifugal force. This results in an increase in pressure and produces airflow at the outlet of the fan. Below is an example of what a typical centrifugal fan can produce at its outlet at a given speed.



The curve is a plot of outlet pressure (in static inches of water) versus the flow of air (in cubic feet per minute). Standard fan curves will usually show a number of curves for different fan speeds and includes fan efficiency and power requirements. These are useful for selecting the optimum fan for any application, and are required to predict fan operation and other parameters when the fan operation is changed.

The system curve shows the requirements of the vent system that the fan is used on. It shows how much pressure is required from the fan to overcome system losses and produce airflow.



zThe system curve is a plot of “load” requirement independent of the fan. The intersection of the fan and the system curve is the natural operating point. It is the actual pressure and flow that will occur at the fan outlet when this system is operated. Without external influences, the fan will operate only at this point.

Many systems require operation at a wide variety of points. There are several methods used to modulate or vary the flow (or CFM) of a system to achieve the optimum points. These include:

> Cycling – As done in home heating systems. This produces erratic airflow and is unacceptable for commercial or industrial uses.
>
> Outlet Dampers – Control louvers or dampers are installed at the outlet of the fan. To control airflow, they are turned to restrict the outlet, which reduces the airflow.
>
> Variable Inlet Vanes – By modifying the physical characteristics of the air inlet, the fans operating curve is modified which changes the airflow.
>
> Variable Frequency Drives – By changing the actual fan speed, the performance of the fan changes producing a different airflow.
>
> By changing the airflow, or the fan speed, the system or fan curves are affected which produces a different natural operating point. In so doing, they also may change the fan’s efficiency and power requirements.

Outlet Dampers

The outlet dampers affect the system curve by increasing the resistance to airflow. The system curve can be stated as,

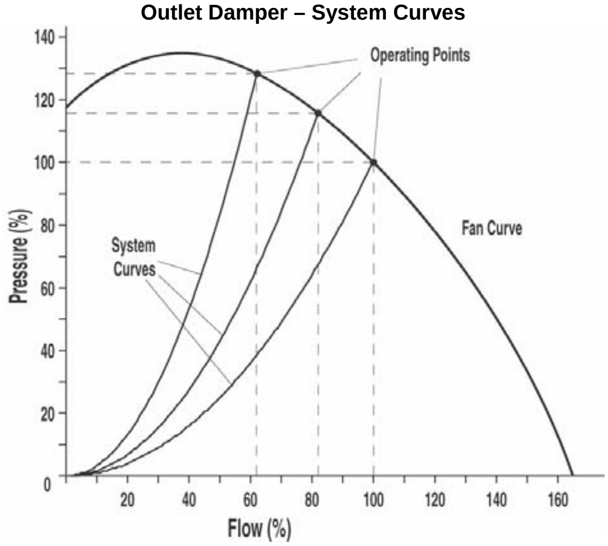
$$P = K \times (CFM)^2$$

Where:

P is the pressure required to produce a given flow in the system.
K is a function of the system that represents the friction to airflow.
CFM is the airflow desired.

The outlet dampers affect the K portion of the formula. The diagram below shows several different system curves indicating different outlet damper positions.

Outlet Damper – System Curves



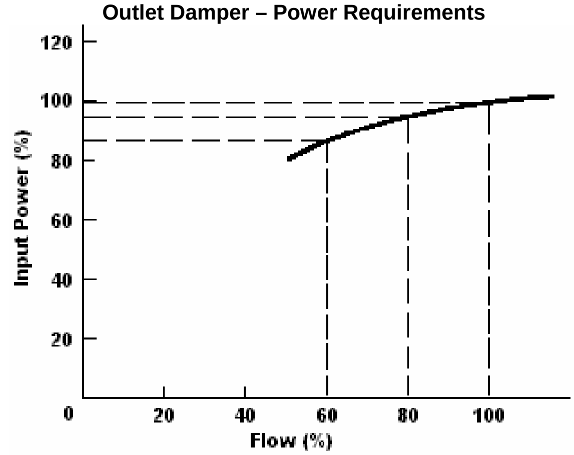
The power requirements for this type of system decrease gradually as flow is decreased as shown in the following diagram.

$$HP = \frac{CFM \times LbFt^2}{33{,}000 \times Eff_{Fan}} \qquad \text{Where: CFM} = \text{Cubic feet per minute}$$

$$HP = \frac{CFM \times PIW}{6356 \times Eff_{Fan}} \qquad \text{PIW} = \text{Inches of water gauge}$$

$$HP = \frac{CFM \times LbIn^2}{229 \times Eff_{Fan}} \qquad \text{Eff}_{\text{Fan}} = \%/100$$

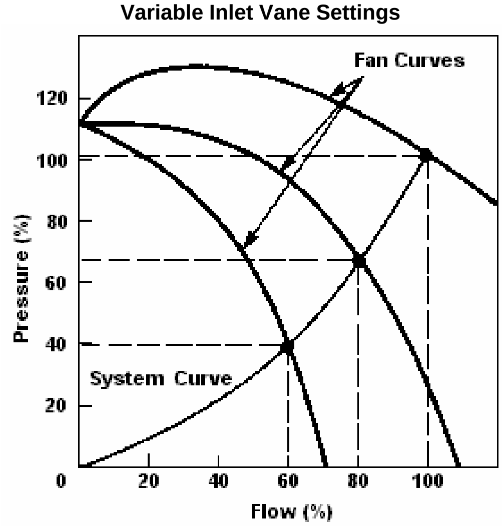
Outlet Damper – Power Requirements



Variable Inlet Vanes

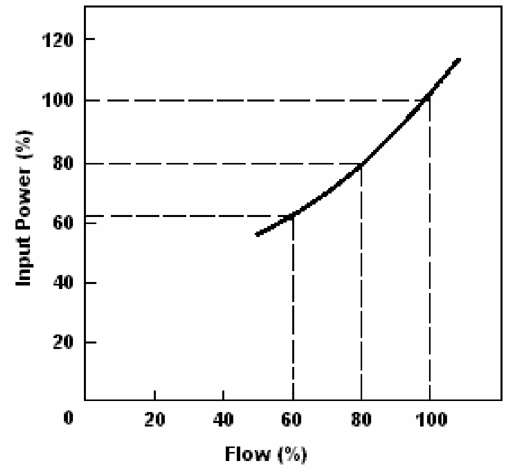
This method modifies the fan curve so that is intersects the system curve at a different point. Below is a representation of the changes in the fan curve for different inlet vane settings.

Variable Inlet Vane Settings



The power requirements for this method decrease as airflow decreases, and to a greater extent than the outlet damper.

Variable Inlet Vane – Power Requirements



Variable Frequency Drives

This method takes advantage of the change in the fan curve that occurs when the speed of the fan is changed. These changes can be quantified in a set of formulas called the affinity laws.

$$\frac{Q_2}{Q_1} = \frac{N_2}{N_1} \qquad \frac{P_2}{P_1} = \left(\frac{N_2}{N_1}\right)^2 \qquad \frac{HP_2}{HP_1} = \left(\frac{N_2}{N_1}\right)^3$$

Where:

N = Fan speed
Q = Flow (CFM)
P = Pressure (Static Inches of Water)
HP = Horsepower

Note that when the flow and pressure laws are combined, that the result is a formula that matches the system curve formula – $P = K \times (CFM)^2$.

$$P_2 = P_1 \times \left(\frac{N_2}{N_1} \right)^2$$

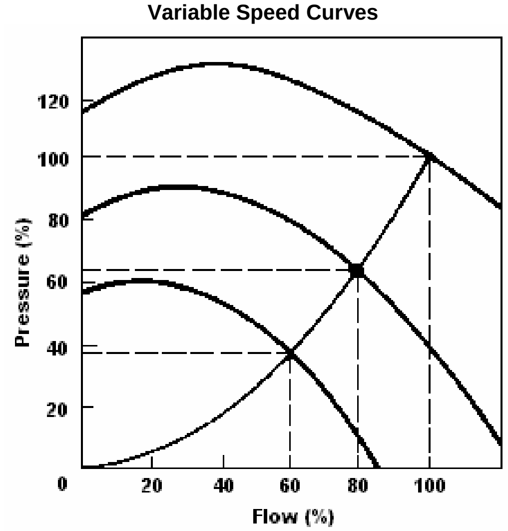
$$\frac{Q_2}{Q_1} = \frac{N_2}{N_1} \rightarrow \left(\frac{Q_2}{Q_1} \right)^2 = \left(\frac{N_2}{N_1} \right)^2$$

By substituting $(Q_2/Q_1)^2$ for $(N_2/N_1)^2$ in the first equation gives us:

$$P_2 = P_1 \times \left(\frac{Q_2}{Q_1} \right)^2 \quad \text{or} \quad P_2 = \left[\frac{P_1}{(Q_1)^2} \right] \times (Q_2)^2$$

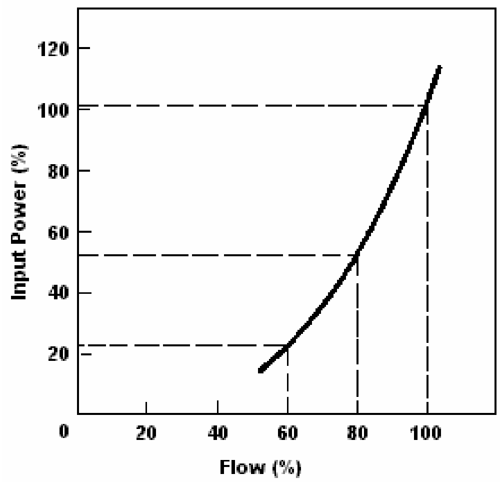
The quantity $P_1/(Q_1)^2$ coincides with the system constant, K. This shows that the fan will follow the system curve when its speed is changed.

Variable Speed Curves



As the fan speed is reduced, a significant reduction in power requirement is achieved.

Variable Speed – Power Requirements

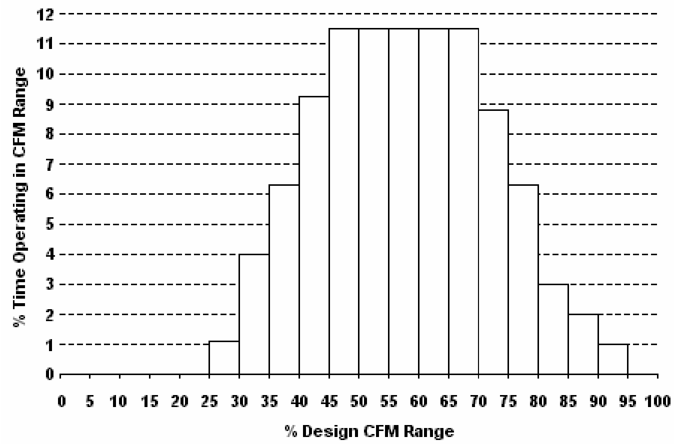


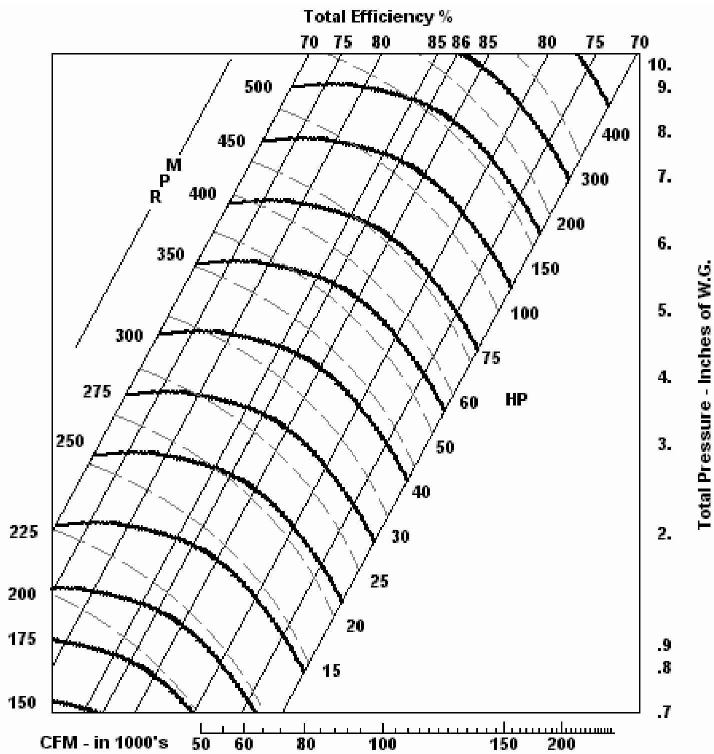
The variable speed method achieves flow control in a way that closely matches the system or load curve. This allows the fan to produce the desired results with the minimum of input power.

Fan Energy Savings

It is possible to estimate the power consumption for reach of these various methods and associate a cost of operation with them. To accomplish this, an actual load profile and fan curve is required as shown below.

Load Profile





As an example, a simple analysis of the variable speed method compared to the outlet damper method follows.

Using the fan curve shown previously, assume the fan selected is to be run at 300 RPM and 100% CFM is to equal 100,000 CFM as shown on the chart. Assume the following Load Profile.

CFM	Duty Cycle (% of Time)
100%	10%
80%	40%
60%	40%
40%	10%

For each operating point, we can obtain a required horsepower from the fan curve. This horsepower is multiplied by the percent of time (divided by 100%), that the fan operates at this point. These calculations are then summed to produce a “weighted horsepower” that represents the average energy consumption of the fan.

Outlet Damper Method

CFM	Duty Cycle	Horsepower	Weighted HP
100	10	37	3.7
80	40	35	14.0
60	40	31	12.4
40	10	27	2.7
		Total	32.8

Similar calculations are done to obtain a weighted horsepower for variable speed operation. However, the fan curve does not have enough information to read all the horsepower values for our operating points. We can use the formulas from the affinity laws to overcome this.

The first point is obtained from the fan curve. 100% flow equals 100% speed equals 37 HP.
The flow formula $Q_2/Q_1 = N_2/N_1$ can be substituted into the horsepower formula, $HP_2/HP_1 = (N_2/N_1)^3$ to give us:

$$\frac{HP_2}{HP_1} = \left(\frac{Q_2}{Q_1}\right)^3$$

When Q_1 = 100% and HP_1 = 35HP, Q_2 and HP_2 will have the following values:

Q_2	80	60	40
HP_2	19	8	2.37

Now sufficient information is available to calculate the weighted horsepower.

Variable Speed Method

CFM	Duty Cycle	Horsepower	Weighted HP
100	10	35	3.5
80	40	19	7.6
60	40	8	3.2
40	10	2.37	0.237
		Total	14.537

Comparing the results of the two methods of control indicates the difference in energy consumption.
In order to get a dollar value of savings kilowatt-hours used must be known. To calculate this, multiply the horsepower by 0.746 and then multiply the result by the hours the fan will operate in a period of time. This would typically be for a month.

	Outlet Damper	Variable Speed
Weighted HP	32.8	14.537
X kW / HP	0.746	0.746
X Hours per Month	730	730
= kWH per month	17,862	7,916.55
X Cost	$ 0.07	$ 0.07
= Total Cost	$ 1,250.34	$ 554.16

This example shows a cost saving of more than $700 per month by using a variable speed method. Note that the example is very basic and does not motor and drive efficiency.

Centrifugal Pump

Pumps are generally grouped into two broad categories, positive displacement pumps and dynamic (centrifugal) pumps. Positive displacement pumps use a mechanical means to vary the size (or move) of the fluid chamber to cause the fluid to flow. Centrifugal pumps impart a momentum in the fluid by rotating impellers immersed in the fluid. The momentum produces an increase in pressure or flow at the pump outlet.

Positive displacement pumps have a constant torque characteristic, where centrifugal pumps are variable torque in nature. This section will discuss only the centrifugal pump.

Pump Terms

Head – A measurement of pressure, usually in feet of water. A 30 FT head is the pressure equivalent to the pressure found at the base of a column of water 30 feet high.

Static Head – The pressure required to overcome an elevation change in the system. To get water from the base to a spout at the top of a 10 FT vessel would require a static head of 10 FT.

Dynamic Head - (or Friction Head) Pressure losses within the pipe or pipe system due to flow. To get water to flow into the vessel at a particular volume may require 10-FT static head plus 1-FT dynamic head. The dynamic head usually increases proportional to the square of the flow rate, Q.

$$Head = K \times Q^2$$

where K = system constant

System Head – The curve of the head required to satisfy both static head and the dynamic head for a range of flows on a given system.

Pump Head – The pressure the pump produces at its outlet.

Pump Curve – A characteristic curve of a pump showing the head-flow relationship of the pump.

Water Horsepower – The energy output of the pump derived directly from the outlet parameters.

$$Water\ HP = Flow \times \frac{Head}{3960} \times (specific\ gravity)$$

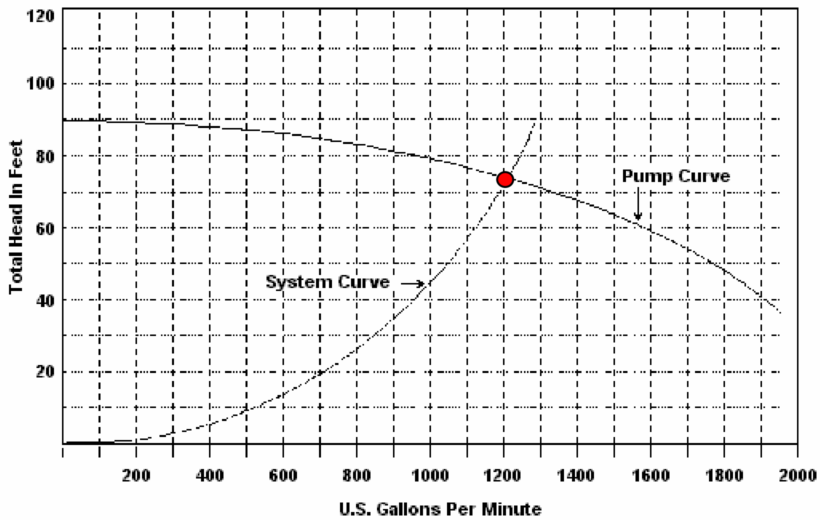
(For water, specific gravity = 1.0)

Brake Horsepower – The horsepower required to operate the pump at a specific point.

$$Brake\ HP = \frac{Water\ HP}{Pump\ Efficiency}$$

The pump curve is solely a function of the physical characteristics of the pump. The system curve is completely dependent on the size of pipe, the length of pipe, the number and location of elbows, and other factors. Where these two curves intersect is the natural operating point. That is where the pump pressure matches the system losses and everything is balanced. See the following diagram.

Pump and System Curves

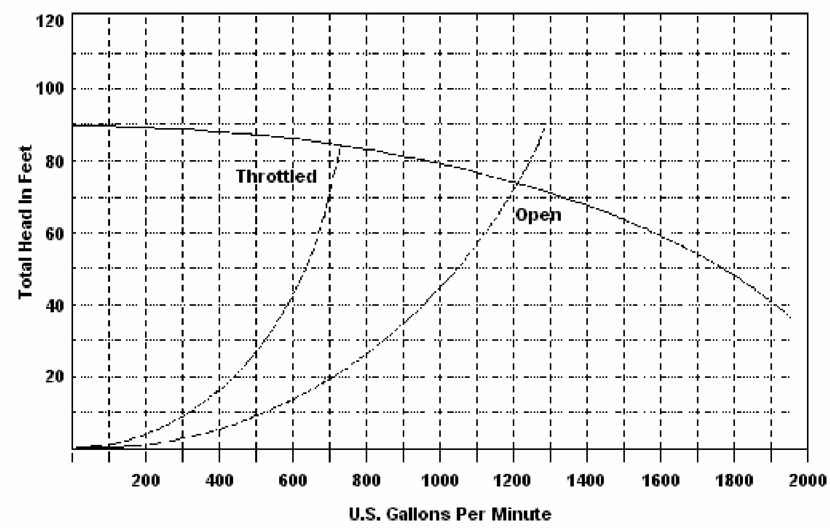


If the system is part of a process that changes often or continuously, then some method of altering the pump characteristics or the system parameters is necessary.

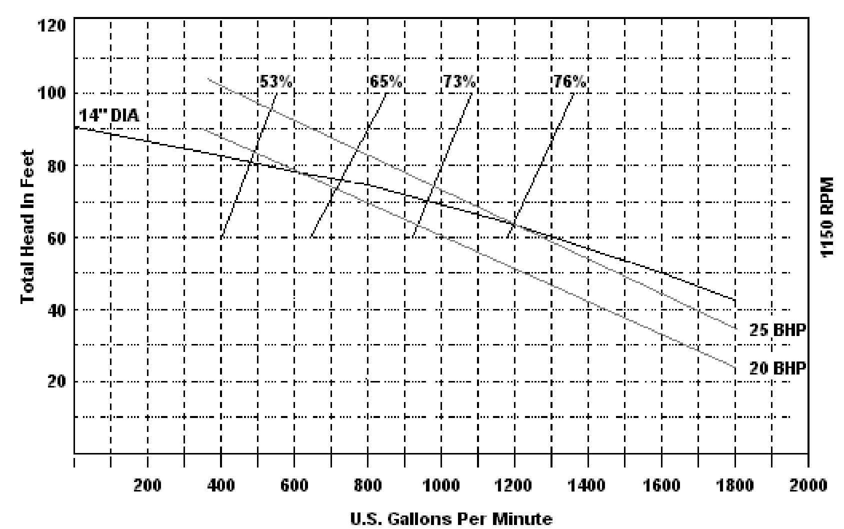
There are two methods used to accomplish the continuously varying flow objective. One method is throttling which changes the system curve by use of a control or throttling valve. The other method is to vary the speed of the pump, which modifies the pump curve.

Throttling System

With this method, obstructing flow increases the head pressure. A system with two different valve settings is shown below.



For comparison, let's use an example to determine power requirements for the throttling system, then the variable speed system. A pump (with a 14" impeller) operating at a base speed of 1150 RPM is used. This pump is to operate a system requiring a 63-FT head at 1,200 GPM. See Pump Curve Below.



From the information shown on the graph, we can obtain the various horsepower requirements at the flow rates shown in the table below for a throttling system. They are:

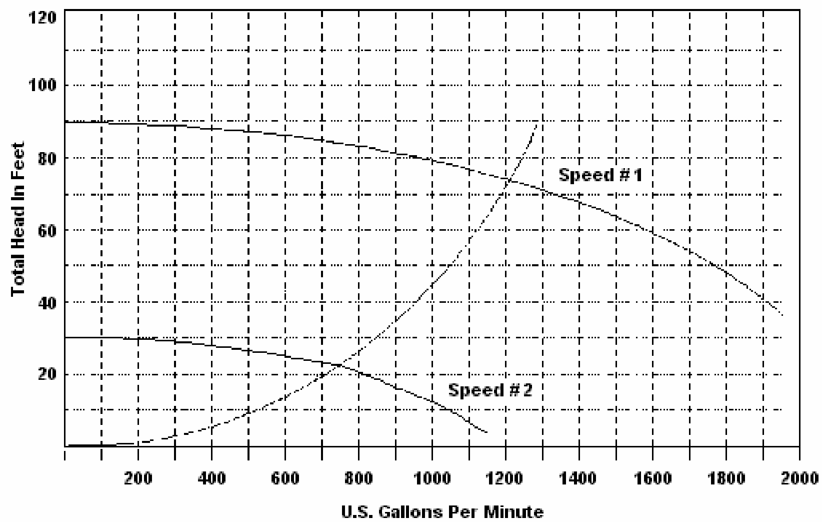
GPM	1,200	960	720	480
% FLOW	100	80	60	40
BRAKE HP	25	23	21	19

$$Water \quad HP = Flow \;\; \text{x} \;\; \frac{Head}{3960} = 1200 \;\; \text{x} \;\; \frac{63}{3960} = 19.09$$

$$Brake \quad HP = \frac{Water \quad HP}{Pump \quad Efficiency} = \frac{19.09}{0.76} = 25$$

Variable Speed System

In comparison, the variable speed method takes advantage of the change in pump characteristics that occur when the impeller speed is changed.



A set of formulas that are used to predict the operation of a centrifugal pump at any operating point based on the original pump characteristics is known as the affinity laws.

Affinity laws

$$\frac{Q_2}{Q_1} = \frac{N_2}{N_1} \qquad \frac{P_2}{P_1} = \left(\frac{N_2}{N_1}\right)^2 \qquad \frac{HP_2}{HP_1} = \left(\frac{N_2}{N_1}\right)^3$$

Where:

N = Pump speed
Q = Flow (CFM)
P = Pressure (Feet of Water)
HP = Horsepower

Using the same pump example as the throttling system, we can calculate the power requirements for the system when the pump speed is varied.

GPM	1,200	960	720	480
% FLOW	100	80	60	40
% SPEED	100	80	60	40
BRAKE HP	25	12.8	5.4	1.6

Note: Use 25HP for HP_1 and 100% for N_1 to fill in the table above.

$$BHP \text{ at } 960GPM = \left(\frac{80\%}{100\%}\right)^3 \times 25 \quad \text{therefore } \left(\frac{0.8}{1}\right)^3 \times 25 = 12.8BHP$$

It is obvious that varying the speed requires much less power. To determine the actual power required, the efficiency of the drive should be factored in. The example also did not have a static head associated with it. A system with static head does change the system curve and the horsepower requirements. The energy savings will depend on the amount of time the pump is operated at each reduced speed point.

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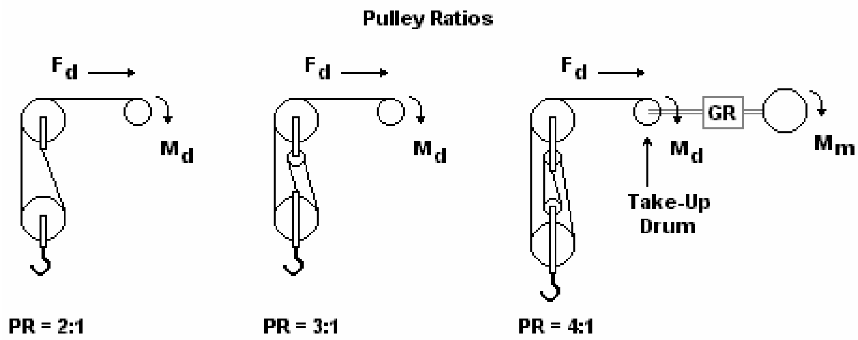
Lift

In this application example, a hoist is required to lift material of 3 tons (USA) maximum. The load is sensitive and must be gently raised from rest. The block-and-tackle arrangement has two pulley sheaves at the top and two at the hook. The fixed end of the rope is secured at the top sheave block.

The hoist is to be operated by a standard 3-phase, 4-pole, 460V 60hz induction motor with a full load speed of 1750rpm.

Application Data

Diameter of lifting drum	200mm
Gearbox ratio, motor to drum	10:1
Coefficient of hoisting friction	0.095
Maximum Load	3 US tons (2.721×10^3 kg)



Procedure

First, convert all data to SI units, (converted data in parenthesis)
1. Determine the pulley ratio of the hoist block-and-tackle arrangement.
2. Determine the speed and acceleration of the hook.
3. Determine the lifting force and torque required to accelerate up to full speed.
4. Determine the lifting force and torque required to maintain full speed.
5. Determine the motor and drive power rating.

Calculations

1. The pulley ratio is the numerical ratio determined by the number of falls (ropes passing between pulleys). Or simply counting the number of pulley wheels in both sheaves will also generate the ratio. The data given is shown above, and has a ratio of 4:1.

2. Speed and acceleration of the hook

2.1 The speed of the hook is a function of the motor speed, gear ratio, diameter of lifting drum, and the pulley ratio.

$$\text{Drum Speed} = \frac{\text{Motor Speed}}{\text{Gear Ratio}} \times \frac{1}{60} \qquad \frac{\text{rev}}{\text{s}}$$

$$\text{Hook Speed} = \text{Drum Speed} \times \frac{\text{Drum Circumference}}{\text{Lifting Ratio}}$$

$$\text{Hook Speed} = \frac{1750}{10} \times \frac{1}{60} \times \frac{0.2\pi}{4} \qquad \frac{\text{m}}{\text{s}}$$

$$= 0.4581 \qquad \frac{\text{m}}{\text{s}}$$

2.2 Since the load to be raised is sensitive, a slow acceleration from rest is required. An acceleration time of 9 seconds should be adequate. The linear acceleration of the load is derived from the following.

$$v = v_0 + at \qquad \text{where } v_0 = 0$$

$$a = \frac{v}{t} \qquad \frac{\text{m}}{\text{s}^2}$$

$$= \frac{0.4581}{9} = 5.09 \times 10^{-2} \qquad \frac{\text{m}}{\text{s}^2}$$

Lifting force and torque required to accelerate to full speed

3.1 The linear force, F_a required at the hook to raise the load from rest up to full speed is the algebraic sum of the forces necessary to:

a) Hold or suspend the load *mg*,
b) Accelerate the load to full speed *ma*
c) Overcome rolling friction *mgu*

$$F_a = mg + ma + mg\mu \qquad N$$

$$= m[a + g(1 + \mu)] \qquad N$$

3.2 The equivalent force, F_{da} at the winding drum is F_a multiplied by the inverse of the lifting ratio (inverse, since the calculation is from output to input).

$$F_{da} = F_a \times \frac{1}{4} = \frac{m[a + g(1+\mu)]}{4} \qquad N$$

3.3 The acceleration torque at the drum is the force multiplied by the drum radius.

$$M_{da} = F_{da} \times \text{drum radius} \qquad Nm$$

$$= \frac{m[a + g(1+\mu)]}{4} \times \frac{d}{2} \qquad Nm$$

$$= \frac{2.721 \times 10^3 \left[\left(5.09 \times 10^{-2}\right) + 9.81(1 + 0.095)\right]}{4} \times \frac{0.2}{2} \qquad Nm$$

$$= 734.2 \qquad Nm$$

4. Lifting force and torque required to maintain full speed.

4.1 The linear force F_s required at the hook to maintain the load at full speed is the algebraic sum of the forces necessary to:
a) Hold or suspend the load, *mg*
b) Overcome rolling friction, *mgu*

$$F_s = mg + mg\mu \qquad N$$

$$= mg(1+\mu) \qquad N$$

4.2 The equivalent force F_{ds} at the winding drum is F_s multiplied by the inverse of the lifting ratio (inverse, since the calculation is from output to input).

$$F_{ds} = F_s \times \frac{1}{4} = \frac{mg(1+\mu)}{4} \qquad N$$

4.3 The full speed torque at the drum is the sum of the force multiplied by the radius the drum.

$$M_{ds} = F_{ds} \times \text{drum radius} \qquad Nm$$

$$= \frac{mg(1+\mu)}{4} \times \frac{d}{2} \qquad Nm$$

$$= \frac{2.721 \times 10^3 \times 9.81(1+\mu)}{4} \times \frac{0.2}{2} \qquad Nm$$

$$= 730.7 \qquad Nm$$

5. Motor and drive power rating

Power is the multiple of torque and speed. It does not matter if the calculation is done at the motor or at the winding drum as long as the efficiency, η, of the gearbox is considered (power is equal on either side of the gearbox less efficiency losses of the gearbox). For this example, the efficiency, η, will be assumed at 97%.

