Basic Motor Formulas And Calculations

The formulas and calculations which appear below should be used for estimating purposes only. It is the responsibility of the customer to specify the required motor Hp, Torque, and accelerating time for his application. The salesman may wish to check the customers specified values with the formulas in this section, however, if there is serious doubt concerning the customers application or if the customer requires guaranteed motor/application performance, the Product Department Customer Service group should be contacted.

Rules Of Thumb (Approximation)

At 1800 rpm, a motor develops a 3 lb.ft. per hp
At 1200 rpm, a motor develops a 4.5 lb.ft. per hp
At 575 volts, a 3-phase motor draws 1 amp per hp
At 460 volts, a 3-phase motor draws 1.25 amp per hp
At 230 volts a 3-phase motor draws 2.5 amp per hp
At 230 volts, a single-phase motor draws 5 amp per hp
At 115 volts, a single-phase motor draws 10 amp per hp

Mechanical Formulas

Torque in lb.ft. = \( \frac{\text{HP} \times 5250}{\text{rpm}} \)

\( \text{HP} = \frac{\text{Torque} \times \text{rpm}}{5250} \)

\( \text{rpm} = \frac{120 \times \text{Frequency}}{\text{No. of Poles}} \)

Temperature Conversion

Deg C = (Deg F - 32) \times \frac{5}{9}

Deg F = (Deg C \times \frac{9}{5}) + 32

High Inertia Loads

\( t = \frac{\text{WK}^2 \times \text{rpm}}{308 \times \text{T av.}} \)

\( \text{T} = \frac{\text{WK}^2 \times \text{rpm}}{308 \times t} \)

\( \text{T} = \text{Av. accelerating torque lb.ft.} \)

\( t = \text{accelerating time in sec.} \)

inertia reflected to motor = Load Inertia \( \left( \frac{\text{Load rpm}}{\text{Motor rpm}} \right)^2 \)

Synchronous Speed, Frequency And Number Of Poles Of AC Motors

\( n_s = \frac{120 \times f}{P} \)

\( f = \frac{P \times n_s}{120} \)

\( P = \frac{120 \times f}{n_s} \)

Relation Between Horsepower, Torque, And Speed

\( \text{HP} = \frac{T \times n}{5250} \)

\( T = \frac{5250 \times \text{HP}}{n} \)

\( n = \frac{5250 \times \text{HP}}{T} \)
Motor Slip

\[
\text{% Slip} = \frac{n_s - n}{n_s} \times 100
\]

<table>
<thead>
<tr>
<th>Code</th>
<th>KVA/HP</th>
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<tbody>
<tr>
<td>A</td>
<td>0-3.14</td>
</tr>
<tr>
<td>B</td>
<td>3.15-3.54</td>
</tr>
<tr>
<td>C</td>
<td>3.55-3.99</td>
</tr>
<tr>
<td>D</td>
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<tr>
<td>E</td>
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<tr>
<td>F</td>
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<tr>
<td>G</td>
<td>5.6 -6.29</td>
</tr>
<tr>
<td>H</td>
<td>6.3 -7.09</td>
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<tr>
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<tr>
<td>S</td>
<td>20.0-22.39</td>
</tr>
<tr>
<td>T</td>
<td>22.4 &amp; Up</td>
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</table>

Symbols

- \( I \) = current in amperes
- \( E \) = voltage in volts
- \( KW \) = power in kilowatts
- \( KVA \) = apparent power in kilo-volt-amperes
- \( HP \) = output power in horsepower
- \( n \) = motor speed in revolutions per minute (RPM)
- \( n_s \) = synchronous speed in revolutions per minute (RPM)
- \( P \) = number of poles
- \( f \) = frequency in cycles per second (CPS)
- \( T \) = torque in pound-feet
- \( EFF \) = efficiency as a decimal
- \( PF \) = power factor as a decimal

Equivalent Inertia

In mechanical systems, all rotating parts do not usually operate at the same speed. Thus, we need to determine the "equivalent inertia" of each moving part at a particular speed of the prime mover.

The total equivalent \( WK^2 \) for a system is the sum of the \( WK^2 \) of each part, referenced to prime mover speed.

The equation says:

\[
WK^2_{EQ} = WK^2_{part} \left( \frac{N_{part}}{N_{prime \ mover}} \right)^2
\]

This equation becomes a common denominator on which other calculations can be based. For variable-speed devices, inertia should be calculated first at low speed.

