POWER FACTOR CORRECTION OF ELECTRIC MOTORS ON BEAM TYPE PUMPING UNITS

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In recent years the cost of electrical energy to pump oil wells has become a prime concern. The terms Kilowatt costs, Kilowatt demand, Fuel adjustments and Power Factor Penalties are showing up on monthly power bills. Utilities have numerous methods to influence the bills which have caused some misunderstandings of the true meaning of each of these. Power Factor and the methods to obtain a desired Power Factor may be the least understood. Power Factor may be improved by connecting capacitors to the load side of motor contractors or connected in the primary line of electrical distribution systems. This paper will be limited to the discussion of Power Factor improvement of induction motors by capacitors connected to the motor terminals.

By definition the power factor is the cosine of the angle in electrical degrees that the amps in an AC circuit leads or lags the voltage. The source of electrical power which is supplied to the beam type pumping unit is normally three phase alternating voltage and current. Figure 1 shows how three phase voltage consists of three different phase voltages, each separated by 120 electrical degrees. Associated with each of these voltages will be a three phase current which will be separated by the 120 electrical degrees, as shown in figure 2. A graphic representation of the three currents and volts shown simultaneously would have the appearance as shown by figure 3. This representation would be difficult to work with because of the number of variables being considered. It is normal practice to consider only a single phase source of voltage which is typical of each of the three phases, as shown in figure 4. This is a fundamental sine wave that will represent one phase of a three phase circuit. The current corresponding to this voltage can also be represented as a single phase sine wave, as shown in figure 5.

By superimposing the single phase representation of AC amps on the single phase sine wave for volts, the amplitude and phase angle of each can be observed as shown in figure 6. Each cycle of AC voltage or current is divided into 360 electrical degrees. When the current and voltage cross the axis at the same time and maintain the same polarity as shown in figure 6 the currents are in phase with the voltage and the phase angle is zero. The horizontal axis measured in electrical degrees also represents a time axis. T = 0 at the left hand point where the X and Y axis cross. If the current crosses the axis at some point after T = 0, the current lags the voltage. In figure 7 the current crosses the X axis at 30° lagging. If the current crosses the axis prior to the point T = 0 the current leads the voltage, as shown in figure 8. With reference to the original definition of power factor the cosine of the angle in electrical degrees that the current leads or lags the voltage is the power factor. Current which leads the voltage results in a leading power factor. Current which lags the voltage has a lagging power factor.

Figure 9 shows a voltage and current sine wave where the current lags the voltage by 30°. It is significant to point out that only in-phase quantities of current and volts will produce kilowatts, shown by the shaded area of figure 9. This can be said in another way in that work is done only when current and voltage have the same polarity. In the three phase electrical system work is designated as kilowatts. When current and voltage do not have the same polarity they produce what is referred to as watt less power, reactive volt amps, or KVAR's as shown by the shaded areas in figure 10. In a three phase circuit the energy furnished to the pumping motor will be kilowatts and the other one is kilovars. It is customary to take the information which is presented in sine wave form and present as a vector diagram to show the magnitude and phase relation between the kilovolt amps, kilowatts, and kilovars as shown in figure 11.

KVA = Kilovolt Amps
KW = Kilowatts
KVAR = Kilovars
Ø = Angle of Lead or Lag

$$KVA = \frac{VOLTS \times AMPS \times \sqrt{3}}{1000} \qquad EQ1$$

$$POWER\ FACTOR = COS\ Ø \qquad EQ2$$

$$KW = KVA \times POWER\ FACTOR \qquad EQ3$$

$$KVAR = KVA \times SINE\ Ø \qquad EQ4$$

$$Ø = Cos^{-1}\ (Power\ Factor) \qquad EQ5$$

If the KVA and the power factor are known, a power triangle can be constructed. The use of equations 1 thru 5 provide the information which will allow determination of each side of the triangle, as well as the phase angle between KVA and KW sides. This angle is actually the power factor angle and also represents the amount in electrical degrees that the current lags the voltage. The following is an example for building a power triangle.