During acceleration, the speed ramps from zero to full speed, therefore the power has no particular value. The worst case power demand is at full speed, so the torque demand at full speed will be used to calculate the acceleration power required.

$$P = M\omega\eta \qquad W$$

5.1 Motor power required for acceleration

$$P_a = M_{da} \times \omega_d \times \frac{1}{\eta} \qquad W$$

$$\text{Where: } M_{da} = \text{acceleration torque at the drum}$$

$$\omega_d = \text{rotational speed of the drum in radians per second}$$

$$\eta = \text{efficiency of the gearbox}$$

Note that the inverse of the gearbox efficiency is used since greater torque and power is required from the motor than the calculated torque at the winding drum.

$$\text{Drum Rotational Speed} = \frac{\text{motor speed}}{\text{gear ratio}} \times \frac{1}{60} \times \pi \qquad rad\ s^1$$

$$= \frac{1750}{10} \times \frac{1}{60} \times \pi \qquad rad\ s^1$$

$$= 9.163 \qquad rad\ s^1$$

Accelerating power is:

$$P_a = M_{da} \times \omega_d \times \frac{1}{0.97} \qquad W$$

$$= 734.2 \times 9.163 \times \frac{1}{0.97} \times 10^{-3} \qquad kW$$

$$= 6.935 \qquad kW$$

5.2 This is the rating of a motor capable of delivering continuous accelerating lifting torque. Standard motors are capable of delivering a short-term overload of 150%. The acceleration time of 9 seconds is well within the maximum overload time of the motor. If the overload capability is to be used, then the size is calculated as follows.

$$6.935 \times \frac{100}{150} \qquad kW$$

$$= 4.62 \qquad kW$$

Motor power is directly proportional to torque. The power demand at full lifting speed can be determined from the ratio of full speed torque to accelerating torque.

$$4.62 \times \frac{730.7}{734.2} \qquad kW$$

$$= 4.6 \qquad kW$$

A standard 5.5kW motor will be adequate.

5.3 Drive power rating

Calculate the currents involved, having found the starting current demand, find the rating of the drive. Starting current is based on the motor rating of 5.5kW.

$$P = \sqrt{3} \times V_L \times I_L \times p.f. \qquad kW$$

The working power factor (p.f.) will be assumed to be the full load, full speed, full voltage rated power factor of the motor, 0.85.

$$\text{Total } I_L = \frac{P}{\sqrt{3} \cdot V_L \cdot p.f.} = \frac{5.5 \times 10^3}{\sqrt{3} \times 460} \times \frac{1}{0.85} \quad A$$
$$= 8.12 \quad A$$

A drive capable of delivering 8.5 amperes continuous is suitable. Like the motor, the drive will have a short duration overload, but we are not going to take advantage of it in this application.

In some applications, such as a long acceleration time, the drive may need to be oversized. For these applications, the overload capability of the motor is not used to reduce the motor rating.

Calculated Torque Proving

Principles of Torque Proving focus on monitoring a drive parameter that represents the level of torque produced at the motor shaft, and comparing that value to a setpoint threshold, before releasing a mechanical brake. The objective is to produce enough lifting torque so a load suspended will not drop or sag when the brake is released.

A Run command in either direction will initiate flux and torque to be built, in the raising direction, in the motor. Motor flux must be at the rated value and the torque component must be at or above the threshold.

Brake Permissive

The brake permissive circuitry will need to take into account the torque proving circuit and any safety circuits that must be satisfied prior to release of the mechanical brake.

This logic process controls release of the mechanical brake, regardless of up (forward) or down (reverse) direction by monitoring for a positive torque working against gravity and the brake before release. All conditions must be satisfied before an output signal changes state.

The controller and drive or drives can implement a speed profile to put the lifting mechanisms in motion. Once the brake is released and the lift is operating in a controlled fashion, the motor flux component and all other Permissive Interlocks must stay maintained throughout the cycle. The torque threshold need only be a momentary condition. The Brake Output maintains an energized state until a NOT RUN condition occurs. The brake must stay released until the end of the cycle.

This is also necessary because once the motor and drive are in control of the load (including working against the brake for a time), the value of torque reference, will immediately reflect the values dictated by process conditions, gravity, pressure, etc. The value of Torque Reference could swing significantly after the brake releases, and as the drive responds to the work profile commanded. These values are very likely not to satisfy, nor are necessary to satisfy, the setpoints during the rest of the cycle.

The plot in Figure 3 represents a profile of a typical “start-lift-stop” cycle without any dwell time after the start and stop commands. Although a viable method of control, this method may cause undue wear and stress on the equipment. See Figure 4 and explanation for a more equipment friendly method of control using the precise torque regulation capability of the 1336 Impact drive.

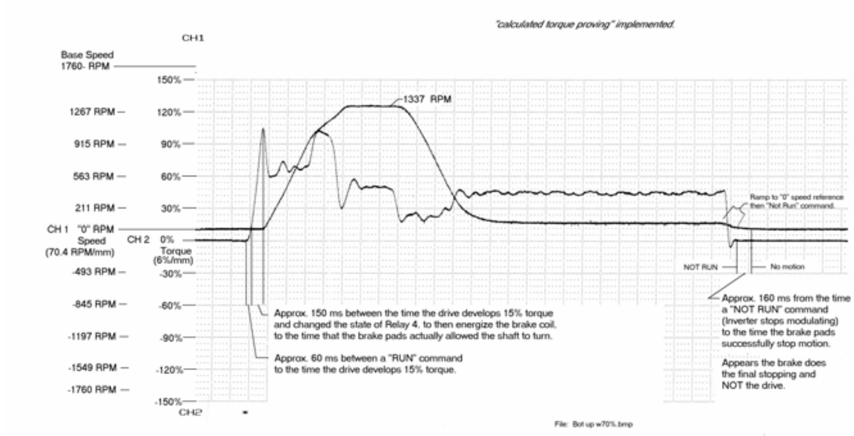


Figure 3

At the end of the cycle, a NOT RUN or Stop command de-energizes the brake coil allowing the brake pads to stop and secure the load. When the drive senses "0" speed feedback it turns off the Inverter.

> **Note:** The recommended end of cycle sequence (figure 4) is to decel to "0" speed and have the drive/motor hold the load and dwell for a duration, long enough to insure that the mechanical brake secured the load. The physical brake settting delay time needs to be considered.

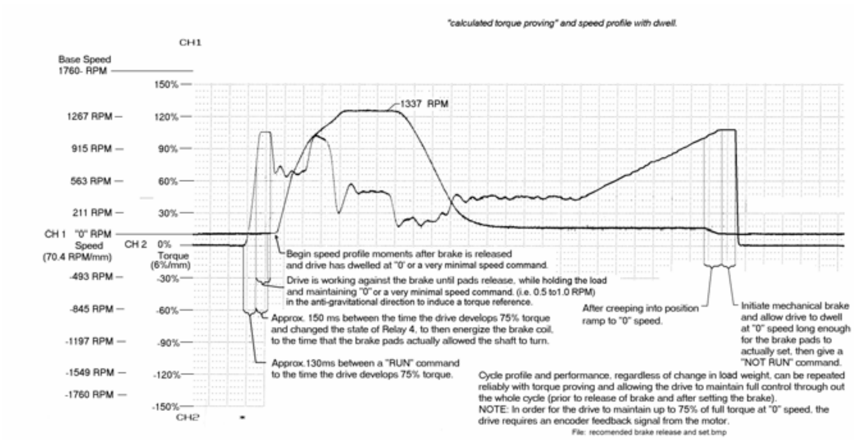

"calculated torque proving" and speed profile with dwell.
CH1
Base Speed
1760- RPM
150%
1267 RPM
120%
915 RPM
90%
563 RPM
60%
211 RPM
30%
CH 1 "0" RPM
Speed
(70.4 RPM/mm)
CH 2 0%
Torque
(6%/mm)
-493 RPM
-30%
-845 RPM
-60%
-1197 RPM
-90%
-1549 RPM
-120%
-1760 RPM
-150%
CH2
1337 RPM
Begin speed profile moments after brake is released and drive has dwelled at "0" or a very minimal speed command.
Drive is working against the brake until pads release, while holding the load and maintaining "0" or a very minimal speed command. (i.e. 0.5 to1.0 RPM) in the anti-gravitational direction to induce a torque reference.
Approx. 150 ms between the time the drive develops 75% torque and changed the state of Relay 4, to then energize the brake coil, to the time that the brake pads actually allowed the shaft to turn.
Approx.130ms between a "RUN" command to the time the drive develops 75% torque.
After creeping into position ramp to "0" speed.
Initiate mechanical brake and allow drive to dwell at "0" speed long enough for the brake pads to actually set, then give a "NOT RUN" command.
Cycle profile and performance, regardless of change in load weight, can be repeated reliably with torque proving and allowing the drive to maintain full control through out the whole cycle (prior to release of brake and after setting the brake).
NOTE: In order for the drive to maintain up to 75% of full torque at "0" speed, the drive requires an encoder feedback signal from the motor.
File: recomended brake release and set bmp

Figure 4

Using Drives in Lifting Applications

Variable Frequency Drives can be an excellent control solution for lifting applications. the ONLY PROPER application of a VFD in lifting applications, are those that truly regulate TORQUE at any speed, even zero speed. This is because we strongly feel that the ONLY responsible control design involves a legitimate form of "torque proving" prior to release of a mechanical brake and true control of torque throughout the range of motion.

The drives do not stand alone to perform a safe control scheme. The whole control picture requires additional logic control outside of the drive, interfacing with our drives to implement "torque proving" and other safety criteria. Our drive products have the means to do such applications, but require the additional logic. Our drives do not have "canned features" supporting lifting applications. Our drive products can be applied to a multitude of applications. The essential features, parameters, sensing information, etc. are there to use in lifting applications. Like with most involved applications of various sophistication levels, there is engineering control design work and set up added to properly use the drive. Our drives are not typically labeled as a "hoist drive" or a "winder drive" or a "….. drive".

A second critical criteria that must be promoted, is the use of encoder feedback from the motor shaft back to the drive. This is essential to safely control speed; direction and torque at slow speeds and to hold the load at rated torque at zero speed. Encoderless operation is neither reliable nor safe for lifting applications and must be avoided in control designs. Or there needs to be additional logic control outside the drive with significant safety backup logic and third party monitoring input to compensate.

Lifting applications have a rather high degree of risk for danger to safety and cost of damage potential, should something go wrong. There needs to be agreed upon understandings of Rockwell Automation's role or involvement, particularly if we did not engineer the control scheme, and if torque proving or the right choice of drives has not been implemented.

When we become aware that a drive is being purchased for lifting application, or if the customer asks for advice in using our VFDs on lifting applications, we try to alert them of the proper choice of drive and key control criteria they ought to consider designing in. We suggest you do the same. We, here in Commercial Application Engineering, will boldly tell you or an inquirer, that if they do not utilize our drives as recommended, we would rather not sell you or them the drives and walk away from the opportunity. That is how strongly we feel about doing a lifting application correctly.

The volts per hertz VFD varieties can safely perform the other non-lifting functions associated with the lifting function like bridge and trolley traversing.

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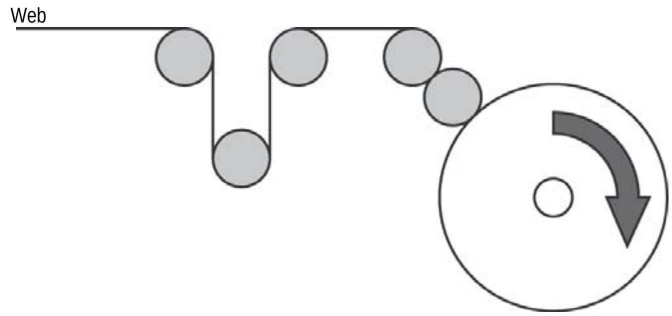
Winders

Sizing a motor for a Center Driven Winder Paper product. Center driven winders have the benefit of controlling tension via directly controlling the torque of the wound product, Tension taper can be applied as the diameter increases

Application Data	Data Given	Converted to SI Units
Maximum Line Speed:	400fpm	(2.03 m/s)
Density of Material:	75 lb/ft^3	(1201.4 kg/m^3)
Width of Material:	60 in	(1.52 m)
Core Diameter:	6.6 in	(0.17 m)
Maximum Roll Diameter:	35 in	(0.89m)
Maximum Line Tension:	240 lbf	(1067.57 N)
Desired Acceleration:	4 sec	

Center Driven



Procedure

Convert units to SI units, if not already done.
Determine maximum roll speed for minimum roll diameter.
Determine torque required for maximum tension at minimum and maximum diameters.
Calculate ratings of motor and drive.

Calculations

1. Data not in SI units converted, values shown in parenthesis

2. Speeds and Gearing

2.1 Determine RPM of core at line speed maximum.

$$\omega = \left(\frac{v}{r}\right) \qquad \frac{\text{rad}}{\text{s}}$$

$$\omega = \left(\frac{2.03}{.08382}\right) \qquad \frac{\text{rad}}{\text{s}}$$

$$\omega = 24.2 \qquad \frac{\text{rad}}{\text{s}}$$

$$RPM = \quad \omega * \frac{30}{\pi} \quad = 231$$

2.2 Determine RPM at maximum roll diameter

$$\omega = \left(\frac{2.03}{0.445}\right)$$

$$\omega = 4.56 \qquad \frac{\text{rad}}{\text{s}}$$

$$RPM = \omega * \frac{30}{\pi} = 43.56$$

2.3 Determine gear ratio, using 3000 RPM maximum safe speed

$$Gearing = \left(\frac{3000}{231}\right)$$

$$Gearing = 12.98$$

Using 12:1 Gear ratio which will give 2772 maximum motor RPM.

Notes:

- Output speeds are determined by the application but input speeds can be varied. If the gearbox calculated for the particular application is unacceptably high, a motor with more pole pairs may be a better solution.
- The rotational speed *n* of a motor, where *p* is the number of poles and *f* is the rated frequency, is

$$n = \frac{f * 120}{p} \qquad rpm$$

3.0 Load & Force

3.1 Determine mass of material on maximum roll diameter

$$m = \pi \rho l (r_2^{\,2} - r_1^{\,2})$$
$$m = \pi * 1201.4 * 1.52 * (0.445^2 - 0.16764^2)$$
$$m = 1094.46 kg$$

3.2 Torque required to accelerate load to maximum speed

$$M = \left(\frac{m(kg) * (r_1^{\,2} + r_2^{\,2}) * (\Delta RPM / \Delta t_{(\sec)}}{19.1_{(\sec\, rev / \min\, rad)}} \right) \qquad \text{Nm}$$
$$M = \left(\frac{1094.46 * (0.198 + 0.007225) * (228.06 / 4)}{19.1} \right) \qquad \text{Nm}$$
$$M = 670.48 \qquad \text{Nm}$$

3.3 Torque required to hold tension on sheet

$$M = (Tension_N * r) \qquad \text{Nm}$$
$$M = (1067 * 0.445) \qquad \text{Nm}$$
$$M = 474.8 \qquad \text{Nm}$$

3.4 Torque required accelerating to maximum speed at rated tension with maximum roll size.

$$M = M_a + M_T \qquad \text{Nm}$$
$$M = 670.48\ \text{(accelerating)} + 474.8\ \text{(tension)} \qquad \text{Nm}$$
$$M = \frac{1145.28}{12\ \text{(Gear ratio)}} \qquad \text{Nm}$$
$$M = 95.44 \quad \text{motor required} \qquad \text{Nm}$$

Notes

- Torque for acceleration and tension must be added together for the motor sizing. Tension is required during acceleration on center driven winder systems.

4.0 Motor selection.

4.1 Calculate required torque at minimum diameter to hold tension.

$$M = (Tension_N * r) \quad \text{Nm}$$

$$M = (1067 * 0.08382) \quad \text{Nm}$$

$$M = \frac{89.43}{12\ (gear\ ratio)} \quad \text{Nm}$$

$$M = 7.453 \quad \text{Nm}$$

4.2 Calculate kW at minimum diameter to hold tension.

$$kW = \frac{7.453 * 2772}{9500}$$

$$kW = 2.1$$

4.3 Calculate motor rating. In order to make use of the full 150% overload rating of the motor the actual rating is:

$$kW = \frac{Nm * RPM}{9550}$$

$$kW = \frac{95.4 * 1750}{9550}$$

$$kW = 17.48 \quad \text{Total kW}$$

$$kW = 17.48 * \frac{100}{150}$$

$$kW = 11.65 \quad \text{Continuous kW}$$

A standard 15kW motor will be used because a standard 11kW motor would be at 160%.

4.4 Calculate current required. After finding current, determine rating of the drive. The starting point will be with 17.48kW.

$$P = \sqrt{3} * V_L * I_L * p.f. \qquad kW$$

Where the working power factor (p.f.) is assumed to be the full load, full speed, full voltage rated power factor of the motor. 0.85 (from data).

$$Total\ I_L = \frac{P}{\sqrt{3} * V_L * p.f} = \frac{17.48 * 10^3}{\sqrt{3} * 460} * \frac{1}{0.85} \qquad \text{A}$$

$$= 25.8 \qquad \text{A}$$

4.5 Like the motor, the drive will have a short duration overload. For this example, 150% for 60 seconds is assumed. The drive efficiency must me taken into account (98% assumed). The full load rated current of the drive is also affected by the difference in motor rating to total kW rating.

$$25.8 * \frac{15}{17.48} * \frac{1}{0.98} \qquad \text{A}$$

$$= 22.59 \qquad \text{A}$$

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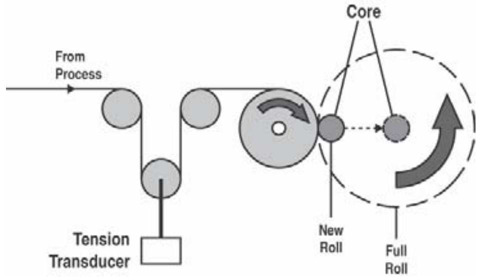
Surface Driven

Winder drives that are not center driven are surface driven. They may be speed regulated or armature current (torque) regulated. Buildup does not appreciably affect winder horsepower. Taper tension is difficult to provide, and the quality of roll will not be as good as with center driven winders.



Application Data	**Data Given**	**Converted to SI Units**
Maximum Line Speed:	800fpm	(4.06 m/s)
Density of Material (Driven Drum):	495 lb/ft^3	(7929 kg/m^3)
Diameter of Driven Drum:	12 in	(0.3048 m)
Inside Diameter of Driven Drum:	8 in	(0.2032 m)
Width of Drive Drum:	192 in	(4.88 m)
Density of Process Material:	75 lb/ft^3	(1201.4 kg/m^3)
Core Diameter:	6.0 in	(0.1524 m)
Maximum Material Diameter:	60 in	(1.52 m)
Material Width:	192 in	(4.88m)
Maximum Line Tension:	200 lbf	(889.64 N)
Desired Acceleration:	10 sec	

Procedure
Convert units to SI units, if not already done.
Determine mass of driven roll.
Determine maximum roll speed.
Determine torque required for maximum tension.
Calculate ratings of motor and drive.

Calculations
1. Conversions - Data not in SI units converted, values shown in parenthesis

2. Mass - Determine the mass of the driven roll

$$m = \pi * p * l * (r_2^{\ 2} - r_1^{\ 2}) \quad \text{kg}$$
$$m = \pi * 7929 * 4.88 * (0.02322 - 0.0103) \quad \text{kg}$$
$$m = 1555 \quad \text{kg}$$

2.1 Determine mass of maximum material diameter.

$$m = \pi * p * l * (r_2^{\,2} - r_1^{\,2}) \quad \text{kg}$$
$$m = \pi * 1201.4 * 4.88 * (0.5776 - 0.0058) \quad \text{kg}$$
$$m = 10531 \quad \text{kg}$$

3. Speeds and Gearing

3.1 Determine RPM of Drive Drum at maximum speed.

$$\omega = \left(\frac{v}{r}\right) \quad \frac{\text{rad}}{\text{s}}$$
$$\omega = \left(\frac{4.06}{0.1524}\right) \quad \frac{\text{rad}}{\text{s}}$$
$$\omega = 26.64 \quad \frac{\text{rad}}{\text{s}}$$
$$rpm = \omega * \frac{30}{\pi} \quad \text{rpm}$$
$$rpm = 254.4 \quad \text{rpm}$$

3.2 Determine Gear Ratio

$$\text{Gearing} = \left(\frac{1750}{254.4}\right)$$
$$\text{Gearing} = 6.879$$

Gearbox selected 6:1, maximum motor speed of 1526.4.

3.3 Determine v (velocity) of maximum material roll.

$$\omega = \left(\frac{v}{r}\right) \quad \frac{\text{rad}}{\text{s}}$$
$$\omega = \left(\frac{4.06}{0.76}\right) \quad \frac{\text{rad}}{\text{s}}$$
$$\omega = 5.342 \quad \frac{\text{rad}}{\text{s}}$$
$$rpm = \omega * \frac{30}{\pi} \quad \text{rpm}$$
$$rpm = 51 \quad \text{rpm}$$

4. Torque Requirements

4.1 Torque required to accelerate driven drum.

$$M = \left(\frac{m(kg) * (r_1^{\ 2} + r_2^{\ 2}) * (\Delta RPM / \Delta t_{(\sec)})}{19.1_{(\sec\ rev/\min\ rad)}} \right) \quad \text{Nm}$$

$$M = \left(\frac{1555 * (0.02322 + 0.0103) * (254.4/10)}{19.1} \right) \quad \text{Nm}$$

$$M = 69.4 \quad \text{Nm}$$

4.2 Torque required to hold tension.

$$M = (Tension_N * r) \quad \text{Nm}$$

$$M = (889.64 * .1524) \quad \text{Nm}$$

$$M = 135.6 \quad \text{Nm}$$

4.3 Torque required to accelerate maximum material.

$$M = \left(\frac{m(kg) * (r_1^{\ 2} + r_2^{\ 2}) * (\Delta RPM / \Delta t_{(\sec)})}{19.1_{(\sec\ rev/\min\ rad)}} \right) \quad \text{Nm}$$

$$M = \left(\frac{10531 * (0.58064 + 0.0058) * (51/10)}{19.1} \right) \quad \text{Nm}$$

$$M = 1649 \quad \text{Nm}$$

Notes:

- Torque for acceleration tension, and Maximum material must be added together for the motor sizing. Tension is required during acceleration on winder systems.
- Maximum material must be used for accelerating and stopping the system, also Emergency Stop considerations must be included in calculations.

5.0 Motor Ratings

5.1 Calculate kW of motor for tension and acceleration.

Summarize the known torque demands
Accelerating torque (Driven Drum)= 69.4 Nm
Accelerating torque (Maximum Material) = 1649 Nm
Tension(Running) torque = 135.6 Nm

Torque and acceleration do not need to be referred to the motor since power is equal on both sides of a gearing mechanism. The power demand at the Driven Drum is the power demand at the motor.

$$P = M\omega \qquad W$$

Per the data given, the starting and acceleration period is 10 seconds. Since this is well within the intermittent overload time of a typical motor, the overload capability may be used for acceleration power.

5.2 Motor power to accelerate the Driven Drum is the accelerating torque plus the tension Torque, multiplied by the rotational speed of the Drum at full speed. Taking into account the efficiency (η) of the gearing. For this example, η is 95%, but it must be verified fot the gearing installed.

$$P_a = M_a \omega \eta \qquad \text{W}$$

$$= 205 \text{ Nm (Sec 4)} * 26.64 \text{ Nm (Sec 3.1)} * \frac{1}{0.95} \qquad \text{W}$$

$$= 5748.63 * 10^{-3} \qquad \text{W}$$

$$= 5.75 \qquad \text{Driven Drum} \qquad \text{kW}$$

$$= 1649 \text{ Nm (Sec 4.3)} * 5.342 * \frac{1}{0.95} \qquad \text{W}$$

$$= 9272.6 * 10^{-3} \qquad \text{W}$$

$$= 9.3 \qquad \text{Maximum Material} \qquad \text{kW}$$

$$= 9.3 + 5.75 \qquad \text{kW}$$

$$= 15 \qquad \text{System Total} \qquad \text{kW}$$

5.3 This would be the rating of a motor able to deliver the total torque continuously. To make use of the 150% overload rating of the motor, the actual rating is:

$$15 * \frac{100}{150} \quad \text{kW}$$
$$= 10 \quad \text{kW}$$

A standard 7.5 kW motor will work.

5.4 Calculate the current involved, find the rating of the drive based on the 98.75 kW rating.

$$P = \sqrt{3} \times V_L \times I_L \times p.f. \quad \text{kW}$$

Where the working power factor (p.f.) is assumed to be full load, full speed, full voltage rated pwer factor of the motor, 0.85 (from data).

$$\text{Total } I_L = \frac{P}{\sqrt{3} \cdot V_L \cdot p.f.} = \frac{7.5 \times 10^3}{\sqrt{3} \times 460} \times \frac{1}{0.85} \quad A$$
$$= 11.1 \quad A$$

Additional application data required in designing winder drives includes the following:

Line Speed Range.
Tension range.
Product Width Range.
Product Thickness Range.
Core Outside Diameter
Maximum Roll Diameter.
Product Modulas of Elasticity.
Taper Range.
Roll Change Procedure.
Accelerating and Decelerating times.
Dancer loop Active Storage.
Static Losses in Dancer Air Loading System.
Load Cell Tension Roll Weight, Diameter, Angle of Wrap, Mounting Position and Continue.
Inclination of the Pass Line with respect to horizontal.
Lineal feet of material between the Driven Roll and the Feedback device.
Number of, and inertia of Strip Driven Idler Rolls between the Driven Roll and the feedback device.
Turret Rotation Direction and Speed.
Type of winder Web Severing and transfer, Bump and Cut or Enveloping Roll or J Arm.
Rate of change of position of Hold Down Rolls, Bump and Cut Rolls or Enveloping Rolls.

It is usually not possible to determine all the above exactly for any one application. However, going through all of them, step by step will avoid the necessity to make assumptions, and ensure a better winder installation.

DC to AC Retrofit

The following is intended to point out important considerations, when converting from existing DC drive installations to an AC Drive solution.

Definitions

The most critical focus when specifying or sizing drive inverter hardware is the magnitude and duration of the current demanded by the process to be controlled. Particular characteristics and limitations of both types of drives require an understanding before proceeding. The following definitions apply:

Maximum Drive current limit is the maximum rated capacity current output from the drive to the motor to develop torque at the shaft. It is the maximum magnitude of output current limited by the Drives current regulator for a specified period of time, established to protect the drive components.

i.e. DC drives typically have the following specifications;	100% of rated current continuously
	150% of rated current for 1 minute
	200% of rated current for 10 seconds
and some DC drives may have an additional rating of;	250% of rated current for 2 or 3 seconds
i.e. AC drives typically have the following specifications;	100% of rated current continuously
	150% of rated current for 1 minute
and more recently, some may have an additional rating of;	200% of rated current for 2 or 3 seconds

FLA - Full Load Amperes is the nameplate value representing the maximum magnitude of motor current necessary to develop full rated torque at the motor shaft. Any amount above this value is considered harmful to the motor in terms of overheating damage. Drives are designed to monitor the level of current and time the duration (I^2t current squared times time) before turning off the output to protect the motor and register a “Motor Overload” fault. There are acceptable duration’s of time to operate above the FLA level and are determined by the I^2t algorithm.

Motor Torque is the mechanical torque produced at the shaft of the motor. 100% torque is equal to the maximum rated torque the motor is designed to produce continuously. Typically motors can develop anywhere from 200 to 400% of rated torque but cannot sustain these levels for extended durations of time before self-destroying due to heat. Torque development is directly related to the amount of armature current flowing through a DC motor and directly related to the Iq (the torque producing current vector) current flowing through an AC motor.

I^2t (square of the motor current x time) is the protection algorithm implemented by the drive to protect the motor from overload.

It (current x time) is the protection algorithm implemented by the drive to protect itself from component damage, due to heat from handling too much current for too long a period of time.

Existing DC equipment installation considerations

For many drive conversions or retrofits, it becomes critical to determine the specific operating demands of the present installation. There are applications where the existing DC Drive may be operating at/or near the maximum of its capacity, or is being subjected to significant short term loading that must be known and considered. *Caution! Do Not Assume!* The current demands may be greater than the rated performance capability of the replacement AC Drive, if the natural assumption to specify a one for one match of HP for HP of an AC motor and drive to a DC motor and drive. Do Not be Careless!

Also make particular note of the motor base speed rating. *Caution! Do Not Make Assumptions!* Many DC motor installations have 1200 RPM ratings, which are not the same as traditional AC 1800 RPM motor installations. Gearbox ratios and pulley sheave ratios dictate the speed and torque range of the equipment and ought not to be taken for granted. (N = 120 * f / # of poles).

First, assess as much of the existing installation as possible for nameplate information and monitor loading profiles throughout the process cycle by reading drive parameters, or with measurement equipment. Particularly note the peak levels of torque demand or armature current requirements and the duration of time. When possible, measure and capture this information first hand, or request that the Armature current levels and the respective durations of time be monitored and noted.

Second, determine regenerative energy handling requirements. Some DC drives have regeneration to the AC line capability. This means that the DC drive has the capacity to channel regenerative current from the motor up to its rating, back to the AC line.

Realize that stand-alone AC drives do not have the inherent capability to regenerate back to the AC line. The AC drive is not likely to be able to absorb significant regenerated energy levels due to decelerating loads and will require some form of dynamic braking.

This information is very valuable and necessary in determining the extremes that are being demanded of the existing DC drive and motor.

Extruder

DC to AC Retrofit

An ABS plastic extruder produces a variety of different stocks. It has an existing DC motor with nameplate data of 200 HP, 500/300 VDC, 322 Armature Amps, 1750 RPM / 2100 max. RPM. From information provided or obtainable we determine the motor can develop 590 ft-lb. of torque. The motor is also forced air cooled so it can operate at very low speeds at full rated torque. The customer confirms that some types of stock require operating at slow speeds to allow the material to cool and solidify before its shape would deform due to gravity.

The largest cross section stock is made with the motor producing rated torque right at rated Armature current and running at 15% of base speed. When the extruder is required to start up with material in the barrel, the armature motor current consistently reaches peaks at/or near 634 Amps (197% of FLA) for about 2 seconds. You have been asked to size the appropriate AC Drive and motor for conversion and replacement.

Considerations:

1st understand what type of control the application requires and what the DC drive provides. Extruders require precise control of torque across the whole speed range of operation including at very slow speeds. DC drives inherently provide good torque control by regulating armature current. An equivalent type of AC drive appropriate for this application is a Field Oriented Control vector drive, because of the need to accurately control torque.

2nd realize that AC Field Oriented Control vector drives are typically rated:

100% of rated current continuously
150% of rated current for 1 minute.

Some AC drives may have an additional rating of 200% of rated current for 2 or 3 seconds, but not all choices have this capability. Focus on what rating facts are available.

From our measurements we are aware that the DC machine requires 634 Amps (197% of FLA) to develop approximately 197% of the motors rated torque for about 2 seconds. Focus on this and the fact that the AC Field Oriented Control vector drives precisely limit current (thus an equivalent limit of torque) to 150% of its rating. There is no extra overshoot of current or torque for the required 2 seconds.

Choosing an AC motor at 200 HP 460VAC 1736 RPM, 240 FLA, 590 ft-lb appears straightforward. By relative association, 197% of rated torque will require approximately 197% of FLA (240A x 197%) or 471 Amps. A direct replacement 200 HP AC Field Oriented Control vector drive will limit its current output to (290 Amps x 150%) or 435 Amps for up to1 minute. This is short of the 471 Amps required to develop 197% of rated torque for 2 seconds. We should recommend using the next larger size drive, a 250 HP drive with a limit of its current output to (325 Amps x 150%) or 487 Amps for up to1 minute for this application. *Caution:* Even if the calculations may come out marginally close to the capacity limit of the drive, we should round up to insure a margin for performance.

Another consideration has to do with a voltage utilization phenomenon.

