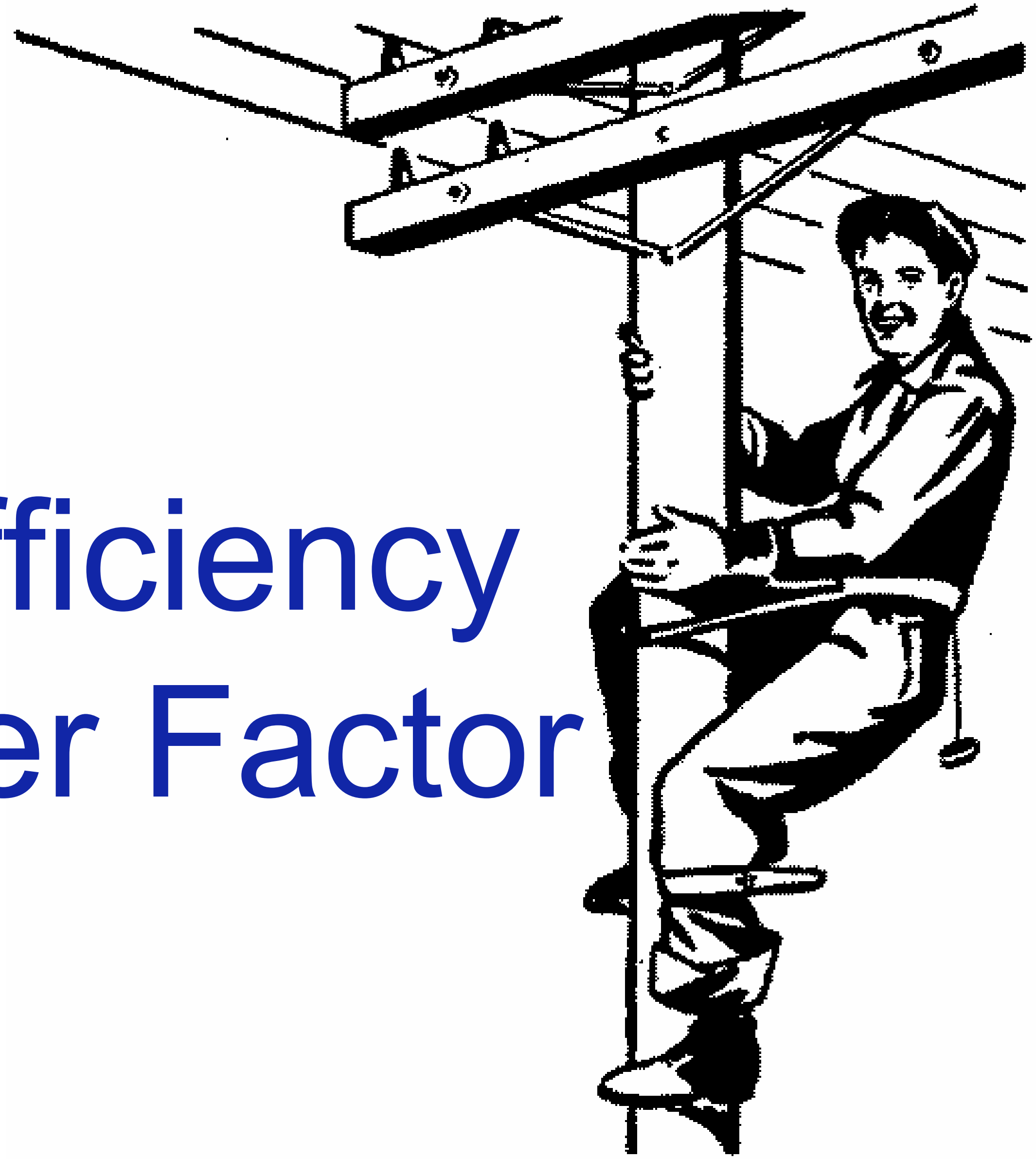
Motor Efficiency and Power Factor



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Motivation

- More than half of all electric energy generated goes to power **electric motors**.
- Electric motor converts electric power into shaft power. In thermodynamics terms, this is simply converting work from one form to another.
- The Second Law allows electric motors to have a theoretical efficiency of 100%.
- In reality, several types of power loss occur from where electricity leaves power plant to the point where shaft power leaves the motor.

