Power Factor and Oil Production

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Many attempts have been made to define power factor in a simple and concise manner in order that all may have a basic concept and understand the term after being exposed to its simple definition.

One definition is, "Power Factor is simply a name given to the ratio of actual power being used in a circuit, expressed in watts or kilowatts (KW), to the power which is apparently being drawn from the line, expressed in volt-amperes or kilovolt-amperes (KVA)."

Another definition neglecting transformer and electrical distribution line losses is, "Power Factor is the term used to express the portion or percentage of the electric power being supplied that is doing useful work."

Neglecting transformer and electrical distribution line losses in a system that has a power factor of 70 per cent means that only 70 per cent of the power being supplied to the system is doing useful work such as rotating the shaft of an electric motor.

A time-worn but still true analogy of power factor is the mule-drawn wagon shown in Fig. 1.

The distance that the mule is out of line with the wagon (reactive power), determines how much energy the mule has to put out (apparent power) to move the wagon along the path in a straight line (actual power).

The sine waves of different power factor situations are shown in Fig. 2.

1. UNITY POWER FACTOR.—All of the current is in phase with the voltage, the apparent power is equal to the actual

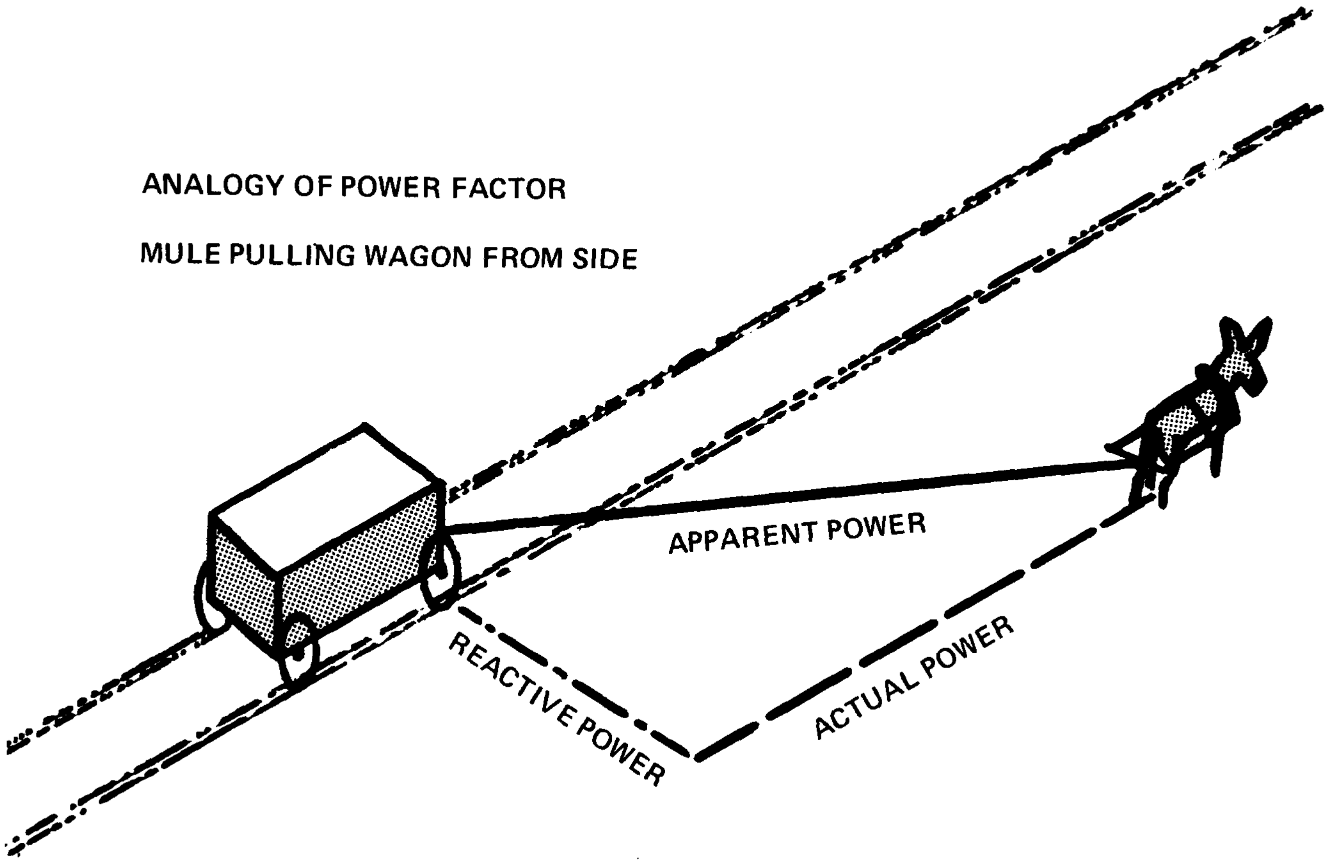


FIGURE 1

power.

2. LAGGING POWER FACTOR.—The current lags the voltage, creating negative power. The actual power is an average represented by line A - A', discounting the high peaks on the cycle. This is the apparent power. Subtracting the negative power (the shaded portion below the zero line) from the positive power, gives the actual power represented by Line B - B'.

3. LEADING.—The current leads the voltage, here again creating negative power. Actual power is derived by subtracting the negative power from the positive power. The general effect of a leading

