Determining Motor Load & Efficiency from Measured Data

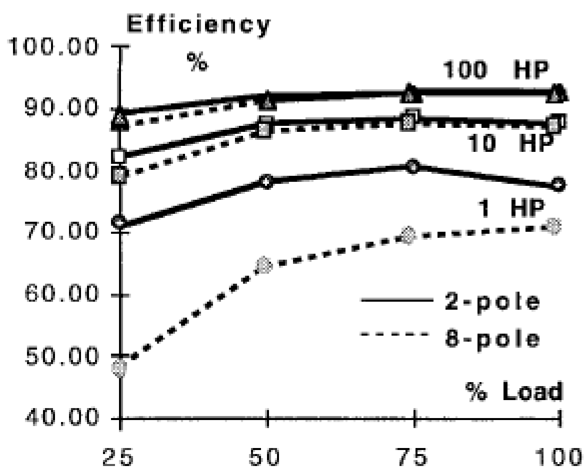
A. Bhatia

Course Content

Those familiar with motors know that just because a motor has a nameplate rating of 50 horsepower doesn't mean that it actually delivers 50 horsepower to its load. The load itself determines the horsepower needed to drive it, and whatever motor is connected to that load will try to deliver the power that the load demands. If the motor is called upon to deliver more power than it is designed to deliver, it will surely overheat, possibly stall, and eventually burn out. If it is called upon to deliver much less than rated power, it will operate inefficiently, wasting energy and energy dollars. The evaluation of motors focuses on the operating efficiency and motor load to identify energy efficiency gains and possible reliability improvements. This requires a reliable method for assessing motor performance in the field.

REASONS TO DETERMINE MOTOR LOADING

Motors are typically most efficient around 75% of their rated load. Their efficiency decreases slightly as the load increases to 100% of the rated load. Going the other way, efficiency starts dropping off a little more rapidly, down to around 50% load. Beyond that, motor efficiency drops off precipitously. Although the exact part-load efficiency curve of a motor will vary with size, type, manufacturer and other factors, the following graph provides a general overview of part-load efficiency curves.



Typical Efficiency Values v/s Load

Motor is considered under loaded when it is in the range where efficiency drops significantly with decreasing load. The figure above shows that the efficiency is not a strong function of load for a two-pole motor between 50% and 100% of load. However, the efficiency of an eight-pole, 1-hp motor shows a marked decline over that load range. Hence, the nameplate method may be applicable for some motors, but could result in substantial inaccuracies for other motor types.

LOAD FACTOR (LF)

The ratio of the actual power coming out of a motor to its rated power is called the motor's *load factor* — **LF**. It is usually expressed in per cent:

LF (%) = 100 x Actual Power Out / Rated Power Out

Of course, if you happen to know the load factor, you can calculate the **Actual Power Out**:

Actual Power Out = LF (%) x Rated Power Out / 100

The actual power out shall always be less than the rated power out due to the efficiency constraints of the motors under different operating scenarios such under load operation, rewound motors, fluctuating electrical parameters etc in addition to the inherent fixed motor losses.

MOTOR LOSSES

Power Losses in a motor are that portion of the input power that becomes heat rather than driving the load. These losses can be divided into two categories-

- **Fixed Losses**
- **variable Losses**

Fixed losses are assumed to be constant at all conditions of motor loading from no load to full rated load. This is not exactly true, but it is nearly so, and little significant error is created by this approximation. Fixed losses include magnetic core losses (hysteresis and eddy current) and mechanical friction losses (bearing friction, brush friction, and air friction or windage).

Variable Losses are those that vary with the load on the motor and thus with the motor current. These losses increase as the load on the motor, and therefore the current drawn by the motor, increase. They are primarily the power lost in the resistance of the motor windings and are often called copper losses, or I^2R losses. Variable losses also include stray load losses such as minor variations in fixed losses with load and speed and other small miscellaneous losses. Variable losses are approximately proportional to the square of the motor load current.

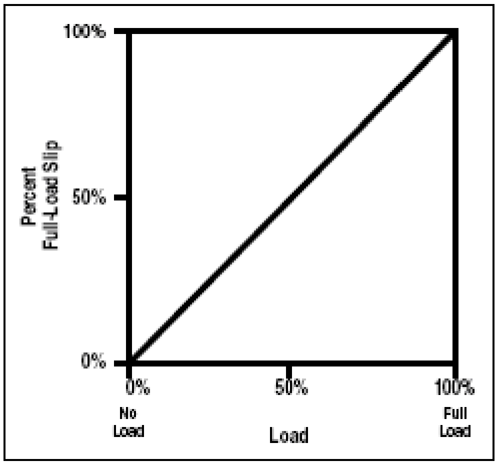
Field measurements for determining motor efficiency pose challenges that require developing various methods and devices. Power readings must be taken with the motor running under load, then uncoupled and running unloaded. Winding resistance must be measured. Temperature corrections must be performed.

DETERMINING MOTOR LOAD FACTOR

There is no way of knowing, just by glancing at an operating motor, how much power it is currently delivering to its load. There are 5 main ways to estimate a motor's load based on in-situ field measurements (and a sixth way suitable for laboratory use). These are described below, from least accurate to most accurate. Typically, the more accurate calculations require more measurements and input data.

Method 1: SLIP METHOD

Slip is the difference between synchronous and shaft speed. A motor's speed and slip is proportional to its load. The amount of slip present is proportional to the load imposed upon the motor by the driven equipment (see Figure below). The no-load speed of induction motors is always close to the synchronous speed and at full load; the motor operates at its rated speed. For example, a motor running with a 50% load has a slip halfway between the full load and synchronous speeds.



Percent Motor Slip as a Function of Motor Load

The slip method for estimating motor load is recommended when only operating speed measurements are available. The motor shaft speed under load conditions can be taken from an accurate strobe tachometer.

The synchronous speed of an induction motor is usually available from motor nameplate rating or can be calculated. It depends on the frequency of the power supply and on the number of poles for which the motor is wound. The higher the frequency, the faster a motor runs. The more poles the motor has, the slower it runs. Table below indicates typical synchronous speeds.

Poles	60 Hertz
2	3600
4	1800
6	1200
8	900
10	720
12	600

Induction Motor Synchronous Speeds

Conditions for Slip Method Application:

1) The slip method presumes that the percentage of load is closely proportional to the percentage of the ratio of measured slip to full-load slip.
2) Applied voltage should be within 5% of nameplate rating
3) Should not be used on rewound motors
4) Motors should be operating under steady load conditions
5) Method is only applicable to induction motors

Procedure:

1) Read and record the motors nameplate Full Load Speed.
2) Determine the synchronous speed No Load Speed (RPM) (750, 1000, 1500, and 3000)
3) Measure and record the Operating Load Speed with a tachometer (RPM): By using a tachometer to measure actual motor speed, it is possible to calculate motor loads. The safest most convenient and usually most accurate tachometer is a battery powered stroboscopic tachometer. Mechanical tachometers, plug-in tachometers, and tachometers which require stopping the motor to apply paint or reflective tape should be avoided.

Measurements required:

S = Measured motor speed, RPM

Inputs required:

S_s = Motor's synchronous speed (RPM)

S_R = Motor's nameplate full load speed (RPM)

Formula:

The motor load can be estimated with slip measurements as shown in equation below:

$$Load = \frac{Slip}{S_S - S_R} \times 100\%$$

$$Slip = S_S - S$$

$$S_S = \frac{120 \times F}{P}$$

Where:

Load = Output power as a % of rated power

S_S ***= Synchronous speed in rpm***

S_R ***= Nameplate full load speed***

S ***= Measured speed in rpm***

F ***= Frequency in Hz***

P ***= Number of poles***

The term *slip* refers to the difference between synchronous speed and actual speed. In the equation above, the numerator is *operating slip* and the denominator is *full-load slip*.

Example:

Given

- Synchronous speed (S_s) = 1800 RPM
- Name plate full load speed (S_R) = 1750 RPM
- Measured motor speed (S) = 1770 RPM
- Name plate rated horsepower = 25 hp
- Load = (1800 - 1770) / (1800 - 1750) = 60%
- Actual output horsepower would be 60% x 25 = 15 hp

Accuracy of Slip Method

The slip method is quick and easy. It only requires one measurement, motor speed. However, it is not very accurate. It depends on the manufacturer's reported full load speed reported on the nameplate.

NEMA MG-1 Section 12.46 states that variation from the nameplate speed of AC integral horsepower induction motors shall not exceed 20% of the difference between synchronous speed and rated speed when measured at rated voltage, frequency, and load and with an ambient temperature of 25ºC. This means that the largest uncertainty relates to the 20% tolerance that NEMA allows manufacturers in their reporting of nameplate full-load speed. Given this broad tolerance, manufacturers generally round their reported full-load speed values to some multiple of 5 rpm. While 5 rpm is but a small percent of the full-load speed and may be thought of as insignificant, the slip method relies on the difference between full-load nameplate and synchronous speeds. Given a 40 rpm "correct" slip, a seemingly minor 5 rpm disparity causes a 12% change in calculated load.