VOLTS = 460
AMPS = 50
PHASE ANGLE = 30° LAG

EQ1 $$KVA = \frac{460 \times 50 \times \sqrt{3}}{1000} = 39.84$$

EQ2 $$POWER\ FACTOR = COS\ 30° = .866$$

EQ3 $$KW = 39.84 \times .866 = 34.50$$

EQ4 $$KVAR = 39.84 \times .5 = 19.92$$

This information shows the power factor, and how it is used to determine the power components which makes up three phase power.

It has previously been mentioned that the current may lag or lead the voltage resulting in lagging or leading power factors. All magnetic devices such as motors, transformers, relay coils, and holding coils are magnetic devices which result in lagging power factors. Devices which cause lagging power factors each have what is called an inductive reactance. The power triangle figure 11 shows the normal position of the components for a system which has a lagging power factor. Devices such as capacitors which create leading power factors have capacitive reactance.

Figure 12 shows the vector relation for the system in gure 8 which contained a 30° phase angle with leading current. Equations 1 thru 4 can be used to construct the power triangle for this condition. The polarity of the angle has changed which provides KVA and KVAR above the KW axis. The values for KVA, KW and KVAR will be the same as the previous case when the current was lagging the voltage. From the examples in figures 11 and 12 it should be noted that the inductive reactance and capacitive reactance have opposite effects on the power factor polarity in a circuit. If a circuit had both inductive reactance and capacitive reactance, and the inductive kilovars is the same in magnitude as the capacitance kilovars, the power factor angle would be zero. This characteristic between inductive kilovars and capacitive kilovars demonstrates the use of capacitors for power factor correction. Based on this feature the power factor of an inductive circuit which contains magnetic devices can be changed to a new value by adding to that circuit devices which contain capacitive reactance. Power factor correcting capacitors are nothing more than a group of capacitors sized in capacitance and voltage to be connected into a three phase system to give the desired kilovars of capacitive reactance. For an example of power factor correcting consider an industrial plant application which has a power factor of 0.55 and desires a power factor is 0.90. For this industrial application there will be tables which list existing power factor, desired power factor and the amount of capacitive kilovars to be added per kilowatt load. For this example build a power triangle which satisfies the original condition where the applied voltage is 460, the motor amps is 50 and the power factor angle is that angle which has cosine of 0.55. Using the four equations calculate KVA, kilovar and kilowatt for the existing condition.

VOLTS = 460 AMPS = 50
POWER FACTOR = .55

EQ5 $\emptyset = COS^{-1}$ (Power Factor) $= Cos^{-1}$ .55 = 56.6°

EQ1 $$KVA = \frac{Volt \times Amp \times \sqrt{3}}{1000} = \frac{460 \times 50 \times \sqrt{3}}{1000} = 39.84$$

EQ3 KW = KVA X Power Factor = 39.84 X .55 = 21.91

EQ4 KVAR = KVA X Sine Ø = 39.84 X .835 = 33.26

It is interesting to note from the preceeding example and figure 13 that the utility provides more reactive kilovars (33.26) than kilowatts (21.91). This demonstrates why the utility wants good power factors and in many cases is penalizing users when their power factor does not meet certain specified values. By using the information furnished calculations can be performed to construct a power triangle for the desired conditions. Figure 14 shows superimposed on the triangle with power factor = 0.55 the triangle with 0.90 power factor. Use the equations 3 thru 5 to solve the required information to construct the new triangle.

Known: VOLTS = 460
KW = 21.91
POWER FACTOR = .9

EQ3 $$KVA = KW/PF = 21.91 / .9 = 24.34$$

EQ5 $$\emptyset = COS^{-1} .9 = 25.84°$$

EQ4 $$KVAR = KVA \times SINE\ \emptyset$$

$$= 24.34 \times .44 = 10.71$$

If the power factor is 0.9 the new phase angle is 25.84°. Changing the power factor by the use of power factor correcting capacitors will not change the kilowatts of the circuit therefore, the new circuit will have the same kilowatt as the original circuit which is 21.91. If 10.71 KVAR is subtracted from the original circuit KVAR which is 33.26, the amount of capacitive kilovars (22.55) required to be added to the system can be determined. This is the method industry uses to determine the amount of capacitive kilovars required to obtain desired power factors.