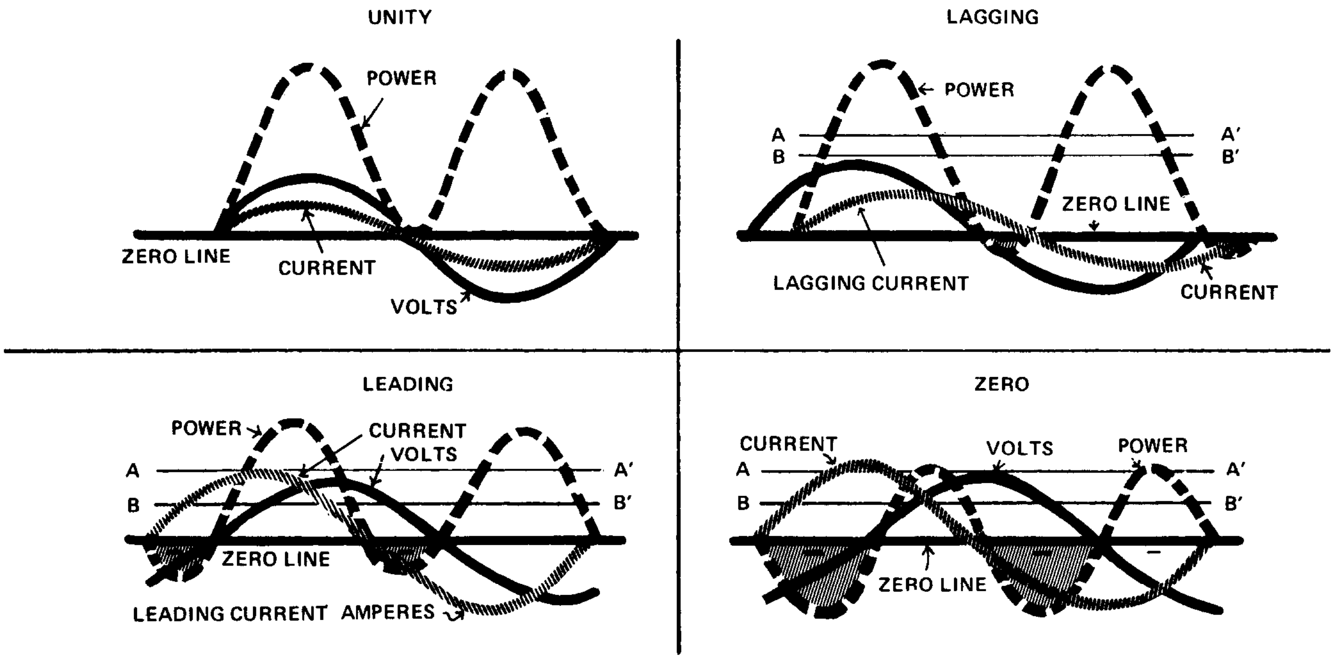


FIGURE 2

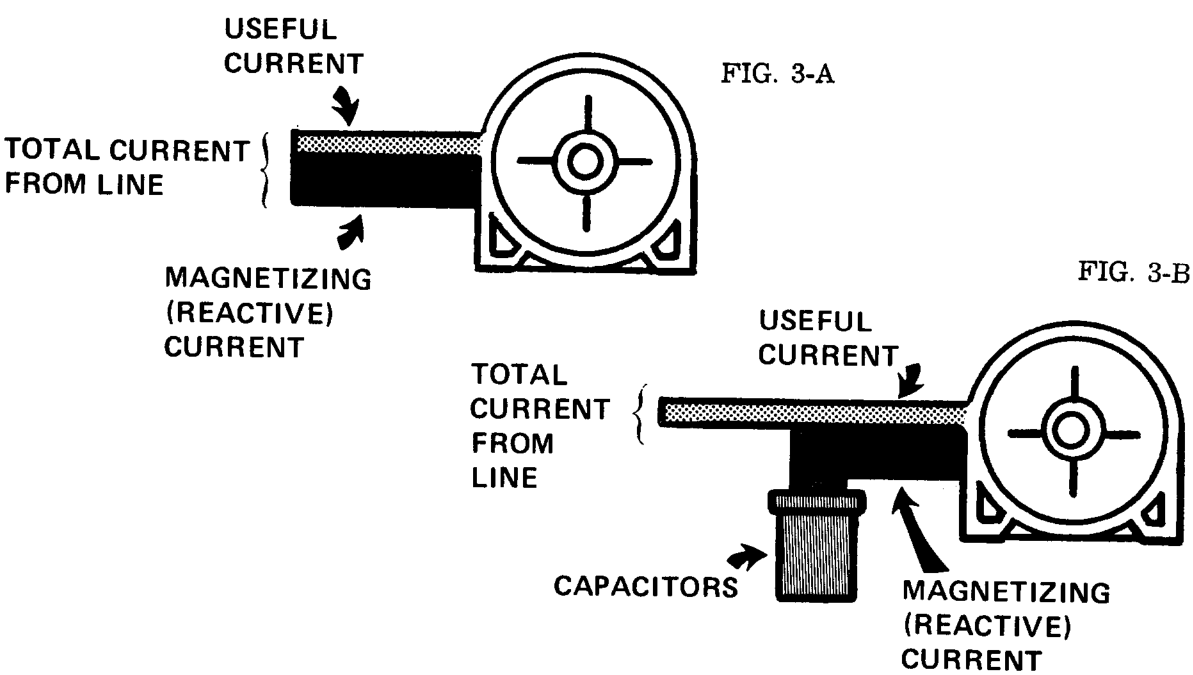


FIGURE 3

power factor is the same on the distribution system as a lagging power factor.

4. ZERO.—This is a situation where the negative power equals the positive power and the actual power is zero. As far as oilfield distribution is concerned, this is a theoretical situation. This can be caused by either a leading or lagging power factor.

Figure 3 graphically shows the line current of a motor on Fig. 3-A. The dark line is the actual current to furnish the power to run the motor. The cross-hatched line represents the exciting current (reactive current) of the motor.

Figure 3-B shows the installation of capacitors equal to the reactive current of the motor. The reactive current flows between the motor and the capacitors, but the only current on the line beyond the capacitors is the actual working current.

The exciting current of an inductive machine lags the voltage by 90 electrical degrees, and hence becomes reactive power. The main source of reactive power in oilfield operations is the induction motor. The amount of reactive power produced by a motor depends on several factors including size, speed and the percentage of rated load on the motor.

The exciting current of a motor is reduced a small amount from 100 per cent to a 20 per cent load. Figure 4 shows the power factor of a 75-HP, 1800-rpm motor at 100 per cent load as 92 per cent. This same motor at 20 per cent load has a power factor of 58 per cent. This is the greatest cause of poor power factor.

The oilfield distribution system being used is broken down into three load centers, each operating at a different power factor. These will be combined to produce the power factor for the distribution system.