Another problem with the slip technique is that the rated full load speed assumes the motor is operating at the rated voltage. Slip also varies inversely with respect to the motor terminal voltage squared—and voltage is subject to a separate NEMA tolerance of ± 10% at the motor terminals. Operating a motor at other voltages requires a voltage correction, shown below.

Method 1b Voltage Compensated Slip

A motor's slip varies inversely with the square of the voltage. Therefore, if a motor is operating at a voltage other than the rated voltage, its full load speed will be different from its rated full load speed. Therefore, the "slip" load calculation needs to be corrected for operating voltages other than the rated voltage, as shown below:

Measurements required:

S = measured motor speed, RPM

V = RMS voltage, mean line to line of 3 phases

Inputs required:

S_s = Motor's synchronous speed

S_R = Motor's full load speed

V_R = Motor's rated voltage

Formula:

$$Load = \frac{Slip}{(S_S - S_R) \times (V_R / V)^2} \times 100\%$$

$$Slip = S_S - S$$

$$S_S = \frac{120 \times F}{P}$$

Where:

Load = Output power as a % of rated power

S_S = Synchronous speed in rpm

S_R = Nameplate full load speed

S = Measured speed in rpm

F = Frequency in Hz

P = Number of poles

V = RMS voltage, mean line to line of 3 phases

V_R = Nameplate rated voltage

Example:

Motor nameplate data: S_s = 1800 RPM, $S_{Full\ Load}$ = 1750 RPM,

V_R = 240 V

Measured motor speed = S = 1770 RPM

V = average RMS line-line current = 224 V

Load = (1800 - 1770) / [(1800 - 1750) x $(240/224)^2$] = 52%

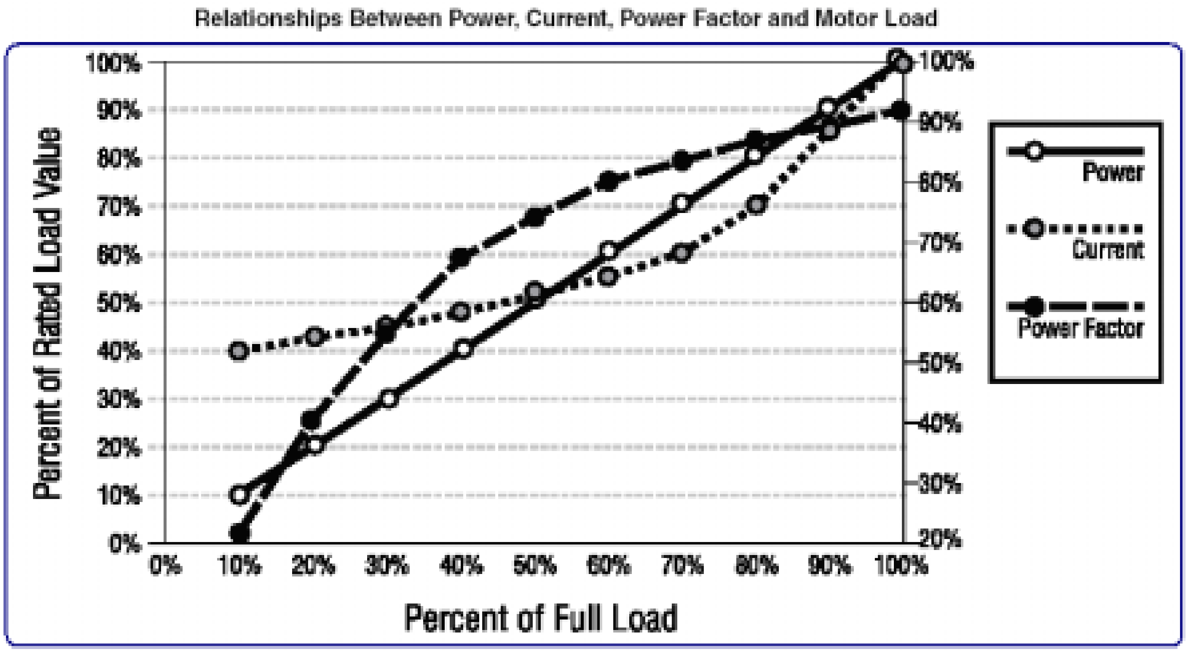
Accuracy

While the voltage-compensated slip method is attractive for its simplicity, its precision should not be overestimated. The shortcomings with this measurement are that S_R is subject to a ± 20% reporting tolerance and V_R is subject to a ± 10% reporting tolerance (NEMA). Again, due to inaccuracies, this method is not recommended for energy load measurements. Typically, the projection of a light load through the basic slip method is relatively more accurate than the projection of a heavy load.

The slip method is generally not recommended for determining motor loads in the field.

Method 2: VOLTAGE COMPENSATED CURRENT RATIO

This method presumes that the percentage of load is closely proportional to the percentage of the ratio of measured current to full-load current. The amperage draw of a motor varies approximately linearly with respect to load, down to about 50 - 60% load. Below this load range, due to reactive magnetizing current requirements, power factor degrades and the other inefficiencies cause increasing non-linearity. In the low load region, current measurements are not a useful indicator of load.



Source: "Fact Sheet: Determining Motor Load & Efficiency," US DOE Motor Challenge Program

The current load estimation method is recommended when only amperage measurements are available. If the nameplate full-load current is known and the actual current is measured, one can estimate the motor load. As with rated speed in the slip calculations, the rated full load current is based on operation at the rated voltage. If the actual operating voltage is different from the rated voltage, the full-load current must be corrected.

Conditions:

- Applied voltage must be within 5% of nameplate rating
- The indicated line amperage must be below the full load nameplate rating

Procedure

- Measure and record line amperage with load connected and running
- If possible, disconnect motor from load. Measure and record line amperage when motor is running without load
- Read and record the motor's nameplate amperage for the voltage being used
- Insert the values in the formulae indicated below

Measurements required:

I = RMS motor current, average of 3 phases.

V = average RMS voltage, mean line to line of 3 phases

$I_{no\text{-}load}$ = No load amperage

Inputs required:

I_r = nameplate rated current at full load

V_r = nameplate rated voltage at full load

Formula:

The equation that relates motor load to measured current values is shown in equation below.

$$Load = \frac{I}{Ir} \times \frac{V}{Vr} \times 100\%$$

The above equation tends to overestimate

Another equation below is available, but the drawback is it tends to underestimate.

$$Load = \frac{(I - I_{noload})}{(Ir - I_{noload})} \times \frac{V}{Vr}$$

Average of two may give most accurate result.

Where:
Load = Output power as a % of rated power
I = RMS current , mean of 3 phases
Ir = Nameplate rated current
I_{noload} = No Load Amperage
V = RMS voltage, mean line to line of 3 phases
Vr = Nameplate rated voltage

Example:

Given

- Motor nameplate data: I_r = 20 Amps, V_r = 240 V
- Measured RMS line current: I_a = 16.2 Amps, I_b = 15.5 Amps, I_c = 16.8 Amps
- Measured RMS line-line voltage: V_{ab} = 232 V, V_{bc} = 228, V_{ac} = 236 V
- $I = (I_a + I_b + I_c) / 3 = (16.2 + 15.5 + 16.8)/3 = 16.167$ Amps
- $V = (V_{ab} + V_{bc} + V_{ac})/3 = 232$ V
- Load = (16.167/20) x (232/240) = 78.1%

Accuracy of Voltage Compensated Current Ratio Method

This method is more accurate than the slip methods. An advantage of using the current-based load estimation technique is that NEMA MG1-12.47 allows a tolerance of only 10% when reporting nameplate full-load current. In addition, motor terminal voltages only affect current to the first power, while slip varies with the square of the voltage. NEMA MG-1, Section 12.47, states that, when operated at rated voltage, rated frequency, and rated horsepower output, the input in amperes shall not vary from the nameplate value by more than 10%. In contrast, the slip methods must deal with a 20% reporting tolerance for rated full load speed, and the 10% tolerance in rated voltage which is squared.

Method 3: **DIRECT POWER (kWh) CALCULATION**

Measuring the motor's actual power provides a convenient and accurate way to determine the load. In this case, the motor's measured kW (or V, I and PF) is required.

Measurements required:

$P_{measured}$ = measured motor load, kW (straight from the instrument)

Or

I = RMS motor current, average of 3 phases.

V = average RMS line-line current

PF = measured power factor

Inputs required:

HP = Motor's rated power output, HP (or kW)

N_{Rated} = Motor's full load rated efficiency

Formula:

With measured parameters taken from hand-held instruments, use equation 1) to calculate the three-phase input power to the loaded motor.