Electric Power Losses

1. Transmission and transformer I^2R and hysteresis losses of real power component.
2. Transmission and transformer losses of imaginary power component.
3. Losses in the motor resulting from winding losses, frictional losses, etc.

- Loss 1 can be reduced by transmitting power at higher voltage: Power = $V \cdot I$ and Loss = I^2R.
- Same power can be transmitted by increasing V and reducing I: losses are reduced as $1/V^2$.

Electric Power Losses (Cont'd)

- Losses can also be reduced by decreasing R, but this means larger conductors (heavier wire) and copper is expensive.
- Loss 2 can be reduced by lowering imaginary, reactive part of current, which is accomplished by power factor improvement, discussed next.
- Loss 3 can be reduced by using more efficient motors, where electric motor efficiency is defined as:

η = Shaft Power Out/Electric Power In

Motor Ratings

- An electric motor's ***nameplate*** or rated power is its output power, not its electric input power.
- Electric power consumption is rated power divided by motor efficiency.
- Rated power depends on class of motor (which considers intended duty). Industrial grade motors usually are rated for continuous duty.
- Motor efficiency requirements are set by 1992 Energy Policy Act (EPACT), primarily for larger motors as used in industry and HVAC.

1992 EPACT Selected Full-Load Motor Efficiency Requirements

	Open Motors			Closed Motors		
hp	2 pole	4 pole	6 pole	2 pole	4 pole	6 pole
1	---	82.5	80.0	72.5	82.5	80.0
5	85.5	87.5	87.5	87.5	87.5	87.5
10	88.5	89.5	90.2	89.5	89.5	89.5
20	90.2	91.0	91.0	90.2	91.0	90.2
50	92.4	93.0	93.0	92.4	93.0	93.0
100	93.0	94.1	94.1	93.6	94.5	94.1
200	94.5	95.0	94.5	95.0	95.0	95.0

Energy Savings through Electric Motor Efficiency Improvement

- EPACT was passed in 1992 but motor efficiency provisions took effect in 1997.
- Commercial, institutional and, particularly, industrial operations use substantial amounts of power for electric motors.
- Although “high” or “premium” efficiencies may have only a few percentage points better efficiencies and may cost thousands of dollars more, they often are good investments.

Example- Elevator Motor

- An elevator in an Orange Beach condominium lifts an elevator weighing 5500 lbf at a rate of 5 ft/s. The elevator operates 7 hr/day in APCo summer months and 3 hr/day in winter months using an 85% efficient motor installed when the condo was built. Consider a replacement 95% efficient Baldor Super-E motor costing $3500 + $500 installation. Assuming an interest rate of 4%, electricity inflation rate of 4%, overall inflation rate of 2.5%, 40% tax rate, 5-yr depreciation, a 10% tax credit and no salvage value, does it make sense to change motors? The condo is a APCo Rate LPM customer.

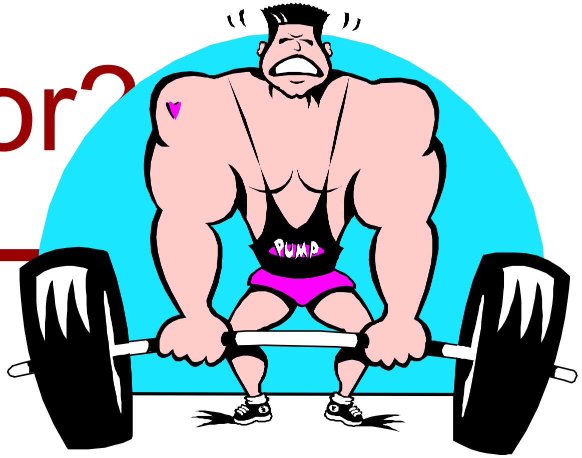
Example (Cont’d)

- See Elevator Example Excel Spreadsheet

Power Factor Correction

- Electrical loss 2 between power plant and useful work output of motor was the transmission and transformer I^2R and hysteresis losses resulting from the imaginary component of the power.
- This loss applies whenever an imaginary component is present- not just for motors.
- Power factor (PF) correction can reduce loss by reducing imaginary component magnitude.
- PF correction is relatively simple and economical, and often yields large energy and cost savings.