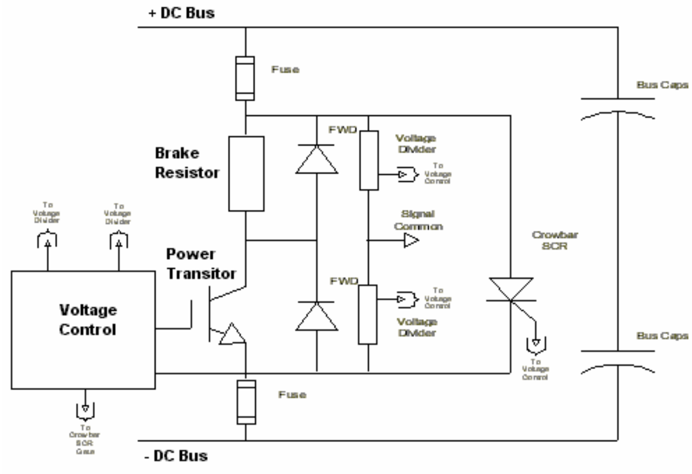
In the case of the current regulated drive (AC Field Oriented Control vector drive), motor current as in any electrical circuit, current is determined by the circuit impedance and applied voltage. Since the motor speed and load determine the motor impedance, we are left with only the voltage as a means to regulate current. The current regulator, therefore, must be able to adjust the voltage in order to regulate current. The regulator also requires some margin for proper operation. That is to say, it needs some extra voltage headroom to regulate any instantaneous current demand; least it should drop too low. This voltage headroom is roughly responsible for a 3 to 5% reduction in the maximum output voltage when the motor is at full speed and full torque, typically 437V – 445V. This reduced voltage will result in approximately 3 to 5 % higher output current above FLA rating, which must be planned for during continuous operation at frequencies 55Hertz and above.

Large drives are the main concern. Though this voltage utilization phenomenon exists for all current regulated drives, Larger drives (300 horsepower and up) tend to show more signs of it than smaller ones. There are a few reasons for this. Large drives are more likely to be fed from a transformer more closely matched to the drive size with little over sizing of the transformer. This results in a higher source impedance and lower peak line voltage. The bus voltage will be lower because of this. Larger drive and motor sets are expensive and may not be oversized in order to save on installation costs. Also, the user may be more concerned about the operating condition, reluctant to let the motor run at 105% since the cost of this motor failing is much larger than the cost of a small motor failure.

For this reason, if the customers incoming line voltage is chronically lower than 460 V, it would be better to suggest a 400 or 415 V rated motor with a corresponding higher FLA. This will allow for more than adequate voltage headroom.

Dynamic Braking

"Dynamic braking" is one of the simplest and most common methods of dealing with regenerative energy that is of a decelerating nature. This is not usually a good solution for overhauling loads. It is a voltage regulator that attempts to control the DC bus voltage from reaching the overvoltage trip point of the drive. The figure below is a schematic diagram of a dynamic brake circuit. The three major components are the transistor (switching device), the resistor and the control circuit.



The control circuit monitors the DC bus voltage level and turns the switching device on and off at the appropriate level. In the case of a 460 volt drive, the nominal DC bus voltage is about 650 volts. If the voltage increases to 750 volts the control circuit will turn on the switching device connecting a resistor across the DC+ and DC- Bus.

Some variable speed drives have the switching device incorporated into its packaging. If this is the case, a resistor need only be connected to the proper terminals to function. This resistor must be within the boundaries of the drive specifications. If the switching device is not within the drive packaging, a separate electronic package needs to be connected to the DC bus, usually called a "chopper". The resistor is then connected to the chopper.

How to size the resistor

Note: The methods described in the following text apply to decelerating applications.
The simplest way to connect a resistor to a drive with a switching device is to consider the horsepower of the motor connected to the drive. Most drives have the ability to supply more current than the rating of the motor for a short period of time. Usually this is 150%. Take the motor HP x 746 x 1.5 for total worst case wattage dissipation that the drive will be able to handle without going into an internal over current protection mode. Now check the specifications of the drive for the minimum resistance that can be connected to the drive. Connecting a resistance that is smaller than this value will result in damaging the switching device.

Select a resistance greater than the minimum allowed with a wattage rating equal to HP x 746 x 1.5. This method will typically result in unnecessary expense in resistors and is not the preferred way to address decelerating regenerative energy.

The preferred method of calculating DB resistors is as follows.
Gather the following information:
1. The nameplate power rating of the motor in watts, kilowatts, or horsepower.
2. The nameplate speed rating of the motor in rpm, or rps.
3. The motor inertia and load inertia in kilogram-meters^2, or lb-ft^2.
4. The gear ratio, if a gear is present between the motor and load, GR.
5. The motor shaft speed, torque, and power profile of the drive application. Figure 2 shows the speed, torque and power profiles of the drive as a function of time for a particular cyclic application that is periodic over t_4 seconds. The desired time to decelerate is known or calculable and is within the drive performance limits. In Figure 2, the following variables are defined:

$$\omega(t) = \text{The motor shaft speed in Radians / second. } \omega \text{ Rad / s} = \frac{2\pi N}{60} \text{RPM}$$

$$N(t) = \text{The motor shaft speed in Revolutions Per Minute, or RPM}$$

$$T(t) = \text{The motor shaft torque in Newton - meters, } 1.0 \text{ lb - ft} = 1.355818 \text{ N - m}$$

$$P(t) = \text{The motor shaft power in Watts, } 1.0 \text{ HP} = 746 \text{ Watts}$$

$$-P_b = \text{The motor shaft peak regenerative power in Watts}$$

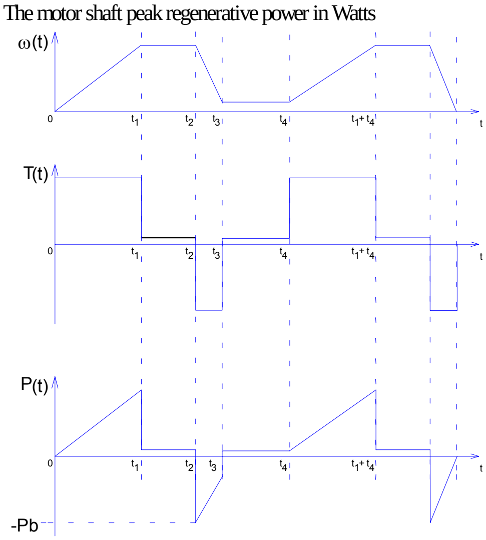


Figure 2 Application speed, torque, and power profile

Step 1 – Determine the Total Inertia

$$J_T = J_m + GR^2 \times J_L$$

J_T = total inertia reflected to the motor shaft, kilogram-meters^2, kg-m^2, or pound-feet^2, lb-ft^2

J_m = motor inertia, kilogram - meters^2, kg-m^2, or pound-feet^2, lb-ft^2

GR = the gear ratio for any gear between motor and load, dimensionless

J_L = load inertia, kilogram - meters^2, kg-m^2, or pound-feet^2, lb-ft^2

1.0 lb-ft^2 = 0.04214011 kg-m^2

Step 2 – Calculate the Peak Braking Power

$$P_b = \frac{J_T \times \omega_b(\omega_b - \omega_o)}{t_3 - t_2}$$

J_T = total inertia reflected to the motor shaft, kg-m^2

ω_b = rated angular rotational speed, Rad/s $= \frac{2\pi N_b}{60}$

ω_o = angular rotational speed, less than rated speed and can be zero, Rad/s

N_b = rated motor speed, RPM

$t_3 - t_2$ = total time of deceleration from ω_b to ω_o, seconds

P_b = peak braking power, watts

1.0 HP = 746 Watts

Compare the peak braking power to that of the rated motor power, if the peak braking power is greater than 1.5 times that of the motor, then the deceleration time, (t_3-t_2), needs to be increased so that the drive does not go into current limit.

Step 3 – Calculating the Maximum Dynamic Brake Resistance Value

$$R_{db1} = \frac{0.9 \times V_d^2}{P_b}$$

V_d = the value of DC Bus voltage that the chopper module regulates at and will equal 375 Vdc, 750 Vdc, or 937.5 Vdc

P_b = the peak braking power calculated in step 2

R_{db1} = the maximum allowable value for the dynamic brake resistor

The choice of the Dynamic Brake resistance value should be less than the value calculated in step 3. If the value is greater than the calculated value, the drive can trip on DC Bus overvoltage. Do not reduce P_b by any ratio because of estimated losses in the motor and inverter. This has been accounted for by an offsetting increase in the manufacturing tolerance of the resistance value and the increase in resistance value due to the temperature coefficient of the resistor element.

Step 4 – Choosing the Chopper Module

$$I_{d1} = \frac{V_d}{R_{db1}}$$

I_{d1} = the minimum current flowing through the chopper module transistor

V_d = the value of DCBus voltage chosen in step 3

R_{db1} = the value of the dynamic brake resistor caculated in Step 3

The value of I_{d1} sets the minimum value of current rating for the Chopper Module. When the Chopper Module choice has been made, the current rating of the Module Transistor must be greater than or equal to the calculated value for I_{d1}. See Chopper Tables in the back of this booklet.

Step 5 – Calculating the Minimum Dynamic Brake Resistor Value

$$R_{db2} = \frac{V_d}{I_{d2}}$$

R_{db2} = the minimum value of the dynamic brake resistor

V_d = the value of DC Bus voltage chosen in step 3

I_{d2} = the value of the current rating for the chopper module

This step calculates the minimum resistance value that the Dynamic Brake Resistor can have. If a lower resistance were to be used with the Chopper Module of choice, the IGBT could suffer damage from overcurrent.

Step 6 – Choosing the Dynamic Brake Resistance Value

Choose a resistor value that lies between R_{db1} (Step 3) and R_{db2} (Step 5), with the preferred values of resistance as close to R_{db1} as possible.

Step 7 – Estimating the Minimum Wattage requirements for the Dynamic Brake Resistor

It is assumed that the application exhibits a periodic function of acceleration and deceleration. If $(t_3\text{-}t_2)$ = the time in seconds necessary for deceleration from $_b$ speed to $_o$ speed, and t_4 is the time in seconds before the process repeats itself, then the average duty cycle is $(t_3\text{-}t_2)/t_4$. The power as a function of time is a linearly decreasing function from a value equal to the peak regenerative power to some lesser value after $(t_3\text{-}t_2)$ seconds have elapsed.

The average power regenerated over the interval of (t_3-t_2) seconds is:

$$\frac{P_b}{2}\left(\frac{\omega_b + \omega_o}{\omega_b}\right).$$

The average power in watts regenerated over the period t_4 is:

$$P_{av} = \frac{(t_3 - t_2)}{t_4} \times \frac{P_b}{2}\left(\frac{\omega_b + \omega_o}{\omega_b}\right)$$

P_{av} = average dynamic brake resistor dissipation, watts
$t_3 - t_2$ = elapsed time to decelerate from ω_b speed to ω_o speed, seconds
t_4 = total cycle time or period of process, seconds
P_b = peak braking power, watts
ω_b = rated motor speed, Rad / s
ω_o = a lower motor speed, Rad / s

The Dynamic Brake Resistor power rating in watts that will be chosen should be equal to or greater than the value calculated in step 7.

It should be noted at this point that if the deceleration time is unusually long it is possible that the resistors may become very hot. This is because the constant temperature curve may be exceeded. Should you have an application that decelerates a huge inertia longer than 50 seconds, you may experience stress on the resistor bank. How much stress depends on the size of the inertia and length of the time the chopper is conducting.

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Section - 4 Power Quality

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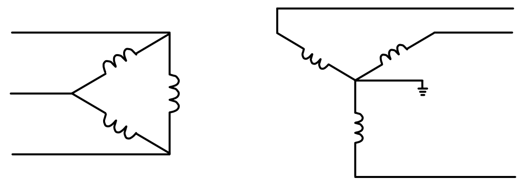
Transformers and Grounding

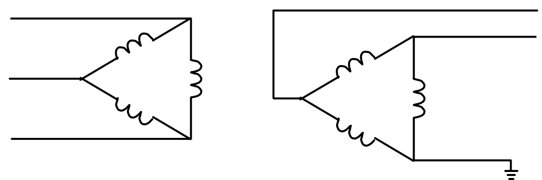
The type of transformer and the connection configuration feeding a drive plays an important role in its performance and safety. The following is a brief description of some of the more common configurations and a discussion of their virtues and shortcomings.

Delta / Wye with grounded Wye neutral:



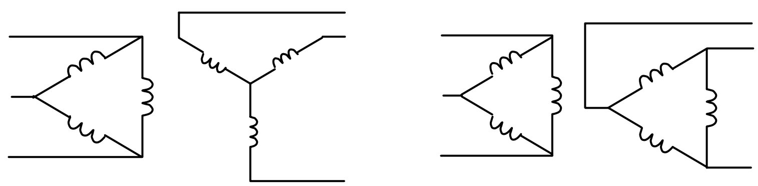
This configuration is one of the most common. It provides re-balancing of unbalanced voltage with a 30-degree phase shift. Depending on the output connections from the drive to motor, the grounded neutral may be a path for common mode current caused by the drive output.

Delta / Delta with grounded leg:



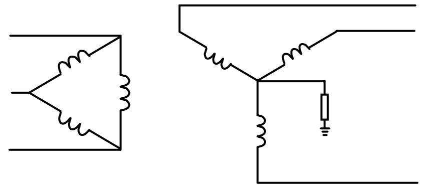
Another common configuration providing voltage re-balancing with no phase shift between input and output. Again, depending on the output connections from the drive to motor, the grounded neutral may be a path for common mode current caused by the drive output.

Ungrounded secondary.



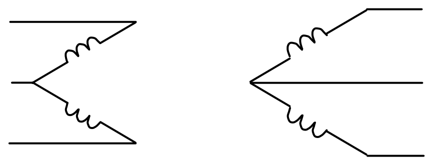
Grounding of the transformer secondary is essential to the safety of personnel as well as the safe operation of the drive. Leaving the secondary floating can permit dangerously high voltages between the chassis of the drive and the internal power structure components. In many cases this voltage could exceed the rating of the input MOV protection devices of the drive causing a catastrophic failure. In all cases, the input power to the drive should be referenced to ground. If the transformer can not be grounded, then an isolation transformer should be installed with the secondary of the transformer grounded.

Resistance grounding and ground fault protection:



Connecting the Wye secondary neutral to ground through a resistor is an acceptable method of grounding. Under a short circuit secondary condition, any of the output phases to ground will not exceed the normal line to line voltage. This is within the rating of the MOV input protection devices on the drive. The resistor is often used to detect ground current by monitoring the associated voltage drop. Since high frequency ground current can flow through this resistor, care should be taken to properly connect the drive motor leads using the recommended cables and methods. In some cases, multiple drives on one transformer can produce a cumulative ground current that can trigger the ground fault interrupt circuit.

Open Delta:



This type of configuration is uncommon. From time to time it may be encountered where only single phase power is available and three-phase power is required. The technique uses two single phase transformers to derive a third phase. When used to power a drive this configuration must be derated to about 70% of the single phase rating of one transformer. This system provides poor regulation and it is possible that only the two line connected phases will provide power. In this case the drive must be derated to 50% of its rating.

Single Phase Connection:

For a small drive with a diode rectifier front end it is possible to run a three phase output with a single phase input. Only part of the three phase input bridge is used. Ripple current becomes 120 hertz rather than 360. This places a greater demand on the DC filter components (Capacitor bank and DC choke). The result is that the drive must be derated to 50% current. Single phase will not work with an SCR front end drive.

Sizing transformers for drive applications

The transformer supplying power to the drive needs to be sized relative to the drive rating. The transformer VA should be limited to no more than 4-5 times the drive VA rating. Use the formula below to determine the maximum VA rating of the transformer. Typical Source Leakage is 5-6%.

$$Z_{Drive} = \frac{V_{L-L}}{\sqrt{3} \times \text{Input Amps}} \qquad VA_{Max} = \frac{(V_{L-L})^2 \times \%\text{Source Leakage}}{Z_{Drive} \times 0.01}$$

Installation Considerations for VFDs

Reflected Wave Phenomenon

This phenomenon occurs when cable surge impedance does not match load (motor) surge impedance. Up to 2 per unit (twice) VFD DC bus voltage may exist on line to line motor terminals. Waveform (A) shows an the reflected wave voltage for a 450VAC drive. A combination of reflected wave voltage magnitude and rise time has a major influence on the dielectric withstand capability of the motor.

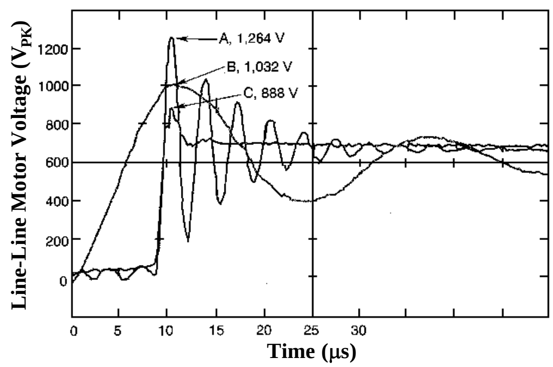
Reflected wave magnitude is dependent on the extent of the impedance mismatch.

Reflected wave rise time is affected by the rise time of the VFD's output devices.

Solutions to Reflected Wave Phenomenon

- Select NEMA MG1 Part 31 Inverter Duty Motors.
- Limit motor cable length.
- Terminator (RC network) at the motor to absorb the energy.
- Attenuate the noise at the drive's output terminals with a filter such as an eliminator or sine wave filter.
- Attenuate the noise at the drive's output terminals with a reactor. This is probably the least desirable solution. Although the reactor does reduce the rise time of the reflected wave voltage, it can still reach high peaks.

Motor Reflected Wave Pulse Amplitude [5us/div:200v/div]
(A) Unterminated (B) Reactor at Drive (C) Terminator



Common Mode Noise

Common mode noise is a type of electrical noise induced on signals with respect to a referenced ground. Problems due to common mode noise imply a source of noise, a means of coupling that noise from the source to the ground plane, and equipment sensitive to that noise.

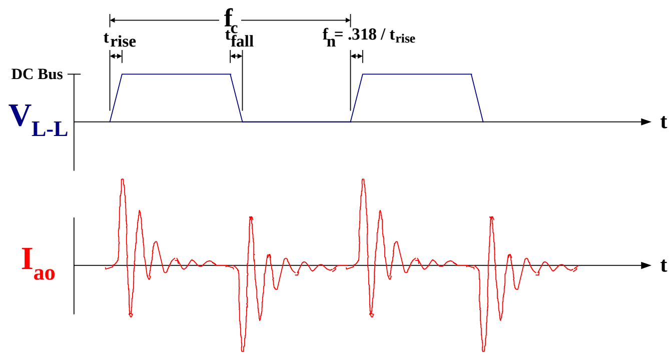
Signals and Equipment Sensitive to Common Mode Noise

- Control signals sensitive to noise include encoder feedback, 0-10V I/O, 4-20mA current loop sensors, and PLC communication links.
- Equipment sensitive to noise include ultrasonic sensors, weighing sensors, temperature sensors, bar code/vision systems, capacitive proximity or photoelectric sensors, and computers.

Source of Common Mode Noise: VFD Common Mode Output Current

VFDs have abrupt voltage transitions on the drive output that are a source of radiated and conducted noise. The magnitude of these currents is determined by the amount of stray capacitive coupling phase to ground during the fast switching voltage transitions on the drive output. These voltage transition times are determined by the semiconductor technology used.

Noise Source: Drive Induced Common Mode Current



Noise Coupling: Conducted Common Mode Current to Ground

Common mode current can flow thru the motor cable capacitance to ground and thru the motor stator winding capacitance to ground.

Noise Abatement Solutions

- Grounding Practices:
  Bringing the motor ground directly back to the VFDs ground terminal allows a more direct path for the common mode current to flow back to the VFD. Whereas a motor grounded to a sub-panel or ground terminal block not located at the VFD allows common mode current to flow through other paths.

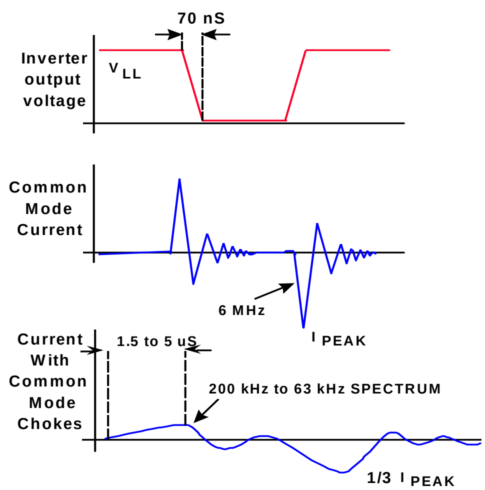
  A solid grounded wye secondary system is a low impedance to the transient CM noise current and completes the return path back to the drive input leads from the ground grid. Highest CM current magnitude occurs with this system but very little CM noise goes out into the PE grid beyond the transformer neutral connection, so that CM noise is contained.

  A high resistance ground system would add typically 150-200 Ω to the T1 secondary neutral circuit that is grounded. This resistor is in the series path of the CM noise current return and significantly reduces peak CM current magnitude to small levels such that potential differences in the plant ground grid caused by CM noise is minimal. Surge testing has shown acceptable primary to secondary line to ground transient voltage reduction.

An ungrounded secondary system breaks the CM return current path back to the drive input so that very little CM current in the ground grid exists. Thus, CM noise is reduced. However, a disadvantage is that surge test results show primary to secondary line to ground high voltage transients are passed directly to the secondary side without attenuation. Also, safety concerns must be addressed with this system.

- Attenuate the Noise Source:
  The best way to eliminate system noise is to attenuate it at the source (the drive) before it gets out into the system grid and takes multiple high frequency sneak paths which are hard to track down in an installation. Past experience has shown Common Mode Chokes on the drive output and CM cores on the interface equipment are highly effective in ensuring fully operational tripless systems in medium to high risk installations. A Common Mode Choke (CMC) is an inductor with output Phase A, B and C conductors all wound in the same direction thru a common magnetic core.

Attenuation of Drive Noise with Common Mode Chokes



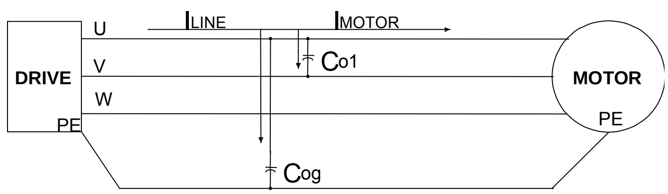
- Shield Noise Away from Equipment
  Use 3-conductor w/ ground shielded or armored cable. CM noise currents are generated from cable phase conductor to the cable green ground wire, from phase to cable shield and from motor winding to ground. These currents have 3 return path options back to the drive; the 60 Hz green Safety wire, the cable shield/armor or the customer ground grid. The predominant return path is the shield/armor since it has the lowest impedance to the high frequency noise. The shield/armor is isolated from accidental contact with grounds by a PVC outer coating so that the majority of noise current flows in the controlled path of the cable and very little high frequency noise goes into the customer PE ground grid.

Divert Noise from Susceptible Equipment with Proper Cabinet Layout: Grouping the input and output conduit/armor to one side of the cabinet and separating the Programmable Logic Controller (PLC) and susceptible equipment to the opposite side will eliminate many effects of CM noise currents on PLC operation.

Cable Charging Current

A drive to motor 3 wire plus ground cable consists of *Co1* line to line stray distributed capacitance and *Cog* distributed line to ground cable capacitance. There also exists a motor line to ground capacitance, defined by the stator winding capacitance to the motor PE frame ground, which may be added to *Cog* . During each *dv/dt* transition on the drive output line to line pulse, a capacitive coupled cable charging current is sourced from the drive, flows through *Co1* and returns through another phase. The drive switching transition in a given phase output also sources another cable charging current path from line to ground through *Cog*.

Cable Charging Current Paths



Capacitively coupled currents could exceed the drive rating.

C_{o1} = Line to line capacitance path

C_{og} = Capacitance path line to ground

This phenomenon exists for all drives. However, drives < 2 hp are more susceptible to overload and overcurrent trips due the additional charging currents.

This phenomenon is exhibited to a greater degree on 460 V drives than on 230 V drives due to the higher output transition voltage.

Shielded motor cable has higher capacitance line to line and line to ground than wires in a conduit and may increase the charging current magnitude.

Capacitively coupled currents can also exist between the output wires of different drives that are routed in the same conduit. It is recommended that no more than 3 drive output wires be routed in the same conduit to prevent additional drive to drive capacitive currents resulting from tightly bundled output wires in a conduit.

Techniques to mitigate cable charging current

- Reducing carrier frequency
- Reducing cable lengths to manufacturer recommended values
- Over-sizing the drive hp for a smaller motor hp load is also effective to insure cable charging limits are not met
- Add a 3 phase inductor on the drive output to reduce the cable charge current magnitude

Grounding and Bonding

An effectively grounded system or product is one that is "intentionally connected to earth through a ground connection or connections of sufficiently low impedance and having sufficient current-carrying capacity to prevent the buildup of voltages which may result in undue hazard to connected equipment or to persons" (as defined by the US National Electric Code NFPA70, Article 100B). Grounding of a drive or drive system is done for 2 basic reasons: safety as defined above and noise containment or reduction.

The object of safety grounding/bonding is to ensure that all metalwork is at the same, ground (or earth) potential at power frequencies. Impedance between the drive and the building system ground must conform to the requirements of national and local industrial safety regulations and/or electrical codes. .

Because the output of a PWM ac drive can produce high frequency common mode (coupled from output to ground) electrical, care should be taken in those installations where the presence of such noise may cause other sensitive equipment to malfunction. The grounding scheme used can greatly affect the amount of noise and its impact on the system.

While the safety ground system and the noise current return circuit may sometimes share the same path and components, they should be considered as totally different circuits with different requirements.

Use the best ground point

If intentionally bonded at the service entrance, the incoming supply neutral or ground will be bonded to the building ground. Building steel is judged to be the best representation of "ground" or "earth". The structural steel of a building is generally bonded together to provide a consistent ground potential. If other means of grounding are used, such as ground rods, the user should understand the voltage potential, if any, between ground rods in different areas of the installation. Type of soil, ground water level and other environmental factors can greatly affect the voltage potential between ground points if they are not bonded to each other.

1. If painted surfaces are involved, make certain that surfaces are scraped and cleaned for solid connection.
2. Connect the supply transformer secondary neutral / ground directly to the drive PE terminal.
3. Use wire with XLPE insulation with good concentricity and insulation thickness greater than 15 mils.
4. If conduit is used, use quality wire inside the conduit. Do not route more than 3 sets of drive cables in any one conduit. Avoid or understand the effects of accidental or unrecognized contact between conduit and ground point along the run.
5. When laying cable in cable trays, do not randomly distribute them. Cables for each drive should be bundled together and anchored to the tray.
6. Use shielded cable with a PVC outer jacket where possible to contain or properly route noise. Route power and control separately and ground all shields per instructions. Always use shielded cable for encoder signals and route in a separate conduit. Use shield terminating connectors whenever possible. If a pigtail must be used, pull and twist the exposed shield after separation from the conductors. Solder a flying lead to the braid and connect to the proper ground terminal.

Panel Layout

Plan the cabinet layout so that drives are separated from sensitive equipment. Choose conduit entry points that allow any common mode noise to remain away from PLCs and other equipment that may be susceptible to noise. Common mode noise current returning on the output conduit, shielding or armor can flow into the cabinet bond and most likely exit through the adjacent input conduit/armor bond near the cabinet top, well away from sensitive equipment (such as the PLC). Common mode current on the return ground wire from the motor will flow to the copper PE bus and back up the input PE ground wire, also away from sensitive equipment.

Motor Cables

Commonly Used Cable Types and Insulation

Typical cable constructions used in industrial applications are:

- Tray Cable (TC) or shielded TC laid in a 12" – 24" tray
- PVC, galvanized steel or box type conduit with individual phase and ground conductors
- Metal Clad (MC) armor cables

Common cable insulations used are cross-linked polyethylene (XLPE) and Poly Vinyl Chloride (PVC). Many reasons exist for selecting a specific cable construction and insulation type. Final selection may be based on important non-electrical characteristics such as mechanical rigidity, fire retardency, chemical resistance, moisture resistance, UL and agency approval listing, as well as past historical experience.

Effect of Reflected Wave on Cable Life of XLPE and PVC Individual Phase Conductor Cable

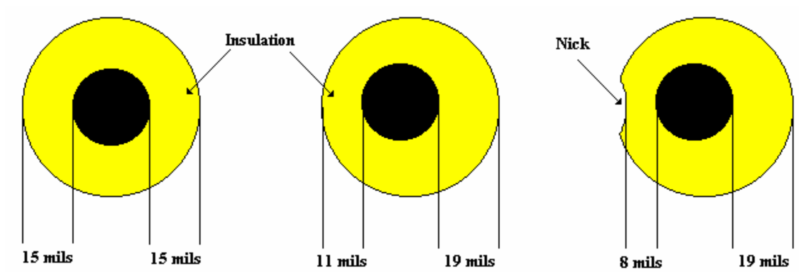
All 600v rated XLPE cables are adequate to handle the 2 per unit reflected wave transient per our test results. 600v PVC cables will be suspect based on insulation thickness and environment conditions. Applications where moisture is prevalent in the environment should refrain from using THHN (PVC insulation) wire with IGBT based drives.

Considerations with THHN Wire

Due to inconsistencies in manufacturing processes or wire pulling, air voids can occur in THHN wire between the nylon jacket and PVC insulation. Because the dielectric constant of air is much lower than the dielectric of the insulation, the transient reflected wave voltage may appear across the small air void capacitance. The CIV (Corona Inception Voltage) for the air void may be reached, which attacks the PVC insulation and produces carbon tracking, leading to the susceptibility of insulation breakdown as in the above case.

Asymmetrical construction of the insulation has also been observed for some manufacturers of PVC wire. A wire with 15 mil specification was observed to have an insulation thickness of 11 mil at some points. The smaller the insulation thickness, the less voltage the wire can withstand.

Wire Insulation Inconsistencies



THHN jacket material has a relatively brittle nylon coating that lends itself to damage (i.e. nicks, cuts) when pulled through conduit on long wire runs. This issue is of even greater concern when the wire is pulled through multiple 90 degree bends in the conduit. Nicks reduce the thickness of the installation. It is these nicks that may be a starting point for corona that leads to insulation degradation.

Cable Recommendations

A 3 conductor with ground, PVC jacketed, shielded type Tray Cable with XLPE conductor insulation designed to meet NEC code designation XHHW-2 (wet locations) is recommended. It is superior to loose wires in dry, damp and wet applications and can significantly reduce capacitive coupling and common mode noise.

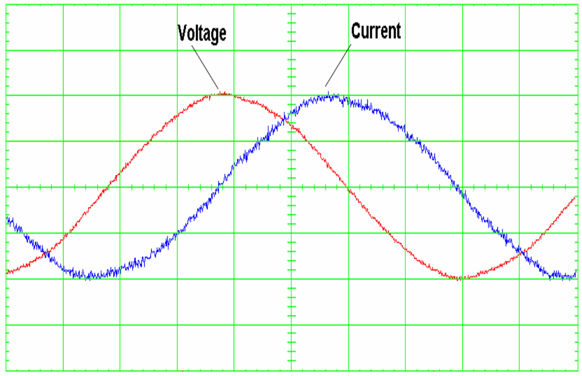
3 conductor armored cable is also superior to loose wires in dry, damp and wet applications and can significantly reduce capacitive coupling and common mode noise.

Harmonics

Nonlinear loads cause harmonics. The distorted waveforms can be represented as a series of waveforms, with each waveform having a frequency that is an integer multiple of the fundamental frequency.

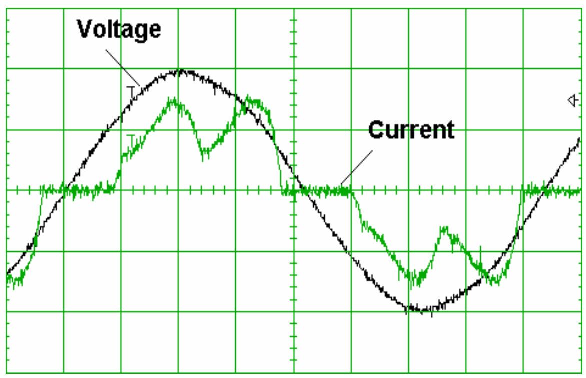
Linear Load: in a linear load, the voltage is proportional to current and the waveforms are undistorted sine waves consisting of one fundamental frequency. The figure below shows the voltage and current waveforms for a linear load with a fundamental frequency of 60 Hz.

