# ELECTRICAL APPLICATION

## Study

Electrical power costs are about one-third of industrial production operating costs. They represent a major part of most industrial companies' operating budget. Furthermore, electrical operations receive very little attention in proportion to their impact. Moreover, most operations are critically dependent on electrical energy. Whether for motors, computers or environmental systems electricity has become the most used and flexible energy form.

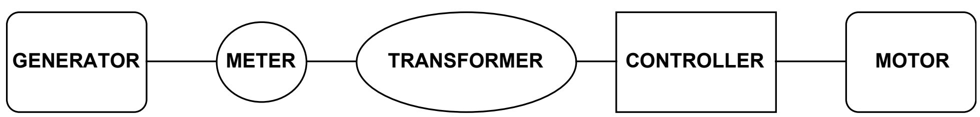
The major reasons that study of electrical system is shunned are three fold. The first reason is fear because of the perceived hazards associated with electricity. The second obstacle is lack of understanding of the fundamental theory. The third hurdle is electrical concepts must be explained by nebulous models. One cannot taste, smell, see, hear, or touch the stuff without significant hazard.

Nevertheless, a good grasp and working knowledge of the electrical fundamentals can be obtained without being a graduate electrical engineer. This presentation will be made in outline form to assist future quick reference.

## Overview

The outline covers equipment from the top of the pole to the bottom of the hole. Every electrical power circuit has the same form. The items of discussion will be basic terminology, application, and safety.

A typical power system is shown in the figure. Electrical systems always convert an available energy source to electrical energy. The electricity is then conveniently transferred to a load which converts the electrical energy back to another energy form.




## Considerations

In addition to technology, the design and installation of any electrical system must consider three major items - safety, environment, and cost.

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10/15/95

# TERMINOLOGY

**Trinity**
All physical systems operate based on the Trinity Principle which states: *Any item than can be uniquely identified can be further explained by three components.* The necessary terms for an electrical system can be identified using this grouping of three quantities.

**Basic**

1. *Voltage* (V) - measured as volts - is the potential force or pressure in a circuit. It exists whether anything is connected or not. Voltage is measured across or as the difference between two points. Voltage is the analog of pounds per square inch.

2. *Current* (I) - measured as amps - is the rate or quantity of flow through a path. Current can be measured only if a load is connected and operating. An amp is a quantity of electrons per second. Current is the analog of gallons per minute.

3. *Time block* (t) - measured in seconds - is the difference in time between events. The reciprocal of time is the frequency.

**Derived**
All electrical relationships can be calculated from the two terms - voltage and current - in conjunction with time.

1. *Impedance* (Z) - measured in ohms - is the ratio of voltage to current. Impedance is the opposition to current flow. The relationship is called Ohm's Law.
   $$Z = V / I$$

2. *Power* (S) - measured in volt-amps - is the product of voltage and current. Power is energy or work that occurs in some period of time.
   $$S = V * I^*$$

3. *Power Factor* (PF) - is the time block between voltage and current expressed in angular terms. It is the phase shift between voltage being at a maximum and current being at a maximum.

**Wiring Systems**
All common electrical power is carried in conductors or wires. The arrangement of these wires determines their function.

*1.* *Single-phase* (1 ∅) is an electrical system that uses only two current carrying conductors.

*2.* *Three-phase* (3 ∅) is a system that uses three current carrying conductors.

3. A *ground* is used for safety purposes. A *grounding* wire may be present in either system. The wire will have green insulation or will be bare.

A *neutral* is a carrying wire that is also *grounded*. It may be present in either system. It is the common for a single-phase system. It is the fourth wire of a three-phase system. The insulation is white.

# VOLTAGE RATINGS

**General**
There are many different system voltage levels. Some of the common ones are listed. Others are in use at various locations.

**Controls**
Controls are often less than 50 volts for safety considerations. Voltages less than this usually can be contacted without fatal consequences. The most common systems employ 48, 24, 12, 6, and 5 volts. Nevertheless, some systems safely retain 120 volts for convenience.

< 48    120

**Secondary (Utilization)**
Most power equipment operates at these levels. The first number represents the voltage between a line and ground, while the second number represents the voltage between two lines. The line-to-line voltage is the number used for nominal system voltage rating on three-phase systems.