Manufacturers of power factor correcting capacitors furnish charts or columns of data used to size power factor correcting capacitors. The columns will list the existing power factor, the desired power factor, and the amount of capacitive kilovars that must be added to the circuit for each kilowatt load. This is somewhat simple and very straight forward for industries where the load maintains a constant RMS value. This is typical for water injection wells or processing equipment where the load is constant.

In the case of the oil field beam type pumping unit, the motor amps, motor KVA, motor power factor, and motor kilovars are constantly changing. If values are constantly changing, then a single power triangle cannot be obtained which is representative of the motor power requirements. From this it can be concluded that the use of power factor correcting capacitor tables cannot be used to correct power factor of the beam type pumping units. Other methods must be used for calculating the amount of capacitance used for correcting power factor on beam type pumping units in the oil field. When correcting the power factor of a motor on the oil field pumping unit, it is important not to drive the power factor into a leading condition. The reason for this will be discussed later in this paper. Figure 15 will show the typical kilovar input to an oil field pumping motor for motor RPM values from 0 to 1300. This curve represents the kilovar input to the motor from starting at 0 RPM to speeds above synchronous RPM where regeneration will occur. It is interesting to notice that the KVAR input to the motor is approximately a straight line in the area where it should be operated. If the motor could be operated at any point along that curve continuously, the power factor could be made 0 by connecting to the motor an amount of capacitive reactance equivalent to input kilovars shown on this curve. As mentioned previously the amount of reactive kilovars connected to the motor should never be an amount which would cause leading power factor. This would mean that the amount of capacitive reactance which is used should be something less than the amount shown between the RPM axis and the straight line portion near the full load to no load part of the curve. The maximum amount of KVAR is equal to approximately that value of KVAR demanded by the motor under no load conditions. This information should be obtained from the motor manufacturer. Trying to improve the power factor with capacitance larger than that indicated above will result in a leading power factor at the motor. If the amount of capacitive kilovars required is known then the capacitance which must be connected to the motor circuit can be calculated.

$$C = \frac{KVAR \times 10^9}{2\pi FV^2} \qquad \text{EQ6}$$

V = VOLTS
F = FREQUENCY
C = CAPACITANCE(in Farads)
π = 3.14172

IF VOLTS = 460, FREQUENCY = 60
C = 12.5 KVAR

There are three basic methods or approaches to improving power factors.

These are:

1. Devices are selected which have characteristics of providing a predetermined power factor.
2. Equipment should be selected to operate at its optimum condition to provide maximum power factor.
3. Power factor correcting capacitors are installed to improve the power factor of an operating system.

Number 1 is with reference to equipment such as synchronous motors which can be excited to produce leading power factor. This motor is adaptable to constant torque loads which require low starting torque demands. They are not desirable for the beam type oil well pumping motor.

Number 2 is an extremely important part and probably the most important for obtaining favorable power factor in the oil field. Large motors which are only partially loaded demonstrates an extremely poor power factor are the largest contributor to poor power factors. By referring to the graph of figure 16 there are two items to note. For motor load from starting to full load, the power factor falls within a range of approximately .8 to .9. Poor power factor does not appear until the motor is lightly loaded where the speeds of the motor are near 1150 RPM or higher. This information verifies that poor power factor is most predominantly due to lightly loaded indication motors. Multiple torque motors which are operated in too high a torque mode, when could be operated in a lower torque mode provide the same results of selecting motors too large for a specified application. A multiple torque motor when operated in the lowest mode possible without exeeding the thermal limit of the motor will provide maximum power factor for that motor. Pumping units which are improperly balanced may have exceptionally high load during one half stroke where the power factor will be excellent. During the other portion of the stroke it may be overhauling the motor which causes extremely poor power factor. This results in an overall poor power factor.

Number 3 The use of power factor correcting capacitors to improve the power factor of the system should be the last resort to improving power factor in view that this method has a very limited capability.