Figure 5 (Load 1) illustrates the load center of an oilfield distribution system with thirty-six 50-HP, 1200-rpm beam pumping units, operating at 22 per cent of their rated load.

The load on this portion of the sytsem would be 400 KW, 722 KVAR and 825 KVA to give a

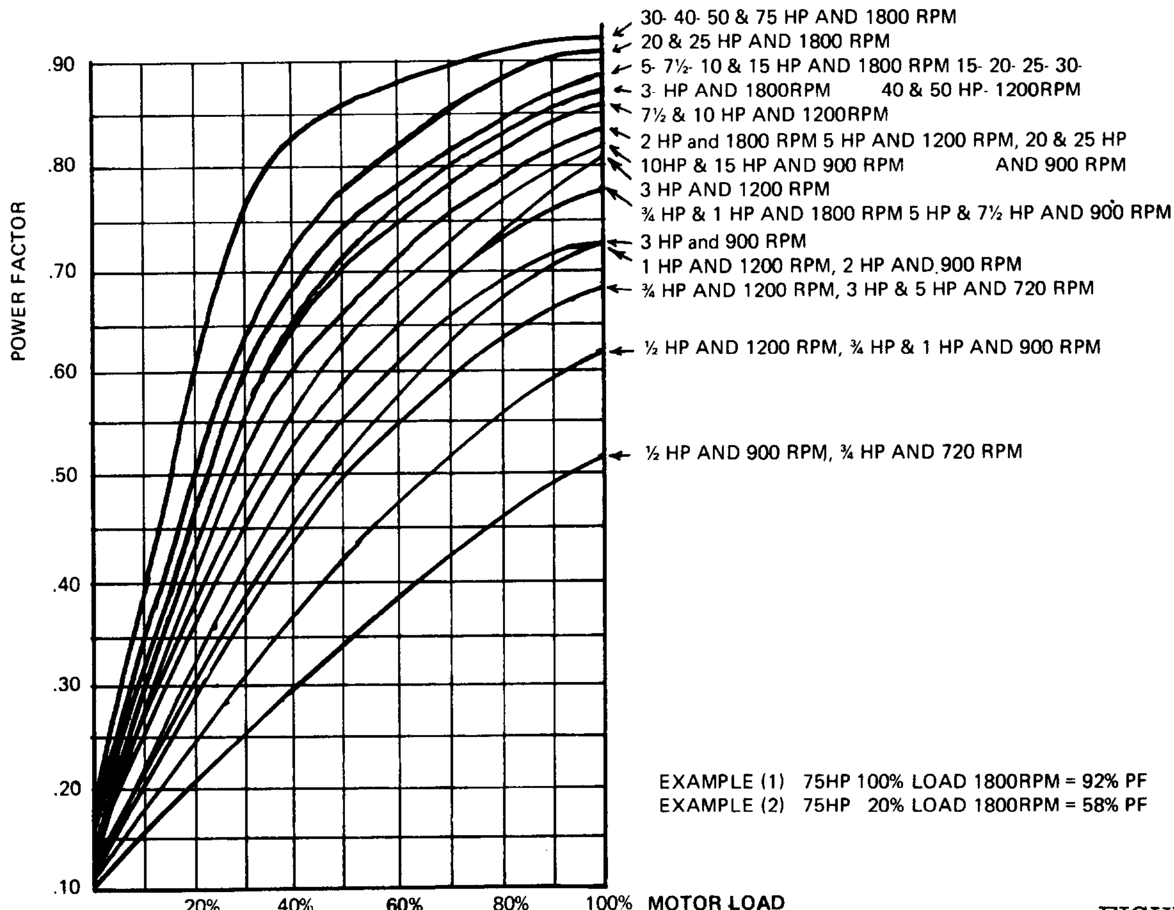


FIGURE 4

power factor of 48.5 per cent. The power triangle shows 18.5 working amps, 33.4 reactive amps, and the actual load on the distribution line is 38.2 amps.

Figure 6 shows the addition of load 2 to the system. This load is comprised of forty 20-HP, 1200-rpm beam pumping units operating at 42 per cent of their rated load.

This portion of the system would produce 300 KW, 300 KVAR and 425 KVA to give a power factor of 70.6 per cent. The power triangle shows 13.9 working amps, 13.9 reactive amps, and the line amps are 19.7.

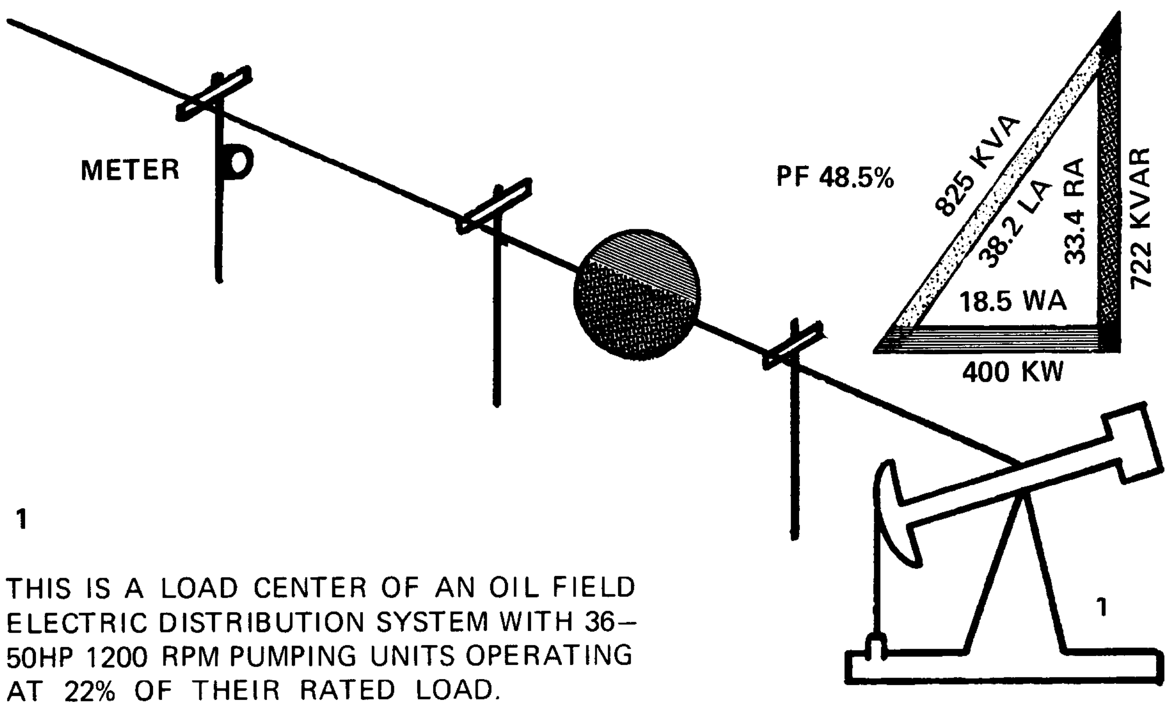
The individual power factors of these two loads will remain the same until they join the main feeder back to the source. At that point they will combine to produce a power factor that is a combination of both loads. The total load at this point is 700 KW, 1022 KVAR, and 1254 KVA. This gives a 55.8 per cent power factor. The power triangle now shows 32.4 working amps, 47.3 reactive amps, and 58 line amps.