2400 / 4160    277 / 480    240    120 / 208

Typical applications fit in the matrix. System requirements may dictate other combinations.

| Volts | Phase | Class | Size |
|---|---|---|---|
| 4160 | 3 | extra large | >1000 Hp |
| 2400 | 3 | very large | >250 Hp |
| 480 | 3 | large | >3 Hp |
| 277 | 1 | lighting | commercial |
| 240 | 1 | general | >1 Hp |
| 208 | 3 | motors | >1 Hp |
| 120 | 1 | general | <1 Hp |

**Primary (Distribution)**
For distribution voltages, typically one suspension insulator bell corresponds to approximately 10,000 volts.

2400 / 4160    7200 / 12470    7620 / 13200
7970 / 13800    14400 / 24940    19920 / 34500

**Transmission**
For transmission voltages, typically one suspension insulator bell corresponds to approximately 20,000 volts.

34500    69 KV    138 KV    240 KV

**Extra High Voltage**
There are only a limited number of these systems. Cost and concerns about hazards have limited their acceptance.

345 KV    700 KV    1 MV    >500 KV DC

# CONDUCTORS

1. A conductor or wire is necessary to move electricity.

2. The current rating is based on the wire size (diameter). This is correlated to an American Wire Gauge (AWG) designation. Compare this to pipe size.

3. The voltage rating of insulation is based on potential to arc. Use distance separation or insulation thickness to achieve a higher voltage rating. Compare this to pipe wall thickness schedules.

4. The temperature rating of insulation is based on insulation material thermal characteristics and maximum conductor operating temperatures. Compare this to pipe material.

5. Different materials for insulation are determined by where the wire is used. Some considerations are wet or dry, oil immersed, direct burial, and other applications.

6. Generally overhead power wires are ACSR - Aluminum Conductor Steel Reinforced. Most other applications use copper conductor material.

7. Great care must be exercised in connections with aluminum wire, especially to copper, because of potential fire hazards from dissimilar metallurgy, corrosion, and expansion.

8. The most common wire in use is 600 volt, $90^{o}$ C THHN insulation with copper conductor sized for current carrying requirements. However, this may be restricted, since many splicing connectors are limited to $60^{o}$ C.

9. The ampacity for a single load is 1.25 times the current required for the load. The ampacity for multiple loads is 1.25 times the largest current load plus the remaining current.

To buy wire you need:

Length
AWG
Conductor Material (Copper)
Voltage Rating
Insulation Material (THHN)

**Question:**
For a 52 amp, 460V motor, $75^{o}$ C conductor, what would be the

a. Wire Size

b. Insulation Material

# TRANSFORMERS

1. Transformers have no moving parts. They simply convert from one voltage to another.

2. Transformers convert primary side voltage to secondary side voltage.

3. Transformer size is based on voltage and current capacity.

4. The size rating for a single-phase (1 ∅) transformer is the product of the voltage and current. To scale the size of the units divide by 1000.

$$KVA = \frac{Volts * Amps}{1000}$$

5. Similarly, the size rating for a three-phase (3 ∅) bank is the same as a single-phase multiplied by a phase factor of 1.732.

$$KVA = \frac{Volts * Amps * 1.732}{1000}$$

6. There are three transformers in a three-phase bank. For a balanced system, each transformer capacity is one-third of the total bank rating.

7. Taps are switches on a transformer that allow small changes in voltage. Taps are rated in percent of nameplate voltage rating. The most common arrangement is two 2 1/2% taps above and below the nominal voltage rating.

8. The size rating (KVA) is the same for both the primary and secondary. If the voltage is stepped down from the primary to the secondary, then the current is stepped up from the primary to the secondary by the same factor. This scaling factor is the turns ratio.

$$KVA = (Volt * Amp)_{primary} = (Volt * Amp)_{secondary}$$

To order a transformer you need:

Primary Voltage
Secondary Voltage
Size Rating (KVA)
Voltage Adjustments (taps)
Where transformer will be used

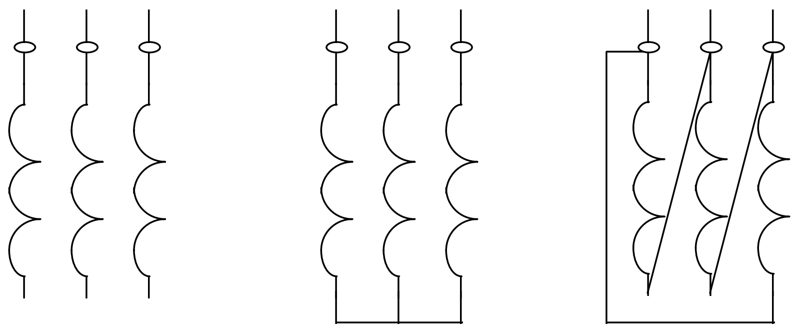
**Question:**

1. For a 480 volt, 52 amp, 3-∅ motor, what would be transformer KVA required?

2. A control transformer is 100 VA, single-phase, 120V / 12V. What is the current on the primary and secondary?

# WYE - DELTA

1. Three-phase power systems have three current carrying conductors. Three-phase power systems also use three transformers in a balanced system. Each transformer winding has two end terminals. One terminal of each transformer is connected to a line conductor. This gives only two possible combinations for connecting the remaining transformer terminals.