While the induction motor which is utilizing power factor correcting capacitors is connected to the utility, the utility controls the frequency, voltage level and in general the performance of the motor as well as the capacitors. An elementary diagram of this electrical system is shown by figure 17. At the instant following the opening of the contactors which happens every time the motor is stopped whether it be from the control switch or pump off controller, the capacitor and motor circuit is disconnected from the utility. Figure 18 shows the elementary circuit with the motor winding in series with the power factor correcting capacitors. At the instant contactors open, electrical power will be disconnected from the motor. The pumping unit will continue to drive the motor as a result of the inertia. If this driving of the motor causes motor RPM anywhere in the area of synchronous RPM plus or minus several hundred RPM, a condition will exist where the capacitors can provide excitation for the motor winding. This condition can cause two possible areas of damage to the motor. These areas are overvoltages and transient torques. If the capacitive reactance of the capacitors and the inductive reactance of the motor winding are equal, there will be a resonance condition where opposition to current flow is a minimum. This will result in a very high current flow which produces elevated voltages. This overvoltage will be in the area of 140% to 160% the applied voltage to the motor. Each time this voltage is applied to the motor the insulation will be stressed. On a pumping unit where there is repeated interruption of the power caused by pump off controls, utilities or remote operation, the motor will have repeated overvoltages which will eventually weaken the insulation to the point of failure. This will result in a motor winding failure requiring the motor to be taken out of service and rewound.

Transient torques develop when the contactor is momentarily opened and reclosed. This can happen when operators stop and start the motor or during lightning storms when utility reclosures operate or malfunctions of equipment which causes restriking of the motor contactor. During the time that the motor contactor is open the voltage of the motor may be maintained or elevated above the rated voltage, due to excitation available from power factor correcting capacitors. When the contact closes the voltage of the motor may be out of phase of the voltage of the utility. This out of phase voltage can cause transient torques as high as 20 times full load motor torques for short periods of time. This torque has been known to twist shafts, break off motor feet and cause cracking of the motor frames. The amount of capacitance required to cause the conditions described will be approximately that amount which normally is required to cause leading power factors of the induction motor. This is a case where the capacitive reactance of the capacitors and inductive reactance of the motor winding are of the same value. Another way of approximating the value of capacitance which is large enough to cause high elevated voltages is the case where the capacitive current is approximately equal to the no load magnetizing current of the motor.

The National Electrical Code prior to 1979 specified in section 460-7 the maximum amount of capacitance that could be connected to a motor. "Power factor correcting-motor circuit. The total kilovar rating of capacitors that are connected on the load side of a motor controller shall not exceed the value required to raise the no load power factor to unity" Note that this instruction makes reference to adding no more capacitance than is required to improve the power factor to unity under a no load condition. At no load we are furnishing the magnetizing kilovar requirements of the motor. It is the intent not to exceed this amount of capacitive kilovars when improving the power factor of an induction motor.

SUMMARY:

To improve the power factor on beam pumping unit motors proper motor size and proper counter balancing should be done first. If further improvement is necessary then power factor correcting capacitors can be utilized. When using power factor correcting capacitors the improved power factor should not cause leading power factors. Leading power factors can result in winding failure or mechanical damage to the oil field pumping motor.

References

1. National Electric Manufacturers Association 1982, Part 14, Page 10, MG 1-14.44.

2. National Electric Manufacturers Association 1983, Part 2, Page 23, MG 2.16.10.

3. F.P. DeMello, G.W. Walsh, Reclosing Transients in Induction Motors with Terminal Capacitors, AIEE Transactions, Part III, Number 52, February 1961, paper No. 60-1257, p. 1206.