Load Sketch #3 (Fig. 7) shows the addition of a 400-HP injection station. This unit is operating at full load and has a 90 per cent power factor. The load is 300 KW, 146 KVAR, and 333 KVA. Here the power triangle shows 13.9 working amps, 6.8 reactive amps, and 15.5 line amps.

At the point that this load joins the feeder, the over-all power factor is again affected as a result of the combination of all the loads. The total demand is 1000 KW, 1168 KVAR, and 1538 KVA. This gives a 65 per cent power factor. When the load from #3 (Fig. 7) is added to the feeder we have 46.3 working amps, 54.8 reactive amps, and 71.7 line amps. This is the load that the meter sees.

One point to clear up here is the addition of the three loads. The working amps and the reactive amps are added numerically, but the line amps are added vectorially.

The power factors for loads 1 and 2 were obtained from the power factor curves presented in Fig. 4. The power factor for load 3 came from



= LINE AMPS = KVA
= REACTIVE AMPS = KVAR
= WORKING AMPS = KW

FIGURE 5
Load Sketch No. 1

a table in a sales manual. Figure 4 points out the effects of the lightly loaded motors on the power factor. The main concern of a poor power factor can be pointed out by Fig. 8. This is loading on the facilities. Figure 8-A represents a piece of conductor with a power factor that varies from 100 per cent to 40 per cent. The cross-hatched area is the capacity of the conductor and the horizontal lines represents reactive current. This simply means that with a 50 per cent power factor, 50 per cent of the conductor is available for productive use. This brings up another consideration; line loss and voltage drop since they both vary with the line current. This could be a problem on an extended oilfield circuit. This will be covered later.

Figure 8-B shows the same thing on a transformer. A transformer with a 100-amp secondary rating, a 50 per cent power factor, and a 50-amp load has reached its rated load.

The greatest harm to motors by a poor power factor is excessive voltage drop. Low voltage at the motor raises the current in the motor, and therefore reduces the life of the motor.

The life of switchgear and other equipment can be extended by improving the power factor, and in some cases equipment can actually be reduced in size.

There are several ways to improve the power factor; one is to size the motor as near as possible to the load it is to carry. This is not always possible on pumping units within secondary recovery units since their load is subject to change; but, it is worth taking a look at the possibility of increasing the motor sizes in smaller increments. Example: 10 to 25 to 40 HP rather than 10 to 40 HP. Quite often these units can be relocated in the field when they reach their load limit at one location.

Another way to correct power factor is with synchronous motors. These motors have a separate excitation system and can operate at a