Equation 1); $P_{measured} = \sqrt{3} * V * I * PF / 1000$ [kW] (if not measured directly from the meter)

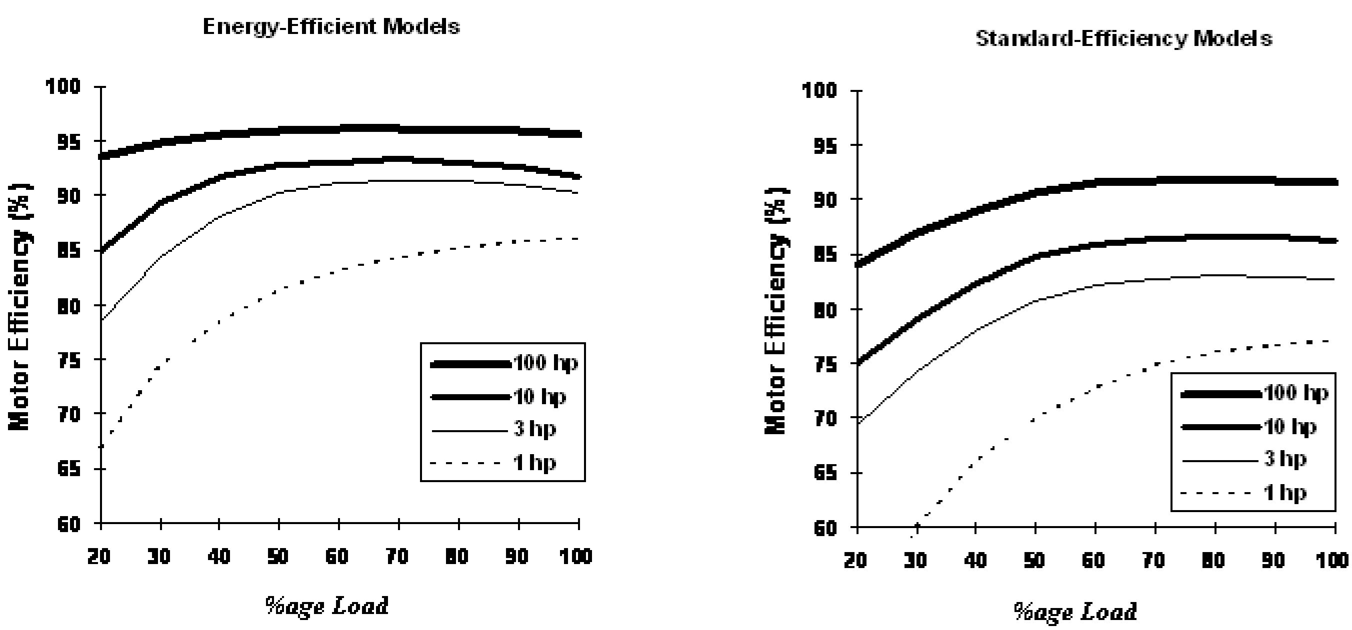
Equation 2): $P_{rated} = HP * (0.7457 \text{ kW/HP}) / N_{rated}$ [kW] = motor's power input at rated full load

Equation 3): $Load = P_{measured} / P_{rated}$

With equation 2, the exact efficiency ($N_{rated)}$) is almost never known, but there are several ways to arrive at a reasonable approximation.

- Refer to the motor manufacturer's literature or motor nameplate data.
- Use *typical* efficiency information such as that presented in the two graphs, or a combination of typical curves and single-point *actual* data.

TYPICAL EFFICIENCY PROFILES — SEVERAL 1800 RPM 3-PHASE MOTORS



Example:

Motor nameplate data: HP = 40 HP, $N_{Full\ Load}$ = 91.2%

Measured RMS line current: I_a = 36 Amps, I_b = 38 Amps, I_c = 37 Amps

Measured RMS line-line voltage: V_{ab} = 469 V, V_{bc} = 473, V_{ac} = 467 V

Measured PF: PF_a = 0.75, PF_b = 0.78 Amps, PF_c = 0.76 Amps

$I = (I_a + I_b + I_c)/3$ = 37 Amps

$V = (V_{ab} + V_{bc} + V_{ac})/3$ = 469.67 V

$PF = (PF_a + PF_b + PF_c)/3 = 0.763$

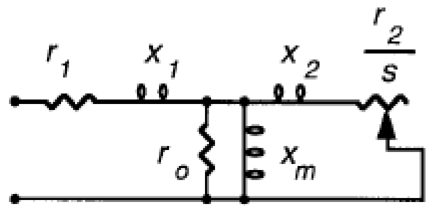
$P_{measured} = \sqrt{3} * 469.67 * 37 * 0.763$ = 22.9 kW

$P_{rated} = 40 * (0.7457 \text{ kW/HP})$./ kW

Load = 22.9 / 32.7 = 70%

Method 4: **EQUIVALENT CIRCUIT METHOD**

Efficiency assessed through an equivalent circuit method is based on the impedance values of an equivalent circuit, shown in figure below. The six impedances are stator resistance, stator leakage reactance, magnetizing reactance, core-loss resistance, rotor leakage reactance, and rotor resistance. The slip affects the load of the equivalent circuit.



A six-impedance equivalent circuit

The advantage of the equivalent circuit method is that the performance of a motor can be predicted at any load when the impedance values are known. On the other hand, the impedance values can change a great deal when the motor speed varies between standstill and no load, due to deep bar effects and magnetic saturation. There are different approaches for obtaining the impedance values. When the six-impedance equivalent circuit is used, all the losses other than the friction and windage loss that are not represented by the stator copper, rotor copper, and no-load core-loss resistances, are grouped together in a collective loss named stray-load loss.

The US Department of Energy's Oakridge National Lab has developed a program called ORMEL 96 that uses an equivalent circuit technique, based on IEEE's standard 112 Method F, to determine motor load. It involves the use of motor nameplate data in conjunction with selected combinations of input power, voltage, current, and/or operating speed. With the percent load known, the software determines as-loaded efficiency from default tables based on the motor type, condition, and horsepower. *Motor Master+* automatically chooses the best available method based upon the data it is given.

Measurements required:

S = measured motor speed, RPM

Inputs required:

Motor nameplate data, including kVA code.

Formula:

Unavailable & complex; this technique is a software model, currently implemented in the Motor Master+ 4.0 software. The *Motor Master+ 4.0* software incorporates several methods for determining motor load. This method has been shown to be very effective and accurate.

Method 5: **SPECIALIZED MOTOR TESTING EQUIPMENT**

A number of manufacturers produce specialty motor performance testing equipment. These include the Vogelsang and Benning Motor-Check (www.vogelsangbenning.de), the ECNZ Vectron Motor Monitor, and the Niagra Instruments MAS-1000 (www.bwdarrah.com/productgs/prod02a3.htm). These instruments perform testing to IEEE standard 112 Method E, or similar. Typically, these tests require the motor to be disconnected from the load for a no load test, and disconnected from power for a resistance test. These systems have shown to be accurate to within 3% for adverse conditions (e.g., voltage deviation, voltage unbalance, damaged or rewound windings, etc.) and within 2% for normal conditions. These systems perform all calculations internally. The equipment is relatively expensive, requires some expertise for correct operation, and requires the motors to be temporarily taken out of service.

Method 6: **LABORATORY METHODS**

Credible efficiency ratings are normally obtained in a laboratory, following carefully controlled dynamometer testing procedures as described in IEEE Standard 112(b). Dynometers and other test equipment can be used to directly measure the actual motor shaft power, input power, efficiency, etc. generally, these are not suitable for field-use.

CALCULATING MOTOR EFFICIENCY FROM MEASURED LOAD DATA

By definition, a motor of a given rated horsepower is expected to deliver that quantity of power in a mechanical form at the motor shaft. A motor's efficiency is given by:

Efficiency = shaft power out / electrical power in

Measuring the actual shaft power requires a dynometer or similar device; however, as discussed above, it is possible to approximate the motor's load from a variety of field measurements. In some cases, the motor's efficiency can be calculated based on these load estimates, as shown below:

Efficiency = P_{rated} * (0.7457 kW/HP) *Load / P_{in}

Where:

P_{rated} = nameplate rated power output, in HP

Load = % part load at which the motor is operating

P_{in} = measured electrical input power, kW

Or

Efficiency = P_{rated} * (0.7457 kW/HP) *Load / P_{in}

Where:

P_{rated} = nameplate rated power output, in kW

Load = % part load at which the motor is operating at

P_{in} = measured electrical input power, kW

One caveat is that if the motor load was calculated using the kWh measurement technique, this method will not work since the motor's rated efficiency was used in this calculation:

$P_{measured}$ = √3 * V * I * PF / 1000 [kW]

P_{rated} = HP * (0.7457 kW/HP) / E_{rated} [kW] = motor's power input at rated full load

Load = $P_{measured}$ / P_{rated}

Minimum Efficiency Standards and Efficiency Ratings

Minimum motor efficiency standards are evolving, and vary from country to country. Nameplate efficiencies of a given motor can be evaluated according to different standards. The three most frequently used standards are the National Electrical Manufacturers Association (NEMA) that uses IEEE Standard 112, the Japanese Electrotechnical Committee (JEC), and the International Electrotechnical Commission (IEC). These three standards are not in agreement and may result in a given motor being stamped with rather different efficiencies. A typical example below illustrates the confusing international nameplate data situation:

EFFICIENCIES OF A MOTOR EVALUATED BY DIFFERENT STANDARDS

IEEE 112 Method B	*JEC37*	*IEC34-2*
90.0%	*93.1%*	*92.7%*

The actual field efficiency may be quite different from the nameplate rating. This is because of two factors viz. the motor may have been rewound and secondly the field environment pertinent to the voltage unbalance and harmonics content may be different from that for which the nameplate data is derived.