4. W.C. Bloomquist, Capacitors for Industry, Chapter 9, John Wiley & Sons Inc., New York.

5. General Electric Co., A.C. Motor Selection and Application Guide, Power Factor Pg. 14-15.

6. General Electric Co., GIZ-1601-24, Power Factor Correction, Transient Overvoltages and Torques.

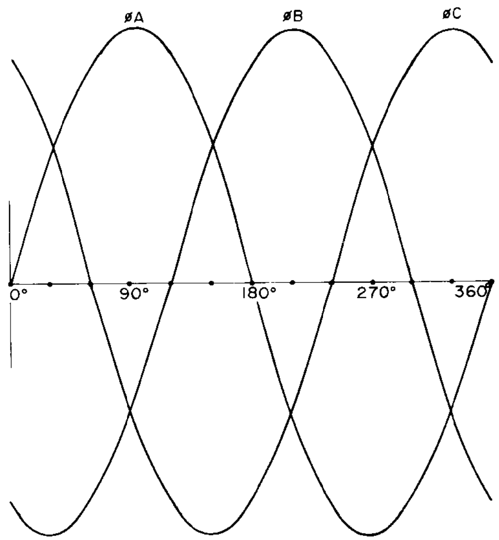

Figure 1 - Three phase voltage sine waves

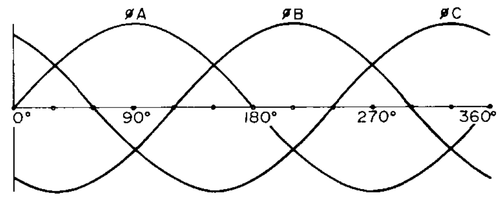

Figure 2 - Three phase amp sine waves

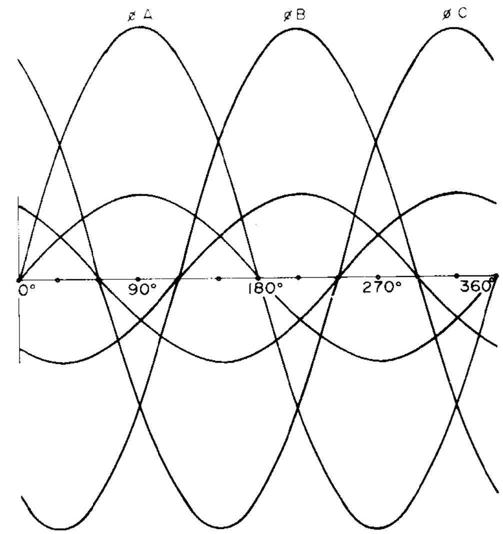

Figure 3 - Three phase amp and volt sine waves

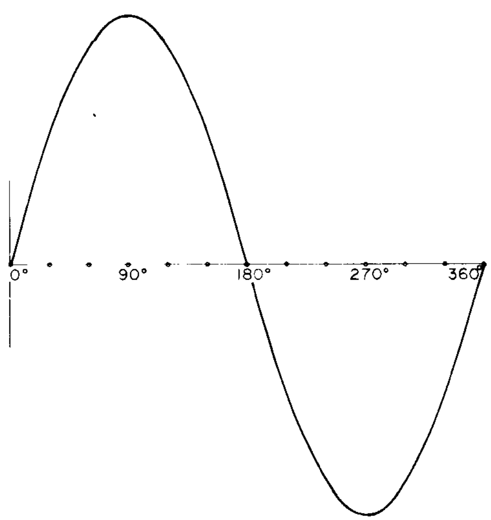

Figure 4 - Phase 1 of 3 phase voltage

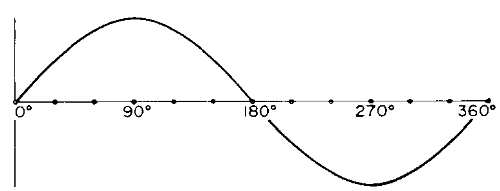