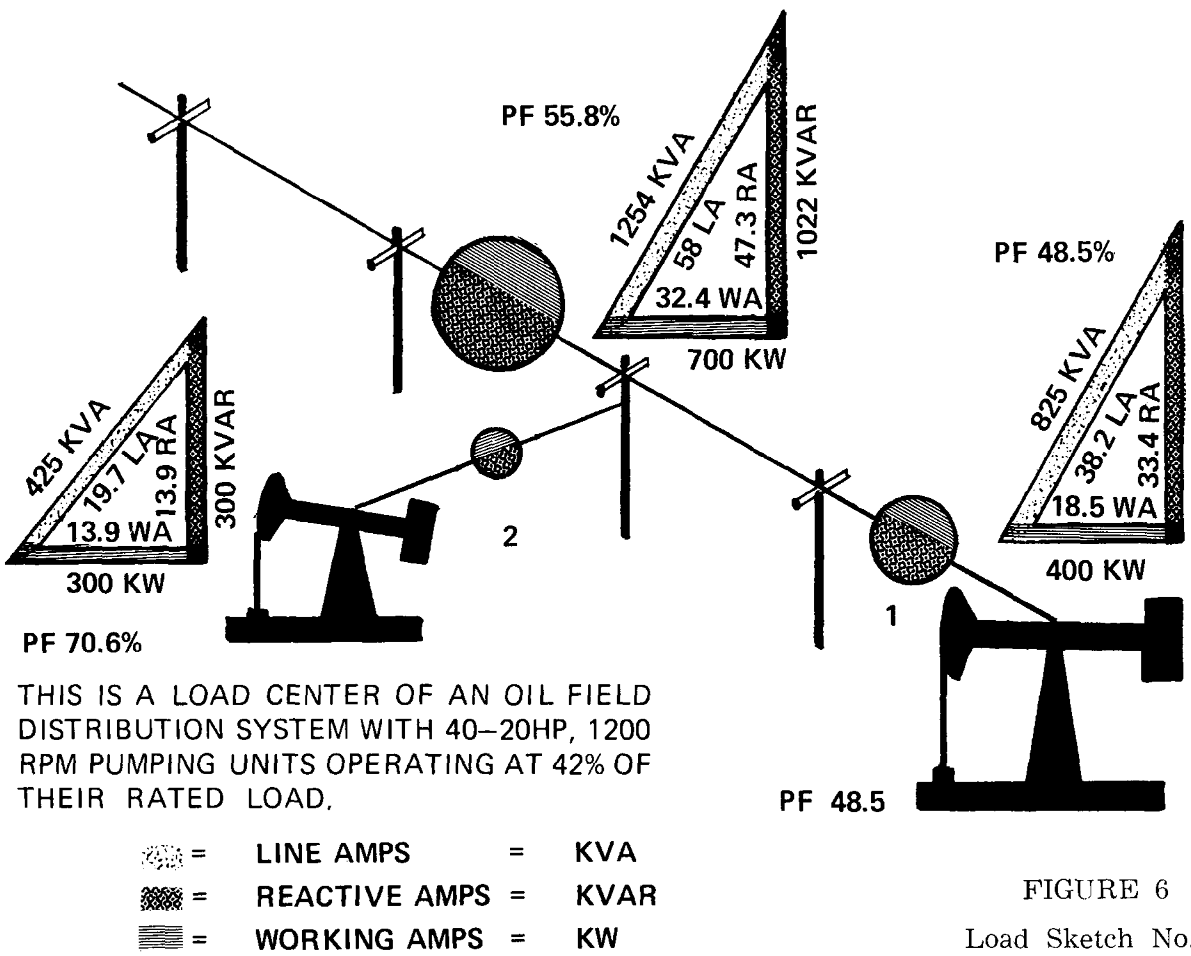
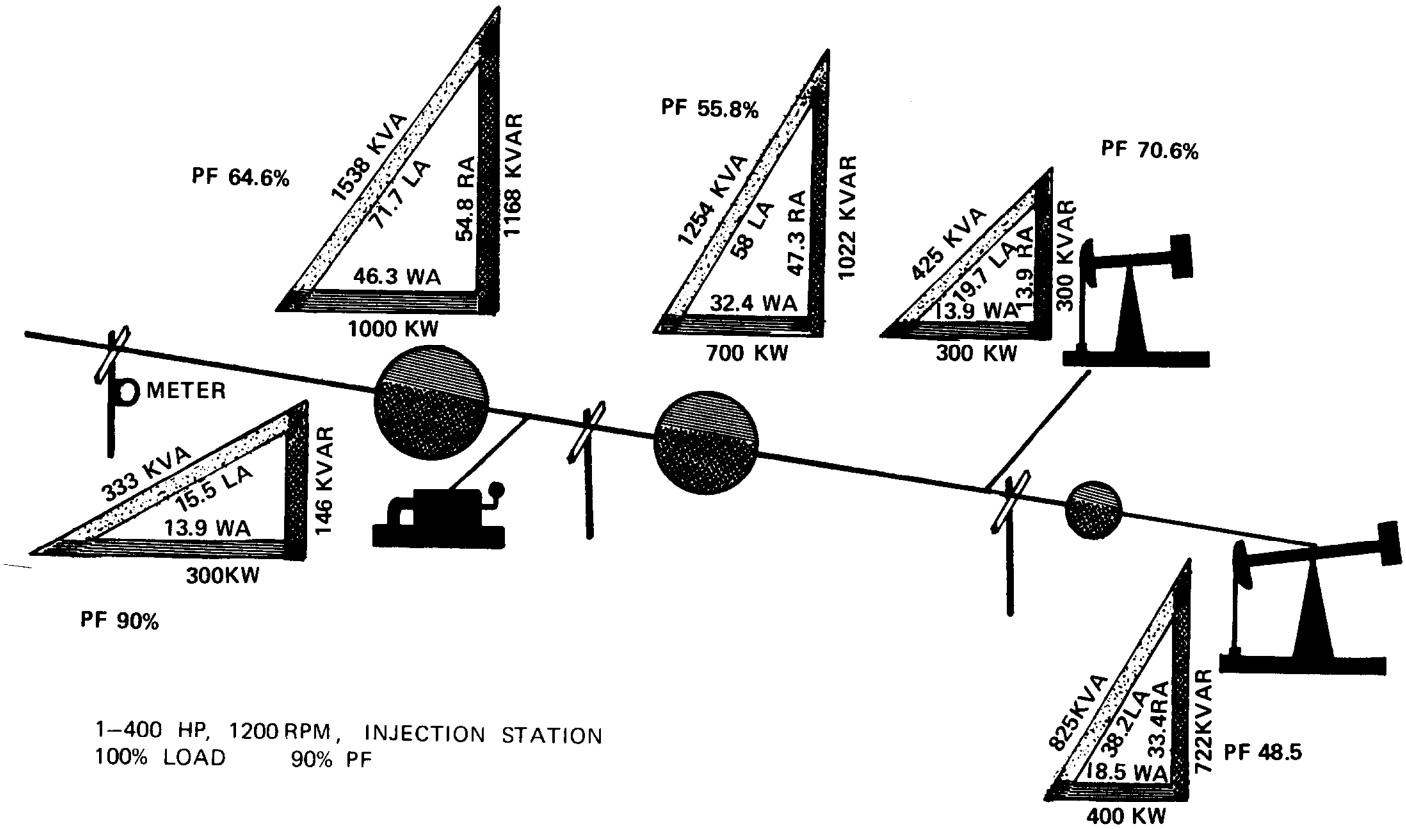