Input Line to Neutral Voltage and Input Current on phase A of a Linear Load



Nonlinear load: in a nonlinear load, current is not proportional to voltage. The waveform is distorted.

Input Line to Neutral Voltage and Current on Phase A of a 6 Pulse AC drive w/ DC Link Choke



Current harmonics seen on the AC line side PWM AC drives are a result of the 3-phase converter section. The figure above shows typical waveforms for a 3-phase AC drive with a DC link choke.

In an AC drive, the 5th and 7th harmonics are the dominant harmonics (besides the fundamental).

Typical harmonic current spectrum for a 3-phase, PWM AC drive with DC link choke:

Category	6-Pulse Drive	12-Pulse Drive	18-Pulse Drive
Current THD	30-35%	6.5-9.5%	4.5-5%
Power Factor	0.92-0.95	0.97-0.98	0.98-0.99
DPF	0.95-0.97	0.96-0.98	0.98-0.99
K-Factor	3.0-5.0	2.0-3.0	1.0-2.0
Efficiency	96.5-97.5	97.0-98.0	97.5-98.0
5th	20-30%	4.0-6.0%	2.0-3.0%
7th	4.0-7.0%	2.0-4.0%	1.5-2.5%
11th	3.0-5.0%	4.0-7.0%	1.0-2.5%
13th	2.5-4.5%	3.5-5.0%	1.0-2.0%
17th	1.5-2.5%	1.0-2.0%	0.5-1.5%
19th	1.0-2.0%	1.0-1.5%	0.5-1.0%

THD (Total Harmonic Distortion) and TDD (Total Demand Distortion)

Harmonic distortion measurements are normally given in “total harmonic distortion” or THD. THD defines the harmonic distortion in terms of the fundamental current drawn by a load:

$$THD\ \% = \frac{\sqrt{\sum_{h=2}^{h=\infty} (M_h)^2}}{M_{fund}} \times 100\ \%$$

Where *Mh* is the magnitude of either the voltage or current harmonic component and *Mfund* is the magnitude of either the fundamental voltage or current. It is important to note that THD uses the instantaneous fundamental current as the denominator. Therefore, if a consumer’s plant is running at a small percentage of their peak loading, the THD calculated may be very high.

IEEE-519 is a standard that provides guidelines for limits on harmonic distortion. Refer to IEEE-519 tables in Appendix III. IEEE-519 uses a term called TDD (total demand distortion) to express current distortion in terms of the maximum fundamental current that the consumer draws:

$$TDD\ \% = \frac{\sqrt{\sum_{h=2}^{h=\infty} (I_h)^2}}{I_{load}} \times 100\ \%$$

I_{load} is the maximum fundamental current that the consumer draws and it could be measured over a specified time period, or estimated. Keep in mind that TDD is only used to measure current distortion, not voltage distortion. Because TDD uses the maximum fundamental current consumed as the denominator, TDD will most likely less that THD.

The limits IEEE-519 places on current distortion also depend on the ratio of I_{sc}/I_{load} where I_{sc} is the short circuit current. I_{sc} for a supply transformer can usually be obtained from the utility. I_{sc} can also be calculated knowing the supply transformer impedance using the following formula:

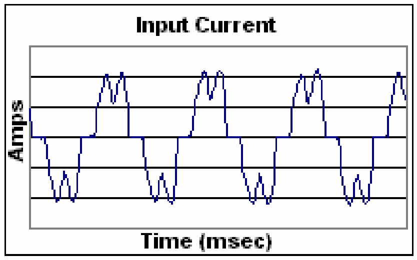
$$Isc \approx \frac{KVA \times 1000}{Z_{xfrm,\ pu} \times V_{secondary} \times \sqrt{3}}$$

The ratio of I_{sc}/I_{load} determines the "stiffness" of the supply. Therefore, the "stiffer" the supply, the higher the ratio I_{sc}/I_{load} will be, and the more current TDD allowed.

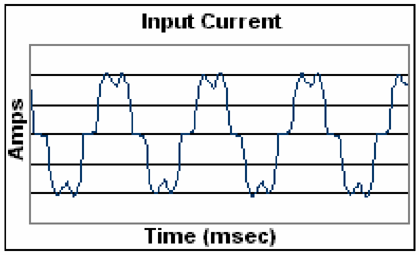
Techniques for reducing harmonics in PWM AC Drives (in order from least harmonic reduction to most harmonic reduction)

- DC Link Choke
  A DC Link Choke installed right in the drive significantly reduces current peaks.
- AC Line Reactor
  Especially for drives with no DC Link Choke, this can be an effective means of reducing harmonics and will provide a similar level of harmonic reduction as a DC link choke.
- Passive Filter
  A network of capacitors and inductors tuned to reduce mainly the 5^{th} and 7^{th} harmonics.
- 12-Pulse Converter with phase-shifting transformer
  A 12-pulse converter replaces the standard 6-pulse converter to give a more sinusoidal input current waveform.
- Active Filter
  This technique works by using an active switch arrangement (IGBTs) that looks very much like the inverter side of a drive. Using current sensors this device adds the sine wave complement of the current it measures to the line, making the current up stream from the drive look sinusoidal.
- Active (Regenerative) Converter
  This technique uses an active switch arrangement (IGBTs) that looks very much like the inverter side of a drive. The active converter takes the place of the diode or SCR converter section of the drive. This technique has the added benefit of being able to regenerate to the AC line.
- 18-Pulse Converter with phase-shifting transformer
  An 18-pulse converter replaces the standard 6-pulse converter to give a more sinusoidal input current waveform.

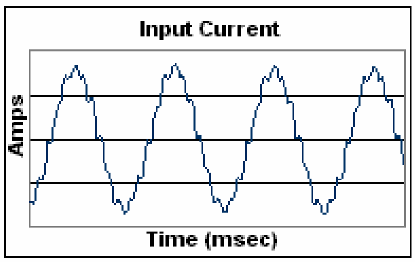
Input Current Waveforms



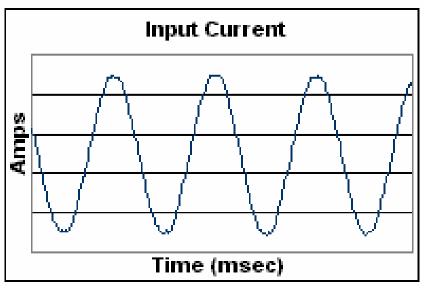
6-Pulse Front-End with DC Link Reactor Current THD = 31.4%



6-Pulse Front-End with 3% Line Reactor Current THD = 24.2%



12-Pulse Front-End with DC Link Reactor Current THD = 9.1%



18-Pulse Front-End with DC Link Reactor Current THD = 4.8%

Reactors

To calculate the reactance (X_L) of a reactor of a given inductance (L in Henries):

$$X_L = 2\pi f \bullet L \qquad \Omega$$

To calculate the % impedance based on a given VFD rating the following formula can be used:

$$X_{\%} = \frac{2\pi f \bullet L \bullet S}{E^2} \bullet 100 \qquad \%$$

Where S is the input VA rating of the VFD and E is the line to line voltage rating.

Applications for line reactors on VFDs

- Add line impedance when supply transformer is more than 6 times power rating of the VFD and the VFD has no DC link choke. (refer to “sizing transformers” section)
- To provide some light buffering against low magnitude line voltage spikes.
- To reduce AC line Harmonics, especially when the VFD has no DC link choke.
- To compensate for a low inductance motor and when multiple motors are running on one VFD.
- As part of a filter for reflected wave reduction.

Inductance of 1 & 3 Phase reactors

$$L = E^2 \times Z \bullet 10^6 / kva \times 1000 \times 2\pi f \qquad uh$$

Cable Inductance

$$L \approx 0.5uh / m$$

Resonant Frequency

$$f = \frac{1}{2\pi\sqrt{LC}}$$

Capacitance of known kVar

$$C = \left(\frac{k\,\mathrm{var} \times 1000}{3}\right) / 2\pi f \times \left(\frac{v}{1000}\right)^2 \qquad uf$$

Ride-Through

Types of Ride-through

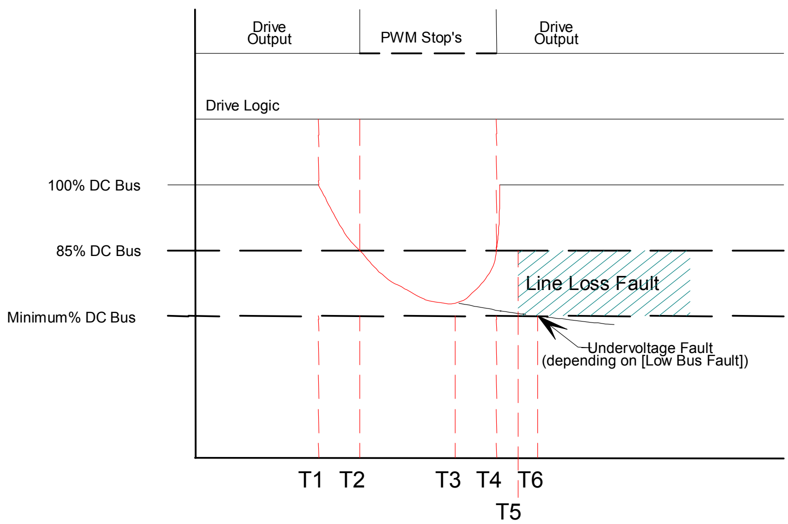
- Power loss ride-through is defined as maintaining output current to the motor.
- Logic ride-through is keeping the control circuit active and ready to reconnect to the motor when line power is restored.

Precharge

Precharge is the drives way of protecting itself from current inrush during power up or a power dip or line loss event. For a drive with a diode front end, the precharge method may be a series resister in the DC bus with a relay or solid state switch such as an SCR or transistor in parallel with this resistor. When precharge is complete, the parallel switch is closed.

For a drive with an SCR converter bridge, precharge is taken care of by phasing up the firing angle (alpha) on the gate of each of the six SCR's. During a line dip or power loss, alpha is reduced or " phased back".

With either method of precharge, the inverter section of the drive is disabled since it is not possible to source power through the precharge resistor or through a "phased back" SCR front end. During precharge the drive is de-coupling itself from the line in order to protect itself from potentially excessive inrush. When the DC voltage level drops low enough (typically 15 to 20% of a rolling, time weighted average) the drive pre-charge mode is invoked as shown.



T1: power into the drive is lost and DC bus voltage begins to drop rapidly.

T2: the level where the drive goes into precharge. With some drives this can be a fault or perhaps a configurable fault that may be disabled. In any case, output to the motor stops.

T2 to T3: the drive is in "Logic ride-through" and the rate of decay on the bus voltage is much slower since the drive is not producing output power to the motor. In some cases the drive will fault if the DC bus voltage falls below a Minimum level. This minimum DC voltage level may be the lowest safe point to operate the internal control power supply.

T3: if the AC line power is restored, the DC bus will begin to climb. Keep in mind, at this point the precharge circuit limits the input line current as it charges the DC capacitor bank. This prevents large inrush currents and controls the rate of rise in DC bus voltage.

T4: the DC bus is back above the precharge level and output to the motor resumes.

T5 and T6: if we had not restored line power at T3, a line loss fault or undervoltage fault could occur at T5 or T6. The type of ride-through is in essence dependent on bus voltage level and precharge level.

Power Loss Ride-through

Power loss ride-through is the ability of the drive to maintain power out to the motor with a power line loss at the input to the drive.

The energy supplied to the motor during a power ride-through is supplied by the internal dc bus capacitors in the drive power structure. It is then necessary to know the total drive DC bus capacitance, DC bus voltage and load level to determine ride-through time. The equation for stored energy in a capacitor bank is:

$$W = \frac{1}{2} C V^2$$

Where W is in joules or watt-seconds, C is capacitance in Farads and V is DC bus voltage. We only get the energy between the starting voltage before the power loss event and the voltage level at the point where the drive goes into pre-charge mode. Thus the ride-through energy for a drive can be calculated:

$$W = \frac{1}{2} C (V_1 - V_2)^2$$

Where W is in Joules, C is DC bus capacitance in Farads V1 and V2 are the DC bus voltage levels at the instant of the input power loss and the DC voltage at the pre-charge point respectively.

<u>Example:</u>

- 30 horsepower drive and motor running at a 55% load.
- Nominal DC bus voltage of 640 volts.
- Pre-charge drop level of 20%.
- DC bus capacitance value of 4,700 mfd.

Let's calculate ride-through for this 30 horsepower 460 volt drive.

The energy available in Joules is = $\frac{1}{2}C(V_1\text{-}V_2)^2$ or $\frac{1}{2}*4{,}700((640\text{-}(640*.8))^2)$. This gives us about 38.5 Joules.

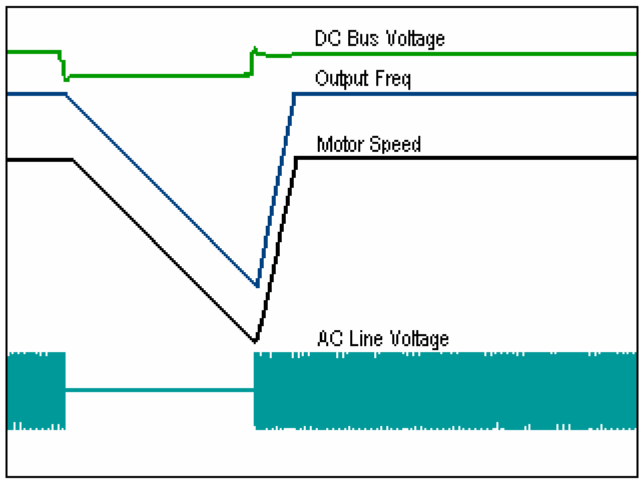
There are 746 watts per horsepower giving us a motor kw rating of (30X746) or 22.380kw. Multiplying 22.38 by the 55% load level we see that we are running at about 12.309Kw.

Power ride-through = 38.5 Joules (or watt-seconds) / 12,309 watts = about 3.1 milliseconds.

Additional capacitance could be connected to the DC bus of the AC drive. In general, bus capacitance can be used to ride-through very short power losses.

Techniques to Provide Extended Power Loss Ride-Through

- Inertia Ride-through
  This method of ride-through requires a load with an inherently large moving or spinning mass and relatively little friction. Under a line loss condition when the DC bus voltage begins to drop, the drive responds by slightly decreasing the output frequency. This causes a regenerative condition and will maintain the bus voltage at a level determined by the drive's software.



Since the drive never stopped producing output power to the motor, a very quick and smooth recovery can be seen when line power is restored.

We can calculate a maximum time for inertia ride-through.

$$W = J(\Delta rpm \frac{2\pi}{60})^2$$

Where W is in Joules or (watt-seconds), J is moment of inertia in kilogram-meters squared and rpm is revolutions per minute of the spinning mass.

Example:
Moment of inertia for motor and coupled load = 10 kgm^2.
Normal operational speed = 1,500 rpm.
Nominal power consumption 22,000 watts.

W = 10 X (1500 (6.28 / 60)) ^{2}

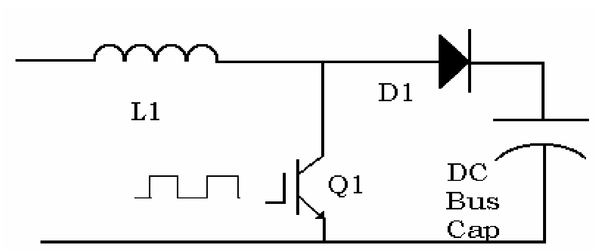
W = 246,740 watt – seconds.

Dividing by 22,000 watts we get a ride-through time of 11.2 seconds.

This calculation assumes that the nominal power consumption is a constant 22,000 watts total. In reality the power consumption may not be constant. For a fan or pump load the power consumption will diminish with the inverse square or inverse cube of the speed. Drive and motor efficiency will also have some small and perhaps varying degree of an effect in reducing the theoretical calculated ride-through time since the motor and drive will run at varying current levels as the inertia ride-through progresses.

- Battery Back Up
  This source of energy might be as simple as a battery or it may be an uninterruptable power supply. A battery back up tied to the DC bus through a series diode works well on a common bus type drive or a drive with a simple diode bridge converter.

- Boost Converter For Brown Out Conditions
  A boost converter is wired into the DC bus of an AC drive. It works by storing energy in the L1 inductor when the AC line is at normal levels. During a brown out condition, the Q1 transistor



turns off, releasing stored energy from L1 to the DC bus of the drive. This method of ride-through can be used as long as some reasonable level of line voltage (roughly 50% or more) is present.

- An Active Front End (also known as a Regenerative Front End)
  Another method for brown out ride-through is to replace the drive diode or SCR converter front end with an active front end. It is possible to boost the DC bus voltage to a desired set point with this device. The active front end uses energy stored in the input reactor to "boost" the DC bus voltage and keep it at the set point. This method of ride-through can be used as long as some reasonable level of line voltage (roughly 50% or more) is present.

Logic Ride-through

For some applications power ride-through may not be critical, while maintaining the drive control logic is important. Once the output to the motor stops, most of the energy in the capacitor bank is available to run logic power. In most cases the logic power is supplied by a switch mode power supply tied to the DC bus. The switch mode power supply can operate under a wide ranging DC bus voltage level, typically down to about 250 volts DC for a 460 volt drive. In theory this should be able to provide logic power for several minutes on a large drive.

Generally the limitation is an Underwriters Laboratory requirement for the drive to have less than 50 volts on any internal component within 1 minute of a power shut down. To comply with this requirement, an active discharge circuit is often used to discharge the capacitor bank in under a minute.

In many cases the logic ride-through can be extended indefinitely by using a separate, low voltage logic supply, if the drive has this input capability.

Reconnecting to the Motor after Logic Ride-through

Starting the drive from a 0 Hz output may work, but often it will not give the best response/reconnect time.

- "Flying Start"
  "Flying Start" (available on some drives) allows a drive to connect more quickly to a motor by using motor speed information. Motor speed could come from encoder feedback, could be found using CEMF (counter electro-motive force), or could be found using another speed search method.

- Run On Power Up
  Though not technically a ride-through feature, run on power up can be useful in some applications where it is important for the drive to run anytime input line power is applied. One example of where this is used is for remote / unmanned pumping stations where a temporary power loss can occur but it is not practical for someone to go on site and restart the system.

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Section – 5 Networks

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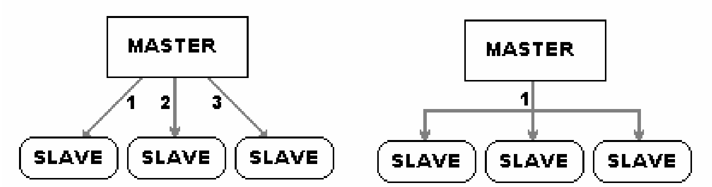
Basics

Network Performance

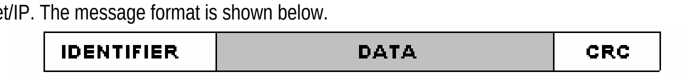
The performance of a network is measured in through-put time. Several factors determine the actual time it takes for a signal to be processed and sent to a device which then reacts to the data it receives. The main factors are:

<u>Network Model</u> is the most important factor in determining throughput because it determines information flow (the number and how often messages are exchanged). Some Network Models require 10 messages to talk to 10 nodes whereas others only require 1 message to talk to 10 nodes.

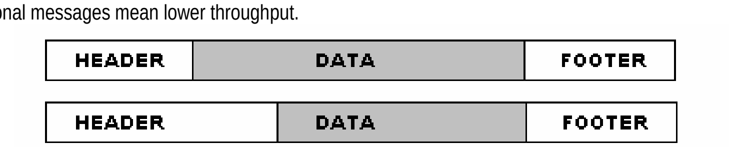


The Source/Destination model shown above left is also known as a polled or Master/Slave network. The master communicates to its slave sequentially one at a time. The slaves are passive and respond to the master's commands. Examples of this are RIO, Profibus, Polled I/O on DeviceNet. The messaqe format is shown below.

A Producer/Consumer model is shown above right. Using this model, a device *produces* a message on the network and all other devices have the option to *consume* it. Examples of this are DeviceNet, ControlNet and EtherNet/IP. The message format is shown below.



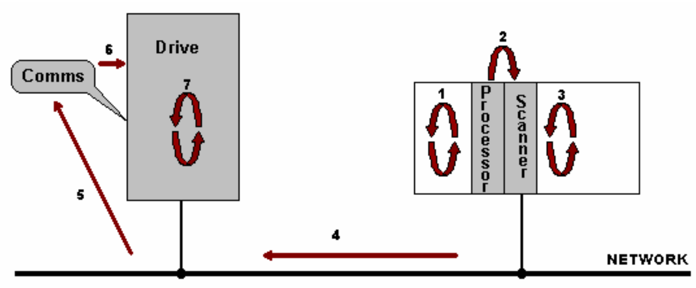
<u>Protocol Efficiency</u> refers to the percentage of actual data within a given message. The slide shows two examples of equal length messages. The key difference is the first example contains more actual data. It takes the second example 2 messages to transmit the amount of data available in the first example. Additional messages mean lower throughput.



<u>Baud Rate</u> determines the "time on the wire" which is important, but not as significant as Protocol Efficiency (#2) and Network Model (#1). As the number of messages increase on the network, the time on the wire can become a burden on the bandwidth.

Determining Throughput Time

The total time for data exchange from the controller to a device on the network must take into account scan times, processing times and wire times. The following diagram shows all of the pieces that add to the throughput time.



1. Processor Scan Time
2. Processor to Scanner communications
3. Scanner update time
4. Time on the wire
5. Communication module processing
6. Communication module to drive
7. Drive update or scan time

Note: The time on the wire is typically the smallest contributor to the overall throughput time.

General Terms

Media Access Control Identifier (Mac ID) - An identification value assigned to each node, which distinguishes a node among all other nodes on the same network (node address).

I/O Messaging - Data transfers that are run-time in nature which can have COS, Cyclic or Polled production triggers. They may be unidirectional or bi-directional. The data field is all data (contents defined by the application) It is also referred to as “Implicit Messaging” since the receiving device already knows what the data is for (implied).

Explicit Messaging – Are Request-Response type messages triggered by the device’s application. This type of message contains explicit protocol in the data field which includes internal object addressing information (Class, Instance, and Attribute). It can be Connected or Unconnected (with limited services).

Objects – is an abstract representation of a particular component within a product.

Class - A set of Objects that all represent the same kind of system component.

Instance - The actual representation of a particular Object within a Class.

Attribute - A characteristic of an Object and/or Object Class.

Service - A function supported by an Object and/or Object Class.

Producer - is a *sender* of data that transmits data packets on the wire.

Consumer - is a *receiver* of data. Any and all interested consumers can pick data packets off the wire.

Polled – Is a Master / Slave based I/O method where each slave is queried and may or may not respond before the next device is queried.

Change Of State (COS) – is an I/O method where data is transmitted when a change of data occurs.

Cyclic – Is an I/O method where data is transmitted on a user-configured time interval.

DeviceNet

Collision Sensing Multiple Access / Non-destructive Bit-wise Arbitration (CSMA/NBA) - All nodes can transmit on the wire and can detect when a collision occurs. The collisions are non-destructive.

Physical Signaling – (Bus level 0 = *dominant*, Bus level 1 = *recessive*, Bus idle = *recessive*) The *dominant* level overrides the *recessive* level.

UCMM / Group 2 Only - DeviceNet is a connection based protocol, but connections must be created and configured before they are used. There are two ways to do this in DeviceNet: UnConnected Message Manager (UCMM) or Group 2 Unconnected Port. A UCMM device can speak for itself whereas a Group 2 device requires a scanner to proxy for it.

ControlNet

Concurrent Time Domain Multiple Access (CTDMA) – Is a time-slice algorithm which regulates a node's opportunity to transmit in each network interval (NUI).

Network Update Time (NUT) - The repetitive time interval in which data can be sent on the network. The complete NUT is the sum of scheduled, unscheduled, and maintenance messages sent.

Network Update Interval (NUI) – Is a single occurrence of the network update time (NUT).

Requested Packet Interval (RPI) – The time interval set by the user for a nodes Scheduled data on the network. Rates supported will be binary multiples of the NUT. Binary multiples - 1, 2, 4, 8, 16, 32, 64, 128 Each node on ControlNet can send at a different rate.

Actual Packet Interval (API) – Is the actual packet interval for Scheduled data on the network. ControlNet will meet or beat the requested time (RPI) or provide feedback that the configuration can not be supported.

Deterministic – The ability to predict when data is received from a transmitting device.

Repeatable - The determinism is fixed regardless of nodes entering or leaving the system.

Scheduled - Communication used to control I/O and has the highest priority because it is the deterministic and repeatable portion of ControlNet. Examples: Logic Command / Reference, Logic Status / Feedback, Datalinks.

Unscheduled - Communication used for event-driven peer-to-peer messaging, HMI, and programming Examples: “Get Single” Parameter read via an explicit message, “Set Scattered” Parameter writes via an explicit message.

Keeper - A keeper is a ControlNet node with the capability to store and apply network parameters for a unique network configuration.

In a single keeper network the active keeper can only be node 1.

In a multi-keeper network, there can be more than one keeper capable device on the network, but the lowest node number keeper capable device will be the only active keeper.

The active keeper is a keeper capable node responsible for sending a periodic keeper broadcast every fourth NUT. This packet contains information about which keeper should be active, the overall signatures, pending network change operations, and network management resources to all nodes on the network. The active keeper is also responding to requests for scanner signatures from nodes with scheduled connections.

If both single keeper and multi-keeper devices are on the same network, the single keeper device cannot be node 1.

EtherNet / IP

Carrier Sensing Multiple Access / Collision Detection - When a node wants to transmit it will listen to the network and if it does not detect that any other node is transmitting (Carrier Sensing), it will begin transmitting. “MA” refers to all devices having equal access to the network. Therefore, it is possible that two (or more) devices listen to the network at the same time, determine no one is transmitting, and then begin to transmit. If two nodes begin transmitting at the same time a “collision” will occur. The collision will cause both signals to be corrupted. There is special circuitry in each node that can detect if a collision occurred. If so, the transmitting nodes will know they have to retransmit their message. Each node will wait an arbitrary amount of time before retransmitting.

Bridge - is a device that isolates traffic between segments by selectively forwarding packets to their proper destination. It is transparent to the network and protocol independent.

Hub - is the center component of a star topology that utilizes twisted pair or fiber cable to connect to devices. A hub broadcasts everything it receives on any channel out all other channels.

Switch - Is the center component of a star topology that utilizes twisted pair or fiber cable to connect to devices. A switch is different than a hub in that a switch has the intelligence to only transmit out the port that the message needs to be transmitted. A switch is really a multi-port bridge.

Router - Is a device that connects network segments and routes messages between networks. Routers use routing tables to route packets. Routers are used extensively on the Internet. The term “Gateway” is sometimes used to refer to a router which also translates data between different formats.

IP Address - The node address of the device which other nodes will use to communicate to the device. IP addresses are 32-bit numbers that are normally grouped into 4 bytes to make them easier to read.
For example, an IP address of: 129 . 8 . 128 . 31

Is actually:

10000001	00001000	10000000	00011111
(binary 129)	(binary 8)	(binary 128)	(binary 31)

Subnet masks - are used to identify which part of an IP address is the network part, and which part is the host part. Subnet masks are commonly seen as: 255.255.0.0 Subnet masks are 32-bit numbers that are represented as 4 bytes to make them easier to read. Wherever a “1” appears in the subnet mask, it is identifying that the corresponding bit in the IP address is part of the network address. The subnet mask is used to determine if a message is for a node on the local network, or it must be routed to a remote network. All nodes on the local network must have the same subnet mask.

Gateway Address - Is the address of the device which all remote packets must be sent in order to be routed. If the network portion of the IP address does not match, then the packet will be sent to the router.

Transport Control Protocol / Internet Protocol (TCP/IP) - is one of the most popular protocols used on Ethernet. TCP is used primarily to make sure the messages arrived correctly, and in the case where multiple transmissions are needed for a single message, to make sure the message is broken up at the sending station and put together in the receiving device correctly. IP is used primarily for routing the message to its ultimate destination

User Datagram Protocol (UDP) - Used for Implicit, or I/O control messages. It is a protocol designed for speed When we are controlling I/O, we stay on one subnet and construct the network to limit collisions. We do not allow you to route I/O messages, so UDP is an ideal choice for I/O since it uses less overhead and allows for faster communication than TCP.

Half-Duplex - Is a communication method where a device may either send or receive data at a given moment, but not at the same time.

Full-Duplex - Is a communication method where a device may simultaneously send and receive data.

Bootstrap Protocol - When a device that is configured for BootP joins the network, it will send out a broadcast message asking for an IP address. The message will be ignored by all other devices except the BootP server. If a BootP server is on the network, it will look at the hardware address of the device and compare it to its BootP table. If it finds an entry for that hardware address, it will send a message back to the device with an IP address.

Communications Interface

This is the communications interface between the network and the drive microprocessor. Typical interfaces use a UART, Anybus, dual-ported RAM, or CAN. The first interface to use this is referred to as SCANport which is used in the 1336 product family. The PowerFlex Architecture Class products interface is referred to as DPI. The PowerFlex Component Class uses DSI.

SCANport / DPI / DSI Comparison

Feature	SCANport	DPI	DSI
Baud Rate	125K	125K, 500K	19.2K
Minimum I/O Update Time	10ms, adding peripherals increases time	5ms	The ‘master’ peripheral must continually poll and allocate time for a ‘slave’. Adding a 2nd peripheral increases the I/O update time.
Peripheral-to-Peripheral Communications	No	Yes	Yes
Routing	Yes - DF1 port (GU6, CN1)	Yes – Port 2 on Drive (using V3.xx AnaCANda)	Yes
Reference/Feedback Size	16-bit only	16-bit & 32-bit	2 Words In / 2 Words Out
Datalink Size	16-bit only	16-bit & 32-bit	No
Max # of peripherals	Up to 6	Up to 6	Up to 2
Data Types	Integer	16 & 32-bit Integer, Floating Point, Boolean	16-bit Integer

Network Specifications

Network	Network Model	Max Nodes	Baud Rate	Data Size Max
EtherNet IP	Producer/Consumer	Unlimited	100 M bps	1500 bytes
ControlNet	Producer/Consumer	99	5 Mbps	510 bytes
DeviceNet	Producer/Consumer	64	125-500 kbps	8 bytes
Remote I/O	Master/Slave	1 scanner, 32 nodes	57.6–230 kbps	128 bytes
RS485 DF-1	Master/Slave	254	4.8-38.4 kbps	244 bytes
Modbus RTU	Master/Slave	247	4.8-38.4 kbps	252 bytes
MetaSys N2	Master/Slave	32	9600 bps	252 bytes
Siemens P1	Master/Slave and Producer/Subscriber	32	4800, 9600 bps	251 bytes
Profibus DP	Master/Slave	126	9.6k -12M bps	244 bytes
Interbus – S	Master/Slave	512	500 kbps	512 bytes
LonWorks	Master/Slave	32k per domain	78 kbps	228 bytes

Network	Deterministic	Media	Redundancy	Max Length
EtherNet IP	No	Twisted-pairs	No	World wide
ControlNet	Yes	Coax, Fiber	Yes	1km (coax), 3km (fiber)
DeviceNet	No	Twisted-pairs	No	500m
Remote I/O	No	Twisted-pair	No	3km
RS485 DF-1	No	Twisted-pair	No	1200m
Modbus RTU	No	Twisted-pair	No	1200m
MetaSys N2	No	Twisted-pair	No	1200m
Siemens P1	No	Twisted-pair	No	1200m
Profibus DP	No	Twisted-pair	No	1200m
Interbus – S	No	Twisted-pairs	No	12.8km
LonWorks	No	Twisted-pair	No	1200m

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Section – 6 Appendix

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Appendix I

Mechanical Systems

This section is dedicated to the power transmission section of the machinery being controlled. These components are necessary to transmit and or control power and motion.