Conductors Wye (Star) Delta

2. A wye or star has the three remaining terminals connected together.
   A delta has each remaining terminal connected across to another line.

3. Since the transformers of both combinations are connected to the same conductors, the line voltages are the same.

   VOLTAGE line to line (delta) = VOLTAGE line to line (wye)

4. The voltage rating of the transformer depends on the connection used. For the same line voltage, the transformer winding voltage will be different for wye and delta connections.

   VOLTAGE line to line = VOLTAGE transformers (delta)

   VOLTAGE line to line = 1.732 * VOLTAGE transformers (wye)

5. Think of line to neutral as the voltage a person's eyeball would see if he stood on a ground wire and touched a phase line. He would be more excited if he released the ground and touched two phases. That would be the line to line voltage. A bird does not receive a charge since he only touches one wire and the distance between his feet is small enough to prevent a voltage change.

**Question:**

For a 12470 volt power system, what would be the transformer voltage rating

1. Delta connection (between two lines)

2. Wye connection (between line and ground)

## PRIMARY - SECONDARY COMBINATIONS

1. There are only two transformer connections for the primary.
   Delta or Wye

2. There are only two secondary connections.
   Delta or Wye

3. These are independent of each other.

4. The decision about which connection to use must be based on operations and the availability of primary equipment.

5.

| *Primary* | *Secondary* | *Precautions* |
|---|---|---|
| Wye | Wye | Must ground the neutral mid-points |
| Wye | Delta | Do not ground wye mid-point |
| Delta | Wye | Best connection - can monitor ground faults |
| Delta | Delta | All transformers impedance must match |

6. For the most universal applications, a delta primary - wye secondary is the most flexible. Many industrial installations use a delta secondary to reduce the cost associated with a fourth wire.

# CONTROL PANEL

1. The generic name is controller. These are devices to start and stop electrical devices such as motors.

2. Controllers are sometimes called starters or contactors. These are actually parts of the unit. The contactor is an electrical solenoid that switches the power. A starter is a combination of contactor and overload protection.

3. Controllers include fuses, overloads, and a start/stop switch. The devices include timers and other shutdowns.

4. National Electrical Manufacturer's Association (NEMA) sizes are based on current carrying capacity. International Electrical Commission (IEC) rated units have less capacity range. A NEMA size will support multiple horsepower rataing, while an IEC size may be limited to one.

5. Typical industrial motors use full voltage, non-reversing starters, 3-phase, 60 Hertz with starting open-phase protection in a weatherproof enclosure. International motors are frequently 50 Hz.

6. Fuses are for short-circuit protection. Always use three fuses in a 3-phase system. Fuses for motors should be dual element (time delay) type such as BUSS-FRS. This permits motor starting without blowing fuses. With IEC starters, use low peak fuses. Low peak fuses cost approximately 50% more than standard fuses. These have a yellow cartridge.

| AMP | Fusetron | IEC |
|---|---|---|
| 30 A | ~ $7 | ~ $10 |
| 200 A | ~ $45 | ~ $65 |

7. Fuse size should be at least motor full load current rating up to 1.75 times motor rating for best protection. Fuses have a fault interrupting capacity of 100,000 to 300,000 amps. The major disadvantage is only one fuse may blow on a multiple wire circuit.

8. Circuit breakers are switches that trip on high current. Standard breakers are applied at up to 7 times current rating, while motor current protection breakers are applied at rating. Breakers have a fault interrupting capacity of 10,000 to 25,000 amps. A major advantage is these can be mechanically linked to provide simultaneous protection for multiple wires.

9. Overloads are heat sensitive devices that cause shutdown of the contactor if the motor current gets too high. Heater elements are sized to trip off at a maximum motor current. Heaters are manufacturer specific. Electronic overloads simulate the heater characteristics.

10. Fused disconnects are often used to feed a control panel. Typically the control panel fuse is 1.25 times the motor rating and the disconnect is 1.5 times the motor rating. This assures the closed devices will trip first.