FIGURE 6

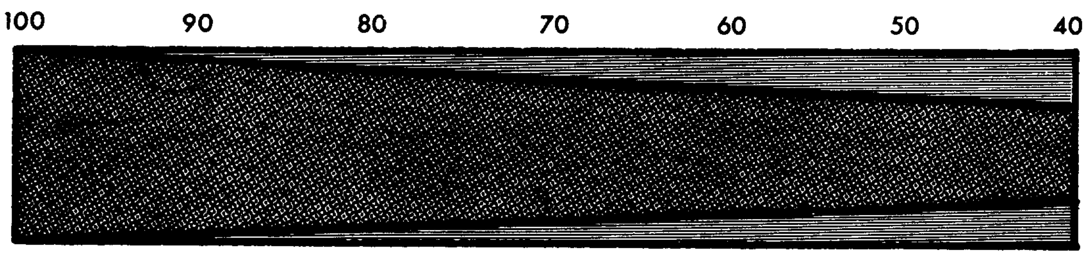
Load Sketch No. 2



= LINE AMPS = KVA
= REACTIVE AMPS = KVAR
= WORKING AMPS = KW

FIGURE 7

Load Sketch No. 3



CONDUCTOR CAPACITY
SKETCH I FIG. 8-A

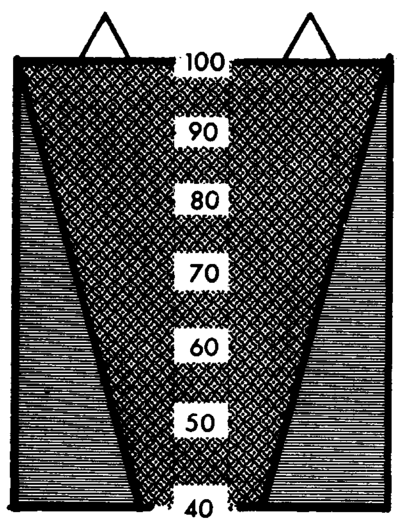


FIGURE 8

TRANSFORMER CAPACITY
SKETCH II FIG. 8-B

leading power factor. The amount of leading power factor can be varied within the limits of the motor by raising or lowering the exciting current. These motors cost more than induction motors especially in the smaller sizes. These motors can work well in a large plant with a concentrated load, but they do not lend themselves to the oilfield type of system.

The most economical way to correct power factor is with capacitors. The capacitor on an electric system works like the air chamber on the hydraulic system shown on Fig. 9. The pres-

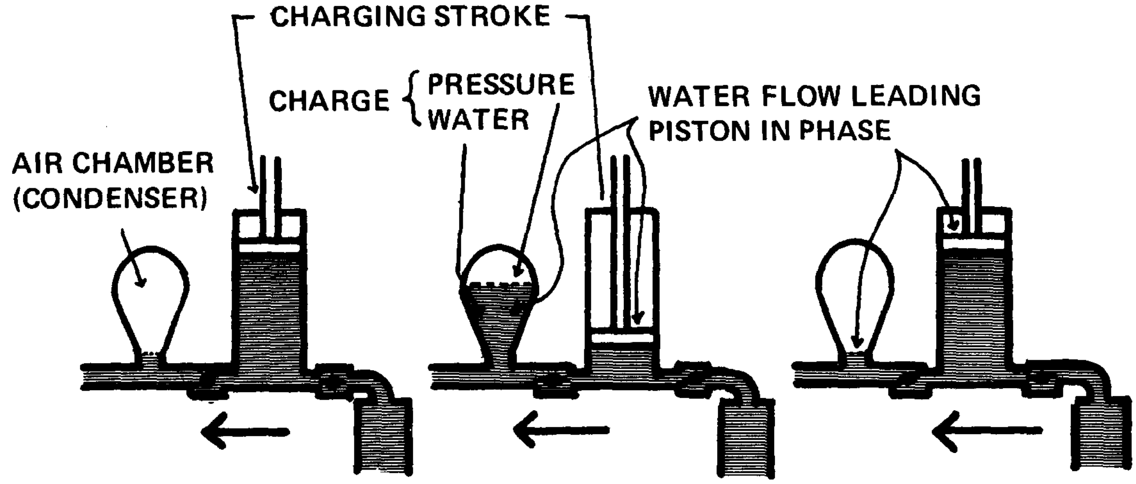
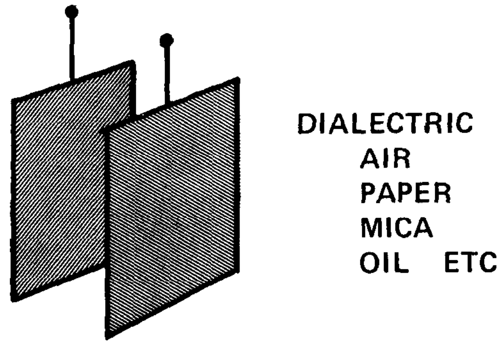


FIGURE 9

FIGURE 10

FIG. 10-A



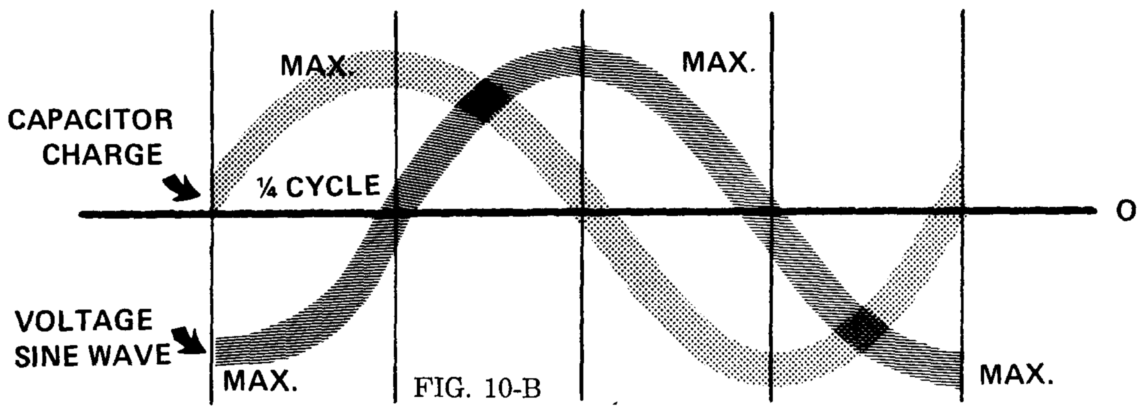


FIG. 10-B

sure pump on the downstroke forces (impressed voltage) the water into the air chamber (capacitor) charging it against an increasing back-pressure, which at the end of the stroke is in excess of the pressure due to the head (resistance) pumped against. This accumulation of pressure in the air chamber keeps the water (current) flowing while the piston is on the return stroke, and the impressed pressure (volts) is zero, the water flow (current) leading in phase with the power stroke (volts) of the pump.