Couplings

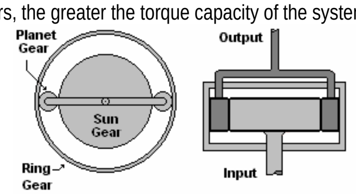
Many types of couplings are available for a variety of applications. Flexible couplings such as bellows, shear, rubber block and flexible-sleeve types allow slight misalignment by absorbing torsional shock loads. Other couplings like the helical type are designed to reduce backlash.

Gearboxes

A gearbox may have one or more gear pairs. The gear pairs may be on parallel or non-parallel axes and on intersecting or non-intersecting shafts. If it has more than two pairs, the setup is called a gear train. Generally, they permit higher speed ratios than are feasible with a single pair of gears.

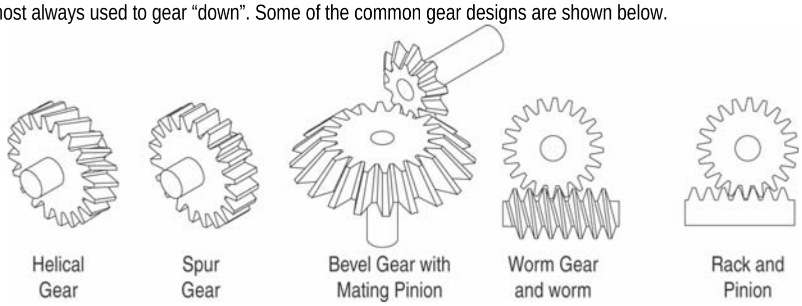
Series trains: The overall ratio is input speed divided by the output speed. It's also the product of individual ratios at each mesh, except in planetary gears. Ratio is most easily found by dividing the product of numbers of teeth of driven gears by the product of numbers of teeth of driving gears.

Planetary gearing: It is a gear train in which a planet gear rotates about another gear called the sun gear. Generally, the more planet gears, the greater the torque capacity of the system.



Planetary Gear

Speed reducers: Gearboxes usually offer only a single, fixed-reduction ratio. As the name implies, a reducer is almost always used to gear "down". Some of the common gear designs are shown below.



The larger gear is referred to as the "gear" while the smaller one is called a "pinion".
Worm gears generally cannot be back-driven at ratios greater than 20:1.

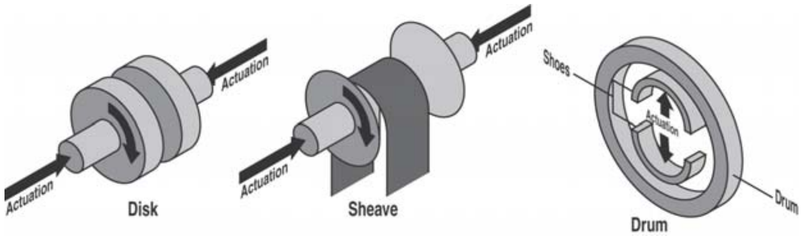
Clutches

Clutches rely on mechanical or electro-magnetic action for torque transmission. Mechanical type clutches use friction to couple torque from input to output while electro-magnetic use magnetism to transmit torque.

Mechanical

Axial clutches can be a simple cone type such as a sheave. The sheaves move axially to engage or disengage a belt. A disc type clutch drives the clutch plate into the driven plate to engage.

Drum clutches are designed so that a set of shoes connected to one shaft travel outward to engage a rim or drum connected to the other shaft.

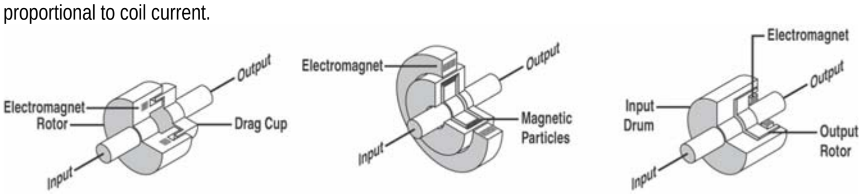


Electric

Hysteresis clutches use a coil inside the input rotor to generate a magnetic field in the rotor and drag cup. The hysteresis loss sets up a torque reaction in drag cup as the rotor is turned. The torque is proportional to the coil current.

Magnetic-particle types use an input disk that is closely fitted within the output housing that contains magnetic particles. When the coil is energized, the particles form a rigid bond between the input disk and output housing to transmit torque.

The Eddy Current coil sets up a magnetic field that links the input drum and output rotor. Eddy currents induced in the input drum interact with the magnetic field in the output rotor creating coupling torque proportional to coil current.



Hysteresis Magnetic-Particle Eddy Current

Brakes

Mechanical

Brakes absorb energy and convert it to heat. Mechanical brakes all act by generating frictional forces as two surfaces rub against each other. The stopping power or capacity of a brake depends largely on the surface area of frictional surfaces as well as on the actuation force applied. The friction and wear encountered by the working surfaces are severe, and the durability of a brake depends heavily on the type of material used to line the shoe or pad which is the "wear" item. The drum or disc is designed to undergo minimum wear and is a permanent part of the brake.

Electric

Electric brakes operate according to the same principles as electric clutches. The most common is a friction brake, which is a mechanical brake that is electrically actuated.

Hysteresis brakes provide constant torque (braking force) for a given control current. Torque is independent of speed and is a linear function of control current except at low currents or near magnetic saturation. This type has precise control, but may overheat when used at high slip.

Eddy current brakes have no holding power and are used only for drag load. They tend to run hotter than other nonfriction brakes and sometimes require special cooling provisions.

Magnetic particle brakes require less control current than hysteresis brakes for the same holding torque. They also provide considerable holding torque at zero speed. Operating in slip, they generate considerable heat and have a limited thermal capacity.

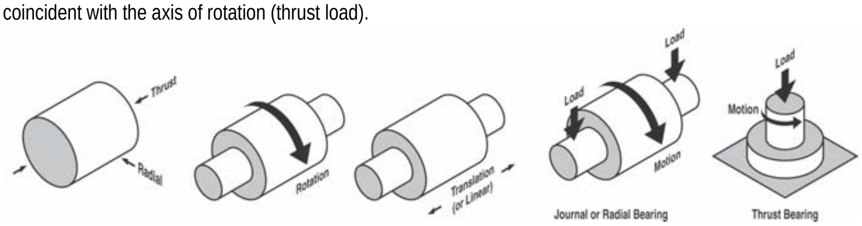
Belts

Belts provide an efficient load transfer between shafts as well as tasks such as speed ratio variations, clutching, and torque limiting. Some applications may require retentioning periodically to avoid slippage.

V-belts wedge in the pulley, which multiplies the frictional force produced by tension, and reduces the tension required for an equivalent torque. Not recommended for low speed, high torque applications.

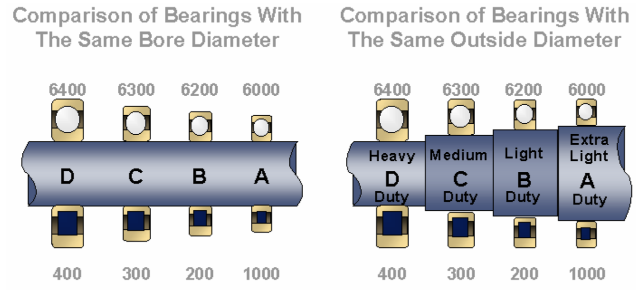
Bearings

Bearings accommodate rotational or translation motion. If the motion is not specified, it is generally assumed to be rotational. Translation bearings, called linear bearings, are loaded perpendicular to the direction of motion. In rotational bearings, the load can be either perpendicular to the axis of rotation (radial load) or coincident with the axis of rotation (thrust load).

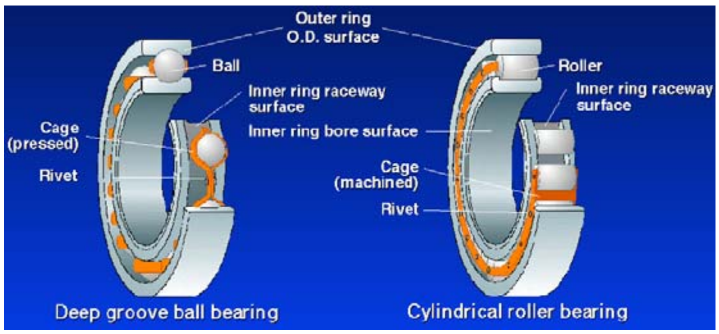


Bearing dimensions and tolerances are governed by standards for inside/outside diameter, width machining precision and radial clearance.
AFBMA – Anti Friction Bearing Manufacturer Association
JIS – Japanese Industrial Standards
DIN – Deutsche Industrial Normen

Most bearings are designed to fit into one of four series of standard dimensions for the bore and outside diameter.



Anti friction bearing types



Bearing comparison guide

	Radial Load Capacity	Thrust Load Capacity	Combined Load Capacity	Life Expectancy	Operating Speed
Single Row Deep Groove	2	3	2	1	1
Single Row Max Capacity	1	3	3	2	2
Double Row Deep Groove	1	2	2	1	3
Angular Contact	2	1	1	1	1
Cylindrical	1	4	4	1	2

Rating: (1) excellent, (2) good, (3) fair, (4) unacceptable

Appendix II

Conversion Factors

To Convert	*Multiply By*	*To Obtain*
Acceleration		
m / sec^2	3.281	ft / sec^2
m / sec^2	3.6	km / hr / sec
m / sec^2	2.237	mph / sec
mph /sec	4.47×10^1	cm / sec^2
mph /sec	1.467	ft / sec^2
mph /sec	1.6093	km / hr / sec
mph /sec	4.47×10^{-1}	m / sec^2
Acceleration - Linear		
km / hr / sec	2.778×10^1	cm /sec^2
km / hr / sec	9.113×10^{-1}	ft / sec^2
km / hr / sec	2.778×10^{-1}	m / sec^2
km / hr / sec	6.214×10^{-1}	mph / sec
Angular		
degrees	1.111×10^{-2}	quadrants
degrees	1.745×10^{-2}	rad
degrees	3.6×10^3	sec
Angular Displacement		
radians	5.7296×10^1	degrees
radians	3.438×10^3	minutes
radians	6.366×10^{-1}	quadrants
radians	2.063×10^3	seconds
revs	3.6×10^2	degrees
revs	4	quadrants
revs	6.283	radians
Angular Velocity		
rad /sec	5.7296×10^1	deg / sec
rad /sec	9.549	rpm
rad /sec	1.592×10^{-1}	rps
rpm	6	deg / sec
rpm	1.047×10^{-1}	rad / sec
rpm	1.667×10^{-2}	rps

To Convert	*Multiply By*	*To Obtain*
Area		
cm^2	1.973×10^5	circular mills
cm^2	1.076×10^{-3}	ft^2
cm^2	1.55×10^{-1}	in^2
cm^2	1×10^{-4}	m^2
cm^2	1×10^2	mm^2
circular mills	5.067×10^{-6}	cm^2
circular mills	7.854×10^{-1}	sq mills
circular mills	7.854×10^{-7}	in^2
ft^2	2.296×10^{-5}	acres
ft^2	1.833×10^8	circular mills
ft^2	9.29×10^2	cm^2
ft^2	1.44×10^2	in^2
ft^2	9.29×10^{-2}	m^2
ft^2	1.111×10^{-1}	yd^2
hectares	2.471	acres
hectares	1.076×10^5	ft^2
km^2	2.471×10^2	acres
km^2	1.076×10^7	ft^2
km^2	1×10^6	m^2
km^2	3.861×10^{-1}	sq miles
km^2	1.196×10^6	yd^2
m^2	1×10^4	cm^2
m^2	1.076×10^1	ft^2
m^2	1.55×10^3	in^2
m^2	1×10^6	mm^2
m^2	1.196	yd^2
mm^2	1.973×10^3	circular mills
mm^2	1×10^{-2}	cm^2
mm^2	1.076×10^{-5}	ft^2
mm^2	1.55×10^{-3}	in^2
sq miles	6.4×10^2	acres
sq miles	2.788×10^7	ft^2
sq miles	2.59	km^2
sq miles	2.59×10^6	m^2
sq miles	3.098×10^6	yd^2

To Convert	*Multiply By*	*To Obtain*
Density		
gm / cm^3	6.243×10^{1}	lb / ft^3
gm / cm^3	3.613×10^{-2}	lb / in^3
kg / m^3	1×10^{-3}	gm / cm^3
kg / m^3	6.243×10^{-2}	lb / ft^3
kg / m^3	3.613×10^{-5}	lb / in^3
kg / m^3	3.405×10^{-10}	lb / mil-ft
lbs / ft^3	1.602×10^{-2}	grms / cm^3
lbs / ft^3	5.787×10^{-4}	lbs / in^3
lbs / ft^3	1.602×10^{1}	kg / m^3
parts / million	5.84×10^{-2}	grains / gals
parts / million	8.345	lbs / million gals
Displacement		
cm	3.281×10^{-2}	ft
cm	3.937×10^{2}	mills
cm	1×10^{4}	microns
fathoms	6	ft
hectometers	1×10^{2}	meters
in	2.54	cm
in	2.54×10^{-2}	m
in	2.54×10^{1}	mm
in	1.578×10^{-5}	miles
in	1×10^{3}	mills
in	2.778×10^{-2}	yds
in	2.54×10^{8}	angstrom units
in	5.0505×10^{-3}	rods
m	1×10^{10}	angstrom units
m	5.4681×10^{-1}	fathoms
m	3.281	ft
m	3.937×10^{1}	in
m	6.214×10^{-4}	miles
m	1.094	yards
m	1×10^{-3}	km
m	1×10^{2}	cm
microns	1×10^{-6}	meters

To Convert	*Multiply By*	*To Obtain*
Distance		
ft	3.048×10^{-1}	m
ft	1.894×10^{-4}	miles
ft	1.2×10^{4}	mills
league	3	miles
light year	5.9×10^{12}	miles
light year	9.4609×10^{12}	km
miles	1.6909×10^{5}	cm
miles	5.28×10^{3}	ft
miles	6.336×10^{4}	in
miles	1.609	km
miles	1.76×10^{3}	yd
miles	1.69×10^{-13}	light years
rods	5.029	m
rods	1.65×10^{1}	ft
rods	1.98×10^{2}	in
rods	3.125×10^{-3}	miles
yds	9.144×10^{1}	cm
yds	9.144×10^{-4}	km
yds	9.144×10^{-1}	m
yds	5.682×10^{-4}	miles
Energy		
btu	1.055×10^{10}	ergs
btu	7.7816×10^{2}	ft lbs (work)
btu	2.52×10^{2}	gram-calories
btu	3.927×10^{-4}	hp hours
btu	1.055×10^{3}	joules = N m
btu	2.928×10^{-4}	kw hours
joules	9.486×10^{-4}	btu
joules	1×10^{7}	ergs
joules	7.736×10^{-1}	ft lbs
joules	2.389×10^{-4}	kg-calories
joules	1	N m
kg-calories	3.968	btu
kg-calories	3.086×10^{3}	ft lbs
kg-calories	1.558×10^{-3}	hp-hrs
kg-calories	4.183×10^{3}	joules
kg-calories	4.269×10^{2}	kg-meters
kg-calories	1.163×10^{-3}	kw-hrs

To Convert	*Multiply By*	*To Obtain*
kw-hrs	3.413×10^{3}	btu
kw-hrs	3.6×10^{13}	ergs
kw-hrs	2.655×10^{6}	ft lbs
kw-hrs	8.5985×10^{5}	gm-calories
kw-hrs	1.341	hp-hrs
kw-hrs	3.6×10^{6}	joules
kw-hrs	3.6×10^{6}	Nm
kw-hrs	8.5985×10^{2}	kg-calories
kw-hrs	3.671×10^{5}	kg-meters
Flow Rate		
gpm	2.228×10^{-3}	ft^3 / sec
gpm	6.308×10^{-2}	liters / sec
liters / min	5.886×10^{-4}	ft^3 / sec
liters / min	4.403×10^{-3}	gps
liters / sec	1.585×10^{1}	gpm
million gal / day	1.54723	ft^3 / sec
Force		
joules / cm	1×10^{7}	dynes
joules / cm	1×10^{2}	N (newtons)
joules / cm	2.248×10^{1}	lbs
N	1×10^{5}	dynes
N	2.248×10^{-1}	lb
N	1	joules / meter
N	1.0197×10^{-1}	kg (mass)
poundals	1.383×10^{4}	dynes
poundals	1.383×10^{-3}	joules / cm
poundals	1.383×10^{-1}	joules / m
poundals	1.383×10^{-1}	N (newtons)
poundals	3.108×10^{-2}	lbs
lbs	4.448×10^{5}	dynes
lbs	4.448×10^{-2}	joules / cm
lbs	4.448	joules / m
lbs	4.448	N (newtons)
lbs	3.217×10^{1}	poundals
Inertia		
Kgm^2	2.373042×10^{1}	$lbft^2$
Kgm^2	3.4172×10^{3}	$lbin^2$

To Convert	*Multiply By*	*To Obtain*
$Lbft^2$	4.214×10^{-2}	Kgm^2
$Lbft^2$	1.440×10^{2}	$lbin^2$
$Lbin^2$	6.944×10^{-3}	$lbft^2$
$Lbin^2$	2.926×10^{-4}	Kgm^2

Linear Velocity

fpm	1.667×10^{-2}	fps (ft / sec)
fpm	3.048×10^{-1}	m / min
fpm	1.136×10^{-2}	mph (milies / hr)
km / hr	2.778×10^{1}	cm /sec
km / hr	5.468×10^{1}	fpm
km / hr	9.113×10^{-1}	fps
km / hr	5.396×10^{-1}	knots
km / hr	1.667×10^{1}	m / min
km / hr	6.214×10^{-1}	miles / hr
knots	6.076×10^{3}	ft / hr
knots	1.852	km / hr
knots	1.151	mph
knots	1.688	ft / sec
knots	5.144×10^{1}	cm / sec
mph	4.47×10^{1}	cm / sec
mph	8.8×10^{1}	fpm
mph	1.467	fps
mph	1.6093	km / hr
mph	2.682×10^{-2}	km / min
mph	8.684×10^{-1}	knots
mph	2.682×10^{1}	meters / min
mph	1.667×10^{-2}	miles / min

Mass

kg	9.807×10^{5}	dynes (force)
kg	1×10^{3}	gm (mass)
kg	9.807	joules /m (force)
kg (mass/weight)	9.807	N (force /weight)
kg	2.2046	lbs (force / weight)
kg	3.527×10^{1}	oz (force / weight)
kg	1×10^{1}	hectograms
kg	1×10^{-6}	milligrams
slugs	1.459×10^{1}	kg (mass)
slugs	3.217×10^{1}	lb (force)

To Convert	*Multiply By*	*To Obtain*
Pressure		
bars	9.869×10^{-1}	atmospheres
cm-mercury	1.316×10^{-2}	atmospheres
cm-mercury	4.461×10^{-1}	ft-water
cm-mercury	1.36×10^{2}	kg / m^2
cm-mercury	1.934×10^{-1}	lb / in^2
dynes / cm^2	1×10^{-6}	bars
ft-water	2.95×10^{-2}	atmospheres
ft-water	8.826×10^{-1}	in-mercury
ft-water	3.048×10^{2}	kg / m^2
ft-water	4.335×10^{-1}	lb / in^2
gm / cm^2	2.0481	lb / ft^2
in-mercury	3.342×10^{-2}	atmospheres
in-mercury	1.133	ft-water
in-mercury	3.453×10^{2}	kg / m^2
in-mercury	7.073×10^{1}	lb / ft^2
in-mercury	4.912×10^{-1}	lb / in^2
in-water @ 4^0C	2.458×10^{-3}	atmospheres
in-water @ 4^0C	7.355×10^{-2}	in-mercury
in-water @ 4^0C	2.54×10^{2}	kg / cm^2
in-water @ 4^0C	5.781×10^{-1}	oz / in^2
in-water @ 4^0C	5.204	lb / ft^2
in-water @ 4^0C	3.613×10^{-2}	lb / in^2
kg / m^2	9.678×10^{-5}	atmospheres
kg / m^2	9.807×10^{-5}	bars
kg / m^2	3.281×10^{-3}	ft-water
kg / m^2	2.896×10^{-3}	in-mercury
kg / m^2	2.048×10^{-1}	lb / ft^2
kg / m^2	1.422×10^{-3}	lb / in^2
kg / m^2	9.807×10^{1}	dynes / cm^2
oz / in^2	4.309×10^{3}	dynes / cm^2
oz / in^2	6.25×10^{-2}	lbs / in^2
poise	1	gram / cm^2
lbs / ft^2	4.725×10^{-4}	atmospheres
lbs / ft^2	1.602×10^{-2}	ft-water
lbs / ft^2	1.414×10^{-2}	in-mercury

To Convert	*Multiply By*	*To Obtain*
lbs / ft^2	4.882	kg / m^2
lbs / ft^2	6.944×10^{-3}	lbs / in^2
lbs / in^2	6.804×10^{-2}	atmospheres
lbs / in^2	2.307	ft-water
lbs / in^2	2.036	in-mercury
lbs / in^2	7.031×10^{2}	kg / m^2
lbs / in^2	1.44×10^{2}	lbs / ft^2
lbs / in^2	7.03×10^{-2}	kg / cm^2
lbs / in^2	6.89×10^{-2}	bar

Power

btu / hr	2.1626×10^{-1}	ft lbs / sec
btu / hr	3.929×10^{-4}	hp
btu / hr	2.931×10^{-1}	watts
btu / min	1.296×10^{1}	ft lbs / sec
btu / min	2.356×10^{-2}	hp
btu / min	1.757×10^{1}	watts
hp	4.244×10^{1}	btu / min
hp	3.3×10^{4}	ft lb / min
hp	5.5×10^{2}	ft lb / sec
hp	1.068×10^{1}	kg-calories / min
hp	7.457×10^{-1}	kw
kg-calories / min	9.351×10^{-2}	hp
kg-calories / min	6.972×10^{-2}	kw
kw	5.692×10^{1}	btu / min
kw	4.426×10^{4}	ft lb / min
kw	7.376×10^{2}	ft lb / sec
kw	1.341	hp
kw	1.434×10^{1}	kg-calories / min
kw	1×10^{3}	watts
watts	1×10^{7}	erg / sec
watts	1×10^{-2}	hectowatts

Temperature

centigrade	$(^{0}C \times 9/5) + 32$	fahrenheit (degrees)
centigrade	$^{0}C + 273.18$	kelvin (degrees)

Tension / Unit Width

kN / m	5.711	PLI
PLI	1.751×10^{-1}	kN / m

To Convert	*Multiply By*	*To Obtain*
Torque		
ft lbs	1.356	N m
ft lbs	1.356	kg-m / sec^2
N m	7.376×10^{-1}	ft lbs
Velocity		
mpm	1.667	cm / sec
mpm	3.281	fpm
mpm	5.468×10^{-2}	fps
mpm	6×10^{-2}	km / hr
mpm	3.24×10^{-2}	knots
mpm	3.728×10^{-2}	mph
mps	1.968×10^{2}	fpm
mps	3.281	fps
mps	3.6	km / hr
mps	6×10^{-2}	km / min
mps	2.237	mph
miles / min	2.682×10^{3}	cm / sec
miles / min	8.8×10^{1}	ft / sec
miles / min	1.6093	km / min
miles / min	8.684×10^{-1}	knots / min
miles / min	6×10^{1}	mph
Volume		
centiliters	3.382×10^{-1}	ounce (u.s.-fluid)
centiliters	6.103×10^{-1}	in^3
centiliters	2.705	drams
drams u.s.-fluid	3.6967	cm^3
ft^3	2.832×10^{-2}	m^3
ft^3	1.728×10^{3}	in^3
ft^3	3.704×10^{-2}	yd^3
ft^3	7.48052	gal (u.s.-liquid)
ft^3	2.832×10^{1}	liters
ft^3	5.984×10^{1}	pts (u.s.-liquid)
ft^3	2.992×10^{1}	quarts (u.s.-liquid)
gal	1.337×10^{-1}	ft^3
gal	2.31×10^{2}	in^3
gal	3.785×10^{-3}	m^3
gal	3.785	liters
gal	3.1746×10^{-2}	barrels (u.s.-liquid)
gal (oil)	2.38095×10^{-2}	barrels (oil)

To Convert	*Multiply By*	*To Obtain*
in^3	1.639×10^{1}	cm^3
in^3	5.787×10^{-4}	ft^3
in^3	1.639×10^{-5}	m^3
in^3	4.329×10^{-3}	gal (u.s.-liquid)
in^3	1.639×10^{-2}	liters
in^3	3.463×10^{-2}	pts (u.s.-liquid)
in^3	1.732×10^{-2}	quarts (u.s.-liquid)
in^3	1.417×10^{-4}	barrels (u.s.-dry)
kiloliters	1×10^{3}	liters
kiloliters	1.308	yd^3
kiloliters	3.5316×10^{1}	ft^3
kiloliters	2.6418×10^{2}	gal (u.s. liquid)
liters	1×10^{2}	cm^3
liters	3.531×10^{-2}	ft^3
liters	6.102×10^{1}	in^3
liters	1×10^{-3}	m^3
liters	1.308×10^{-3}	yd^3
liters	2.642×10^{-1}	gal (u.s. liquid)
liters	2.113	pts (u.s. liquid)
liters	1.057	qts (u.s. liquid)
liters	1×10^{3}	milliliters
liters	1×10^{-2}	hectoliters
m^3	1×10^{6}	cm^3
m^3	3.531×10^{1}	ft^3
m^3	6.1023×10^{4}	in^3
m^3	2.642×10^{2}	gal (u.s.-liquid)
m^3	1×10^{3}	liters
m^3	2.113×10^{3}	pts (u.s.-liquid)
m^3	1.057×10^{3}	quarts (u.s.-liquid)
quarts	9.464×10^{2}	cm^3
quarts	3.342×10^{-2}	ft^3
quarts	5.775×10^{1}	in^3
quarts	9.464×10^{-4}	m^3
quarts	2.5×10^{-1}	gal
quarts	9.464×10^{-1}	liters
quarts (dry)	1.05×10^{-2}	barrels (u.s.-dry)
yd^3	7.646×10^{5}	cm^3
yd^3	2.7×10^{1}	ft^3
yd^3	7.646×10^{-1}	m^3

To Convert	*Multiply By*	*To Obtain*
oz (fluid volume)	1.805	in^3
oz	2.957×10^{-2}	liters
pints (dry)	3.36×10^{1}	in^3
pints	5×10^{-1}	qts
pints	5.5059×10^{-1}	liters
pints (liquid)	4.732×10^{2}	cm^3
pints	1.671×10^{-2}	ft^3
pints	2.887×10^{1}	in^3
pints	4.732×10^{-4}	m^3
pints	1.25×10^{-1}	gals
pints	4.732×10^{-1}	liters
pints	5×10^{-1}	qts

Weight

gal-water	8.337	lbs-water
gm	3.527×10^{-2}	ounces (avdp)
gm	2.205×10^{-3}	lbs (force)
oz	4.375×10^{2}	grains
oz	2.8349×10^{1}	grams
oz	6.25×10^{-2}	lbs
poundals	1.41×10^{1}	grama (mass)
lbs	2.56×10^{2}	drams
lbs	7×10^{3}	grains
lbs	4.536×10^{2}	grams
lbs	4.536×10^{-1}	kg
lbs	1.6×10^{1}	oz
lbs	5×10^{-4}	tons
lbs of water	1.602×10^{-2}	ft^3
lbs of water	2.768×10^{1}	in^3
lbs of water	1.198×10^{-1}	gal
tons (metric)	1×10^{3}	kg
tons	2.205×10^{3}	lb
tons	1.1023	short ton
tons (short)	9.0718×10^{2}	kg
tons	2×10^{3}	lb
tons	9.0718×10^{-1}	metric ton

Material Properties

Liquid Material	Specific Gravity				Solid Material	Specific Gravity			
	(g/cc)	(kg/m^2)	(lb/cu ft)	(lb/cu in)		(g/cc)	(kg/m^2)	(lb/cu ft)	(lb/cu in)
Acetone	0.790	790.0	49.318	0.02854	Aluminum	2.640	2640.0	164.810	0.09538
Alcohol, Ethyl	0.789	789.0	49.256	0.02850	Brass	8.560	8560.0	534.383	0.30925
Alcohol, Methyl	0.791	791.0	49.381	0.02858	Bronze	8.160	8160.0	509.412	0.29480
Aviation Gasoline	0.720	720.0	44.948	0.02601	Copper cast	8.690	8690.0	542.499	0.31395
Brine	1.200	1200.0	74.914	0.04335	Copper rolled	8.910	8910.0	556.233	0.32189
Cement Slurry	1.440	1440.0	89.896	0.05202	Gold	19.290	19290.0	1204.235	0.69690
Crude Oil	0.850	850.0	53.064	0.03071	Iron Cast	7.210	7210.0	450.106	0.26048
Diesel Fuel	0.840	840.0	52.439	0.03035	Iron wrought	7.770	7770.0	485.065	0.28071
Gasoline	0.740	740.0	46.197	0.02673	Lead	11.350	11350.0	708.557	0.41004
Hydraulic Fluid	0.860	860.0	53.688	0.03107	Magnesium	1.738	1738.0	108.500	0.06279
Jet Fuel, JP-4	0.780	780.0	48.694	0.02818	Nickel	8.450	8450.0	527.516	0.30528
Sea Water	1.030	1030.00	64.301	0.03721	Platinum	21.510	21510.0	1342.825	0.77710
Water	1.000	1000.0	62.428	0.03613	Silver	10.460	10460.0	652.996	0.37789
					Steel cast	7.850	7850.0	490.059	0.28360
					Steel rolled	7.930	7930.0	495.054	0.28649
					Tin	7.360	7360.0	459.470	0.26590
					Zinc	7.050	7050.0	440.117	0.25470

Temperature and Altitude Correction Factors

Use to “fine tune” the horsepower calculation for Fan and Blowers: (HP) x correction factor = Input HP

Air Temp F°	ALTITUDE (Feet) with BAROMETRIC PRESSURE (I.Hg.)															
	0 29.92	500 29.38	1000 28.86	1500 28.33	2000 27.82	2500 27.31	3000 26.82	3500 26.32	4000 25.84	4500 25.36	5000 24.90	6000 23.98	7000 23.09	8000 22.22	9000 21.39	10000 20.58
-40	.79	.81	.82	.84	.85	.87	.88	.90	.92	.93	.95	.99	1.03	1.08	1.11	1.15
0	.87	.88	.9	.92	.93	.95	.97	.99	1.00	1.02	1.04	1.10	1.12	1.18	1.22	1.27
40	.94	.96	.96	1.00	1.01	1.03	1.05	1.07	1.09	1.11	1.13	1.18	1.22	1.27	1.32	1.37
70	1.00	1.02	1.04	1.06	1.08	1.10	1.12	1.14	1.16	1.18	1.20	1.25	1.30	1.35	1.41	1.45
80	1.02	1.04	1.06	1.08	1.10	1.12	1.14	1.16	1.18	1.20	1.22	1.27	1.32	1.37	1.43	1.48
100	1.06	1.08	1.10	1.12	1.14	1.16	1.18	1.20	1.22	1.25	1.27	1.33	1.37	1.43	1.47	1.54
120	1.09	1.11	1.13	1.16	1.18	1.20	1.22	1.24	1.27	1.29	1.31	1.37	1.42	1.47	1.53	1.59
140	1.13	1.15	1.17	1.20	1.22	1.24	1.26	1.29	1.31	1.34	1.36	1.41	1.47	1.52	1.58	1.65
160	1.17	1.19	1.21	1.24	1.26	1.28	1.31	1.33	1.35	1.38	1.41	1.46	1.52	1.58	1.64	1.70
180	1.21	1.23	1.25	1.28	1.30	1.32	1.35	1.37	1.40	1.42	1.45	1.51	1.56	1.63	1.69	1.76
200	1.25	1.27	1.29	1.32	1.34	1.36	1.39	1.42	1.44	1.47	1.50	1.56	1.61	1.67	1.75	1.82
250	1.34	1.36	1.39	1.41	1.44	1.47	1.49	1.52	1.55	1.58	1.61	1.67	1.72	1.79	1.87	1.96
300	1.43	1.46	1.49	1.51	1.54	1.57	1.60	1.63	1.66	1.69	1.72	1.79	1.85	1.92	2.00	2.08
350	1.53	1.56	1.58	1.61	1.64	1.67	1.70	1.74	1.77	1.80	1.84	1.92	1.96	2.04	2.13	2.22
400	1.62	1.65	1.68	1.71	1.75	1.78	1.81	1.84	1.88	1.91	1.95	2.04	2.08	2.17	2.27	2.38
450	1.72	1.75	1.78	1.81	1.85	1.88	1.92	1.95	1.99	2.03	2.06	2.17	2.22	2.33	2.38	2.50
500	1.81	1.84	1.88	1.91	1.95	1.98	2.02	2.06	2.10	2.14	2.18	2.27	2.33	2.44	2.56	2.63
550	1.91	1.94	1.98	2.01	2.05	2.09	2.13	2.17	2.21	2.25	2.29	2.38	2.44	2.56	2.63	5.78
600	2.00	2.04	2.07	2.11	2.15	2.19	2.23	2.27	2.32	2.36	2.40	2.50	2.56	2.70	2.86	2.94
650	2.09	2.13	2.17	2.21	2.25	2.29	2.34	2.38	2.43	2.47	2.52	2.61	2.71	2.82	2.93	3.04
700	2.19	2.23	2.27	2.31	2.35	2.40	2.44	2.49	2.53	2.58	2.63	2.70	2.86	2.94	3.03	3.13
750	2.28	2.32	2.37	2.41	2.46	2.50	2.55	2.60	2.64	2.69	2.74	2.85	2.96	3.07	3.19	3.32
800	2.38	2.42	2.48	2.51	2.56	2.60	2.65	2.70	2.75	2.80	2.86	3.03	3.13	3.23	3.33	3.45

Friction Coefficients

Ball or Roller Slide	0.02
Dovetail Slide	0.20
Hydrostatic Ways	0.01
Rectangle Ways with Gib	0.1 – 0.25
Chain Drive	0.04 – 0.05
Belt Drive	0.02 – 0.04

Enclosures

Nema Designations

Nema Type 1 – General Purpose Enclosure is designed for indoor use, primarily to provide a degree of protection against contact with the enclosed equipment.