What Is Power Factor?



- For AC service, total power is the vector sum of the real power and reactive (imaginary) power.
- The total power in units of kVA is given by:

$$kVA = Volts * Amps * (N_{ph})^{1/2} * 10^{-3}$$

where Volts and Amps are the measured rms voltage and current and N_{ph} is the number of phases (1 or 3).

- The relation between total power, reactive power and real power is shown in the "power triangle".

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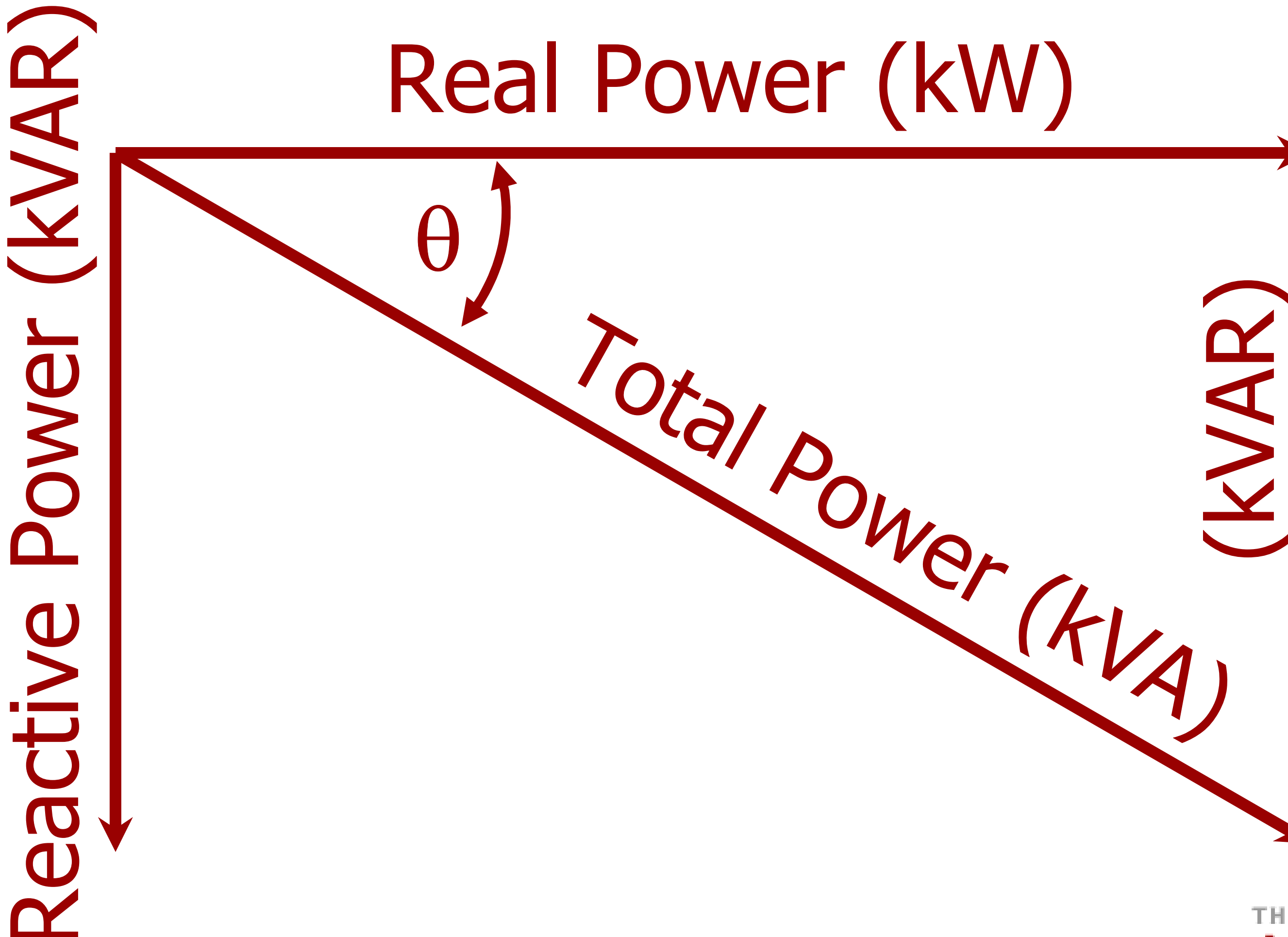
Power Factor Triangle