To order a controller you need:

- Voltage rating
- Size (NEMA or IEC)
- Motor Hp
- Special Features such as time clock

**Question:**
Given: A 40 Hp, 52 amp motor
Find: Size for (a.) starter, (b.) fuse, (c.) heater

# MOTORS

## Motor Application

1. The prime mover for most industrial machines is an electric motor.

2. Fractional horsepower motors are generally single-phase and use 115V or 230V power.

3. Integral horsepower (above 1 HP) motors are generally three phase for 460V power.

4. With the voltage fixed, current must increase as load or horsepower increases. For three phase,

$$\text{Power} = \text{Volts} * \text{Amps} * 1.732$$

5. The current influences the entire system - wire size, fuse size, panel size, transformer size.

6. Full load current is maximum current the motor should consume.

7. Running current is actual current the motor consumes based on load.

8. Motor running current of less than 50% full load indicates equipment is significantly oversized.

9. Starting current lasts for just a few seconds and is generally 6-8 times full load current.

10. For cyclic loads, the average current can be estimated by adding the two maximums and two minimuns, then dividing by four.

11. For a beam pump, the optimum loading occurs when the peak current is 1.5 to 1.75 times the rated current of the motor.

12. For a beam pump, the motor horsepower should be approximately 2.5 times the fluid horsepower. This provides improved efficiency and less peak stress on the system. (gearbox ratio 30:1)

## Question:

Given: A 40 horsepower, 460V motor
Find:

a. full load current

b. maximum starting (locked rotor) current

c. running current

**Motor Enclosure**

1. Most motors in industrial service are for outdoor service with the minimum protection required.

2. *Open drip proof (ODP)* is the cheapest and simplest motor enclosure. It is usually used on most equipment. Rodent screens should be added to deep out debris (Cost 1.0)

3. *Splash proof (SP)* is an open drip proof design to keep water from splashing into the motor. These are not often specified. (Cost about 1.1 * ODP)

4. *Weatherproof type (WT)* is the next level. It uses baffles to knockout water but internally is still exposed to outside air. It is used occasionally in plants. (Cost about 1.25 * ODP)

5. *Totally enclosed, non-ventilated (TEN*V) is a machine that has inside air isolated from the outside. Cooling is accomplished by fins acting as radiators. These are usually smaller sizes. (Cost about 1.5 * ODP)

6. *Totally enclosed, fan cooled (TEFC)* is a device that has inside air isolated from outside. Cooling is accomplished by a fan mounted on the back end of motor. (Cost about 1.5 * ODP)

7. *Explosion proof* is a specialized device used only in Class I, Division 1, classified areas where the continuous existence of combustible liquids or vapors makes ignition likely. These may be open (EXP) or totally enclosed (TEXP). (Cost about 1.85 * ODP)

8. *Dust-ignition proof* is a device for use in Class II classified areas where continuous existance of ignitable dusts makes ignition likely. (Cost about 1.5* ODP).

9. Ares are classified if there is combustible material present and it may be ignited by the electrical equipment. If this is a *normal* condition, the area is Division 1. If this is an *abnormal* condition, the area is Division 2.

**Question:**

Find: What enclosure is used for

a. high pressure water injection plant

b. an inadequately ventilated enclosed LACT unit

**Motor Frame**

1. National Electric Manufacturers Association (NEMA) has established many standards for motors. Frame size is one of the common ones.

2. NEMA frame size describes all the physical dimensions of a motor, such as shaft size, shaft height, and spacing of mounting holes.

3. A motor of the same horsepower will have different sizes based on open or TEFC, and year of manufacture.

4. TEFC motors use larger Nema frames so more area will be available to dissipate heat generated in the motor.

5. T-frame motors are motors built to standards established in 1964. These are smaller frame motors.

6. Older style motors had excess capacity built-in so they could generally be overloaded without detrimental effects.

7. T-frame motors generally cannot be operated with any overload unless the machine has a service factor greater then 1.0.