A capacitor is basically two metal plates with a dielectric (of either air, paper, mica, oil, etc.) between them (Fig. 10-A). When a voltage is applied to the capacitor plates a charge is built up on the plates. The plates will charge and discharge twice each cycle of an alternating current circuit. As shown on Fig. 10-B, the capacitor leads the voltage sine wave 1/4 cycle so that when the voltage is at zero the capacitor has its maximum charge, and when the voltage is at its maximum the capacitor is discharged. The capacity of a capacitor is proportional to the area of the plates and inversely proportional to the dielectric between them.

It is recommended that the power factor be held to about 90 per cent. This can be justified by reduction in the power factor adjustment payment in the monthly power bill. This charge is made by most power companies to offset the cost of extra capacity of equipment required by low power factor.

There are many ways that this power factor adjustment can be applied. Only one of these will be covered, the one used by Southwestern Public Service Company.

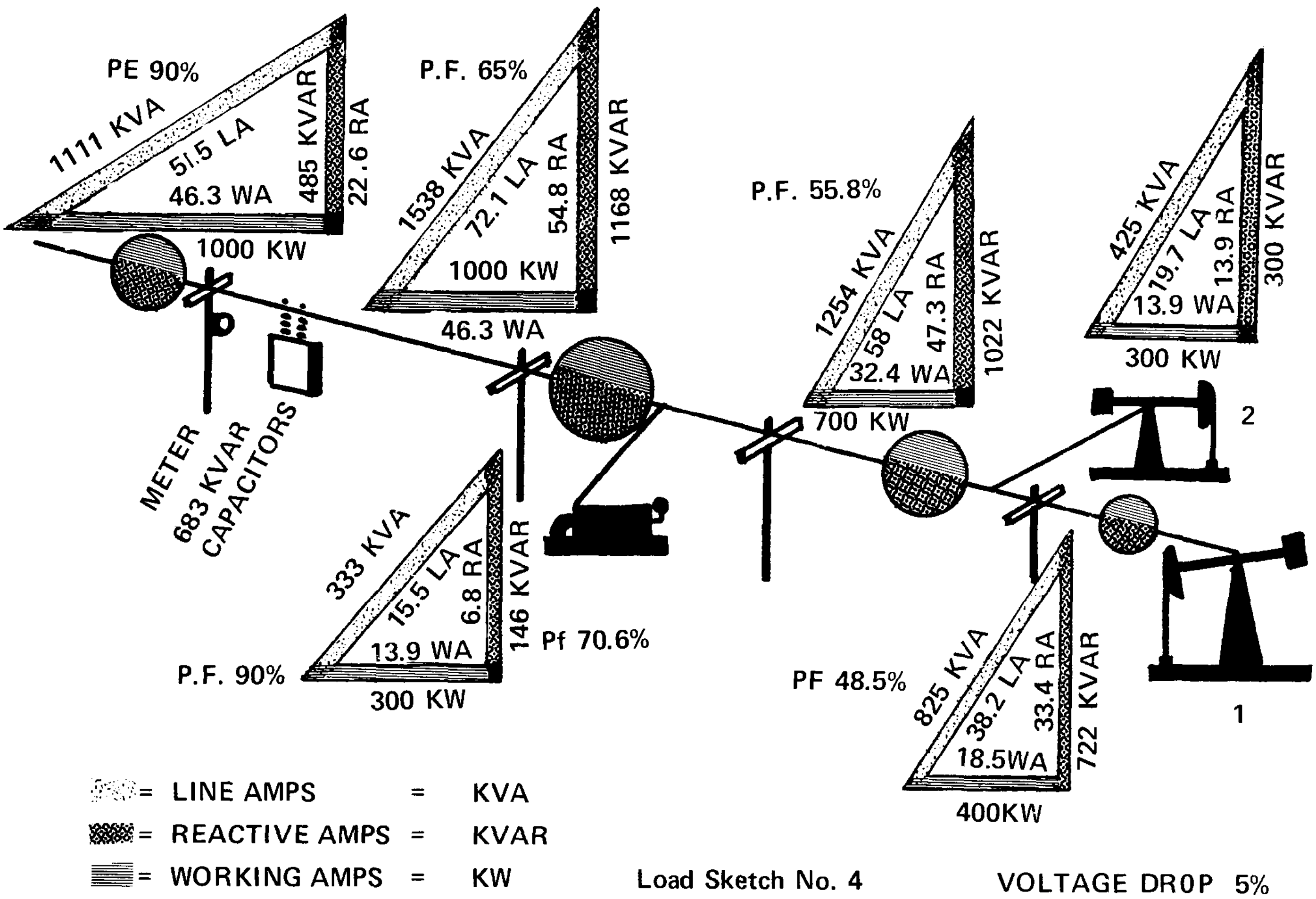


FIGURE 11

Load Sktch No. 4

This company's Power Factor Adjustment reads: Bills computed under the above rate will be increased \$0.25 for each KVAR by which the reactive demand exceeds, numerically, 0.53 times the measured KW demand, and will be reduced \$0.25 for each KVAR by which the reactive demand is less than, numerically, 0.40 times the measured KW demand.

Stated mathematically: PFA = .25 (KVAR - .53 KW) or, PFA = - .25 (.40 KW - KVAR). If the KVAR demand falls between 53 and 40 per cent of the KW demand, the bill stays as it is. This is between 88.4 and 92.8 per cent power factor.

Apply the power factor adjustment to this situation using Fig. 7. The meters read 1000 KW demand and 1168 KVAR demand. This gives Power Factor Adjustment = .25 (1168 - .53 (1000)) = \$159.50. This would be added to the bill each month that this condition existed.

Change the load to 1000 KW and 300 KVAR. The KVAR is less than 40 per cent of the KW so use .25 (.4KW - KVAR) = PFA. This gives .25 (.4 (1000) - 300) = PFA = \$25.00 decrease.

There are several ways to improve the power factor. The easy way to figure how many KVAR of capacitors to add is to find out how many KVAR are now being paid for; 1168 - .53 (1000) = 638 KVAR. One would need to add in excess of 638 KVAR of capacitors to bring the KVAR down to the point that the power bill would not be increased.

If 90 per cent is set as the power factor to shoot for, one must find the difference in KVAR between 90 and 65 per cent power factor.