SECTION-2 IN – SITU MOTOR PARAMETERS MEASURING INSTRUMENTS

This section provides a brief overview of some of the measurements required to determine a motor's load. Depending on which load calculation techniques are used, some or all of these measurements may be required.

Safety First:

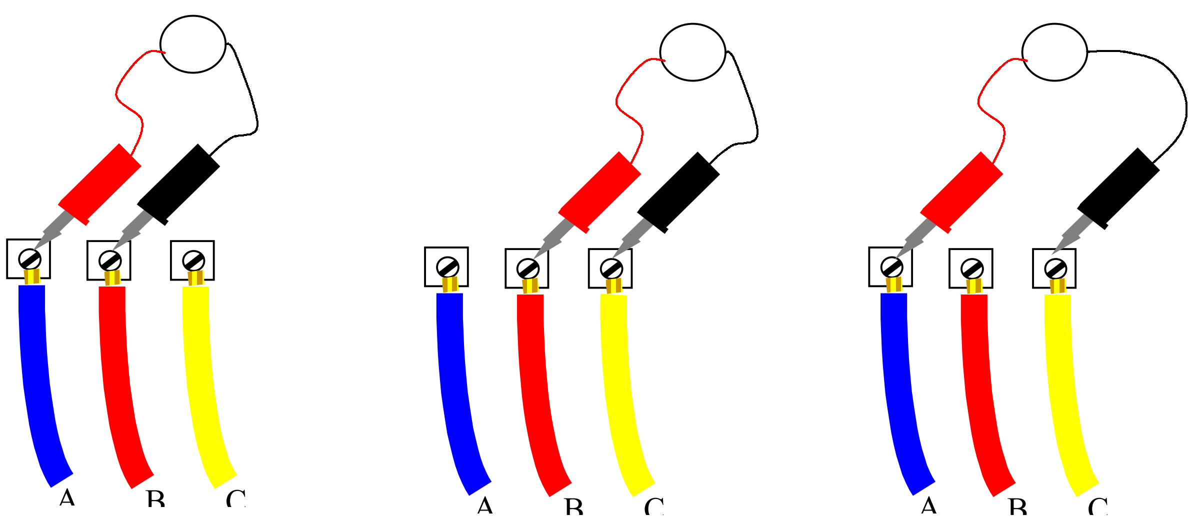
Always wear insulating protective gloves and other appropriate safety gear when working with live circuits. Follow all applicable safety procedures.

VOLTAGE MEASUREMENT

Voltage is a differential parameter; it is always measured between two points. There are two ways to measure three-phase voltage—between two of the three lines or between a line and neutral or ground. Service and motor voltages are quoted as line to line, unless otherwise noted. Because of the phase difference, line-to-line readings are 1.73 times line-to-neutral readings. Service and motor nameplate voltages are usually quoted as line-line values, unless specifically noted differently.

Inside a three-phase motor there are three windings, one for each phase. The easiest three-phase motor connection to visualize is with each of the three windings connected line to neutral. This is called WYE because, schematically, it looks like the letter "Y". A more common connection eliminates the neutral tie and connects the three windings from line to line. This is called delta because, schematically, this looks like a triangle or the Greek letter Delta. The winding experiences 73% higher voltage when connected line to line, so it must be designed for the type of connection it will have. Even if a motor's windings are internally WYE connected, its nameplate voltage rating is the line-to-line value.

Line to line means that the voltage is measured between 2 of the 3 supply lines as shown below (in contrast to measuring the voltage between the line and neutral wires).

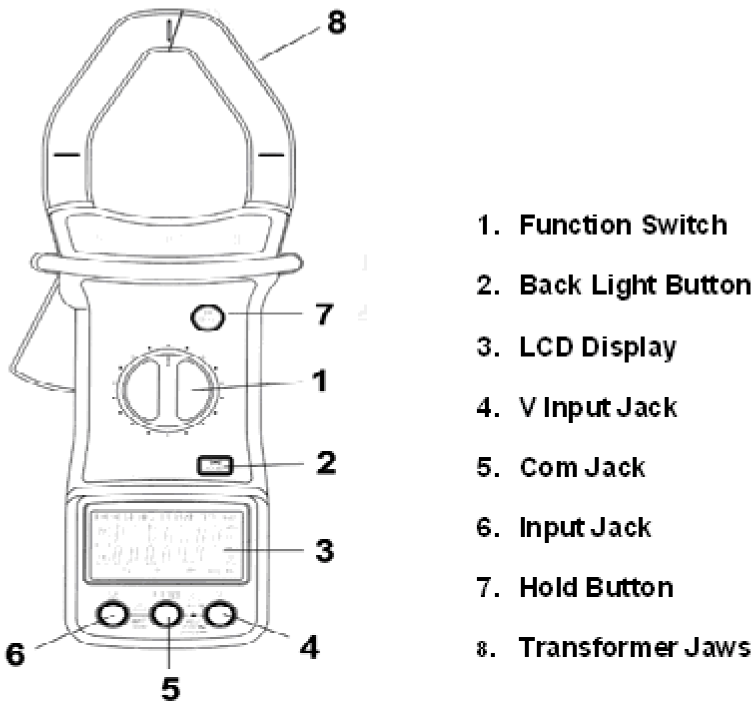


Measurement locations for line-line voltage measurements

In an AC circuit, the current and voltage oscillate back and forth between positive and negative peak values at 50 or 60 cycles per second (Hz). A single "instantaneous" voltage or current reading could be anywhere between the positive and negative peak values. Therefore, some kind of "average" or typical voltage reading is needed. The Root-Mean-Square (RMS) value is the value that is used in AC electrical measurements or calculations. Mathematically speaking, it is calculated by squaring all of the instantaneous readings for a cycle, averaging, and then taking the square root. The RMS value is always 70.7% of the peak value. The RMS value will provide the same heating rate in a resistive load as a DC voltage/current of the same magnitude. Most AC meters measure the RMS value. However, some less expensive meters assume that the voltage or current oscillates in a sine wave. If there are waveform disturbances (e.g., output from an inverter on some variable frequency drives, distortion from electronic equipment, etc.) or at a frequency other than 50 or 60 Hz, a "True RMS" meter should be used.

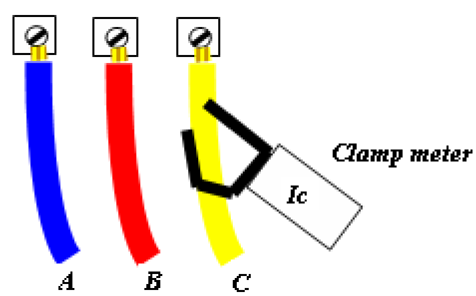
CURRENT MEASUREMENT

The RMS line current is typically used in motor load and efficiency calculations. In the field, current is usually measured with clamp-on split-core or fork-type current probes (shown below). The fork-type meters are nice because they minimize the need to reach in and move wires, etc. in order to make measurements. This can be a safety factor. Both Fluke and Amprobe make fork-type current probes. Alternately, solid-core "donut" current transformers (CTs) can be used, but these require electrical disconnection and are not typically used for temporary measurements.



TYPICAL FORK TYPE AND CLAMP-ON CURRENT METER

The appropriate measurement location is shown below for one phase.



Line Current Measurement at terminal C

PRACTICAL CONSIDERATIONS FOR CLAMP-ON CTs

It should go without saying that use of accurate test equipment is of fundamental importance. IEEE Standard 112 requires high accuracy instruments, with individual errors of less than ±0.5% of full scale, including both amplitude and phase-angle effects.

For field measurements, instrument accuracy is an important issue. When either temporary portable instruments or permanently installed instruments that are not intended for precision metering are used, such accuracies can be extremely difficult to achieve. Portable monitoring instruments typically consist of clamp-on current transformers or Hall-effect pickups and some means of voltage transduction. Some clamp-on style probes are available with manufacturer-specified amplitude accuracies approaching 0.5%, but, even for these high accuracy clamp-on probes; there are practical considerations that can considerably reduce actual accuracies. The practical accuracy, for power monitoring purposes, is dependent upon both phase angle and amplitude.

If compensation for phase-angle shift is not provided, the associated error (for power/power factor consideration purposes) can be significantly greater than amplitude errors. For example, a phase-angle shift of 1.5 , which is typical for high-accuracy clamp-on transformers (although some have much greater shifts), would result in a power/power factor indication error of about 3% at an actual power factor of 0.7, if compensation for the phase shift is not made. Since, as noted above, phase shift is a function of amplitude, it is a difficult proposition to provide full bandwidth compensation.

The other factors that can greatly influence clamp-on accuracies are listed below:

1) Make sure the clamp-on jaws are completely closed

This is essential to completing the magnetic circuit of the CT. If there are tight clearances where the CT is used, the jaws can bind partially open, even when hand tension is released. The indicated current may be considerably in error. To ensure the jaws are fully closed, wiggle the probe a bit, making sure it moves freely and is not bound by adjacent wires or other obstructions. At higher current levels, a magnetic "buzz" created by a slight jaw separation can be heard and felt (through gloves, of course).

2) Measure and average all 3 phases, if possible

Under perfect conditions, all three phases should be equal. However, this is often not the case. A small unbalance in the supply voltage can result in a large current unbalance among the three phases. As a rule, a 1% unbalance in voltage will result in roughly a 7% unbalance in current. Even in the presence of a balanced power supply, there may be current unbalance on the order of 5%. Therefore it is important to measure all 3 phases.