8. Service factor (or safety factor) is a design that provides extra horsepower for some overloading.

**Question:**

1. Given: A 40 HP ODP, 1200 Rpm motor built in 1980

   Find:

   a. NEMA frame

   b. Shaft size

   c. Space between bolt holes on the end

2. Repeat for 3600 RPM

3. Compare for explosion proof

## Motor Speed and Starting

1. Induction motors are machines that are excited and run by line power.

2. Starting torque is the capability of starting a motor under load.

3. Synchronous speed is the speed which the motor theoretically would run if it locked on to power line frequency.

4. Induction motor synchronous speed is an integer fraction of 3600 RPM when used on a 60 Hertz system. The maximum speed of a 50 Hz motor is 3000 RPM.

$$\text{Synchronous speed (RPM)} = \frac{120 * \text{Line Frequency (HZ)}}{\text{\# of Poles (always an even \#)}}$$

5. Slip is the speed variation in the shaft of the motor resulting from load.

6. Rotor speed is the shaft speed of the motor.

$$\text{Rotor speed} = \text{sync speed} - (\text{slip} * \text{sync speed})$$

$$\text{Slip} = \frac{\text{sync speed} - \text{rotor speed}}{\text{sync speed}}$$

**Question:**

Given: A 6 pole, 60 Hz, 5% slip motor

Find:

a. synchronous speed

b. rotor speed

**NEMA Designs Letters (3 phase)**

1. National Electrical Manufacturers Association has established Design letters that relate to starting performance for motors.

2. Design A and Design B motors have normal starting torque and normal slip. These are used on drives that start unloaded or with little load. These are “general purpose” motors. Typical slip is 1-3%. The low slip contributes to high peak loads.

3. Design C motors have high starting torque, normal slip. These are used for drives that start under load but should not be used on applications requiring frequent acceleration.

4. Design D motors have high starting torque, high slip. These are used for drives that start loaded and are cyclic. The high slip smoothes out peak loads. This high inertial cyclic load capability is ideal for beam pumping units.

5. Two normal Design D ratings are available.

   a) Slip of 5% - 8%

   b) Slip of 8% - 13%

6. Ultra high slip motors are available from some manufacturers. These are generally packaged with special motor controllers that incorporate capacitors. The slip may be as high as 45%.

7. Oilfield pumping is a special design that is between a C and D design with characteristics very similar to Design D.

8. In general, Design B will be more efficient than high slip motors.

**Questions:**

1. Can a motor used on a plant pump be used on a cyclic load? Why?

2. Can a motor used on a cyclic load be used for a continuous plant load? What is the penalty?

**NEMA Design Letters (Single Phase)**

1. Design L is for single phase motors that use capacitor start. These are used to drive fans and small pumps.

2. Design M is for single phase motors that use capacitor start, capacitor runs. These are used on small compressors such as refrigeration and air conditioning.

**Motor Requisition**

To buy a motor you need:

Horsepower

Voltage (line to line)

Number of Phases

Frequency (60 Hz in U.S.A.)

Synchronous Speed

Application (NEMA Design)

Enclosure (ODP)

Belt Drive or Direct Coupled (Bearings)

**Question:**

Given: A cyclic-loaded pumping unit in Texas requiring 31 HP

Find:

a. Horsepower

b. Voltage

c. Number of Phases

d. Frequency

e. Synchronous Speed

f. Application

g. Enclosure

h. Coupling

## VOLTAGE DROP

1. Just-as a pipeline experiences pressure drop due to friction, an electrical system experiences voltage drop due to impedance (resistance).

2. Because of wire size and quantity of current flow, the voltage at a transformer will not be the same as the voltage that reaches the motor.

3. Voltage drop actually shows up on the utility bill as power. The power is simply used as waste heat in the wire.

   Power = V (Volt Drop) * I (Current in Wire) * 1.732

4. Prudent design dictates the maximum voltage drop will be less than 5% from the source (transformer) to the load (motor).

5. For a 480 volt transformer, the maximum voltage drop is .05 * 480 = 24 volt.

6. The motor must then be derated.
   480 - 24 = 456 volts, rounded to 460

7. Since the controller is associated with a single motor, it is rated at the same voltage as the motor.

8. Typical system voltages and motor voltages are tabulated.

| *System Voltage (Transformer)* | *Motor Voltage (Controller)* | *Good Old Days* |
|---|---|---|
| 120 | 115 | 110 |
| 240 | 230 | 220 |
| 480 | 460 | 440 |
| 2400 | 2300 | 2200 |

## EFFICIENCY

1. Electric induction motors, in general, consume only as much power as the load requires if it is operating near its rated load.

2. Efficiency in the power output divided by the power input

$$\eta = \frac{out}{in} = \frac{out}{out + loss}$$

3. A standard, integral horsepower, fully loaded motor may have an efficiency of .85. High efficiency motors can be as much as 94 - 96%. The extra investment cost is offset by reduced utility costs.