Let's look at a simple system which has a prime mover (PM), a reducer and a load.

\[ WK^2 = 100 \text{ lb.ft.}^2 \quad WK^2 = 900 \text{ lb.ft.}^2 \quad WK^2 = 27,000 \text{ lb.ft.}^2 \]
The formula states that the system WK² equivalent is equal to the sum of WK² parts at the prime mover's RPM, or in this case:

\[
WK²_{EQ} = WK²_{pm} + WK²_{Red.} \left( \frac{\text{Red. RPM}}{\text{PM RPM}} \right)^2 + WK²_{Load} \left( \frac{\text{Load RPM}}{\text{PM RPM}} \right)^2
\]

Note: reducer RPM = Load RPM

\[
WK²_{EQ} = WK²_{pm} + WK²_{Red.} \left( \frac{1}{3} \right)^2 + WK²_{Load} \left( \frac{1}{3} \right)^2
\]

The WK² equivalent is equal to the WK² of the prime mover, plus the WK² of the load. This is equal to the WK² of the prime mover, plus the WK² of the reducer times \((1/3)^2\), plus the WK² of the load times \((1/3)^2\).

This relationship of the reducer to the driven load is expressed by the formula given earlier:

\[
WK²_{EQ} = WK²_{part} \left( \frac{\text{N}_{part}}{\text{N}_{prime mover}} \right)^2
\]

In other words, when a part is rotating at a speed \(N\) different from the prime mover, the WK² \(\text{EQ}\) is equal to the WK² of the part's speed ratio squared.

In the example, the result can be obtained as follows:

The WK² equivalent is equal to:

\[
WK²_{EQ} = 100 \text{ lb.ft.}^2 + 900 \text{ lb.ft.}^2 \left( \frac{1}{3} \right)^2 + 27,000 \text{ lb.ft.}^2 \left( \frac{1}{3} \right)^2
\]

Finally:

\[
WK²_{EQ} = \text{lb.ft.}^2_{pm} + 100 \text{ lb.ft.}^2_{Red} + 3,000 \text{ lb.ft}^2_{Load}
\]

\[
WK²_{EQ} = 3200 \text{ lb.ft.}^2
\]

The total WK² equivalent is that WK² seen by the prime mover at its speed.

**Electrical Formulas**
To Find | Alternating Current
---|---
| Single-Phase | Three-Phase |
Amperes when horsepower is known | \( \frac{HP \times 746}{E \times \text{Eff} \times \text{pf}} \) \( \frac{HP \times 746}{1.73 \times E \times \text{Eff} \times \text{pf}} \)
Amperes when kilowatts are known | \( \frac{Kw \times 1000}{E \times \text{pf}} \) \( \frac{Kw \times 1000}{1.73 \times E \times \text{pf}} \)
Amperes when kva are known | \( \frac{Kva \times 1000}{E} \) \( \frac{Kva \times 1000}{1.73 \times E} \)
Kilowatts | \( \frac{I \times E \times \text{pf}}{1000} \) \( \frac{1.73 \times I \times E \times \text{pf}}{1000} \)
Kva | \( \frac{I \times E}{1000} \) \( \frac{1.73 \times I \times E}{1000} \)
Horsepower = (Output) | \( \frac{I \times E \times \text{Eff} \times \text{pf}}{746} \) \( \frac{1.73 \times I \times E \times \text{Eff} \times \text{pf}}{746} \)

\( I = \text{Amperes}; \ E = \text{Volts}; \ \text{Eff} = \text{Efficiency}; \ \text{pf} = \text{Power Factor}; \ Kva = \text{Kilovolt-amperes}; \ Kw = \text{Kilowatts} \)

**Locked Rotor Current (I_L) From Nameplate Data**

Three Phase: \( I_L = \frac{577 \times HP \times KVA/HP}{E} \)

Single Phase: \( I_L = \frac{1000 \times HP \times KVA/HP}{E} \) \( \text{See: KVA/HP Chart} \)

**EXAMPLE:** Motor nameplate indicates 10 HP, 3 Phase, 460 Volts, Code F.

\[ I_L = \frac{577 \times 10 \times (5.6 \text{ or } 6.29)}{460} \]

\[ I_L = 70.25 \text{ or } 78.9 \text{ Amperes (possible range)} \]

**Effect Of Line Voltage On Locked Rotor Current (I_L) (Approx.)**

\[ I_L @ E_{LINE} = I_L @ E_{N/P} \times \frac{E_{LINE}}{E_{N/P}} \]

**EXAMPLE:** Motor has a locked rotor current (inrush of 100 Amperes (I_L)) at the rated nameplate voltage (E_{N/P}) of 230 volts.