3) Use properly sized CT's

Using over or under-sized CTs (current transformers--the clamp on "jaws") can result in large inaccuracies. For example, using a 2,000-amp CT with 0.5% of full span accuracy to measure a 20-amp current may result in a 50% measurement error.

4) Measurement Duration:

Particularly for measurements done in the field, it is important to recognize that the load of many machines fluctuates significantly, both over the long term (for instance, from changing plant conditions), as well as the short term (for example, load fluctuations from belt drives). In order to ensure that data accurately reflects the true average load, it is usually necessary to collect either several samples and develop a statistically valid measure or to acquire a relatively long sample of data (long can range from a few seconds to minutes, depending on the nature of the load). Belt driven devices, in particular, can cause relatively large load fluctuations (as much as 10% or more) at belt passing speed. Thus, a single short-duration sample (for example, a few cycles in length) may grossly misrepresent the actual average load condition.

5) Average the current on fluctuating loads

Many motor loads are fluctuating in nature. For example, a slight belt misalignment may cause an increase in motor load every time the pulley or sheaves pass a certain point, etc. Some current monitoring devices grab a very short sample (a few cycles, or milliseconds) of data and display a fixed result. Other devices continuously update the data, but the fluctuations make it difficult to pin down. A more representative measurement can be obtained on a multimeter with a min/max averaging feature. This feature is also helpful in averaging other system parameters that tend to fluctuate, such as pressure. If no such function is available, several samples can be statistically averaged. A computer-based data acquisition system or data logger simplifies the collection and analysis of many (and/or longer duration) samples.

6) Make sure you are measuring the actual motor current

The motor loads are inductive in nature and very often power factor-correcting capacitor banks are often used to compensate for this correction. When capacitors are used, particular care must be exercised in selecting the measurement location. Make sure you are measuring downstream from the power factor correction equipment and reading the actual motor input. Measuring upstream from the power-factor correction equipment can result in large errors--up to a 25% or greater difference in current. The current from the line to the combination of the motor and the capacitor bank will be less than the motor current. This seemingly contradictory behaviour is real, and it occurs because the current to the capacitor bank will lead the voltage by 90°, while the current to the motor will lag voltage by a variable amount, depending on load.

POWER FACTOR

The Basics

1) **Real power (kW) -** The power doing the work in the facility, turning motor shafts, lighting and heating. Real, or productive power, is the actual power used and is measured in kilowatts (kW).

2) **Reactive power (kVAr) -** Does no work. The power required to create magnetic fields in motors and transformers. Reactive power is measured in kilovars (kVAR).

3) **Apparent power (kVA) -** This is the total amount of power consumed by a customer including the real (working power) and the reactive (non-working) power. This is the power the utility company must deliver to the customer. Total power (measured in kVA) is a combination of real power and reactive power.

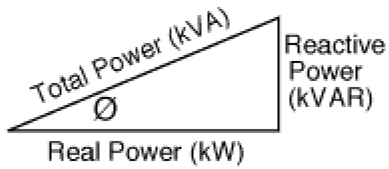
Power Factor (pf) is the ratio of real power (kW) to the apparent power (kVA). It is represented by the cosine of the angle of phase shift. The following diagram shows the relationship between real power (W), apparent power (VA) and reactive power (VAR). This ratio is an effective measure of system electrical efficiency and is represented as a percentage or decimal (e.g., 90% or 0.9).

POWER FACTOR CALCULATIONS

The power factor of a motor is an important reading because this is required for calculating a motor's power input ($P = \sqrt{3} * V * I * PF$). A motors power factor depends on its size, its design and quality, its condition (e.g., a poor rewind, loose connections, etc.), its load, power input (e.g., unbalanced phases, voltage sag, etc. can lower the PF), etc.

$$\text{Power Factor (pf)} = \frac{\text{kW (Real Power)}}{\text{kVA (Total Power)}}$$

Graphically, the Power Triangle on a system would look like this:



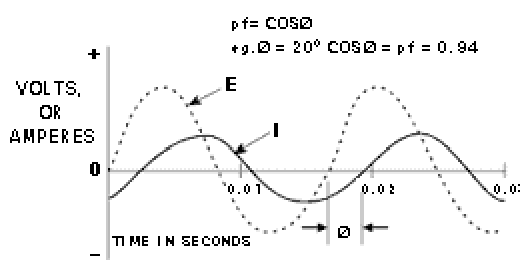
The relationship between kVA, kW, and kVAR is as follows:

$kVA^2 = kW^2 + kVAR^2$ or $VA^2 = W^2 + VAR^2$

Thus, with substitution, another formula for power factor could be derived:

$$pf = \frac{WATTS}{\sqrt{WATTS^2 + VAR^2}}$$

On a single-phase circuit, the current will usually lag behind the voltage. The amount of the lag can be measured in degrees (360° for one complete cycle). The cosine of this phase angle also equals the power factor.



EFFECTS OF POWER FACTOR

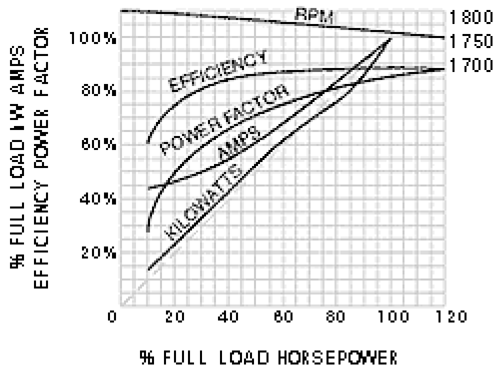
1) **System Capacity** - Your kVA is the total power available. Your useful power kW = (kVA) x (pf). The higher the system power factor, the more shall be the system capacity that is available. With more system capacity, voltage will remain more stable as loads are cycled on and off. Also more loads can be added to the system as needed.

2) **System Losses** - With a higher Power Factor, less current flows through your system. There is less power lost (I^2R losses) to heating of cables, bus bars, transformers, panels, etc. These devices will run cooler and last longer too.

3) **Utility Charges** - Electric utilities must maintain a high Power Factor on their distribution system for efficiency. They will typically bill customers for a low Power Factor or they may bill on kVA demand, which Power Factor will affect. Most utilities that bill a Power Factor penalty require a user to maintain a 95% Power Factor to avoid penalty.

POWER FACTOR & MOTOR LOADING

For most motors, the power factor varies significantly with load; a typical graph is shown below:



Motor Power Factor (as a function of % Full Load Amperage)

Induction motors have typically lagging Power Factor i.e. PF is less than unity. Power Factor is affected significantly by motor loading. Figure above represents a typical T-frame motor curve. It is evident that the highest Power Factor is at full loading. Since this Power Factor will affect the system Power Factor, proper sizing of motors is important. Over-sizing motors will lower the system Power Factor. Electric motor catalogues usually state the efficiency and power factor at full load and at various part loads (for example at no load, 25%, 50%, and 75%).

MEASURING POWER FACTOR

In the ideal AC electrical system the voltage and current are in phase. This condition only occurs on systems where the entire load is resistive, such as electric heat, incandescent lighting, or fluorescent lighting with power factor corrected ballasts. Electrical utilization equipment such as motors have a considerable amount of inductance and the inductive reactance (XL which is measured in ohms) causes the circuit current to lag the applied voltage. The actual amount, or number of degrees of lag, depends on the ratio of the Inductive Reactance (XL) in ohms to the ohmic value of Resistance (R) of the system.

The system power factor is the cosine of the phase angle between the system voltage and the system current expressed as a percent. For example, if the current is determined by measurement to lag the applied voltage by 30 degrees, the power factor of the system would be 86.6 percent. This is determined by finding the cosine of 30 degrees which is 0.866 (you can use either a Trigonometry Table or an Engineering Calculator for this) and multiplying the cosine of the angle by 100 to obtain the percent power factor.

There are several methods to calculate Power Factor. The method is usually determined by the math capabilities of the automation system.