Figure 5 - Phase 1 of 3 phase amps

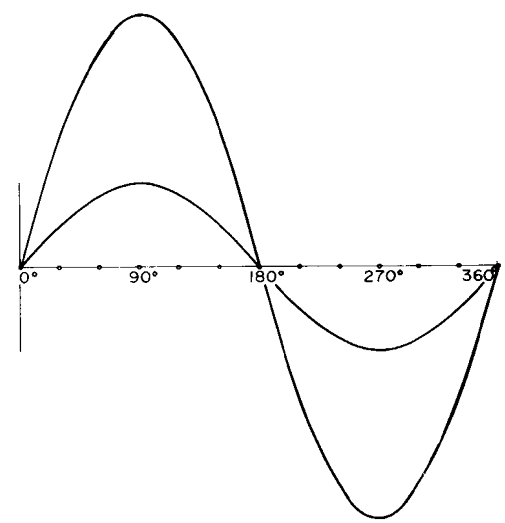

Figure 6 - 1 phase amps and volts in phase

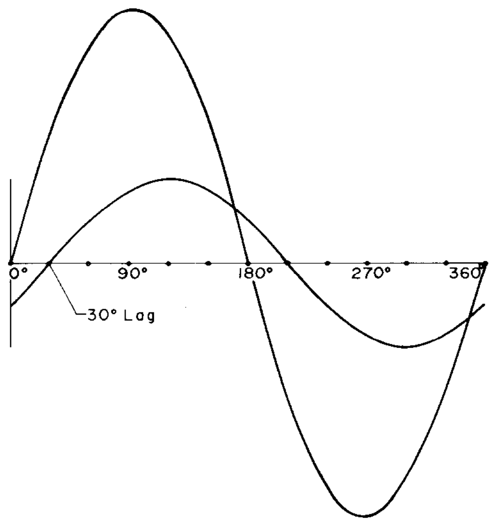

Figure 7 - Amps lag voltage 30°
in three phase system

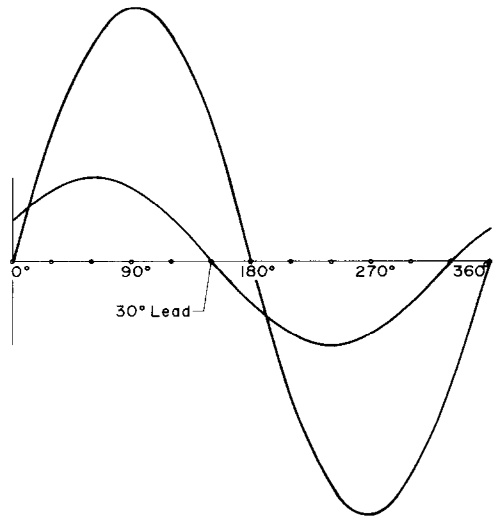

Figure 8 - Amps lead voltage 30°
in three phase system

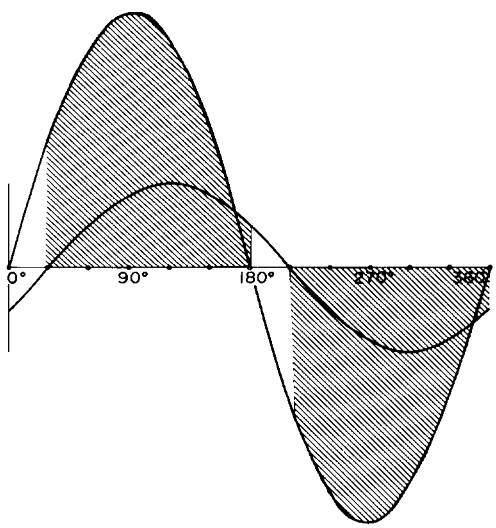

Figure 9 - Kilowatts of 3 phase power

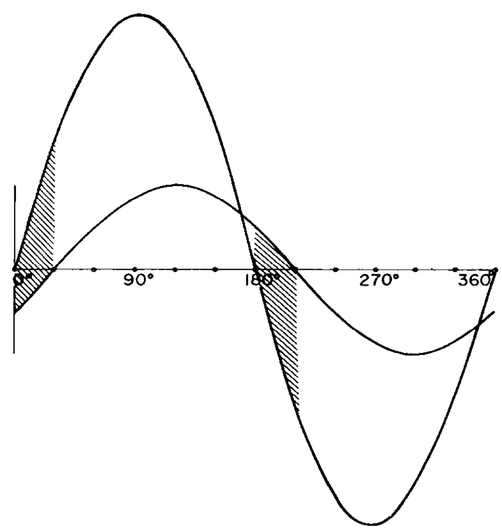

Figure 10 - Kilovars of 3 phase power

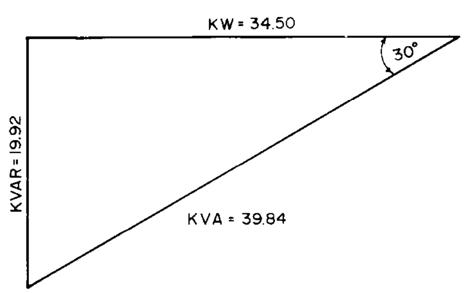

Figure 11 - Power triangle-current lags
voltage 30°

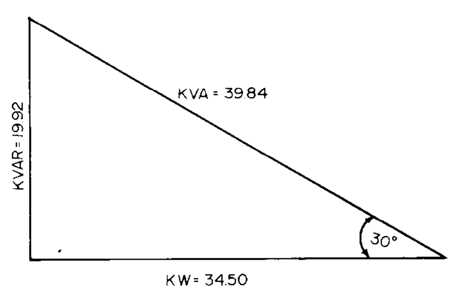