What is I_L with 245 volts (E_{LINE}) applied to this motor?

\[ I_L @ 245 \text{ V.} = 100 \times \frac{254\text{V}}{230\text{V}} \]

\[ I_L @ 245\text{V.} = 107 \text{ Amperes} \]
Basic Horsepower Calculations

Horsepower is work done per unit of time. One HP equals 33,000 ft-lb of work per minute. When work is done by a source of torque (T) to produce (M) rotations about an axis, the work done is:

\[ \text{radius} \times 2 \pi \times \text{rpm} \times \text{lb.} \text{ or } 2 \pi TM \]

When rotation is at the rate N rpm, the HP delivered is:

\[ \text{HP} = \frac{\text{radius} \times 2 \pi \times \text{rpm} \times \text{lb.}}{33,000} = \frac{TN}{5,250} \]

For vertical or hoisting motion:

\[ \text{HP} = \frac{W \times S}{33,000 \times E} \]

Where:

- W = total weight in lbs. to be raised by motor
- S = hoisting speed in feet per minute
- E = overall mechanical efficiency of hoist and gearing. For purposes of estimating
- E = .65 for eff. of hoist and connected gear.

For fans and blowers:

\[ \text{HP} = \frac{\text{Volume (cfm)} \times \text{Head (inches of water)}}{6356 \times \text{Mechanical Efficiency of Fan}} \]

Or

\[ \text{HP} = \frac{\text{Volume (cfm)} \times \text{Pressure (lb. Per sq. ft.)}}{3300 \times \text{Mechanical Efficiency of Fan}} \]

Or

\[ \text{HP} = \frac{\text{Volume (cfm)} \times \text{Pressure (lb. Per sq. in.)}}{229 \times \text{Mechanical Efficiency of Fan}} \]

For purpose of estimating, the eff. of a fan or blower may be assumed to be 0.65.

Note: Air Capacity (cfm) varies directly with fan speed. Developed Pressure varies with square of fan speed. Hp varies with cube of fan speed.

For pumps:
HP = \frac{GPM \times \text{Pressure in lb. Per sq. in.} \times \text{Specific Grav.}}{1713 \times \text{Mechanical Efficiency of Pump}}

Or

HP = \frac{GPM \times \text{Total Dynamic Head in Feet} \times \text{S.G.}}{3960 \times \text{Mechanical Efficiency of Pump}}

where Total Dynamic Head = \text{Static Head + Friction Head}

For estimating, pump efficiency may be assumed at 0.70.

**Accelerating Torque**

The equivalent inertia of an adjustable speed drive indicates the energy required to keep the system running. However, starting or accelerating the system requires extra energy.

The torque required to accelerate a body is equal to the \(W^2\) of the body, times the change in RPM, divided by 308 times the interval (in seconds) in which this acceleration takes place:

\[
\text{ACCELERATING TORQUE} = \frac{W^2N}{308t}
\]

Where:

- \(N\) = Change in RPM
- \(W\) = Weight in Lbs.
- \(K\) = Radius of gyration
- \(t\) = Time of acceleration (secs.)
- \(W^2\) = Equivalent Inertia
- 308 = Constant of proportionality

Or

\[
T_{\text{Acc}} = \frac{W^2N}{308t}
\]

The constant (308) is derived by transferring linear motion to angular motion, and considering acceleration due to gravity. If, for example, we have simply a prime mover and a load with no speed adjustment:

**Example 1**

![Diagram](http://www.reliance.com/mtr/flaclcmn.htm)
The WK^2_{EQ} is determined as before:

\[ WK^2_{EQ} = WK^2_{pm} + WK^2_{Load} \]

\[ WK^2_{EQ} = 200 + 800 \]

\[ WK^2_{EQ} = 1000 \text{ ft.lb.}^2 \]

If we want to accelerate this load to 1800 RPM in 1 minute, enough information is available to find the amount of torque necessary to accelerate the load.

The formula states:

\[ T_{Acc} = \frac{WK^2_{EQ}}{308t} \]

\[ T_{Acc} = \frac{1000 \times 1800}{308 \times 60} \]

\[ T_{Acc} = \frac{1800000}{18480} \]

\[ T_{Acc} = 97.4 \text{ lb.ft.} \]

In other words, 97.4 lb.ft. of torque must be applied to get this load turning at 1800 RPM, in 60 seconds.

Note that \( T_{Acc} \) is an average value of accelerating torque during the speed change under consideration. If a more accurate calculation is desired, the following example may be helpful.

**Example 2**

The time that it takes to accelerate an induction motor from one speed to another may be found from the following equation:

\[ t = \frac{WR^2 \times \text{change in rpm}}{308 \times T} \]

Where:

- \( T \) = Average value of accelerating torque during the speed change under consideration.
- \( t \) = Time the motor takes to accelerate from the initial speed to the final speed.
- \( WR^2 \) = Flywheel effect, or moment of inertia, for the driven machinery plus the motor rotor in lb.ft.\(^2\) (\( WR^2 \) of driven machinery must be referred to the motor shaft).