4. A motor that is partially loaded consumes the power of the load, but at a reduced efficiency. The efficiency may drop to .82.

## POWER FACTOR

1. Power factor is a measure of the electrical work accomplished divided by the total electrical power apparently applied.

$$\text{Power Factor (3 phase)} = \frac{\text{Watts}}{\text{Volts} * \text{Amps} * 1.732}$$

2. For an electric heater and an incandescent light, the power foctor is 1. Other loads such as motors have a power factor less than 1.

3. Fully loaded motors have a power factor of approximately .8 while a motor that is 25% loaded may have a power factor as low as .35.

4. A motor that is too large for the load will use essentially only as much power (watts) as the load needs, but its power factor will suffer significantly. The volts and amps do not change much, but the angle (time) between them changes substantially.

5. Most power companies have penalties that charge additional for electricity if the power factor is less than 0.9.

6. Power factor can be calculated in a number of ways. Generally the methods are not important. They are given only as a reference.

$$\text{pf} = \frac{\text{Watts}}{\text{Volt} * \text{Amps}} = \cos\theta$$

$$VA^2 = WATT^2 + VAR^2$$

```
            |  KVA/|                                  |
            |    / |                                  |
            |   /  |KVAR                              |
            |  /   |                                  |
            |/θ    |                                  |        V ref
------------------------------------------------------------
            |KW                                       |\ θ
            |                                         | \
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            |                                         |   \ I
```

**Question:**

Given: A motor that operates at 460 volts and 52 amps
Find:

a. What is power factor at 33,000 watts input?

b. Is the motor loaded?

c. What size is the motor?

d. What is power factor at 15,000 watts input?

# CAPACITORS

1. Capacitors are electrical devices that can correct or improve power factor problems caused by motor loads.

2. These are gray boxes that connect directly to the power line through switches and fuses.

3. From the definition of power factor, it can be observed that current will be reduced when capacitors are used to improve power factor. Volts and watts do not change significantly.

4. KVAR (Kilo Volt Amp Reactive) is the size rating for power factor correction capacitors. Other capacitors are rated in microfarads.

5. The size of capacitors is determined by the electrical load, the existing power factor, and the desired power factor.

6. Capacitors that are switched on and off with a motor should not exceed manufacturer recommended sizes since unusual currents and switching problems may exist.

7. Capacitors switched with motors should be connected between the motor contactor and the overload. This will prevent resizing the overloads because of the reduced current flow.

8. Large power systems with many motors often use capacitor banks on the line rather than one capacitor at each motor. This is a considerably cheaper installation and has the same effect of improving the power factor at the power company meter.

   To by capacitors you need:

   KVAR rating

   Voltage rating

**Question:**

Given: A 40 HP, 1200 RPM, cyclic-loaded pumping motor
Find:

a. the maximum KVAR capacitor

b. percentage current reduction

# HOMEWORK - SYSTEM DESIGN

Given:

A. 20 hp motor, 480 VAC, 60 Hz, 90% eff, 0.80 PF, cyclic pumping unit, installed on 7200/12470.
B. 100 hp motor, 480 VAC, 60 Hz, 93% eff, 0.85 PF centrifugal pump, installed on 14400/24940.

Find:

1. Motor FLA
2. Starting current
3. Wire size
4. Fuse size
5. Control panel NEMA size
6. Heater size
7. Motor enclosure
8. Frame size
9. Shaft diameter
10. Space between bolts on the back
11. Nominal RPM
12. Rotor RPM
13. Total KVA required
14. Each transformer KVA
15. Connect transformer primary in wye, what is voltage rating

**Optional:**

16. Primary current rating
17. Primary fuse size
18. Conduit size for motor wiring
19. Capacitor size based on motor horsepower
20. Capacitor KVAR to correct to 0.95 PF
21. KW input to the motor

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May 26, 1995
Given: 2 Hp motor, power factor = .866, Vrms 240, 60 Hz

Find:

| | | |
|---|---|---|
| 1. | Power in kilowatts | P = |
| 2. | Complex power magnitude | \|S\| = |
| 3. | Power factor angle | θ = |
| 4. | Reactive power | Q = |
| 5. | Complex apparent power | S = |
| 6. | Voltage angle | /v = |
| 7. | Current magnitude | \|I\| = |
| 8. | Current angle | /I = |
| 9. | Impedance | Z = |
| 10. | Impedance angle | /z = |
| 11. | Resistance | R = |
| 12. | Reactance | X = |
| 13. | Power factor correction impedance | Zpfc = |
| 14. | Peak voltage | |