Figure 12 - Power triangle-current lags
voltage 30°

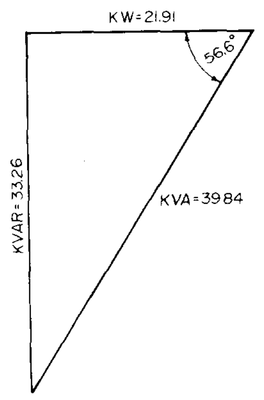

Figure 13 - Power triangle-power factor = .55 lag

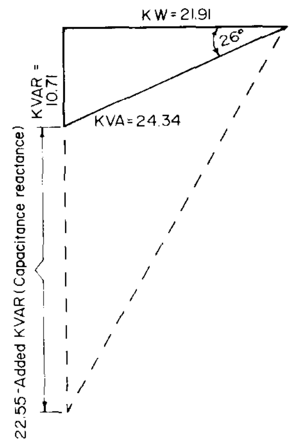

Figure 14 - Power triangle with improved power factor of .90

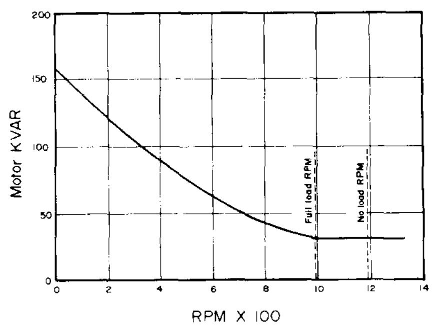

Figure 15 - Kilovar versus motor RPM

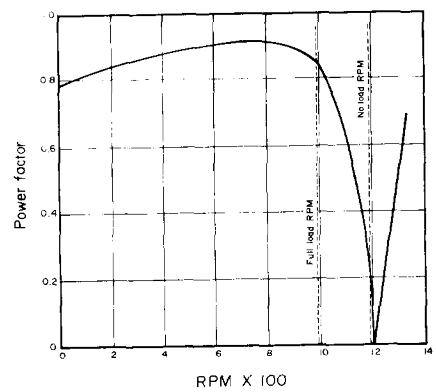

Figure 16 - Power factor versus motor RPM

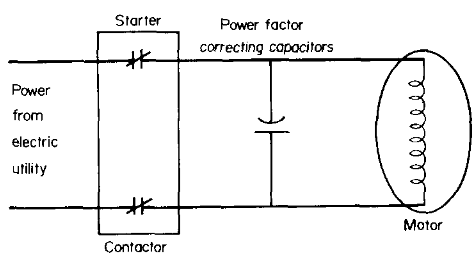

Figure 17 - Elementary control-motor diagram receiving power from electric utility

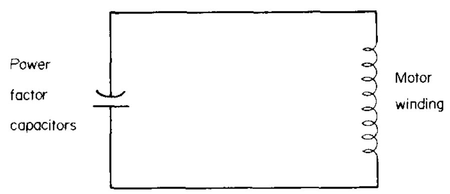

Figure 18 - Elementary circuitry-power factor correcting capacitors and motor winding