Notes on Power Triangle

- Imaginary component of power is due to imaginary impedance elements in the load.
- Pure resistors have no imaginary component, so current and voltage are "in phase" if impedance consists only of resistance elements.
- Capacitance causes voltage to lead the current, i.e., V reaches maximum before current (leading).
- Inductive impedance causes current to lead voltage, i.e., the voltage reaches maximum behind current (lagging).

Power Triangle Notes (Cont’d)

- The cycle angle by which voltage leads or lags behind the current is called the phase angle, θ.
- By simple trigonometry of the power triangle, the real component of power (in units of kW) is:

$$kW = kVA * \cos\theta$$

- Cosine θ is the power factor(PF): **PF = cos θ**
- Similarly, reactive power (in units of kVAR) is:

$$kVAR = kVA * \sin\theta$$

- Also by the Theorem of Pythagoras:

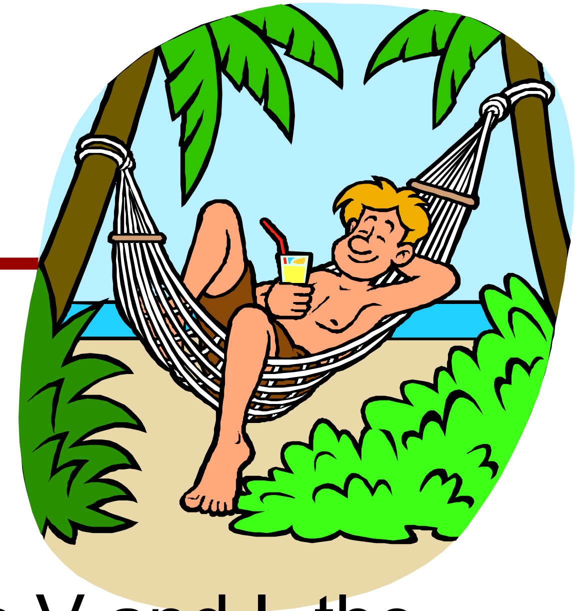
$$kVA^2 = kW^2 + kVAR^2$$

Why IS PF Less than 1?

Many common uses of electricity have inductive components of impedance that produce a lagging power factor:

- induction motors (AC)
- power thyristors for DC motor control
- transformers and voltage regulators
- electric welding equipment
- electric arc and induction furnaces
- neon and fluorescent lights (ballasts)

Why Worry About PF < 1?