Since Power Factor = Cosine 0 then .9 = 25°51" then Tangent 25°51" = .48450.

Tangent 0 X KW = KVAR then .48450 X 1000 = 484.5 KVAR, rounded off to 485 KVAR. The capacitors needed will be 1168 - 485 = 683 KVAR.

What has this done to the line load (KVA)?

$$\frac{KW}{Pf} = KVA \qquad \frac{1000}{.65} = 1538 \text{ KVA}$$

$$\frac{1000}{.9} = \underline{1111} \text{ KVA}$$

427 KVA Reduction in Line Load

Capacitors for primary voltages come in various size banks—150, 300, 600, 900 and 1200 KVAR. In actual field practice one would probably want to install 900 KVAR, but for the purpose of this example the exact amount needed will be installed to correct the power factor as shown on Fig. 11.

The 683 KVAR of capacitors have been installed on the load side of the meters. This has raised the power factor to 90 per cent at the meter. Looking at the power triangles note that it has lowered the line current from 72.1 to 51.5 amps; this is a 20.6 amp reduction in line current. The reactive current is still flowing between the load and the capacitor. The meters read 1000 KW, 485 KVAR and the calculated line load is 1111 KVA.

The advantages of adding capacitors at the meter are; (1) reducing the power bill, (2) reducing voltage drop from the capacitors back toward the power source, and, (3) reducing the cost per KVAR of capacitor installed (the larger the bank the less per KVAR cost).

Now consider installation of the capacitors at the load shown on Fig. 12. 529 KVAR of capacitors were installed at Load #1. The line current is lowered from 38.2 to 20.6 amps—a reduction of 17.6 amps.

At Load #2, 154 KVAR of capacitors were added. This has reduced the line current from 19.7 to 15.5 amps., resulting in a 4.2 amp reduction. The reactive current still flows from the load to the cup.

The meters read 1000 KW, 485 KVAR, and the calculated KVA is 1111. This is the same as with the capacitors located at the meter but

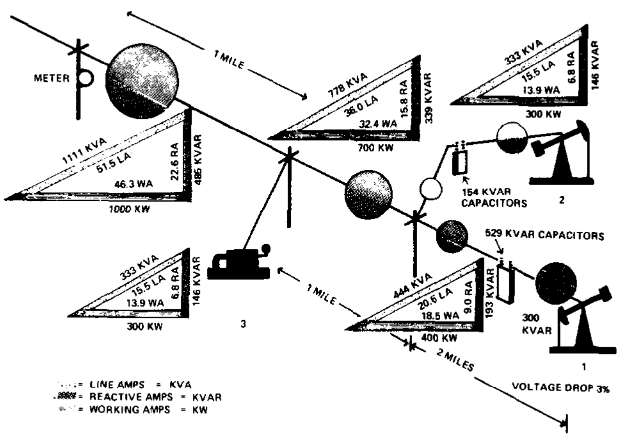


FIGURE 12

Load Sketch No. 5

the line current has been lowered from the load back to the power source. The advantages of the capacitors located at the load are; reducing the power bill, reducing the voltage drop from the load back toward the source, reducing the line loss from the load back to the meter and increasing the available capacity of the conductor.

Assume that this line is aluminum conductor steel-reinforced, commonly referred to as #2 ACSR and that it is one mile from the meter to Load 3, one mile from Load 3 to Load 2, and two miles from Load 2 to Load 1.

First, consider the capacitors located at the meter. To figure the voltage drop, one has to break the line down into sections and calculate the voltage drop to each point that the load changes.

$$\text{Voltage Drop} = \frac{\text{Current} \times \text{Distance} \times 1.73 \times \text{Resistance per thousand feet}}{1000}$$

The sum of the voltage drops from the meter to load 1 is 5 per cent. This means that if starting with 12,500 volts at the meter, one would have 11,875 volts at load 1. This is a drop of 625 volts, resulting in a 5 per cent voltage drop on the secondary of the transformer. If we have a 440 volt secondary, then 440 - (5% X 440) = 418 volts at the secondary terminals of the transformer. The 5 per cent voltage drop would apply regardless of the voltage of the system, since the voltage drop is a function of distance, current, and resistance.

Note the capacitors located at the load. The voltage drop is 3 per cent at load 1. With a starting voltage of 12,500 at the meter of load 1 we would have 12,125 volts. This is a drop of 375 volts. The secondary of a 440-volt system, the voltage would be 440 - (3% X 440 volts) = 427 volts at the secondary terminals of the transformer. The voltage at the terminals of the transformer has been improved, (427 - 418 = 9 volts).

The available capacity of the conductor has been increased from 65 per cent to 90 per cent. On #2 ACSR this would mean one could carry 41 amps, or 887 KW more before reaching the capacity of the conductor. However, the voltage drop is usually the limiting factor rather than the capacity of a conductor.

The line loss with the capacitors at the meter is 22,667 KWH per month. The line loss with the capacitors at the load is 9519 KWH per month. This is a difference of 22,667 - 9519 or 13,148 KWH per month. At one cent per KWH this would be an additional cost of $131.48 per month.

The line loss is a function of the square of the current, and with secondary current the line loss can climb rapidly. This will make secondary losses high as compared to primary losses.

$$\text{Line Loss (KW)} = \text{Current}^2 \times \text{Total Resistance of line}$$

$$\text{Total Resistance of Line} = \frac{\text{Distance} \times 3 \times \text{Resistance per thousand feet}}{1000}$$

$$\text{Line Loss per month (KWH)} = \text{KW} \times 730 \text{ hrs.} \times \text{Load Factor}$$

In Fig. 11, 529 KVAR of capacitors were installed at load 1. Having thirty-six 50-HP motors, and using secondary capacitors one would have 529/36 = 14.7 KVAR. Most manufacturers recommended a 15 KVAR capacitor for a 50-HP motor.

The average cost of capacitors installed per KVAR (including racks, cutouts, arresters, etc.) is (1) primary, $3.00 per KVAR and (2) secondary, $12.00 per KVAR.

This situation would be an extreme, but it does point out the fact that power factor improvement can help reduce the operational cost of oil production.