1) If a watt transducer is used with a voltage and current transducer, the following formula is used:

$$pf = \frac{W}{V \times A \times 1.73}$$

2) If a VAR and Watt Transducer are used, the following formula would be used:

$$pf = \frac{WATTS}{\sqrt{WATTS^2 + VAR^2}}$$

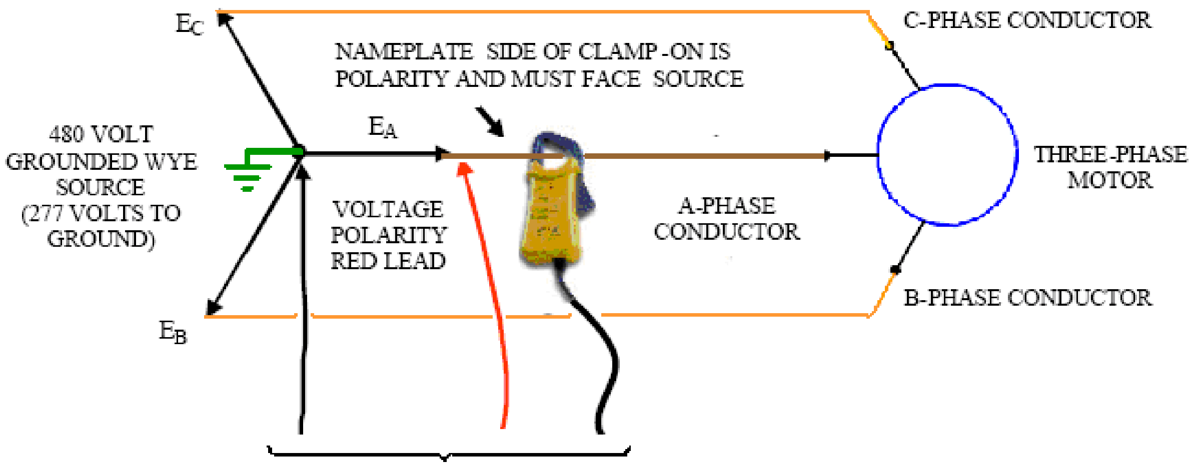
3) If a phase angle transducer is used to determine phase angle, then the following formula is used:

PF = Cos Ø

FIELD CONNECTIONS

Voltage-Current phase angle measurement is easily accomplished on a WYE system because, on any given phase, the phase current and the phase-to-ground voltage are in-phase at unity power factor. The voltage-current phase angle measurement may be taken directly from the phase angle meter. With all phase angle measurements, whether they be voltage-voltage or voltage-current, lead polarity is critical.

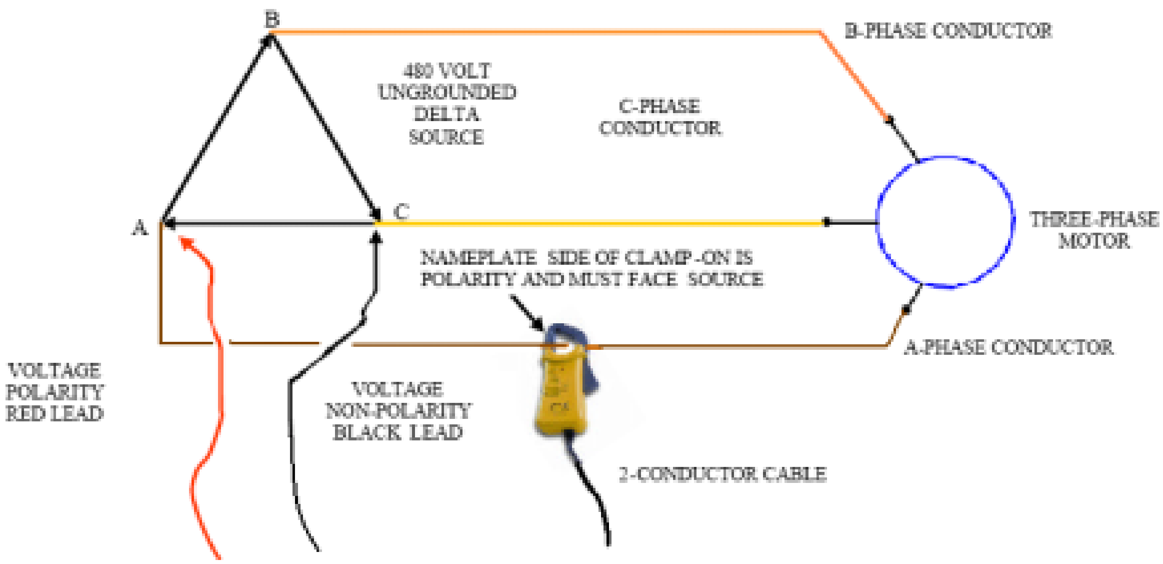
PHASE ANGLE MEASUREMENT - WYE SYSTEM



Leads connected to Power Factor Instrument with Voltage Polarity Red Lead connected to 208- 280V circuit

On a DELTA system, there is an inherent 30° phase shift (at unity power factor) between the line (phase) voltage and the line current which must be accounted for. This is because the line current on a DELTA system is the vector sum of two separate phase currents. In order to obtain a correct reading, voltage and current of the proper phase and polarity must be applied to the instrument.

PHASE ANGLE MEASURMENT- UNGROUNDED DELTA SYSTEM



Leads connected to Power Factor Instrument with Voltage Polarity Red Lead connected to 480V circuit

Once the system power factor is known, power factor correction, if desired, can be applied to the system using power factor correction capacitors or by using synchronous motors, either of which can supply leading Volt Amperes Reactive (VARs) to the system to compensate for the lagging power factor. Most electric utilities charge a penalty for poor system power factor, so keeping the power factor above the required minimum value will result in a lower utility bill and will also improve the voltage drop on the system.

DIRECT POWER MEASUREMENT

Power/Watt meters can also directly measure a motor's power (W, VA or VAR) and other electrical parameters such as the power factor, neutral current, etc. There are handheld meters that measure only a single phase, and larger instruments that simultaneously measure all 3 phases and the neutral. Again, refer to individual meter instructions for details on where to measure.

A typical 3-phase power-meter and logger

ROTATIONAL SPEED (RPM)

The synchronous speed of a motor is the speed at which the magnetic field inside the motor rotates. This provides the motor's driving force. The synchronous speed is determined solely by the frequency of the electrical supply and the number of poles inside the motor:

Synchronous Speed = $S_{synchronous}$ [RPM] = 120 * Frequency [Hz] / (Number of Poles)

Frequency [Hz]	Number of Poles	S_{sync} [RPM]
50	2	3000
50	4	1500
50	6	1000
50	8	750
50	10	600
50	12	500

Frequency [Hz]	Number of Poles	S_{sync} [RPM]
60	2	3600
60	4	1800
60	6	1200
60	8	900
60	10	720
60	12	600

For induction motors, the actual rotational speed (i.e., shaft speed) depends on the both the motors synchronous speed as well as the load. Under no load, the motor would theoretically rotate at the synchronous speed (in reality there is always some friction and other inefficiencies that impose a load). When a motor is loaded, its rotational speed slows down. The difference between the synchronous speed and actual speed is called the slip. The amount of slip is directly proportional to the motor's load.

Slip = Synchronous Speed - Actual Speed

Therefore, measuring the motors speed provides a convenient way to determine its load.

There are several ways to measure motor speed:

1) A mechanical tachometer relies on direct contact with the motors rotating shaft. This can be dangerous to measure in some field situations, and sometimes requires the motor to be temporarily shut down to set up the meter.

2) An optical tachometer senses a piece of reflective tape stuck to the motor shaft. This method also requires the motor to be temporarily shut down to stick on the reflective tape.

A typical optical tachometer

3) A stroboscope is very similar to an automotive timing light, except the frequency is adjustable. The stroboscope can be shined on the rotating motor shaft and the speed adjusted until the shaft "stops turning". Special reflective tape is not required, so the motor does not need to be turned off. This is the safest and preferred method of motor speed measurement, and minimizes interference with the process.

A typical stroboscope for measuring motor speed

SECTION – 3 USEFUL MOTOR TERMINOLOGY AND KEY CONCEPTS

Standard designs of Motors by NEMA:

- NOMINAL TORQUE, NORMAL STARTING CURRENT MOTORS (DESIGN A).
- NOMINAL TORQUE, LOW STARTING CURRENT MOTORS (DESIGN B).
- HIGH TORQUE, LOW STARTING CURRENT MOTORS (DESIGN C).
- HIGH SLIP MOTORS (DESIGN D).

DESIGN A:

- Locked rotor current 6 to 10 times full load current.
- Good running efficiency & power factor.
- High pull out torque
- Low rated slip (= 200% full load torque).

DESIGN B:

- Higher reactance than DESIGN A.
- Starting current = 5 times full load current
- Starting torque, slip, efficiency is nearly the same as DESIGN A.
- Power factor & pull out torque are some what less.

DESIGN C:

- High starting torque than either design A & B
- Break down torque lower than design A & B
- Full load torque same as design A & B

DESIGN D:

- High starting torque (=275% full load torque)
- Low starting current
- High slip
- Low efficiency

DESIGN E:

- Categorized as High-Efficiency Motors
- Allows higher inrush currents than the Design B requirements; this generally enables greater efficiencies as well

TYPES OF MOTORS

There are several major classifications of motors in common use, each with specification characteristics that suit it to particular applications. The main classification is AC and DC motors.

Alternating Current (AC) Motors

- Induction Motors (3-phase) are the most widely used motors in industrial and commercial applications. They fall into two sub classifications:
- Squirrel cage motors
- Wound rotor motors
- Single phase Induction motors are used where three phase power is not available, typically in residential and commercial applications. They are used in applications with power requirements below 1 HP. There are several classifications which describe their starting and running modes.
- Split Phase

- Capacitor Run
- Capacitor start
- Capacitor start-Capacitor run
- Shaded Pole
- Universal Motors
- Synchronous Motors are commonly used in very large Industrial applications or where exact speed in required.

Direct Current (DC) Motors

- Dc motors are used in applications where precise speed control is required. The manner in which their windings are connected sub classifies them into three groups-
- Series
- Shunt
- Compound

MOTOR LOSSES

• Stator electric power (I^2R) losses

• Rotor electric power (I^2R) losses

• Friction and windage losses (including bearing losses, wind resistance, and cooling fan load)

• Stator and rotor core losses

• Stray load losses (miscellaneous other losses).