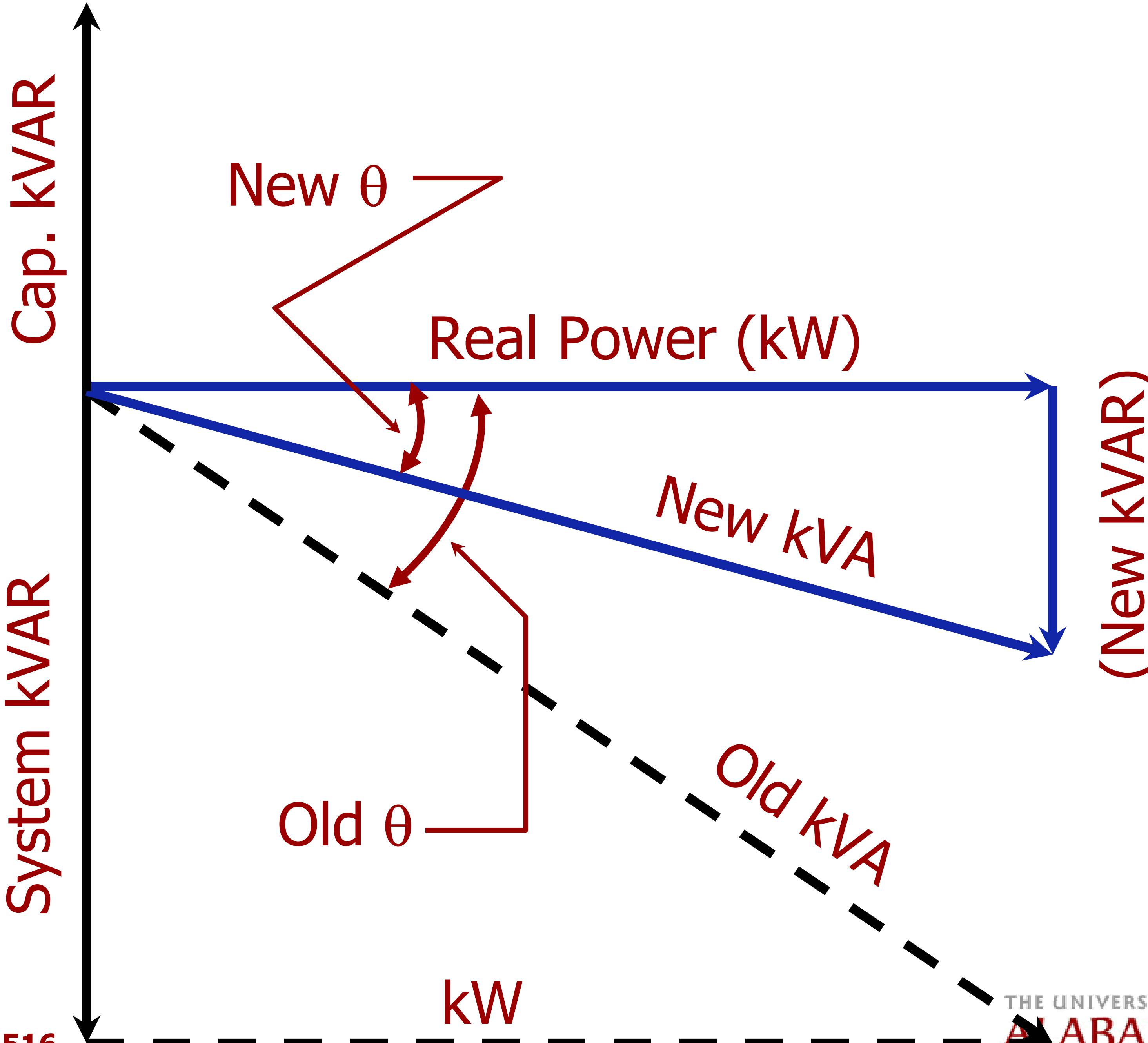
- Because V is fixed, then I is proportional to total power (kVA), and kVA = kW/PF.
- The larger phase angle θ between V and I, the smaller PF, the larger kVA and, thus, the larger the current the utility must send over its lines.
- Larger I causes larger I^2R losses and requires utility to install larger conductors & transformers.
- Although customer uses same ***real*** power, the lower PF costs the utility more to provide it.

Results of Low PF

- It costs the utility more to deliver the same real power to a customer with low power factor, so utilities charge a higher rate for low PF, either:
  - a direct penalty-higher charge for lower power factors levels (e.g., PF > 95%, no extra charge; 90 < PF < 95%, 5% surcharge; 85 < PF < 90%, 10% surcharge, etc.
  - or charge per kVA rather than per kW (APCo).
- The customer also has to buy larger wiring, switches, transformers, etc., because of higher current and kVA.

How Can Low PF Be Improved?