Nema Type 3 – Rain Tight Enclosure is designed for outdoor use primarily to provide a degree of protection against windblown dust, rain and sleet; undamaged by the formation of ice.

Nema Type 4 - Water Tight Enclosure is designed for outdoor use primarily to provide a degree of protection against windblown dust and rain, splashing water, and hose directed water; undamaged by the formation of ice.

Nema Type 12 – Industrial Enclosure is designed for indoor use primarily to provide a degree of protection against dust, falling dirt, and dripping non-corrosive liquids.

IEC Designations

Characteristic letters IP 2 0

The 1st characteristic numeral (2) identifies the protection against solid objects.

The 2nd characteristic numeral (0) identifies the protection against liquids.

First Numeral	Second Numeral
0 – No protection	0 – No protection
1 – Protected against solid objects up to 50 mm from accidental touch	1 – Protected against vertically falling drops of water
2 – Protected against solid objects up to 12 mm from accidental touch	2 – Protected against direct sprays of water up to 15 degrees from vertical
3 – Protected against solid objects up to 2.5 mm from accidental touch	3 – Protected against sprays up to 60 degrees from vertical
4 – Protected against solid objects up to 1 mm from accidental touch	4 – Protected against water sprayed from all directions
5 – Protected against dust	5 – Protected against low pressure jets of water from all directions
6 – Totally protected against dust	6 – Protected against strong pressure jets of water from all directions
	7 – Protected against the effects of immersion between 15cm and 1cm

IP20 – General Purpose Enclosure is designed for indoor use, primarily to provide a degree of protection against contact with the enclosed equipment (objects up to 12mm).

Heat Dissipation in Electrical Enclosures

The accumulation of heat in an electrical enclosure is referred to as temperature rise. This is the difference between the air inside the enclosure and the ambient temperature. The graph below illustrates the temperature rise vs. input power of a painted steel enclosure. Aluminum and stainless steel enclosures have a higher temperature rise due to the poor radiant heat transfer of their metallic finishes. Multiply the results found in the graph by 1.5 for these enclosure materials.

The heat input to the enclosure, the enclosure surface area and the enclosure material all impact the temperature rise.

Enclosure heat input is the sum of all the component watts loss values.

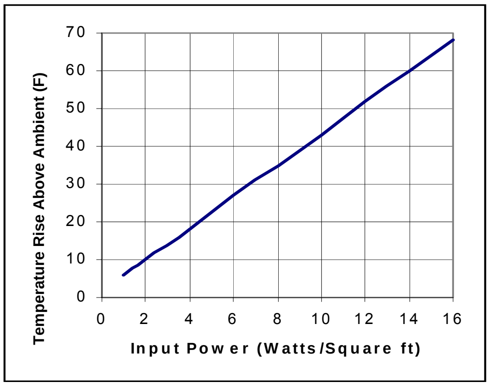
Enclosure surface area in square feet is calculated as follows.

$$\text{Area} = 2\left[(A \times B) + (A \times C) + (B \times C)\right] \div 144$$

where the enclosure size is A x B x C.

This equation includes all six surfaces. If any surface is not available for transferring heat (surface mounted against a wall), it should not be included in the calculation.

Rule of Thumb: Figure heat dissipation of 10 watts per square foot with a 40°F ambient with a 10°F rise inside the enclosure. Don't include any surface that is covered (the bottom, etc.)



Determine the input power in watts per square foot by dividing the heat dissipation in the enclosure (in watts) by the enclosure surface area (in square feet). Then use the graph to determine the temperature rise inside the enclosure.

Airflow requirements are calculated as follows:

$$CFM = \frac{1.76 \times watts}{Temp\ Rise\ (\text{degrees C})}$$

Appendix III

National Electric Code (NEC)

Allowable ampacities of not more than three insulated conductors
Rated 0-2000V in raceway or cable or earth

Size	Temperature rating of conductor					
AWG	60°C	75°C	90°C	60°C	75°C	90°C
	Copper			Aluminum or Copper-Clad Aluminum		
18			14			
16			18			
14	20	20	25			
12	25	25	30	20	20	25
10	30	35	40	25	30	35
8	40	50	55	30	40	45
6	55	65	75	40	50	60
4	70	85	95	55	65	75
3	85	100	110	65	75	85
2	95	115	130	75	90	100
1	110	130	150	85	100	115
1/0	125	150	170	100	120	135
2/0	145	175	195	115	135	155
3/0	165	200	225	130	155	175
4/0	195	230	260	150	180	205
250	215	255	290	170	205	230
300	240	285	320	190	230	255
350	260	310	350	210	250	280
400	280	335	380	225	270	305
500	320	380	430	260	310	350
600	355	420	475	285	340	385
700	385	460	520	310	375	420
750	400	475	535	320	385	435
800	410	490	555	330	395	450
900	435	520	585	355	425	480
Ambient Temp°C	CORRECTION FACTORS Multiply the ampacities above by the appropriate factor below					
21-25	1.08	1.05	1.04	1.08	1.05	1.04
26-30	1.00	1.00	1.00	1.00	1.00	1.00
31-35	.91	.94	.96	.91	.94	.96
36-40	.82	.88	.91	.82	.88	.91
41-45	.71	.82	.87	.71	.82	.87
46-50	.58	.75	.82	.58	.75	.82
51-55	.41	.67	.76	.41	.67	.76
56-60		.58	.71		.58	.71
61-70		.33	.58		.33	.58
71-80			.41			.41

The wire sizing is minimum for the ampacities listed. It may be necessary to increase the wire size for long cable runs.

Full Load Current for 3-Phase AC Motors

	Rated Motor Voltage										
Rated	Squirrel Cage Induction Type							Synchronous Type			
HP	115	200	208	230	460	575	2300	230	460	575	2300
½	4	2.3	2.2	2	1	.8					
¾	5.6	3.2	3.1	2.8	1.4	1.1					
1	7.2	4.1	4.0	3.6	1.8	1.4					
1 ½	10.4	6.0	5.7	5.2	2.6	2.1					
2	13.6	7.8	7.5	6.8	3.4	2.7					
3		11.0	10.6	9.6	4.8	3.9					
5		17.5	16.7	15.2	7.6	6.1					
7 ½		25.3	24.2	22	11	9					
10		32.2	30.8	28	14	11					
15		48.3	46.2	42	21	17					
20		62.1	59.4	54	27	22					
25		78.2	74.8	68	34	27		53	26	21	
30		92	88	80	40	32		63	32	26	
40		119.6	114.4	104	52	41		83	41	33	
50		149.5	143.0	130	65	52		104	52	42	
60		177.1	169.4	154	77	62	16	123	61	49	12
75		220.8	211.2	192	96	77	20	155	78	62	15
100		285.2	272.8	248	124	99	26	202	101	81	20
125		358.8	343.2	312	156	125	31	253	126	101	25
150		414	396	360	180	144	37	302	151	121	30
200		552	528	480	240	192	49	400	201	161	40

Full Load Current for DC Motors

Rated	Armature Rated Voltage					
HP	90	120	180	240	500	550
¼	4.0	3.1	2.0	1.6		
½	6.8	5.4	3.4	2.7		
¾	9.6	7.6	4.8	3.8		
1	12.2	9.5	6.1	4.7		
1 ½		13.2	8.3	6.6		
2		17	10.8	8.5		
3		25	16	12.2		
5		40	27	20		
7 ½		58		29	13.6	12.2
10		76		38	18	16
15				55	27	24
20				72	34	31
25				89	43	38
30				106	51	46
40				140	67	61
50				173	83	75
60				206	99	90
75				255	123	111
100				341	164	148
125				425	205	185
150				506	246	222
200				675	330	294

Underwriters Laboratory (UL)
UL50 – Enclosures for Electrical Equipment
UL508 – Industrial Control Equipment
UL508A – Industrial Control Panels
UL508C – Power Conversion Equipment
UL840 – Insulation Coordination
UL845 – Motor Control Centers

Canadian Standards (CSA)

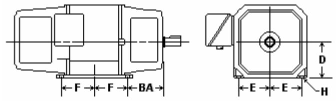
CE
Low Voltage Directive
LV Standards
EN 50178 Electronic equipment for use in power installations
EN 60664 Insulation coordination for equipment within low-voltage systems
EN 60204
IEC 61800-5 Adjustable speed electrical power drive systems

EMC Directive
EMC Standards
EN61800-3 Adjustable speed electrical power drive systems Part 3: EMC product standard

National Electrical Manufacturers Association (NEMA)
Nema standards for motors are acceptable in the United States and in many other countries. These standards include the following specifications: Ambient conditions, frame designation, dimensions, enclosures, methods of cooling, time rating, balance, and power supply type.

Insulation Rating of AC Motors for Inverter Duty Application
Nema MG1 para. 31.40.4.2
Inverter rated motors designed to Nema MG1 para. 31.40.4.2 “Voltage Spikes” must be capable of 1,600 Vpk At 0.1μs risetime.

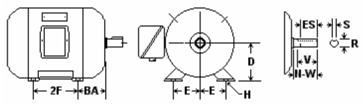
Nema Frame Dimensions – DC Motors and Generators



* Dimensions in inches

Frame	D	E	2F	H	BA	Frame	D	E	2F	H	BA
42	2.62	1.75	1.69	.28	2.06	287AT	7	5.5	12.5	.53	4.75
48	3	2.12	2.75	.34	2.5	288AT	7	5.5	14	.53	4.75
56	3.5	2.44	3	.34	2.75	289AT	7	5.5	16	.53	4.75
56H	3.5	2.44	5	.34	2.75	323AT	8	6.25	9	.66	5.25
142AT	3.5	2.75	3.5	.34	2.75	324AT	8	6.25	10.5	.66	5.25
143AT	3.5	2.75	4	.34	2.75	325AT	8	6.25	11	.66	5.25
144AT	3.5	2.75	4.5	.34	2.75	326AT	8	6.25	12	.66	5.25
145AT	3.5	2.75	5	.34	2.75	327AT	8	6.25	14	.66	5.25
146AT	3.5	2.75	5.5	.34	2.75	328AT	8	6.25	16	.66	5.25
147AT	3.5	2.75	6.25	.34	2.75	329AT	8	6.25	18	.66	5.25
148AT	3.5	2.75	7	.34	2.75	363AT	9	7	10	.81	5.88
149AT	3.5	2.75	8	.34	2.75	364AT	9	7	11.25	.81	5.88
1410AT	3.5	2.75	9	.34	2.75	365AT	9	7	12.25	.81	5.88
1411AT	3.5	2.75	10	.34	2.75	366AT	9	7	14	.81	5.88
1412AT	3.5	2.75	11	.34	2.75	367AT	9	7	16	.81	5.88
162AT	4	3.12	4	.41	2.5	368AT	9	7	18	.81	5.88
163AT	4	3.12	4.5	.41	2.5	369AT	9	7	20	.81	5.88
164AT	4	3.12	5	.41	2.5	403AT	10	8	11	.94	6.62
165AT	4	3.12	5.5	.41	2.5	404AT	10	8	12.25	.94	6.62
166AT	4	3.12	6.25	.41	2.5	405AT	10	8	13.75	.94	6.62
167AT	4	3.12	7	.41	2.5	406AT	10	8	16	.94	6.62
168AT	4	3.12	8	.41	2.5	407AT	10	8	18	.94	6.62
169AT	4	3.12	9	.41	2.5	408AT	10	8	20	.94	6.62
1610AT	4	3.12	10	.41	2.5	409AT	10	8	22	.94	6.62
182AT	4.5	3.75	4.5	.41	2.75	443AT	11	9	12.5	1.06	7.5
183AT	4.5	3.75	5	.41	2.75	444AT	11	9	15	1.06	7.5
184AT	4.5	3.75	5.5	.41	2.75	445AT	11	9	16.5	1.06	7.5
185AT	4.5	3.75	6.25	.41	2.75	446AT	11	9	18	1.06	7.5
186AT	4.5	3.75	7	.41	2.75	447AT	11	9	20	1.06	7.5
187AT	4.5	3.75	8	.41	2.75	448AT	11	9	22	1.06	7.5
188AT	4.5	3.75	9	.41	2.75	449AT	11	9	25	1.06	7.5
189AT	4.5	3.75	10	.41	2.75	502AT	12.5	10	12.5	1.19	8.5
1810AT	4.5	3.75	11	.41	2.75	503AT	12.5	10	14	1.19	8.5
213AT	5.25	4.25	5.5	.41	3.5	504AT	12.5	10	16	1.19	8.5
214AT	5.25	4.25	6.25	.41	3.5	505AT	12.5	10	18	1.19	8.5
215AT	5.25	4.25	7	.41	3.5	506AT	12.5	10	20	1.19	8.5
216AT	5.25	4.25	8	.41	3.5	507AT	12.5	10	22	1.19	8.5
217AT	5.25	4.25	9	.41	3.5	508AT	12.5	10	25	1.19	8.5
218AT	5.25	4.25	10	.41	3.5	509AT	12.5	10	28	1.19	8.5
219AT	5.25	4.25	11	.41	3.5	583A	14.5	11.5	16	1.19	10
2110AT	5.25	4.25	12.5	.41	3.5	584A	14.5	11.5	18	1.19	10
253AT	6.25	5	7	.53	4.25	585A	14.5	11.5	20	1.19	10
254AT	6.25	5	8.25	.53	4.25	586A	14.5	11.5	22	1.19	10
255AT	6.25	5	9	.53	4.25	587A	14.5	11.5	25	1.19	10
256AT	6.25	5	10	.53	4.25	588A	14.5	11.5	28	1.19	10
257AT	6.25	5	11	.53	4.25	683A	17	13.5	20	1.19	11.5
258AT	6.25	5	12.5	.53	4.25	684A	17	13.5	22	1.19	11.5
259AT	6.25	5	14	.53	4.25	685A	17	13.5	25	1.19	11.5
283AT	7	5.5	8	.53	4.75	686A	17	13.5	28	1.19	11.5
284AT	7	5.5	9.5	.53	4.75	687A	17	13.5	32	1.19	11.5
285AT	7	5.5	10	.53	4.75	688A	17	13.5	36	1.19	11.5
286AT	7	5.5	11	.53	4.75						

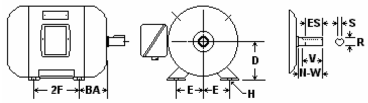
Nema Frame Dimensions – AC Motors and Generators



*Dimensions in inches

Frame	D	E	2F	H	U	BA	N-W	Vmin	R	ESmin	S
48	3	2.12	2.75	.34	.5	2.5	1.5		.453		flat
56	3.5	2.44	3	.34	.625	2.75	1.88		.517	1.41	.188
143	3.5	2.75	4	.34	.75	2.25	2	1.75	.643	1.41	.188
143T	3.5	2.75	4	.34	.875	2.25	2.25	2	.771	1.41	.188
145	3.5	2.75	5	.34	.75	2.25	2	1.75	.643	1.41	.188
145T	3.5	2.75	5	.34	.875	2.25	2.25	2	.771	1.41	.188
182	4.5	3.75	4.5	.41	.875	2.75	2.25	2	.771	1.41	.188
182T	4.5	3.75	4.5	.41	1.125	2.75	2.75	2.5	.986	1.78	.25
184	4.5	3.75	5.5	.41	.875	2.75	2.25	2	.771	1.41	.188
184T	4.5	3.75	5.5	.41	1.125	2.75	2.75	2.5	.986	1.78	.25
203	5	4	5.5	.41	.75	3.12	2.25	2	.643	1.53	.188
204	5	4	6.5	.41	.75	3.12	2.25	2	.643	1.53	.188
213	5.25	4.25	5.5	.41	1.125	3.5	3.5	2.75	.986	2.03	.25
213T	5.25	4.25	5.5	.41	1.375	3.5	3.38	3.12	1.201	2.41	.312
215	5.25	4.25	7	.41	1.125	3.5	3	2.75	.986	2.03	.25
215T	5.25	4.25	7	.41	1.375	3.5	3.38	3.12	1.201	2.41	.312
224	5.5	4.5	6.75	.41	1	3.5	3	2.75	.857	2.03	.25
225	5.5	4.5	7.5	.41	1	3.5	3	2.75	.857	2.03	.25
254	6.25	5	8.25	.53	1.125	4.25	3.37	3.12	.986	2.03	.25
254U	6.25	5	8.25	.53	1.375	4.25	3.75	3.5	1.201	2.78	.312
254T	6.25	5	8.25	.53	1.625	4.25	4	3.75	1.416	2.91	.375
256U	6.25	5	10	.53	1.375	4.25	3.75	3.5	1.201	2.78	.312
256T	6.25	5	10	.53	1.625	4.25	4	3.75	1.416	2.91	.375
284	7	5.5	9.5	.53	1.25	4.75	3.75	3.5	.986	2.03	.25
284U	7	5.5	9.5	.53	1.625	4.75	4.88	4.62	1.416	3.78	.375
284T	7	5.5	9.5	.53	1.875	4.75	4.62	4.38	1.591	3.28	.5
284TS	7	5.5	9.5	.53	1.625	4.75	3.25	3	1.416	1.91	.375
286U	7	5.5	11	.53	1.625	4.75	4.88	4.62	1.416	3.78	.375
286T	7	5.5	11	.53	1.875	4.75	4.62	4.38	1.591	3.28	.5
286TS	7	5.5	11	.53	1.625	4.75	3.25	3	1.416	1.91	.375
324	8	6.25	10.5	.66	1.625	5.25	4.87	4.62	1.416	3.78	.375
324U	8	6.25	10.5	.66	1.875	5.25	5.62	5.38	1.591	4.28	.5
324S	8	6.25	10.5	.66	1.625	5.25	3.25	3	1.416	1.91	.375
324T	8	6.25	10.5	.66	2.125	5.25	5.25	5	1.845	3.91	.5
324TS	8	6.25	10.5	.66	1.875	5.25	3.75	3.5	1.591	2.03	.5
326	8	6.25	12	.66	1.625	5.25	4.87	4.62	1.416	3.78	.375
326U	8	6.25	12	.66	1.875	5.25	5.62	5.38	1.591	4.28	.5
326S	8	6.25	12	.66	1.625	5.25	3.25	3	1.416	1.91	.375
326T	8	6.25	12	.66	2.125	5.25	5.25	5	1.845	3.91	.5
326TS	8	6.25	12	.66	1.875	5.25	3.75	3.5	1.591	2.03	.5
364	9	7	11.25	.66	1.875	5.88	5.62	5.38	1.591	4.28	.5
364S	9	7	11.25	.66	1.625	5.88	3.25	3	1.416	1.91	.375
364U	9	7	11.25	.66	2.125	5.88	6.37	6.12	1.845	5.03	.5
364US	9	7	11.25	.66	1.875	5.88	3.75	3.5	1.591	2.03	.5
364T	9	7	11.25	.66	2.375	5.88	5.88	5.62	2.01	4.28	.625
364TS	9	7	11.25	.66	1.875	5.88	3.75	3.5	1.591	2.03	.5
365	9	7	12.25	.66	1.875	5.88	5.62	5.38	1.591	4.28	.5
365S	9	7	12.25	.66	1.625	5.88	3.25	3	1.416	1.91	.375
365U	9	7	12.25	.66	2.125	5.88	6.37	6.12	1.845	5.03	.5
365US	9	7	12.25	.66	1.875	5.88	3.75	3.5	1.591	2.03	.5
365T	9	7	12.25	.66	2.375	5.88	5.88	5.62	2.021	4.28	.625
365TS	9	7	12.25	.66	1.875	5.88	3.75	3.5	1.591	2.03	.5

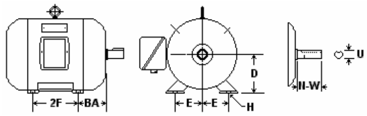
Nema Frame Dimensions – AC Motors and Generators Continued



* Dimensions in inches

Frame	D	E	2F	H	U	BA	N-W	Vmin	R	ESmin	S
404	10	8	12.25	.81	2.125	6.62	6.37	6.12	1.845	5.03	.5
404S	10	8	12.25	.81	1.875	6.62	3.75	3.5	1.591	2.03	.5
404U	10	8	12.25	.81	2.375	6.62	7.12	6.88	2.021	5.53	.625
404US	10	8	12.25	.81	2.125	6.62	4.25	4	1.845	2.78	.5
404T	10	8	12.25	.81	2.875	6.62	7.25	7	2.45	5.65	.75
404TS	10	8	12.25	.81	2.125	6.62	4.25	4	1.845	2.78	.5
405	10	8	13.75	.81	2.125	6.62	6.37	6.12	1.845	5.03	.5
405S	10	8	13.75	.81	1.875	6.62	3.75	3.5	1.591	2.03	.5
405U	10	8	13.75	.81	2.375	6.62	7.12	6.88	2.021	5.53	.625
405US	10	8	13.75	.81	2.125	6.62	4.25	4	1.845	2.78	.5
405T	10	8	13.75	.81	2.875	6.62	7.25	7	2.45	5.65	.75
405TS	10	8	13.75	.81	2.125	6.62	4.25	4	1.845	2.78	.5
444	11	9	14.5	.81	2.375	7.5	7.12	6.88	2.021	5.53	.625
444S	11	9	14.5	.81	2.125	7.5	4.25	4	1.845	2.78	.5
444U	11	9	14.5	.81	2.875	7.5	8.62	8.38	2.45	7.03	.75
444US	11	9	14.5	.81	2.125	7.5	4.25	4	1.845	2.78	.5
444T	11	9	14.5	.81	3.375	7.5	8.5	8.25	2.88	6.91	.875
444TS	11	9	14.5	.81	2.375	7.5	4.75	4.5	2.021	3.03	.625
445	11	9	16.5	.81	2.375	7.5	7.12	6.88	2.021	5.53	.625
445S	11	9	16.5	.81	2.125	7.5	4.25	4	1.845	2.78	.5
445U	11	9	16.5	.81	2.875	7.5	8.62	8.38	2.45	7.03	.75
445US	11	9	16.5	.81	2.125	7.5	4.25	4	1.845	2.78	.5
445T	11	9	16.5	.81	3.375	7.5	8.5	8.25	2.88	6.91	.875
445TS	11	9	16.5	.81	2.375	7.5	4.75	4.5	2.021	3.03	.625
447T	11	9	20	.81	3.375	7.5	8.5	8.25	2.88	6.91	.875
447TS	11	9	20	.81	2.375	7.5	4.75	4.5	2.021	3.03	.625
449T	11	9	25	.81	3.375	7.5	8.5	8.25	2.88	6.91	.875
449TS	11	9	25	.81	2.375	7.5	4.75	4.5	2.021	3.03	.625
504U	12.5	10	16	.94	2.875	8.5	8.62	8.38	2.45	7.28	.75
505	12.5	10	18	.94	2.875	8.5	8.62	8.38	2.45	7.28	.75
505S	12.5	10	18	.94	2.875	8.5	4.25	4	1.845	2.78	.5

IEC Frame Dimensions – Three-Phase Motors



* Dimensions in millimeters

Frame	D	2E	2F	H	BA	U	N-W
56M	56	90	71	5.8	36	9	20
63M	63	100	80	7	40	11	23
71M	71	112	90	7	45	14	30
80M	80	125	100	10	50	19	40
90S	90	140	100	10	56	24	50
90L	90	140	125	10	56	24	50
100S	100	160	112	12	63	28	60
100L	100	160	140	12	63	28	60
112S	112	190	114	12	70	38	80
112M	112	190	140	12	70	38	80
132S	132	216	140	12	89		
132M	132	216	178	12	89		
160S	160	254	178	14.5	108		
160M	160	254	210	14.5	108		
160L	160	254	254	14.5	108		
180S	180	279	203	14.5	121		
180M	180	279	241	14.5	121		
180L	180	279	279	14.5	121		
200S	200	318	228	18.5	133		
200M	200	318	267	18.5	133		
200L	200	318	305	18.5	133		
225S	225	356	286	18.5	149		
225M	225	356	311	18.5	149		
250S	250	406	311	24	168		
250M	250	406	349	24	168		
280S	280	457	368	24	190		
280M	280	457	419	24	190		
315S	315	508	406	28	216		
315M	315	508	457	28	216		
355S	355	610	500	28	254		
355M	355	610	560	28	254		
355L	355	610	630	28	254		
400S	400	686	560	35	280		
400M	400	686	630	35	280		
400L	400	686	710	35	280		

International Electrotechnical Commission (IEC)
These standards may be specified in countries other than the United States.

IEC standards for motors include specifications for the same items as the Nema standards, but differ mainly in frame designation, motor dimensions, and ratings.

IEEE-519

See tables below also refer to Harmonics in Section 4.

Table 10.2
Harmonic Voltage Limits for Low Voltage Systems

Application	Maximum V_{THD}
Special: Hospitals & Airports	3%
General	5%
Dedicated to drive	10%

Table 10.3
Current Distortion Limits for General Distribution Systems
(120 Through 69,000 V)
Maximum Harmonic Current Distortion in Percent of I_L
Individual Harmonic Order (Odd Harmonics)

I_{sc}/I_L	<11	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 < h$	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are limited to 25% of the odd harmonic limits above.
Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.
*All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.
where:

I_{sc} = maximum short-circuit current at PCC.
I_L = maximum demand load current (fundamental frequency component) at PCC

Table 10.4
Current Distortion Limits for General Sub-transmission Systems
(69,001 Through 161,000 V)
Maximum Harmonic Current Distortion in Percent of I_L
Individual Harmonic Order (Odd Harmonics)

I_{sc}/I_L	<11	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 < h$	TDD
<20*	2.0	1.0	0.75	0.3	0.15	2.5
20<50	3.5	1.75	1.25	0.5	0.25	4.0
50<100	5.0	2.25	2.0	0.75	0.35	6.0
100<1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10.0

Even harmonics are limited to 25% of the odd harmonic limits above.
Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.
*All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.
where:

I_{sc} = maximum short-circuit current at PCC.
I_L = maximum demand load current (fundamental frequency component) at PCC

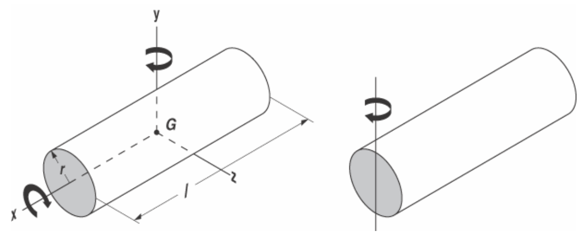
Appendix IV

Moment of Inertia for a given Body Type

Select the appropriate body type shown below and the desired axis of rotation to calculate the moment of inertia for the driven system. If the system includes several shapes, calculate each one of them individually then add them together.

Refer to the “gearing” section to ensure that the inertia reflected to the motor shaft is calculated properly.