The Application of the above formula will now be considered by means of an example. Figure A shows the speed-torque curves of a squirrel-cage induction motor and a blower which it drives. At any speed of the blower, the difference between the torque which the motor can deliver at its shaft and the torque required by the blower is the torque available for acceleration. Reference to Figure A shows that the accelerating torque may vary greatly with speed. When the speed-torque curves for the motor and blower intersect there is no torque available for acceleration. The motor then drives the blower at constant speed and just delivers the torque required by the load.
In order to find the total time required to accelerate the motor and blower, the area between the motor speed-torque curve and the blower speed-torque curve is divided into strips, the ends of which approximate straight lines. Each strip corresponds to a speed increment which takes place within a definite time interval. The solid horizontal lines in Figure A represent the boundaries of strips; the lengths of the broken lines the average accelerating torques for the selected speed intervals. In order to calculate the total acceleration time for the motor and the direct-coupled blower it is necessary to find the time required to accelerate the motor from the beginning of one speed interval to the beginning of the next interval and add up the incremental times for all intervals to arrive at the total acceleration time. If the WR² of the motor whose speed-torque curve is given in Figure A is 3.26 ft.lb.² and the WR² of the blower referred to the motor shaft is 15 ft.lb.², the total WR² is:

\[ 15 + 3.26 = 18.26 \text{ ft.lb.}^2, \]

And the total time of acceleration is:

\[
\frac{\text{WR}^2}{308} \left[ \frac{\text{rpm}_1}{T_1} + \frac{\text{rpm}_2}{T_2} + \frac{\text{rpm}_3}{T_3} + \cdots + \frac{\text{rpm}_9}{T_9} \right]
\]

Or

\[
t = \frac{18.26}{308} \left[ \frac{150}{46} + \frac{150}{48} + \frac{300}{47} + \frac{300}{43.8} + \frac{200}{39.8} + \frac{200}{36.4} + \frac{300}{32.8} + \frac{100}{29.6} + \frac{40}{11} \right]
\]

\[ t = 2.75 \text{ sec.} \]

**Figure A**

Curves used to determine time required to accelerate induction motor and blower

**Accelerating Torques**

- \( T_1 = 46 \text{ lb.ft.} \)
- \( T_4 = 43.8 \text{ lb.ft.} \)
- \( T_7 = 32.8 \text{ lb.ft.} \)
- \( T_2 = 48 \text{ lb.ft.} \)
- \( T_5 = 39.8 \text{ lb.ft.} \)
- \( T_8 = 29.6 \text{ lb.ft.} \)
- \( T_3 = 47 \text{ lb.ft.} \)
- \( T_6 = 36.4 \text{ lb.ft.} \)
- \( T_9 = 11 \text{ lb.ft.} \)
Duty Cycles

Sales Orders are often entered with a note under special features such as:

"Suitable for 10 starts per hour"
Or
"Suitable for 3 reverses per minute"
Or
"Motor to be capable of accelerating 350 lb.ft.²"
Or
"Suitable for 5 starts and stops per hour"

Orders with notes such as these can not be processed for two reasons.

1. The appropriate product group must first be consulted to see if a design is available that will perform the required duty cycle and, if not, to determine if the type of design required falls within our present product line.
2. None of the above notes contain enough information to make the necessary duty cycle calculation. In order for a duty cycle to be checked out, the duty cycle information must include the following:
   a. Inertia reflected to the motor shaft.
   b. Torque load on the motor during all portions of the duty cycle including starts, running time, stops or reversals.
   c. Accurate timing of each portion of the cycle.
   d. Information on how each step of the cycle is accomplished. For example, a stop can be by coasting, mechanical braking, DC dynamic braking or plugging. A reversal can be accomplished by plugging, or the motor may be stopped by some means then re-started in the opposite direction.
   e. When the motor is multi-speed, the cycle for each speed must be completely defined, including the method of changing from one speed to another.
   f. Any special mechanical problems, features or limitations.

Obtaining this information and checking with the product group before the order is
entered can save much time, expense and correspondence.

Duty cycle refers to the detailed description of a work cycle that repeats in a specific time period. This cycle may include frequent starts, plugging stops, reversals or stalls. These characteristics are usually involved in batch-type processes and may include tumbling barrels, certain cranes, shovels and draglines, dampers, gate- or plow-positioning drives, drawbridges, freight and personnel elevators, press-type extractors, some feeders, presses of certain types, hoists, indexers, boring machines, cinder block machines, keyseating, kneading, car-pulling, shakers (foundry or car), swaging and washing machines, and certain freight and passenger vehicles. The list is not all-inclusive. The drives for these loads must be capable of absorbing the heat generated during the duty cycles. Adequate thermal capacity would be required in slip couplings, clutches or motors to accelerate or plug-stop these drives or to withstand stalls. It is the product of the slip speed and the torque absorbed by the load per unit of time which generates heat in these drive components. All the events which occur during the duty cycle generate heat which the drive components must dissipate.

Because of the complexity of the Duty Cycle Calculations and the extensive engineering data per specific motor design and rating required for the calculations, it is necessary for the sales engineer to refer to the Product Department for motor sizing with a duty cycle application.

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