- Recall that capacitance and inductive elements have the opposite effect on the phase angle between voltage and current.
- Inductors have negative imaginary impedances, but capacitors have positive imaginary impedances.
- Capacitors can be added to the power circuitry to increase PF, as described in the power triangle diagram following:


Cap. kVAR
New θ
Real Power (kW)
(New kVAR)
New kVA
System kVAR
Old kVA
Old θ
kW

Capacitor Sizing

- First step is to measure present (old) kVA and PF, or get them from the power bill.
- Calculate kW: $kW = PF_{old} * kVA_{old}$
- Calculate system $kVAR_{sys}$:

$$kVAR_{sys} = \sqrt{kVA_{old}^2 - kW^2}$$

- Identify a target PF_{new}.
- Calculate the new kVA using target PFnew:

$$kVA_{new} = kW/PF_{new}$$

Capacitor Sizing (Cont'd)

- Calculate $kVAR_{new}$ once target PF_{new} is achieved:

$$kVAR_{new} = \sqrt{kVA_{new}^2 - kW^2}$$

- $kVAR_{new}$ is the difference between $kVAR_{sys}$ and the added capacitor's kVAR:

$$kVAR_{new} = kVAR_{sys} - kVAR_{cap}$$

- So kVAR of the capacitors to be installed is:

$$kVAR_{cap} = kVAR_{sys} - kVAR_{new}$$

Who Is Affected by PF Concerns?

- Most utilities only assess a penalty for low PF for relatively large power users.
- For example, to get rate LPL, APCo customers must have a 1200 kVA minimum capacity (this corresponds to a $200,000 per year power bill).
- Consequently, most customers to whom PF correction is most important are industrial or large institutional customers (like UA).
- Both categories have large portion of load made up by power supplied to large electric motors and to fluorescent and HID lighting.

Location of Capacitors

- Effective PF correction begins by installing capacitors at largest motors first and then adding capacitors as required at distribution load centers.
- Capacitors typically are not supplied to motors rated less than 20 hp unless these are the largest motors in service.
- Capacitors are normally installed on the load side of the motor starter so that they are effective only when the motor is operating.

Location of Capacitors (Cont'd)

- For motors that reverse, jog, etc., or where motor may at times be driven by the load (elevators, cranes), capacitors are connected on supply line side of motor controls with a separate switch.
- Adding excess capacitance can result in dangerous or damaging capacitor discharge through motor windings after motor is shut off.
- Capacitance must be controlled to match loads to avoid large discharge through motors and to lower PF from <u>too much</u> leading impedance.

Correcting PF of an Individual Motor

One set of following information is needed:

- Nameplate hp, efficiency, PF
- Nameplate hp, efficiency, voltage, full load amps (FLA)
- Nameplate PF, voltage, FLA
- Measured PF, voltage, FLA

Correcting PF of an Individual Motor (Cont'd)

- Get motor kW and kVA using these equations :

$$kW = hp * 0.746/effic. = kVA * PF$$

$$kVA = FLA * Voltage * (Nph)^{1/2} * 10^{-3}$$

where N_{ph} is the number of phases (1 or 3).

- Find the required kVAR capacitor as shown before.

Example

- **Given:** PF = 0.82 and motor with nameplate info of 100 hp and 94% efficiency.
- **Find:** Capacitor kVAR needed for Pf_{new} = 0.96.
- **Sol'n:** Calculate present power requirement:

kW = 0.746 kW/hp*100 hp/0.94 = 79.4 kW

- Calculate present kVA

$$kVA_{old} = 79.4/0.82 = 96.8\ kVA$$

- Calculate present (system) kVAR:

$$kVAR_{sys} = (96.8^2 - 79.4^2)^{1/2} = 55.4\ kVAR$$

Example (Cont'd)

- Calculate new kVA if PF = 0.96 is reached:

$$kVA_{new} = 79.4\ kW/0.96 = 82.7\ kVA$$

- Calculate combined kVAR after capacitor added:

$$kVAR_{new} = (82.7^2 - 79.4^2)^{1/2} = 23.1\ kVAR$$

- Find kVAR of the capacitor to be installed:

$$kVAR_{cap} = 55.4 - 23.1 = 32.3\ kVAR$$

- The nearest standard size would be installed, probably 30 kVAR. A larger std. capacitor than actually needed would be avoided if PF $\simeq$ 1