Solid Cylinder



The moment of inertia (for rotation about the x-axis), *J*, of a solid cylinder of mass *m*, radius *r*, is

$$J = \frac{1}{2} m r^2 \qquad \text{kg m}^2$$

Or

$$\frac{\pi}{32} \rho l r^4 \qquad \text{kg m}^2$$

Where *p* is density in (Nm^3)

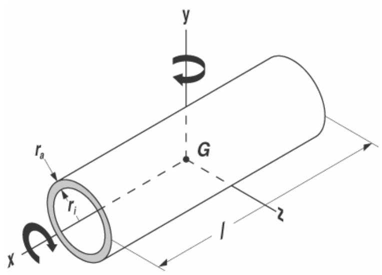
The moment of inertia (for rotation about the y-axis), *J*, of a solid cylinder of mass *m*, radius *r*, is

$$J = m \frac{3r^2 + l^2}{12} \qquad \text{kg m}^2$$

The moment of inertia (for rotation about the end-axis, as shown above right), *J*, of a solid cylinder of mass *m*, length *l*, is

$$J = \frac{m \times l^2}{3} \qquad \text{kg m}^2$$

Hollow Cylinder



The moment of inertia (for rotation about the x-axis), *J*, of a hollow cylinder of mass *m*, radius *r*, is

$$J = m\frac{r_a^{\ 2} + r_i^{\ 2}}{2} \qquad \text{kg m}^2$$

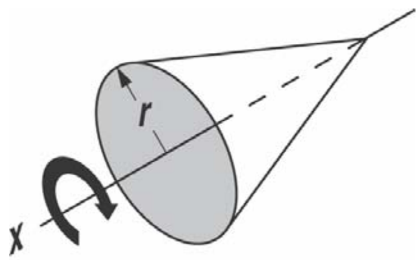
Or

$$\frac{\pi}{32}\rho\ l\left(r_a^{\ 2} - r_i^{\ 2}\right)^2 \qquad \text{kg m}^2$$

The moment of inertia (for rotation about the y-axis), *J*, of a hollow cylinder of mass *m*, radius *r*, is

$$J = m\frac{r_a^{\ 2} + r_i^{\ 2} + l^2/3}{4} \qquad \text{kg m}^2$$

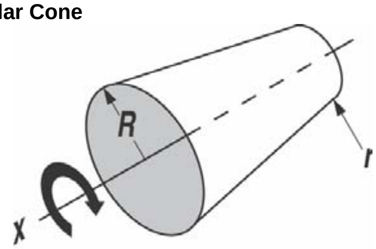
Right Circular Cone



The moment of inertia (for rotation about the x-axis), *J*, of a circular cone of mass *m*, radius *r*, is

$$J = m\frac{3r^2}{10} \qquad \text{kg m}^2$$

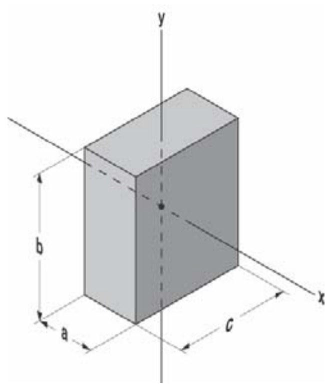
Frustum of Right Circular Cone



The moment of inertia (for rotation about the x-axis), *J*, of a frustum of cone of mass *m*, radius *r*, is

$$J = m\frac{3\left(R^5 - r^5\right)}{10\left(R^3 - r^3\right)} \qquad \text{kg m}^2$$

Cube



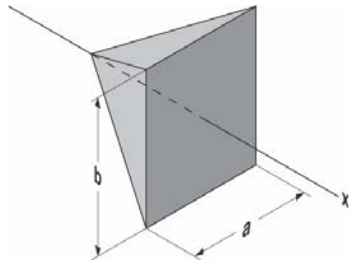
The moment of inertia (for rotation about the x-axis), *J*, of a cube of mass *m*, radius *r*, is

$$J = m\frac{b^2 + c^2}{12} \qquad \text{kg m}^2$$

The moment of inertia (for rotation about the y-axis), *J*, of a cube of mass *m*, radius *r*, is

$$J = m\frac{a^2 + c^2}{12} \qquad \text{kg m}^2$$

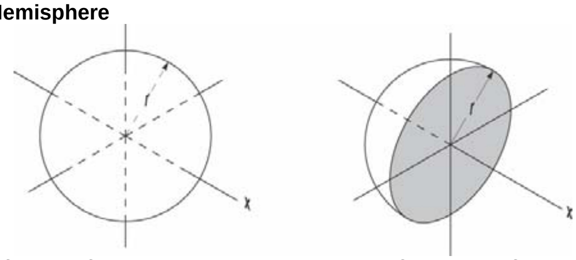
Pyramid



The moment of inertia (for rotation about the x-axis), *J*, of a pyramid of mass *m*, radius *r*, is

$$J = m\frac{a^2 + b^2}{20} \qquad \text{kg m}^2$$

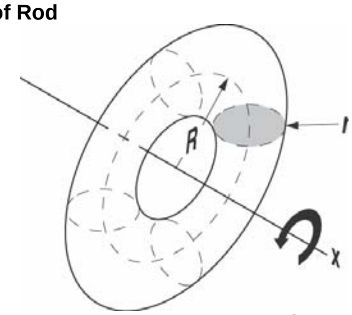
Sphere and Hemisphere



The moment of inertia (for rotation about the x-axis), *J*, of a sphere of mass *m*, radius *r*, is

$$J = m\frac{2r^2}{5} \qquad \text{kg m}^2$$

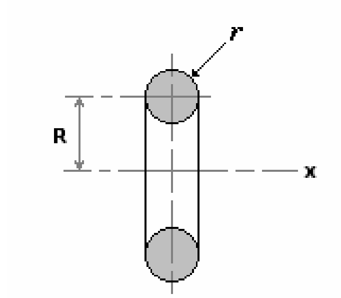
Rotating Object at end of Rod



The moment of inertia (for rotation about the x-axis), *J*, of a rotating object of mass *m*, radius *r*, at a length *l*, is

$$J = m\left(\frac{r^2}{2} + l^2\right) \qquad \text{kg m}^2$$

Torus



The moment of inertia (for rotation about the x-axis), *J*, of a torus of mass *m*, radius *r*, is

$$J = m\left(R^2 + \frac{3}{4}r^2\right) \qquad \text{kg m}^2$$

Flywheel with a web
This should be addressed as the sum of the moments of inertia of a solid cylinder (hub), a hollow cylinder (web), and the rim of a hollow cylinder (rim).

Calculating the mass for the moment of inertia.
Solid Cylinder

$$m = 2\pi\, i^2\, l\, \frac{\rho}{g} \qquad \text{kg}$$

Hollow Cylinder

$$m = 2\pi\left(r_a{}^2 - r_i{}^2\right) l\, \frac{\rho}{g} \qquad \text{kg}$$

Webbed Cylinder

$$m = 2\pi\left[\left(r_a{}^2 - r_i{}^2\right) l_e + \left(r_i{}^2\, l_i\right)\right]\frac{\rho}{g} \qquad \text{kg}$$

Flywheel GD^2 equivalent – G mass (kg), D diameter (m).

$$J = \frac{GD^2}{4} \qquad \text{kg m}^2$$

WK^2 of Solid Steel Cylinders One Inch Long

Dia. (Inches)	WK^2 lb ft^2	Dia. (Inches)	WK^2 lb ft^2	Dia. (Inches)	WK^2 lb ft^2	Dia. (Inches)	WK^2 lb ft^2
1	0.000192	51	1302.2	101	20031	151	100075
2	0.00308	52	1407.4	102	20836	152	102750
3	0.01559	53	1518.8	103	21665	153	105482
4	0.049278	54	1636.7	104	22519	154	108268
5	0.12030	55	1761.4	105	23397	155	111107
6	0.2494	56	1893.1	106	24302	156	114002
7	0.46217	57	2031.9	107	25232	157	116954
8	0.78814	58	2178.3	108	26188	158	119962
9	1.262	59	2332.5	109	27173	159	123028
10	1.924	60	2494.7	110	28183	160	126152
11	2.818	61	2665.2	111	29222	161	129336
12	3.991	62	2844.3	112	30289	162	132579
13	5.497	63	3032.3	113	31385	163	135883
14	7.395	64	3229.5	114	32511	164	139249
15	9.745	65	3436.1	115	33667	165	142676
16	12.61	66	3652.5	116	34853	166	146166
17	16.07	67	3879.0	117	36071	167	149720
18	20.21	68	4115.7	118	37320	168	153339
19	25.08	69	4363.2	119	38601	169	157022
20	30.79	70	4621.7	120	39914	170	160772
21	37.43	71	4891.5	121	41262	171	164588
22	45.09	72	5172	122	42643	172	168472
23	53.87	73	5466	123	44059	173	172424
24	63.86	74	5772	124	45510	174	176446
25	75.19	75	6090	125	46995	175	180537
26	87.96	76	6422	126	48517	176	184699
27	102.30	77	6767	127	50076	177	188933
28	118.31	78	7125	128	51672	178	193239
29	136.14	79	7498	129	53305	179	197618
30	155.92	80	7885	130	54978	180	202071
31	177.77	81	8286	131	56689	181	206599
32	201.8	82	8703	132	58440	182	211203
33	228.2	83	9135	133	60231	183	215883
34	257.2	84	9584	134	62063	184	220640
35	288.8	85	10048	135	63936	185	225476
36	323.2	86	10529	136	65852	186	230391
37	360.7	87	11028	137	67811	187	235386
38	401.3	88	11544	138	69812	188	240461
39	445.3	89	12077	139	71858	189	245619
40	492.78	90	12629	140	73948	190	250858
41	543.9	91	13200	141	76083	191	256182
42	598.8	92	13790	142	78265	192	261589
43	658.1	93	14399	143	80493	193	267081
44	721.4	94	15029	144	82768	194	272660
45	789.3	95	15679	145	85091	195	278325
46	861.8	96	16349	146	87463	196	284078
47	939.3	97	17041	147	89884	197	289920
48	1021.8	98	17755	148	92355	198	295852
49	1109.6	99	18490	149	94876	199	301874
50	1203.07	100	19249	150	97449	200	307988

WK2 is given in lb-ft^2. Based on the specific gravity of steel at 487.889 lb per cubic foot.

WK2 = PI/32 * (487.889 $_{sp\ gravity}$) * (1/12' $_{length}$) * [(d/12')4] = Inertia in lb-ft^2

Moving the decimal point one place in diameter shifts the decimal point four places in the same direction in WK^2.

For cylinders longer or shorter than 1 inch, multiply WK^2 from the table by actual cylinder length in inches.

For materials other than steel, multiply WK^2 from the table by the specific gravity in (lb per cu ft of material / 487.889).

J of Solid Steel Cylinders One centimeter Long

Dia. (cm)	J kgm^2	Dia. (cm)	J kgm^2	Dia. (cm)	J kgm^2	Dia. (cm)	J kgm^2
1	0.00000008	51	0.51907	101	7.98412	151	39.8887
2	0.00000123	52	0.56099	102	8.30505	152	40.9559
3	0.00000621	53	0.60540	103	8.63556	153	42.0443
4	0.00001964	54	0.65240	104	8.97584	154	43.1544
5	0.00004795	55	0.70209	105	9.32608	155	44.2862
6	0.00009944	56	0.75456	106	9.68646	156	45.4402
7	0.00018422	57	0.80992	107	10.05720	157	46.6166
8	0.00031427	58	0.86827	108	10.43847	158	47.8157
9	0.00050340	59	0.92971	109	10.83048	159	49.0377
10	0.00076726	60	0.99437	110	11.23343	160	50.2831
11	0.00112334	61	1.06233	111	11.64753	161	51.5520
12	0.00159099	62	1.13373	112	12.07296	162	52.8447
13	0.00219137	63	1.20866	113	12.50995	163	54.1617
14	0.00294750	64	1.28725	114	12.95869	164	55.5031
15	0.00388425	65	1.36960	115	13.41940	165	56.8693
16	0.00502831	66	1.45585	116	13.89229	166	58.2605
17	0.00640822	67	1.54611	117	14.37756	167	59.6771
18	0.00805437	68	1.64050	118	14.87544	168	61.1194
19	0.00999899	69	1.73915	119	15.38614	169	62.5876
20	0.01227614	70	1.84219	120	15.90987	170	64.0822
21	0.01492172	71	1.94973	121	16.4469	171	65.6034
22	0.01797349	72	2.06192	122	16.9973	172	67.1515
23	0.02147104	73	2.17888	123	17.5615	173	68.7268
24	0.02545580	74	2.30075	124	18.1396	174	70.3297
25	0.02997104	75	2.42765	125	18.7319	175	71.9605
26	0.03506188	76	2.55974	126	19.3386	176	73.6194
27	0.04077527	77	2.69715	127	19.9598	177	75.3069
28	0.04716001	78	2.84001	128	20.5959	178	77.0232
29	0.05426674	79	2.98848	129	21.2471	179	78.7687
30	0.06214795	80	3.14269	130	21.9137	180	80.5437
31	0.07085794	81	3.30280	131	22.5958	181	82.3486
32	0.08045290	82	3.46894	132	23.2936	182	84.1836
33	0.09099081	83	3.64128	133	24.0076	183	86.0491
34	0.10253153	84	3.81996	134	24.7378	184	87.9454
35	0.11513675	85	4.00514	135	25.4845	185	89.8729
36	0.12886998	86	4.19697	136	26.2481	186	91.8319
37	0.14379662	87	4.39561	137	27.0286	187	93.8228
38	0.15998386	88	4.60121	138	27.8265	188	95.8458
39	0.17750075	89	4.81395	139	28.6418	189	97.9014
40	0.19641821	90	5.03398	140	29.4750	190	99.9899
41	0.21681	91	5.26147	141	30.3262	191	102.1116
42	0.23875	92	5.49659	142	31.1957	192	104.2670
43	0.26231	93	5.73949	143	32.0838	193	106.4562
44	0.28758	94	5.99036	144	32.9907	194	108.6798
45	0.31462	95	6.24937	145	33.9167	195	110.9380
46	0.34354	96	6.51668	146	34.8621	196	113.2312
47	0.37440	97	6.79249	147	35.8271	197	115.5598
48	0.40729	98	7.07695	148	36.8119	198	117.9241
49	0.44231	99	7.37026	149	37.8170	199	120.3245
50	0.47954	100	7.67259	150	38.8425	200	122.7614

J is given in kgm^2. Based on the specific gravity of steel at 7.81523207 grams per cubic centimeter.

J =PI/32 * (7.81523207 $_{sp\ gravity}$) * (1cm. $_{length}$) * (dia)$_4$ * (0.0000001Kgm^2/gcm^2) = Inertia in kgm^2.

Moving the decimal point one place in diameter shifts the decimal point four places in the same direction in J.

For cylinders longer or shorter than 1 centimeter, multiply J from the table by the actual cylinder length in cm.

For materials other than steel, multiply J from the table by the specific gravity in (grams per cubic centimeter / 7.815).

Greek Letters

Name	Uppercase	Lowercase
Alpha	Α	α
Beta	Β	β
Chi	Χ	χ
Delta	Δ	δ
Epsilon	Ε	ε
Eta	Η	η
Gamma	Γ	γ
Iota	Ι	ι
Kappa	Κ	κ
Lambda	Λ	λ
Mu	Μ	μ
Nu	Ν	ν
Omega	Ω	ω
Omicron	Ο	ο
Phi	Φ	φ
Pi	Π	π
Psi	Ψ	ψ
Rho	Ρ	ρ
Sigma	Σ	σ
Tau	Τ	τ
Theta	Θ	θ
Upsilon	Υ	υ
Xi	Ξ	ξ
zeta	Ζ	ζ

Metric Prefixes

Prefix	Value	Prefix	Value
Yotta	10^{24}	Deci	10^{-1}
Zetta	10^{21}	Centi	10^{-2}
Exa	10^{18}	Milli	10^{-3}
Peta	10^{15}	Micro	10^{-6}
Tera	10^{12}	Nano	10^{-9}
Giga	10^{9}	Pico	10^{-12}
Mega	10^{6}	Femto	10^{-15}
Kilo	10^{3}	Atto	10^{-18}
Hecto	10^{2}	Zepto	10^{-21}
Deca	10^{1}	yocto	10^{-24}

Section – 7 Glossary

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Glossary

"D" flange	A special end shield with untapped holes for through bolts in the flange. It is primarily used for mounting the motor to gear boxes or bulkheads. They are available in frame sizes 143t through 445t.
"P" base	A special mounting similar to "D" flange except with a machined fit tenon recessed instead of protruding. Usually found on pumps.
"T" frame	Current NEMA designation identifying AC induction motor frames. (NEMA has dimension tables which offer standard frame measurements.) Replaced the previous standard "U" frame in 1965.
"U" frame	A previously used NEMA designation indicating frame size and dimension (prior to 1965 the standard frame sizes per horsepower rating).

A

Absolute position	A position referenced to a fixed zero position.
AC (alternating current)	The commonly available electric power supplied by an AC generator and is distributed in single- or three-phase forms. AC current changes its direction of flow (cycles). A flow of electricity that continually changes in amplitude and periodically changes in direction.
AC contactor	An alternating current (AC) contactor is designed for the specific purpose of establishing or interrupting an AC power circuit.
AC drive	A general term used to describe an electronic device that converts a fixed frequency and voltage to an adjustable frequency and AC voltage. It controls the speed, torque, horsepower, and direction of an AC motor with a rectifier, inverter, and inverter control.
AC input circuit	A circuit on an I/O module that converts AC signals from a machine/process switching device to backplane logic level DC signals. By definition, it is always a digital circuit (on/off). By implication, it usually has a discrete relationship with the data table (i.e., A data table bit reflects its state).
AC motor	A motor operating on AC current that flows in either direction (AC current). There are two general types: induction and synchronous.
Acceleration torque	% of motor rated torque that can be produced, measured from 5%-100% of full load speed. Assumptions: 1. No load to full load step change 2. Connected inertia = 1 x motor inertia 3. Total inertia = 2x motor inertia
Adaptive control	A technique to allow control to automatically compensate for changes in system parameters such as load variations.
Address	1. A character string that uniquely identifies a memory location. 2. A character string that uniquely identifies the physical location of an input or output circuit.
Adjustable speed	The concept of 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)	The adjustable-speed drive is comprised of the motor, drive controller, and operator's controls (either manual or automatic).
Air gap	The space between the rotating (rotor) and stationary (stator) members in an electric motor.

Algorithm — A set of procedures used for solving a problem in a finite number of steps.

Altitude — The atmospheric altitude (height above sea level) at which the motor will be operating; NEMA standards call for an altitude not exceeding 1,000 meters (3,300 feet). As the altitude increases above 1,000 meters (3,300 feet) and the air density decreases, the air's ability to cool the motor decreases. For higher altitudes, higher grades of insulation or motor derating are required. DC motors require special brushes for operation at high altitudes.

Ambient temperature — The temperature of the surrounding cooling medium, such as gas or liquid, which comes into contact with the heated parts of the motor. The cooling medium is usually the air surrounding the motor. The standard NEMA rating for ambient temperature is not to exceed 40 degrees C. The temperature of the medium (air, water, earth) into which the heat of the equipment is dissipated.

American wire gauge (AWG) — A standard system used for designating the size of electrical conductors. Gauge numbers have an inverse relation-ship to size; larger numbers have a smaller cross-sectional area. However, a single-strand conductor has a larger cross-sectional area than a multi-strand conductor of the same gauge so that they have the same current-carrying specification.

Analog-to-digital con-version — Production of a digital value whose magnitude is proportional to the instantaneous magnitude of an analog signal.

Anode — The terminal of an electronic device through which electrons exit onto the line.

ANSI — American national standards institute. An organization that develops and publishes voluntary industry standards in the united states.

Armature — The moving part of a magnetic circuit, such as the rotating part of a motor or generator, or the movable iron part of a relay. A collection of wire coils in a DC motor that are free to rotate about the center line axis within the magnetic field created by the field poles.

Armature coil — A coil of insulated wire within a DC motor that provides electromagnetic properties when rotated.

Armature control — Abbreviated term for armature voltage control of a DC motor, which describes the usual method of changing the speed of a DC motor by controlling the magnitude of applied armature voltage.

Armature core — Highly magnetic material (usually iron) upon which the armature coil is wound to assist in creating a magnetic field in a DC motor.

Armature current — Armature current is the current required by a motor to produce torque and to drive a load. The maximum safe, continuous current is stamped on the motor nameplate. This can only be exceeded for initial for acceleration, and short periods of time. Armature current is proportional to the amount of torque being rises and falls produced; it as the torque demand rises and falls. The current required by a DC motor to produce torque and drive a load. It should only be exceeded for initial motor acceleration, and for short periods of time. Armature current is proportional to the amount of torque being produced.

Armature-voltage feedback — Armature voltage can be used as the velocity feedback signal to an electronic speed regulator. This voltage is approximately directly proportional to motor velocity, assuming a constant motor field and ignoring IR drop. Armature-voltage feedback is used where the expense of a tachometer-generator for velocity feedback is not justified and a regulation accuracy of 2-5% is adequate.

ASCII
American standards code for information interchange. It is a 7-bit code with an optional parity bit used to represent alphanumerics, punctuation marks, and control-code characters.

B

Back end of a motor
The back end of a normal motor is the end that carries the coupling or driving pulley (NEMA). This is sometimes called the drive end (D.E.), pulley end (P.E.) etc.

Bandwidth
The range of frequencies over which a system is designed to operate. The bandwidth is expressed in hertz between the highest and lowest frequencies.

Base frequency
The manufacturer's nameplate rated frequency.

Base speed
The manufacturer's nameplate rating where the motor will develop rated power at rated load and voltage. With DC drives, it is commonly the point where full armature voltage is applied with full-rated field excitation. With AC systems, it is commonly the point where 60Hz is applied to the induction motor. With DC motors, it is the motor shaft speed in revolutions per minute (rpm) with the rated field current and commonly the point where full armature voltage is applied with full-rated current.

Base speed, rpm
The speed in revolutions per minute (rpm) which a DC motor develops at rated armature and field voltage with rated load applied.

Baud
A unit of signaling speed, equal to the number of discrete conditions or signal events per second. Where one bit is en-coded on each signaling event, the number of baud is the same as the number of bits. See dibit.

Bearing life
Rating life, l10 (b10), is the life in hours or revolutions in which 90% of the bearings selected will obtain or exceed. Median life (average life), l50 (b50), is the life in hours or revolutions in which 50% of the bearings selected will obtain or exceed.

Bearing RTD
A probe used to measure bearing temperature to detect an overheating condition. The RTD's resistance varies with the temperature of the bearings.

Bending radius
The minimum radius to which a cable can be bent without damage.

Boost
A voltage adjustment made to an AC motor to produce enough torque to start an application.

Brake Resistor
A load resistor that is used to absorb the energy produced by an overhauling mechanical load. Refer to Dynamic Braking.

Brakes
An external device or accessory that brings a running motor to a standstill and/or holds a load. Can be added to a motor or incorporated as part of it.

Braking
A method of stopping or reducing the time required to stop an AC or DC motor, accomplished in several ways: DC-injection braking (AC drives) - a method which produces electromagnetic braking forces in the motor by removing two AC motor (stator) phases and injecting DC current. The result is a linear braking characteristic that (ramp) does not diminish with motor speed. Application is normally limited to 10-20% of rated motor speed due to increased heating in the rotor. Dynamic braking (AC drives) - a method which produces electromagnetic braking forces in the motor by

Braking (cont'd 1)
Dissipating generated power into the DC bus through a resistive load. Braking force remains constant and is only limited by the thermal capacity of the resistors. The result is a linear braking characteristic (ramp) that does not diminish with motor speed. Dynamic braking (DC drives) - a method which produces electromagnetic braking forces in the motor by dissipating generated power from armature/shunt field reaction into a

resistive load. Braking force is deter-mined by the field strength, armature voltage, and thermal capacity of the resistors. The result is a logarithmic braking

Braking (cont'd 2)

Characteristic (curve) that diminishes with motor speed. Regenerative braking - a method which produces electromagnetic braking forces in the motor by electronically controlling the return of generated power to the AC supply. The result is a controllable linear braking characteristic (ramp) that does not diminish with motor speed. Motor-mounted or separately mounted holding brake - a positive-action mechanical friction device. Normal configuration is such that when the power is removed, the brake is set. This can be used as a holding brake. (Note: a separately mounted brake is not one which, is located on some part of the mechanical drive train other than the motor.)

Braking torque

The torque required to bring a motor down to a standstill. The term is also used to describe the torque developed by a motor during dynamic braking conditions.

Breakaway torque

The torque required to start a machine from standstill. It is always greater than the torque needed to maintain motion. % of motor rated torque that can be produced, measured from 0-5% of full load speed. Assumptions: 1. No load to full load step change 2. Connected inertia = 1 x motor inertia 3. Total inertia = 2x motor inertia

Breakdown torque

The maximum torque a motor will develop at rated voltage without a relatively abrupt drop or loss in speed.

Bridge rectifier (diode, SCR)

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

Brush

A conductor, usually composed of some element of carbon, serving to maintain an electrical connection between stationary and moving parts of a machine (commutator of a DC motor). This brush is mounted in a spring-loaded holder and positioned tangent to the commutator segments against which it "brushes." Pairs of brushes are equally spaced around the circumference of the commutator. A carbon-based conductor in a DC motor that provides contact between the power supply and the commutator allowing current to flow through to the commutator. A piece of current conducting material (usually carbon or graphite) which rides directly on the commutator of a com-mutated motor and conducts current from the power supply to the armature windings.

C

Capacitor

A device which, when connected in an alternating-current circuit, causes the current to lead the voltage in time phase. The peak of the current wave is reached ahead of the peak of the voltage wave. This is the result of the successive storage and discharge of electric energy used in single-phase motors to start, or in three-phase motors for power factor correction. An electronic device with the ability to store and electric charge.

Capacitor motor

A single-phase induction motor with a main winding arranged for direct connection to the power source, and an auxiliary winding connected in series with a capacitor. There are three types of capacitor motors: capacitor start, in which the capacitor phase is in the circuit only during starting; permanent-split capacitor, which has the same capacitor and capacitor phase in the circuit for both starting and running; two-value capacitor motor, in which there are different values of capacitance for starting and running.

Capacitor start

The capacitor start single-phase motor is basically the same as the split phase start, except that it has a capacitor in series with the starting winding. The addition of the capacitor provides better phase relation and results in greater starting torque with much less power input. As in the case of the split phase motor, this type can be reversed at rest, but not while running unless special starting and reversing switches are used. When properly equipped for reversing while running, the motor is much more suitable for this service than the split phase start since it provides greater reversing ability at less

	watts input.
Cartesian coordinate system	A coordinate system in two or three dimensions made by using two or three axes (x and y, or x, y, and z, respectively) that intersect each other at right angles at an origin, enabling any point to be identified by the distance from the origin along an axis.
Cathode	The terminal of an electronic device through which electrons enter from the line.
CE	This designation shows that a product such as a motor or control meets European standards for safety and environ-mental protection. A CE mark is required for products used in most European countries.
CEMF	Counter electromotive force, 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. However, the polarity of the CEMF is opposite to that of the power being supplied to the armature.
Central processing unit (CPU)	1. The portion of a computer or programmable controller that controls the interpretation and execution of the user pro-gram stored in memory. 2. The PLC or SLC™ processor.
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, C-face is used where a pump or similar item is to be over-hung on the motor. This type of mounting is a NEMA standard design, available with or without feet.
CIV (corona inception voltage)	The minimum voltage amount that begins the process of ionization (corona) of motor windings.
Class I	Those in which flammable gasses or vapors are or may be present in the air in quantities sufficient to product explosive or ignitable mixtures. Group c - atmospheres containing ethyl or ether vapors. Group d - atmospheres containing gasoline, hexane, benzene, butane, propane, alcohol, acetone, benzol, lacquer solvent vapors, natural gas, etc.
Class II	Those which are hazardous because of the presence of combustible dust. Group e - atmospheres containing metal dust, including aluminum, magnesium, or their commercial alloys. Group f- atmospheres containing carbon black, char-coal, coal or coke dust. Group g - atmospheres containing flour, starch, grain or combustible plastics or chemical dusts.
Closed loop	A path in which output feedback is compared with desired values to regulate drive system operation.
Closed-loop system	A control system involving one or more feedback control loops, which combine functions of controlled signals and commands, to keep stable the relationships between the two.
Cogging	A term used to describe non-uniform angular velocity. It refers to rotation occurring in jerks or increments rather than smooth motion. When an armature coil enters the magnetic field produced by the field coils, it tends to speed up and slow down when leaving it. This effect becomes apparent at low speeds. The fewer the number of coils, the more noticeable it can be. A condition in which a motor does not rotate smoothly, but "steps" or "jerks" from one position to another during shaft revolution. Cogging is most pronounced at low speeds and can cause objectionable vibrations in the driven machine.
Coil (stator or armature)	The electrical conductors wound into the core slot, electrically insulated from the iron core. These coils are connected into circuits or windings, which carry independent current. It is these coils that carry and produce the magnetic field when the current

	passes through them. There are two major types: “mush” or “random” wound, round wire found in smaller and medium motors where coils are randomly laid in slot of stator core; and formed coils of square wire individually laid in, one on top of the other, to give an evenly stacked layered appearance.
Common DC bus	Several drives that are connected together by the +/- DC bus terminals
Common mode	
Common mode choke	
Common mode noise	Unwanted electrical signals between grounding conductors and signal conductors or line conductors.
Communication rate (data transmission rate)	The rate at which data is transmitted across a link (in bits).
Commutation (DC motor)	Reversing the current in an armature coil when the coil (ends) moves from one side of the brush to the other side of the same brush. The switching in polarity between the armature and the brushes in a DC motor that allows current to flow through.
Commutation limit	The condition where the commutator segments of a DC motor pass each brush so quickly that current cannot switch polarity in the time allotted.
Commutator	A cylindrical device mounted on the armature shaft and consisting of a number of wedge-shaped copper segments arranged around the shaft (insulated from it and each other). The motor brushes ride on the periphery of the commutator and electrically connect and switch the armature coils to the power source. A cylindrically shaped assembly fastened to the motor shaft and considered part of the armature assembly. It consists of segments of “bars” that are electrically connected to two ends of one (or more) armature coils. Current is from the power supply through the brushes, to the commutator and, hence, through the armature coils. The arrangement of commutator segments is such that the magnetic polarity of each coil changes as the armature rotates.
Commutator bars	A number of separated, parallel metal bars or segments that provide contact between the armature of a DC motor and one or more brushes.
Compound wound	Designed with both a series and shunt field winding, the compound motor is used where the primary load requirement is heavy starting torque and variable speed is not required. Also used for parallel operation. The load must tolerate a speed variation from full load to no-load.
Constant HP (horsepower)	A designation for variable speed motors used for loads requiring the same amount of horsepower regardless of their motor speed during a normal operation.
Constant or variable torque	
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 range	A speed range in which the motor is capable of delivering a constant torque subject to cooling limitations of the motor.
Continuous duty	A motor that can continue to operate without stopping and remain within the insulation temperature limits after it has reached normal operating (equilibrium) temperature.
Converter	1. A device for changing AC to DC. This is accomplished through use of a diode rectifier or thyristor rectifier circuit. 2. A device for 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.

Corona	This is the electrical discharge breakdown of a winding through the application of excessive voltage.
Counter electromotive force (cemf)	The induced voltage in a motor armature caused by conductors moving through or "cutting" field magnetic flux. This induced voltage opposes the armature current and tends to reduce it.
Current	The flow of electricity. This time rate of flow of electrical charge and is measured in amps (amperes).
Current limiting	An electronic method of limiting the maximum current available to the motor. This is adjustable so that the motor's max-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 regulator	A controller that automatically adjusts the output current according to the current feedback and reference signals.
Cycle	1. A sequence of operations that is repeated regularly. 2. The time it takes for one sequence of operations to occur.

D

Daisy-chain configuration (for parallel connection)	1. In a linear arrangement of parallel (bus) connections, a physical configuration such that each device is connected on the bus at the junction of two conductor segments, with no dropline between the device and the junction of the conductor segments. 2. Contrasted with a star configuration or a trunkline/dropline configuration.
Damping	The reduction in amplitude of an oscillation.
DC (direct current)	A current that flows only in one direction in an electric circuit. It may be continuous or discontinuous and it may be constant or varying.
DC bus	A drive's power structure that transmits a rectified AC line power from the bridge rectifier to the output transistors. Circuits that filter the DC voltage to create a smooth flow when voltage enters the power section from the rectifier.
Dead band	The range of values through which a system input can be changed without causing a corresponding change in system output.
Delta connection	A 3-phase connection where windings are connected in series with the power applied to, or taken from, the junctions (contrasted with star or y connection).
Demagnetization	When a permanent-magnet DC motor is subjected to high current pulses, the magnets may become slightly demagnetized, resulting in a lower torque constant.
Design A, B, C, D – for AC motors	NEMA has standard motor designs with various torque characteristics to meet specific requirements posed by different application loads. The design "B" is the most common design.
D-flange (motor mounting)	This type of motor mounting is used when the motor is to be built as 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.
DI/DT	The instantaneous rate of change in current over time. Line reactors and isolation transformers can be used to pro-vide the impedance necessary to reduce high DI/DT, and the harmful effects it can have.

Digital-to-analog conversion (d/a conversion)
Production of an analog signal whose instantaneous magnitude is proportional to the magnitude of a digital value.

Diode
A solid-state, unidirectional conductor. An electronic device that allows current flow in only one direction.

Dither
A small oscillation signal, superimposed on a velocity signal, to overcome the effect of static friction that would other-wise occur at zero velocity. Without a dither, a low-velocity signal may be unable to overcome the static friction.

Drift
A slow change in some characteristic of a device. For a drive, it is the deviation from the initial set speed with no load change over a specific time period. Normally, the drive must be operated for a specified 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.

Drip-proof motor
An open motor in which the ventilating openings are so constructed that drops of liquid or solid particles falling on it, at any angle not greater than 15 degrees from the vertical, cannot enter either directly or by striking and running along a horizontal or inwardly inclined surface.

Drive
An electronic device used to control the speed, torque, horsepower, and direction of a motor.

DV/DT
The instantaneous rate of change in voltage over time. Specifically 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
A time delay of programmed or established duration, not an interlock or hold.

Dynamic braking (AC drives)
The stop mode that slows the motor by dissipating generated power onto the DC bus through a set of external resistors. Braking force is constant and only limited by the thermal capacity of the resistors.