Field measurements for determining motor efficiency pose challenges that require developing various methods and devices. Power readings must be taken with the motor running under load, then uncoupled and running unloaded. Winding resistance must be measured. Temperature corrections must be performed.

MOTOR EFFICIENCY (%)

Motor Efficiency is the output of the motor divided by the electrical input to the motor, usually expressed as a percentage .power or work output is input less losses.

= Watts output / watts input x 100

= 746 x HP / (E x I x PF) x 100

= (Input – Losses) / Input x 100

WHY MOTOR FAILS

Many Motor failures can be averted, or at least the useful life of a motor can be extended, if proper preventive measures are taken. The sources of motor troubles generally falls into one of the following categories-

- Harsh Environment
- Improper motor selection/application
- Inadequate installation
- Mechanical failure
- Electrical problems
- Voltage unbalance
- Inadequate maintenance
- Combination of one or more of the above

EQUIPMENTS TO READ MOTOR PARAMETERS

The following are the various instruments used for measuring the motor parameters:

- Power analyzer for monitoring KW, KVA, KVAR, P.F
- Digital Ammeter, Voltmeter
- Tachometer to measure speed (contact/non contact type)
- Frequency meter
- Tong tester
- Analog/Digital Multimeter (Ac/Dc)
- Temperature Indicator & Thermocouples
- Digital Wattmeter

ENERGY CONSERVATION IN MOTORS

The following formulas can be used to find out % Loading, Motor Losses and Efficiency of the motor:

% Loading of Motor = Actual KW Consumption / Rating of Motor (KW) x 100

The following method has been used to find out motor losses and efficiency

- Take Designed Efficiency at full load and at 75 % to calculate losses at full load and at 75% load. This data can be obtained from the manufacturer or from the software itself.

  Losses at Full Load (L100) = KW of motor x [(1/full load efficiency) - 1]

  Losses at 75 % Load (L75) = KW of motor x [(1/75% load efficiency) - 1]

- Determine variable losses and fixed losses in present % loading of the motor by solving below two equations :

  L100 = (%Load) x (%Load) x A + B

  L75 = (%Load) x (%Load) x A + B

  Where

  - A - Variable Losses (KW)
  - B - Fixed Losses (KW)
  - Total Losses (neglecting windage and frictional losses) = A + B

  - Calculate Motor efficiency

    Efficiency = Output / input = Output (KW) / (Output (KW) + losses)

ENERGY CONSERVATION MEASURES

Energy conservation measures available for an Induction motor are as follows:

1) **Switch off when not required**
2) **Replacement of oversized motors by appropriate size motor:** By knowing the % loading and P.F of compressor motor during full load and off load, it is possible to estimate operating efficiency from motor characteristic curves. If the efficiency is low, the motor may be replaced by a higher efficiency motor after calculating the pay back period.
3) **Conversion of Delta connection in to Star Connection:** The induction motor with a percentage loading below 50% would operate at lower efficiency in delta mode. This efficiency at low loading can be improved by converting delta connection into star connection. The reported savings due to this conversion varies from around 3% to 10% because the rated output of motor drops to 1/3rd of delta configuration without affecting performance and the percent loading increases as compared to delta mode. This option does not require any capital investment and is one of the least cost options available for the energy conservation in induction motors.

- In cases where motors operate in step loading, permanent delta to star conversion is not possible. An automatic delta-star change-over controller could be installed there. It will connect the motor in star mode in 25% & 40% motor load operations; and in delta mode in 80% load operation). For the applications where starting torque requirement is high but otherwise the load is low, Automatic Delta to star converter can give significant energy savings.
- The motors which operate on continuously variable load, feasibility of installing Soft-Starter/Energy Saver is to be worked out.
- This option of permanent Delta to Star conversion can not be implemented for the loads where starting torque requirement is very high. While implementing permanent Delta to Star conversion, care should be taken to decrease the setting of over load protection relay to 2/3 rd of the delta setting.

4) **Conversion of Standard Motor with Energy Efficient Motor:** As the efficiency of standard motor at less loading is low, its operating performance get reduces considerably. If the delta to star change over option is not suitable for improving the efficiency, replacement of existing standard motor with energy efficient motor could be very viable. The conditions which increase viability of installing energy efficient motors are as follows:
   - Standard motor operating at low load is replaced by a lower rated (HP) energy efficient motor
   - Operational hours are high (nearly continuous)
   - Standard motor is old, number of rewinding are more and frequent
   - The efficiency of the Energy efficient motor is almost constant at all percentage loadings. Due to its flat efficiency characteristics, it maintains efficiency almost constant at all loads. Normally, this option is suitable for the motors with rated capacity below 50HP. The efficiencies of standard motors above 50HP rating are almost similar to that of energy efficient motors. In many cases, though the initial cost of energy efficient motor is 15 to 20% higher than the standard motor, the simple payback period is less due to the savings.
5) **Conversion of V-Belts with Efficient Flat Belts:** With conventional V-belts the efficiency for power transmission is low as high frictional engagement exists between the lateral wedge surfaces of the belts which cause less power transmission. Replacement of V-belts with "synchronous" belts which have teeth that engage sprocket lugs on the pulley can typically save 5 to 15% of the transmitted energy. Some of the applications where conversion of V-belts with Flat belts is much effective are Compressors, Milling machines, Sliding lathes, Rotary printing presses, Stone crushers, Fans, Generators in Hydroelectric power plants etc.
6) **Installation of Variable Speed Drive: In**corporation of electronic speed controls for motors driving pumps/fans/compressors requiring variations in throughout on a continuous basis to match production needs. Electronic adjustable speed drives can typically save 14 to 27% of energy.
7) **Soft Starters:** Soft starters control the input voltage according to the torque required by the driven equipment. Thus at almost all the load the motor operates at same efficiency and power factor. This results in smooth starting of the motors by drawing lower current and thus avoiding the high instantaneous current normally encountered. Starting current and torque are directly related to the voltage applied when starting the motor. By reducing the line voltage when the motor is started, soft starter reduces the starting inrush current and eliminates the high impact or jerk starts that causes mechanical wear and damage. Soft starters are useful in cases where motors operate with high impact loads. Some of the applications are Cranes, Conveyors, Hoists, Compressors, Machine tools, Textile machinery, Food processing machinery etc.
8) **Improved maintenance practices:** Improved maintenance practice ranges from the simplest task of using clean hands during lubrication, and to the more complex task of replacing windings in a manner which results in no loss in efficiency.
9) **Energy conserving devices for Motors:** The following are the various energy conserving devices for motors, also improves the motor performance considerably:
   - Capacitor bank
   - Variable speed drive
   - Soft starter/Energy Saver
   - Automatic Delta - Star Controller
   - Flat belt with Nylon fiber core
   - Fluid drive & Fluid coupling
   - Energy Efficient Motors

ECONOMIC EVALUATION METHODS

The following are the various methods used for the economic evaluation of a motor when it is required to install energy conserving device to improve its performance:

- Pay back Period (PP)
- Return on Investment (ROI)
- Net Present Value (NPV)
- Benefit Cost Analysis (BCA)
- Internal Rate of Return (IRR)

The following formulas can be used to evaluate the above mentioned methods:

- PP = FC/ ((AES x PEP) - OC)
- ROI = ((- FC/EL) + NAS)/EL
- NPV = PV - FC
- BCA = PV/FC
- To Calculate IRR the following equation can be used. The IRR is evaluated by trial and error method using this equation.

NAS x (1- $(1+IRR)^{-EL}$) / IRR = FC

Where

- FC: First Cost
- AES: Annual Electricity Saving
- PEP: projected Electricity Price
- EL Estimated Life time
- PV: Present Value
- NAS: Net Annual Saving

GENERAL MOTOR TERMINOLOGY

Acceleration (α): The time rate change of velocity. Torque (T) developed by the rotor (armature) will cause it to accelerate. $\alpha = T/J$, where *J* = polar moment of inertia

Acceleration – Maximum (α m): An expression of maximum theoretical acceleration from stall (locked rotor) of an unloaded motor with maximum current (Im) applied, measured in rad/sec^2.

Ambient Temperature: The temperature of the environment immediately surrounding the motor. It is measured in ºF or ºC.

Armature: The rotating portion of the magnetic structure that is found in machines with commutators.

Armature Inductance (La): The apparent inductance of the armature as seen by the brushes.

Armature Reaction: A magnetic field is produced by the armature current. It is shifted approximately 90 electrical degrees with respect to the direction of the stator field. It causes the armature to rotate and tends to cause demagnetization of the trailing pole tips of the stator.

Armature Resistance (Ra): The resistance of the armature winding, commutator connections and the commutator measured on the commutator bars normally spanned by a pair of opposite polarity brushes. It does not include the brush film. The resistance is usually taken at room temperature (25ºC).

Axial End Play: The shaft displacement along the motor axis which is due to a reversal of the axial force. It is measured in inches or mm.

Free End Play: The displacement measured when the moving force is removed after positioning the shaft axially from one extreme position to the other.