Dynamic braking (DC drives)
The stop mode that slows the motor by dissipating generated power from a set of resistors after disconnection from the DC supply. Braking force is determined by the field strength, armature voltage, and thermal capacity of the resistors.

Dynamometer
A device which places a load on the motor to accurately measure its output torque and speed by providing a calibrated dynamic load. Helpful in testing motors for nameplate information and an effective device in measuring efficiency.

E

Efficiency
Ratio of output to input indicated by a percentage. In a motor, it is the effectiveness with which the motor converts electrical energy into mechanical energy. In a power supply, it is the effectiveness with which the power supply converts AC power into DC power. The efficiency of a motor is the ratio of electrical input to mechanical output. It represents the effectiveness with which the motor converts electrical energy into mechanical energy. NEMA has set up codes, which correlate to specific nominal efficiencies. A decrease in losses (the elements keeping the motor from being 100% efficient) of 10% constitutes an upward improvement of the motor of one code on the NEMA table. Each nominal efficiency has a corresponding minimum efficiency number.

Electromagnetism
A magnetic field resulting from the flow of an electric current through a coil. For example, when an electrical current is passed through a conductor such as iron, a magnetic field is created around that conductor.

Electromotive force (EMF)	A synonym for voltage, usually restricted to generated voltage.
Electrostatic discharge (ESD)	A static-electricity discharge that may damage drive components. Refer to the ESD precautions found in this manual to guard against damage to drive components.
EMI	Electromagnetic interference. Any electromagnetic disturbance that interrupts, obstructs, or otherwise impairs the performance of electronic equipment.
Encapsulated winding	A motor which has its winding structure completely coated with an insulating resin (such as epoxy). This construction type is designed for exposure to more severe atmospheric conditions than the normal varnished winding.
Enclosure	The housing in which equipment is mounted. They are available in designs for various environmental conditions. Refer to NEMA standard for specifications of different types of enclosures.
Encoder	Any feedback element that converts linear or rotary position (absolute or incremental) to a digital signal. A digital de-vice that translates the angular position of a rotating shaft into a corresponding series of digital pulses.
Encoder bandwidth	An expression for maximum encoder speed, in Hz. May also refer to the maximum rate at which the control loop can accept encoder signals. The actual bandwidth of the encoder and the capability of the controller to process encoder signals may not be the same.
Encoder marker	A once-per-revolution signal provided by some incremental encoders to specify a reference point within that revolution. Also known as zero reference signal.
Encoder resolution	A measure of the smallest positional change that can be detected by the encoder. The number of lines per revolution times the encoder multiplier.
End ring	A solid aluminum or copper conductor in an AC motor that connects all of the rotor bars at each end of the rotor to form a closed-loop for current flow.
EPROM	Electrically-erasable programmable read-only memory. A type of prom that can be erased and reprogrammed by electrical signals. As with all proms, it is non-volatile, random-access memory. See PROM. A chip mounted on a circuit board within the drive that stores data so that information is not lost wen power is removed.
Explosion-proof enclosure	A totally enclosed enclosure, which is constructed to withstand an explosion of a specified gas, vapor or dust which, may occur within it. Should such an explosion occur, the enclosure would prevent the ignition or explosion of the gas or vapor which may surround the motor enclosure. These motors are listed with underwriter's laboratories.
Explosion-proof-hazardous locations	Division I – locations in which ignitable concentrations of flammable or combustible material exist and come in contact with the motor. Division II – locations in which ignitable concentrations of flammable or combustible material exist but are contained within closed systems or containers and normally would not come in contact with the motor.
Externally ventilated	A motor using an external cooling system. This is required in applications where the motor's own fan will not provide sufficient cooling. These cooling systems are used in certain duty cycle applications, with slow speed motors, or in environments with extreme dirt. Often a duct with an external blower is used to bring clean air into the motor's air-intake.

F

Feedback loop	A closed signal path from the motor or machine back to the controlling device that transmits either current or voltage readings in order to obtain a corrective error signal.
Feedforward control action	Control action in which information concerning upstream conditions is converted into corrective commands to minimize the deviations of the controlled variable.
Field control	A method of controlling DC motor speed by varying the field current in the shunt field windings.
Field economy	A circuit-design feature of a DC motor shunt field supply that reduces the supply voltage output after a predetermined period of time. On many field supplies, this means a 50% reduction in output voltage two to three minutes after ma-chine shutdown (idle). A field-economy circuit serves to reduce standby power consumption and prolong the insulation life of the motor field windings.
Field flux	The invisible magnetic lines of force that travel between north and south poles. They are drawn to the conductor placed between the two magnetic poles.
Field forcing	Temporarily over-exciting a motor shunt field to overcome the l/r time constant, increase the rate of flux change and rapidly reverse the direction of shunt motor field current.
Field reversing	One method for producing regeneration. It is accomplished by changing the direction of current through the motor field, which reverses the polarity of the motor CEMF to account for generator action.
Field weakening	The action of reducing the current applied to a DC-motor shunt field. This action weakens the magnetic field, allowing motor speed to increase under proper conditions. The introduction of resistance in series with the shunt wound field of DC motor to reduce the voltage and current which weakens the strength of the magnetic field and thereby increases the motor speed.
Floating ground	An electrical-circuit common which is not at earth ground potential or the same ground potential as circuitry with which it interfaces. A voltage difference can exist between the floating ground and earth ground.
Flux	The magnetic field which is established around an energized conductor or permanent magnet. The field is represented by flux lines creating a flux pattern between opposite poles. The density of the flux lines is a measure of the strength of the magnetic field.
Four-quadrant operation	In reference to a regenerative drive, the four combinations of forward and reverse rotation and forward and reverse torque. The four combinations are: forward rotation/forward torque (motoring) forward rotation/reverse torque (regeneration) reverse rotation/reverse torque (motoring) reverse rotation/forward torque (regeneration).
Frequency	The rate at which alternating current makes a complete cycle of reversals. It is expressed in cycles per second. In the U.S., 60 cycles (Hz) is the standard while in other countries 50 Hz (cycles) is common. The frequency of the AC cur-rent will affect the speed of a motor. The number of periodic cycles per unit of time. The number of cycles generated by the drive each second. Calculated as: (hertz = 1 cycle per second).
Full-load current	The current flowing through the line when the motor is operating at full-load torque and full-load speed with rated frequency and voltage applied to the motor terminals.
Full-load torque	That torque of a motor necessary to produce its rated horsepower at full-load speed, sometimes referred to as running torque.

G

Gain — The ratio of the magnitude of the output signal with respect to that of the input signal.

Gain error — The "gain" of an analog input or output is the scale factor that provides the nominal conversion relationship. Typically, this is the slope of the line when analog voltage or current is plotted versus the corresponding digital values. Gain error is the deviation of the scale factor or slope of the line from the ideal or nominal gain value. Gain error is expressed in percent of the input or output value.

H

Harmonics — Additional frequencies produced in multiples of the fundamental frequency that when added together create a distortion in the output.

Horsepower (HP) — The measure of rate of work. One horsepower is equivalent to lifting 33,000 pounds to a height of one foot in one minute. The horsepower of a motor is expressed as a function of torque and speed. For motors the following approximate formula may be used: where hp = horsepower, t = torque (in. Lb. Ft.), And rpm = revolutions per minute. A unit of power: 1hp = 33,000 ft-lb/min. = 746 watts. The rate at which work is produced per unit of time. Calculated as: (horsepower = torque x speed / 5252).

Hunting — Undesirable fluctuations in motor speed that can occur after a step change in speed reference (either acceleration or deceleration) or load.

I

Induction motor — An induction motor is an alternating current motor in which the primary winding on one member (usually the stator) is connected to the power source and a secondary winding or a squirrel-cage secondary winding on the other member (usually the rotor) carries the induced current. There is no physical electrical connection to the secondary winding, its current is induced.

Inductor — A coil of wire in a motor that induces a voltage when the current within its magnetic filed varies.

Inertia — A measure of a 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 (wk2) is the product of the weight (w) of an object and the square of the radius of gyration (k2). The radius of gyration is a measure of how the mass of the object is distributed about the axis of rotation. Wk2 is usually expressed in units of lb-ft2.

Inertial load — A load (flywheel, fan, etc.) Which tends to cause the motor shaft to continue to rotate after the power has been re-moved (stored kinetic energy). If this continued rotation cannot be tolerated, some mechanical or electrical braking means must be applied. This application may require a special motor due to the energy required to accelerate the inertia.

Insulated gate bipolar transistor (IGBT) — A type of transistor commonly used in drive-control devices.

Insulation class — Since there are various ambient temperature conditions a motor might encounter and different temperature ranges within which motors run and insulation is sensitive to temperature; motor insulation is classified by the temperature ranges at which it can operate for a sustained period of time. When a motor insulation class is labeled on the name-plate, the total insulation system is capable of sustained operation at the above temperature.

Intermittent duty — A requirement of service that demands operation for alternate intervals of (1) load and no load; or (2) load and rest; (3) load, no load and rest; such alternative intervals being definitely specified.

Inverter
An AC adjustable-frequency drive. A particular section of an AC drive. This section uses the DC voltage from a previous circuit stage (intermediate DC circuit) to produce a pulse-width-modulated or stepped AC current or voltage waveform that has characteristics similar to the desired sine-wave frequency. A circuit whose output signal is the inverse of its input (a positive-going pulse is inverted to a negative-going pulse, and vise versa). An electronic device that converts fixed frequency and fixed voltages to variable frequency and voltage. Enables the user to electrically adjust the speed of an AC motor.

IR compensation
A way to compensate for the voltage drop across resistance of the AC or DC motor circuit and the resultant reduction in speed. This compensation also 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.

Isolation transformer
1. A transformer that provides DC isolation from other equipment not connected to that transformer secondary. 2. A transformer that provides noise isolation between the primary and secondary by such means as a faraday shield. 3. A set of coils that electrically separates a device from the AC power line.

J

Joule
1. The work done by the force of 1 newton acting through a distance of 1 meter. 2. The energy required to transport 1 coulomb between two points having a potential difference of 1 volt.

K

Kilowatt (kw)
Since the watt is a relatively small unit power, the kilowatt – (kw) 1,000 watts – is used where larger units of power measurement are desirable.

Kinetic energy
The energy of motion of a moving body.

L

Laminations
The steel portion of the rotor and stator cores make up a series of thin laminations (sheets) which are stacked and fastened together by cleats, rivets or welds. Laminations are used instead of a solid piece in order to reduce eddy-current losses.

LEM
A hall-effect current transducer that senses drive output current and generates a signal for the control logic.

Line reactor
A device within the drive that reduces the amount of electrical noise and line notches caused by the switching of power conversion devices.

Locked rotor current
Steady state current taken from the line with the rotor at standstill (at rated voltage and frequency). This is the current seen when starting the motor and load.

M

Magnetic flux
The lines of force that extend in all direction from a magnetic pole.

Multiplexing
1. The time-shared scanning of a number of data lines into a single channel. Only one data line is enabled at any time. 2. The incorporation of two or more signals into a single wave from which the individual signals can be recovered.

Multi-speed motors
A motor wound in such a way that varying connections at the starter can change the speed to a predetermined speed. The most common multispeed motor is a two-speed although three- and four-speeds are sometimes available. Multi-speed motors can be wound with two sets of windings or one winding. They are also available with constant

torque, variable torque or constant horsepower.

N

NEC — National electrical code. A set of regulations governing the construction and installation of electrical wiring and apparatus, established by the National Fire Protection Association and suitable for mandatory application by governing bodies exercising legal jurisdiction. It is widely used by state and local authorities within the United States.

NEMA — The National Electrical Manufacturers Association is a non-profit organization organized and supported by manufacturers of electric equipment and supplies. NEMA has set standards for: horsepower ratings, speeds, frame sizes and dimensions, standard voltages and frequencies with allowable variations, service factors, torque, starting current & KVA, enclosures.

NEMA standards — Consensus standards in the United States for electrical equipment approved by the members of the National Electrical Manufacturers Association (NEMA).

Noise (Electrical) — Unwanted electrical disturbances imposed upon a signal that tend to obscure its data content.

Noise immunity — The measure of a product’s ability to function in the presence of noise.

O

Open (protected) motor — A motor having ventilating openings which permit passage of external cooling air over and around the windings. The term “open machine,” when applied to large apparatus without qualification, designates a machine having no restriction to ventilation other than that necessitated by mechanical construction.

Open bearing — A ball bearing that does not have a shield, seal or guard on either of the two sides of the bearing casing.

Open externally-ventilated machine — A machine which is ventilated with external air by means of a separate motor-driven blower mounted on machine enclosure.

Open machine (motors) — A machine with ventilating openings that permit passage of external cooling air over and around the windings of the machine (NEMA standard). Drip-proof machine - 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 en-closure at any angle from 1 to 15 degrees downward from vertical. Guarded machine - 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 ...

Open machine (motors) — ... 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. Open externally ventilated machine - a machine 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. Open pipe-ventilated machine - basically an open machine except that openings ...

Open machine (motors) — ... for admission of ventilating air are so arranged that inlet ducts or pipes can be connected to them. Air may be circulated by means integral with the machine or by means external to the machine (separately forced ventilated). Semi-guarded - 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. Splashproof - 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 vertical.

Open machine (motors)
Weather-protected machine - an open enclosure divided into two types: type 1 - have ventilating passages constructed to minimize the entrance of rain, snow, airborne particles and prevent passage of a 0.75-inch diameter cylindrical rod. Type 2 - 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 speed range
Ratio of full load speed to the lowest speed at which rated torque can be delivered. The motor cannot be stalled.

Overload capacity
The ability of the drive to withstand currents beyond the system's continuous rating. It is normally specified as a percentage of full load current for a specified 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 by which a controlled variable exceeds the desired value after a change of input.

P

Parallel operation
1. A type of information transfer where all bits within bytes, or words, are handled simultaneously. 2. Contrasted with serial operation.

Paralleling
When two or more DC motors are required to operate in parallel – that is, to drive a common load while sharing the load equally among all motors – they should have speed-torque characteristics which are identical. The greater the speed droop with load, the easier it becomes to parallel motors successfully. It follows that series motors will operate in parallel easier than any other type. Compound motors, which also have drooping speed characteristics (high regulation), will generally parallel without special circuits or equalization. It may be difficult to operate shunt or stabilized-shunt motors in parallel because of their nearly constant speed characteristics. Modifications to the motor control must sometimes be made before these motors will parallel within satisfactory limits.

Phase
Indicates the space relationships of windings and changing values of the recurring cycles of AC voltages and cur-rents. Due to the positioning (or the phase relationship) of the windings, the various voltages and currents will not be similar in all aspects at any given instant. Each winding will lead or lag another in position. Each voltage will lead or lag another voltage in time. Each current will lead or lag another current in time. The most common power supplies are either single- or three-phase (with 120 electrical degrees between the three-phases).

Plug reversal
Reconnecting a motor's winding in reverse to apply a reverse braking torque to its normal direction of rotation while running. Although it is an effective dynamic braking means in many applications, plugging produces more heat than other methods and should be used with caution.

Plugging
A type of motor braking provided by reversing either line voltage polarity or phase sequence so that the motor develops a counter torque that exerts a retarding force to brake the motor.

Poles
In an AC motor, refers to the number of magnetic poles in the stator winding. The number of poles determines the motor's speed. In a DC motor, refers to the number of magnetic poles in the motor. They create the magnetic field in which the armature operates (speed is not determined by the number of poles).

Polyphase motor
Two or three-phase induction motors have their windings, one for each phase, evenly

divided by the same number of electrical degrees. Reversal of the two-phase motor is accomplished by reversing the current through either winding. Reversal of a three-phase motor is accomplished by interchanging any two of its connections to the line. Polyphase motors are used where a polyphase (threephase) power supply is available and is limited primarily to industrial applications. Starting and reversing torque characteristics of polyphase motors are exceptionally good. This is due to the fact that the different windings are identical and, unlike the capacitor motor, the currents are balanced. They have an ideal phase relation, which results in a true rotating field over the full range of operation from locked rotor to full speed.

Power factor
A measurement of the time phase difference between the voltage and current in an AC circuit. It is represented by the cosine of the angle of this phase difference. For an angle of 0 degrees, the power factor is 100% and the volt/ amperes of the circuit are equal to the watts (this is the ideal and an unrealistic situation). Power factor is the ratio of real power-kw to total kva or the ratio of actual power (watts) to apparent power (volt amperes).

PROM
Programmable read-only memory. A type of rom that requires an electrical operation to store data. In use, bits or words are read on demand but not changed. As with all ROMs, it is non-volatile, random-access memory.

Proportional, integral, derivative control (PID)
An intelligent I/O module or ladder diagram instruction providing automatic closed-loop operation of continuous process control loops. For each loop, this module or instruction can perform proportional control and optionally integral control, derivative control, or both: proportional control - causes an output signal to change as a direct ratio of the error signal variation. Integral control - causes an output signal to change as a function of the integral of the error signal over the time duration. Derivative control - causes an output signal to change as a function of the rate of change of the error signal.

Pull-in torque
The maximum constant torque at 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. The minimum torque developed by an AC motor during the period of acceleration from zero to the speed at which breakdown occurs. For motors, which do not have a definite breakdown torque, the pull-up torque is the minimum torque developed during the process of achieving rated speed.

PWM
Pulse-width modulation. A technique used to eliminate or reduce unwanted harmonic frequencies when inverting DC voltage to sine wave ac. Modulating the pulse width control the average voltage to the output.

Q

Quadrature
Separation in phase by 90°. Used on signal channels of feedback devices, such as encoders and resolvers, to detect the direction of motion.

R

RAM
Random access memory. The type of memory in which each storage location is by x/y coordinates, as in core or semiconductor memory. (tape or bubble memory cannot be random access.) Thus, the data access time is independent of the location of the data. Unless stated otherwise, ram usually implies read/write and volatile. A chip mounted on a circuit board within the drive that contains memory locations that can be accessed by

the microprocessor in random order to execute the software functions of the drive. Unlike BRAM, ram information is usually lost when power is removed.

Reactance
Pure inductance or capacitance, expressed in ohms, in a circuit. It is the component of impedance to alternating cur-rent that is not resistance.

Reactance (inductive)
The characteristic of a coil when connected to alternating current, which causes the current to lag the voltage in time phase. The current wave reaches its peak later than the voltage wave reaches its peak.

Rectifier
A device that conducts current in only one direction, thereby transforming alternating current to direct current.

Reflective wave
Reflective waves can occur in variable-speed motor applications when the drive and motor are placed a considerable distance apart. The combination of long lead (cable) lengths and the fast switching semi-conductors in the drive can cause voltage spikes at the motor's terminals. These spikes can cause the motor's insulation to deteriorate.

Regenerative
For DC drives, the characteristic of a motor to act as a generator when the counter EMF is larger than the drive's applied voltage. For AC drives, the point at which rotor synchronous frequency is greater than the applied frequency.

Regenerative braking
The technique of slowing or stopping a motor by regeneration. Also see braking. The stop mode that uses the motor as a generator by converting mechanical power of the motor into electrical power. The generated power is dissipated in the power source through a regenerative bridge circuit in the drive.

Regulation
The ability of a control system to hold a speed once it has been set. 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) - 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 drives utilizing armature voltage feedback, while regulation of 0.01% is possible using digital regulator schemes. Line regulation - the percentage of speed change with a given line voltage change, assuming all other parameters to be constant.

Reluctance synchronous motor
A synchronous motor with a special rotor design which directly lines the rotor up with the rotating magnetic field of the stator, allowing for no slip under load. Reluctance motors have lower efficiencies, power factors and torques than their permanent magnet counterparts.

Resolution
The smallest distinguishable increment into which a quantity can be devised (e.g., Position or shaft speed). It is also the degree to which nearly equal values of a quantity can be discriminated. For rotary encoders, it is the number of unique, electrically identified positions occurring in 360 degrees of input shaft rotation. For D/A or A/D conversion, may be expressed as the number of bits in the digital value that corresponds to a full-scale analog value.

Resolver
A transducer using magnetic coupling to measure absolute rotary position. It requires an analog signal interface and special conditioning electronics. A rugged device used in especially harsh environments.

Response
1. A quantitative expression of the output of a device or system as a function of the input. 2. On a communication link, a signal of a condition such as the acknowledgment of a message being received.

Reversing
... to protect the motor and control. (DC) field reversing - accomplished by changing the DC polarity to the motor shunt field. This type of reversing can be accomplished with DC-rated contactors or by means of an electronically controlled solid-state field supply.

(DC) manual reversing - the act of reversing the DC polarity to the motor armature by changing the position of a single switch. The switch is usually detented to give a degree of mechanical anti-plugging protection. Limit switches and remote stations cannot be used with this system. Dynamic braking is recommended. (AC or DC) static reversing - the act of reversing the DC polarity of the DC motor armature or phase rotation of an AC motor with no mechanical switching. This is accomplished electronically with solid-state devices. Solid-state antiplugging circuitry is generally a part of the design.

Ripple % — The percentage of AC left on a DC signal after rectifying. Measured peak-to-peak of the AC component.

Rise time — The time it takes to raise an analog voltage or current output level from 10% to 90% of maximum.

RMS — Root-mean-square. The effective value of an alternating current, corresponding to the DC value that produces the same heating effect. The RMS value is computed as the square root of the average of the squares of the instantaneous amplitude for one complete cycle. For a sine wave, the RMS value is 0.707 times the peak value.

ROM — Read only memory. A type of memory with data content that cannot be changed in normal mode of operation. In use, bits and words are read on demand, but not changed.

Rotor — The rotating member of an induction motor made up of stacked laminations. A shaft running through the center and a squirrel cage made in most cases of aluminum, which holds the laminations together, and act as a conductor for the induced magnetic field. The squirrel cage is made by casting molten aluminum into the slots cut into each lamination. The rotating part of an AC motor that is made of an aluminum or copper conductor.

RTD (resistance thermal detectors) winding RTD — A resistance device used to measure temperature change in the motor windings to detect a possible over heating condition. These detectors are embedded into the winding slot and their resistance varies with temperature.

S

Saturation — 1) an operational state in which a communication module is sending and/or receiving at maximum capacity. When the module receives more messages than it can process, it inhibits message entry. 2) more generally, the condition of a device or system in which a further increase in input no longer results in an appreciable change in output.

SCR — Silicon controlled rectifier. A solid-state, unidirectional latching switch. A device within the drive that conducts in one direction and requires a trigger to turn on. It uses small electrical currents to control high electrical loads.

Series DC motors — Where high starting torques are required for a DC motor, the series motor is used. The load must be solidly connected to the motor and never decrease to zero to prevent excessive motor speeds. The load must tolerate wide speed variations from full load to light load. Typical areas of application are industrial trucks, hoists, cranes and traction duty.

Service factor (SF) — 1. When used on a motor nameplate, a number which indicates how much above the nameplate rating a motor can be loaded without causing serious degradation (i.e., A 1.15 SF can produce 15% greater torque than the 1.0 SF rating of the same motor). 2. When used in applying motors or gearmotors, 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. Typically, measured loads are multiplied by service factors (experience factors) and the result in an “equivalent required torque” rating of a motor or gearmotor.

Shock load — The load seen by a clutch, brake, or motor in a system that transmits high peak loads.

This type of load is present in crushers, separators, grinders, conveyors, winches, and cranes.

Short-circuit

A defect in a winding which causes part of the normal electrical circuit to be bypassed. This frequently results in reducing the resistance or impedance to such an extent as to cause overheating of the winding and subsequent burn-out.

Shunt wound DC motors

Integral-horsepower shunt motors are used where the primary load requirements are for minimum speed variation from full-load to no-load and/or constant horsepower over an adjustable speed range at constant potential. Shunt motors are suitable for average starting torque loads. Typical applications include individual drives for machine tools such as drills and lathes, and centrifugal fans and blowers which are regulated by means of the discharge opening.

Skew

Arrangement of laminations on a rotor or armature to provide a slight angular pattern of their slots with respect to the shaft axis. This pattern helps to eliminate low speed cogging effects in an armature and minimize induced vibration in a rotor as well as reduce associated noise. It can also help to increase starting torque. In a motor, the arrangement of laminations on a rotor or armature to provide a slight angular pattern of their slots with respect to the shaft axis. This pattern helps reduce low-speed cogging in an armature and minimize induced vibration in a rotor, as well as reduce associated noise.

Slip

The difference between the speed of the rotating magnetic field (which is always synchronous) and the rotor in a non-synchronous induction motor is known as slip. It is expressed as a percentage of synchronous speed. Slip generally increases with an increase in torque.

Slip compensation

Monitors motor current and compensates for speed lost due to increased motor slip. The amount of slip is proportional to the motor load.

Speed regulation

The numerical measure (percent) of how accurately the motor speed can be maintained. It is the percentage of change in speed between full load and no load. The 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.

Speed regulation

(no load speed – full load speed)/full load speed x 100 expressed as a percentage of full load speed and restricted to the specified speed range. Speeds are at steady state, averaged over an extended period of time to eliminate speed ripple.

Star connection

1. The arrangement of phase windings, in a poly-phase circuit, in which one end of each phase winding is connected to a common junction. In a 3-phase circuit, it is sometimes called a y connection. 2. Contrasted with delta connection.

Stator

That part of an AC induction motor’s magnetic structure which does not rotate. It usually contains the primary winding. The stator is made up of laminations with a large hole in the center in which the rotor can turn; there are slots in the stator in which the windings for the coils are inserted. The stationary part of an AC motor that contains a set of electromagnets.

Steel laminations

Slotted steel disks that are stacked and aligned to form channels in which rotor bars are set, near the surface of the core assembly of an AC motor.

Surge protection

A capacitor device usually mounted in the conduit box to flatten the voltage surges that may occur as a result of lighting or a power supply surge (short-period peak). These surges can result in more than twice the rated voltage going to the windings and in turn cause winding damage.

Surge suppression
: The process of 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.

Synchronous motor
: A motor which operates at a constant speed up to full load. The rotor speed is equal to the speed of the rotating magnetic field of the stator – there is no slip. There are two major synchronous motor types: reluctance and permanent magnet. A synchronous motor is often used where the exact speed of a motor must be maintained.

Synchronous speed
: The speed of the rotating magnetic field set up by the stator winding of an induction motor. In a synchronous motor, the rotor locks into step with the rotating magnetic field and the motor is said to run at synchronous speed. Approximately the speed of the motor with no load on it. This is equal to 120 x frequency (frequency measured in hertz) # of poles.

T

Tachometer
: A small generator normally used as a rotational speed sensing device. Tachometers are typically attached to the out-put shaft of DC or AC variable-speed motors requiring close speed regulation. The tachometer feeds its signal to a control which adjusts its output to the DC or AC motor accordingly (called "closed loop feedback" control). A precision, linear, DC generator used to provide velocity feedback. A device used to measure angular velocity by producing a signal proportional to speed.

Temperature rise
: Some of the electrical energy losses inherent in motors are converted to heat causing some of the motor parts to heat up when the motor is running. The heated parts are at a higher temperature than the air surrounding them which causes a rise above room (ambient) temperature. It is important to match the proper motor and insulation system (NEMA temp. Codes) to the expected ambient temperature. If a motor has been built with greater than 1.0 service factor, then it can operate at a temperature somewhat higher than the motor's rated operating temperature. In all cases, the actual insulation thermal capability usually is higher than the motor's operating temperature to allow for any excessive heat areas. This is called hot spot allowance. (see insulation systems for NEMA standard temperature codes.) Each temperature code has an associated temperature rise which when added to the ambient and hot spot should not exceed the temperature handling of the insulation system.

Thermistor – thermally sensitive resistor
: A semiconductor used to measure temperature that can be attached to an alarm or meter to detect motor overheating.

Thermocouple – thermal detection device
: A temperature detecting device made of two dissimilar metals which generates a voltage as a function of temperature. Thermocouples can be attached to a meter or alarm to detect overheating of motor windings or bearings.

Thyristor
: A semi-conductor that is used as an electronic switch to control current flow in the drive. It is made up of an anode, cathode, and a gate.

Torque
: A turning force applied to a shaft, tending to cause rotation. Torque is equal to the force applied, times the radius through which it acts.

Torque regulation
: % regulation = (cold torque – hot torque)/full load torque x 100 expressed as a percentage of rated torque and restricted to the specified speed range. Torques are at steady state, averaged over an extended period of time to eliminate torque ripple.

Totally enclosed machine (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 airtight (NEMA standard): totally enclosed fan cooled machine -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. Explosion-proof machine - a totally

	enclosed machine whose enclosure is designed and constructed to withstand an explosion of a specified gas or vapor that may occur within it, and to ...
Totally enclosed machine (motor)	... prevent the ignition by sparks, flashes or explosions of the specified gas or vapor that may occur near or within the ma-chine casing. Dust-ignition-proof machine - a totally enclosed machine whose enclosure is constructed to exclude ignitable amounts of dust or amounts that might affect performance or rating, and constructed to not permit arcs, sparks, or heat otherwise generated or liberated inside the enclosure to cause ignition or exterior accumulations or atmospheric suspensions of a specific dust on or in the vicinity of the enclosure. Waterproof machine - a totally ...
Totally enclosed machine (motor)	... enlosed machine so constructed that it will exclude a stream of water 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 valve or a tapped hole at the lowest part of the frame that will serve for application of a drain pipe. Totally enclosed water-cooled machine - a totally enclosed machine that is cooled by circulating water, the water or water conductors coming in direct contact with the machine ...
Totally enclosed machine (motor)	... parts. Totally enclosed water-air-cooled machine - a totally enclosed machine that is cooled by circulating air that, 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 for circulating internal air. Totally enclosed, fan-cooled guarded machine - a totally enclosed fan-cooled machine in which all openings with direct access to the fan are limited in size by design of the structural parts or by screens, grills, or expanded metal, to prevent accidental contact with the fan. Such openings shall not permit the pas-
Totally enclosed machine (motor)	Sage 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 - a totally enclosed machine cooled only by a ventilating means external to the machine.
Transient	A momentary deviation in an electrical or mechanical system.
Transient overshoot	The maximum system deviation between a transient value of a controlled variable and the steady-state value of that variable.
Transistor	An active solid-state, three-terminal device that controls current and can be used for switching and control of the drive.

U

U.L. (underwriter's laboratory)	An independent testing organization, which examines and tests devices, systems and materials with particular reference to life, fire and casualty hazards. It develops standards for motors and controls used in hazardous locations through cooperation with manufacturers. U.L. has standards and tests for explosion-proof and dust ignition-proof motors, which must be met and passed before application of the U.L. label.

V

Variable torque	A multi-speed motor used on loads with torque requirements, which vary with speed as with some centrifugal pumps and blowers. The horsepower varies as the square of the speed.
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.
Velocity bandwidth	Velocity regulator frequency response measured as the 3db frequency response point. This is a small signal response and the drive should never reach current limit.

Velocity loop	A feedback control loop in which the controlled parameter is motor velocity. Usually uses a tachometer for a feedback device.
Volatile memory	A memory that loses its information if the power is removed.
Voltage	The voltage of a motor is usually determined by the supply to which it is attached. NEMA requires that motor be able to carry its rated horsepower at nameplate voltage plus or minus 10% although not necessarily at the rated temperature rise. The force that causes a current to flow in an electrical circuit. Analogous to pressure in hydraulics, voltage is often referred to as electrical pressure. Electrical pressure applied to the drive.
VVI	A type of AC adjustable-frequency drive that controls the voltage and frequency to the motor to produce variable-speed operation. The VVI-type drive controls the voltage in a section, other than the output section, where frequency generation takes place. The frequency control is accomplished by an output bridge circuit that switches the variable voltage to the motor at the desired frequency.

W

Watt	The amount of power required to maintain a current of one ampere at a pressure of one volt. Most motors are rated in kwatt equal to 1,000 watts. One horsepower is equal to 746 watts.
Wye connection	Refer to “Start Connection”.

X

Y

Z

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