Cushioned End Play: The displacement measured when a force of known value causes the shaft to move axially from one position to another. When specifying cushioned end play, the force and direction of movement must also be specified.

Breakaway Torque: The value of torque that is required to begin motion of an armature or rotor that is de-energized and has been at rest.

Breakdown Torque: The maximum torque developed by an induction motor at rated voltage and frequency without an abrupt drop in speed.

Brush Resistance (Rb): Circuit resistance created by the brushes and the brush film in a brush type motor (universal, PM, wound field) adding to other power losses in a motor.

Cogging: A cyclical torque variation superimposed on the D.C. motor torque caused by permeance variations as the armature teeth or rotor magnets pass stator pole tips.

Commutation: In D.C. motors the switching (either mechanically or electronically) of the direction of the current in a coil or group of coils to cause a change of magnetic polarity.

Commutation Angle: In a brush type D.C. motors, the angle in electrical degrees that a coil or group of coils on an armature rotate while being commutated. In a brushless D.C. motor, the angular difference in electrical degrees between the rotor and stator poles when the current is reversed in the windings.

Dielectric Strength: A high voltage test of the motor's insulation ability to withstand an A.C. voltage.

The test criterion limits the leakage current to a specified maximum at the test voltage of specified magnitude and frequency, applied between the motor case and windings.

Duty Cycle: The relationship between the operating time and the off time of a motor. Both the on time and the repetition rate must be specified.

Dynamic Braking: A control function that brakes the motor by dissipating its stored energy.

Efficiency (η): The ratio of power output to power input of a machine usually expressed as a percentage.

Electromagnetic Interference (EMI): Electromagnetic interference (EMI), sometimes referred to as

Radio Frequency Interference (RFI) is a phenomenon which, either directly or indirectly can contribute to degradation in performance of an electronic receiver or system. EMI consists of undesirable voltages and currents that reach the victim device either by conduction through the power lines or by radiation through the air and causes the device to exhibit undesirable performance. It is usually caused by switching or winding commutation.

Field Coil Resistance: The resistance of the wire in the field coil as seen at the field leads or terminals.

Form Factor: The ratio of RMS current to average current.

Frictional Damping Coefficient (Kf): In a D.C. motor or BLDC motor, the constant that defines the braking characteristics of the motor with open leads.

Full-Load Torque: The torque developed at rated horsepower and speed with rated voltage and frequency applied.

Heat Sink: This is a piece of metal (usually aluminum) of a specific size and thickness to which a motor is mounted while heat rise tests are conducted. The orientation, such as vertical or horizontal, needs to be stated with the test results.

Horse Power: A unit of measure of motor output power.

Impedance (Z): A measure of the total opposition to the flow of an alternating current. It is the vector sum of resistance, inductive reactance and capacitive reactance.

Impedance Protected: A motor which under stalled conditions will not exceed specified maximum coil temperatures. Implies that the motor can be stalled (maximum temperature condition) without overheating or damage.

Incrementing: A rapid start, move and stop motion.

Inductance (L): A resistance to a change in current. It is measured in henrys.

Locked Rotor: This is a motor test condition in which the rotating element is not allowed to move.

Magnetic Flux (Φ): A term used to describe the amount of magnetism there is in a space around a coil or permanent magnet or in the air gap of a motor. It is measured in lines or webers.

Magnetic Flux Density (B): This is the measure of concentration of magnetic flux (Φ) in a given area. It is measured in lines per square inch or tesla.

Magnetic Field Intensity (H): The vector magnetic quantity that determines the ability of an electric current or a magnetic body to induce a magnetic field at a given point. It is measured in oersterds, amps turns/inch or amps/meter.

Maximum Current: The maximum current limit beyond which demagnetization of the permanent magnet field (in a PM motor) will occur (at 20°C).

Moment of Inertia: The property of matter that causes it to resist any change in its rotational or positional state. Normally it is an important property of the armature or rotor.

Motor Constant (Km): The ratio of the motor torque to motor input power. It is measured in Nm/W

Neutral Zone: The angular distance in electrical degrees between magnet poles or field poles. It is the theoretical space in which field flux is zero.

No Load Current: The current generated at rated voltage with no load on the motor – a function of rotation losses, both electrical and mechanical.

No Load Speed-Actual: The actual speed the motor will run with no load applied at rated voltage.

No Load Speed-True: A theoretical speed to which the motor will rise when rated voltage is applied with no load. This speed is based on the point where back emf is equal to input voltage.

Peak Torque: The maximum torque capability of a motor based on the maximum current limit

Power Dissipated: Power loss due to energy expended in the motor stator and rotor. It appears as heat and is expressed in watts.

Power in (Pin): Input power as a function of volts times amps in D.C. motors and volts times amps times power factor (Pf) in AC motors.

Power Factor (Pf): The ratio of actual or resistive power to the apparent or total power in an AC motor. The total power is the vector sum of the resistive and reactive powers.

Power out (Po): The output power computed by multiplying torque times speed times a constant.

Power out is equal to the power in minus all of the losses.

Pull-In Torque: (synchronous motors) Pull-in torque is obtained by starting the motor from rest at a pre-set torque value and specified motor terminal voltage. The maximum torque setting which the motor will accelerate to synchronous speed is the pull-in torque. Since the inertia of the connected load greatly affects the pull-in torque, this test should be run with minimum external inertia.

Pull-Out Torque: (synchronous motors) Pull-out torque is obtained by steadily increasing the load torque from the normal operating range of a synchronous motor while maintaining specified terminal voltage. The maximum torque reading obtained without having caused the speed to drop from synchronous speed is the pull-out torque.

Pull-Up Torque: (induction motors) Pull-up torque is obtained by starting the motor from rest at a pre-set torque value and specified motor terminal voltage. The maximum torque setting which the motor will accelerate to a speed higher than the speed at which breakdown torque occurs is the pull-up torque.

Resistance (R): The property of a material that limits current through it. It is varied by the material, size and configuration. It is measured in ohms.

$$R = \frac{\rho \ell}{A}$$

Where:

ρ= resistivity of the material

l= length

A= area

Rotor: The rotating element of the magnetic structure which is found in non-commutator machines.

Skew: The angular displacement of the rotor or armature slots from one end to the other. It can be expressed in terms of the angular displacement from parallel. It can be expressed in degrees, bars or slots.

Slip: The difference in speed between the rotating field of an induction motor and the actual rotor speed. Slip is usually expressed as a percentage of the synchronous speed.

Speed No Load: Actual motor speed in rpm with no external load and specified terminal voltage.

Speed Load: The actual motor speed in RPM with a specified external load and specified terminal voltage and frequency.

Speed Regulation Constant: The slope of the speed-torque curve in rpm/oz-in or rpm/Nm.

Speed Synchronous: The speed of the rotating field of an induction or synchronous motor. It may be calculated by multiplying 120 times the frequency of the power supply divided by the number of poles.

Stall Current: This is the current at stall (locked rotor) with rated voltage applied.

Stall Torque: This is the actual torque at the output shaft under stall (locked rotor) conditions.

Starting Current: The minimum current necessary to overcome static friction torque and start motor rotation.

Starting Torque: The minimum torque which is developed at rest for all angular positions of the rotor with rated voltage and frequency applied to the motor.

Static Friction Torque: A measure of the resistance to angular motion. It is due to bearing friction and cog friction. Cog friction is the magnetic drag between the permanent magnet and rotor laminations in a PM motor. It may be taken as the average of four readings taken 90° apart with a torque watch.

Temperature Rise: The increase in temperature in ºC or ºF of the excited winding coil above ambient temperature at locked rotor or any designated load condition.

Terminal Resistance: The resistance of a motor as seen by the power supply. It is measured at the motor power leads or terminals.

Thermal Capacity: The ability of a motor to dissipate changing amounts of power.

Thermal Dissipation Factor (Thermal Resistance): A motor's ability to dissipate heat. It provides a means of evaluating winding temperature as a function of outside surface temperature under steady state conditions, and is measured in ºC/watt.

Time Constant, Electrical (Te): This is the time required for the armature or winding current to reach

63.2% of its steady state conditions. It can be mathematically derived from the following formula:

Time Constant, Mechanical (Tm): The time required for an unloaded motor to reach 63.2% of its final velocity after applying the armature or winding voltage.

Time Constant, Thermal (Th): The time required for a motor to reach 63.2% of its final temperature under known input and load conditions. It is measured in minutes. (The value depends on mounting and motor speed).

Torque (T): A property which produced, or tends to produce, rotation. A force of one pound applied to the handle of a crank, the center of which is displaced one foot from the center of the shaft produces a torque of one pound-foot, provided the force is applied perpendicular to, and not along, the crank.

Torque Constant: In a D.C. motor the torque produced per unit armature current.

Torque Ripple: This refers to the cyclical variation of generating torque within one revolution. The torque variation superimposed on the D.C. torque component. The torque variation is a result of the permeance variation which occurs as the rotating member moves with respect to the stationary member.

Torsional Resistance: The instantaneous change velocities in a motor-load system caused by the elasticity or compliance of the shaft. In certain driving modes, the frequencies of the various parts of the motor-load system or motor-tachometer load system are in opposite directions.

Velocity: A measure of speed or rate of motion. It is measured in revolutions per minute (RPM) or radians per second.