QUESTLINE

We Make Energy Engaging

Improving Your Power Factor

Meet Your Panelist

- Mike Carter

ENLIGHTEN EDUCATE ENGAGE

NEEA Northwest Industrial Training

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Upcoming In-Class Trainings

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http://neea.org/get-involved/calendar

Upcoming In-Class Trainings

- **Special Event:**

  NW Energy Efficiency Summit

  January 15, 2014: Portland, OR

http://neea.org/get-involved/calendar

Contents

Electrical Concepts

- Current
  - Flow of electric charges (amperes)
- Impedance
  - Resistance to flow of current (ohms)
  - Reactance
    - Inductance resists change in current
      - Waterwheel with flywheel
    - Capacitance resists change in voltage
      - Leaking bucket

INDUCTANCE

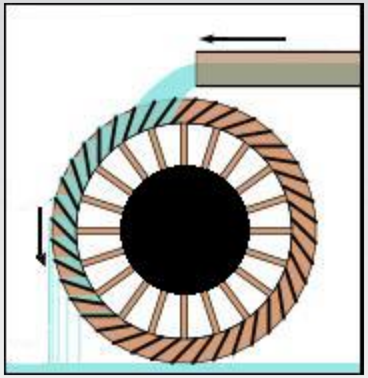
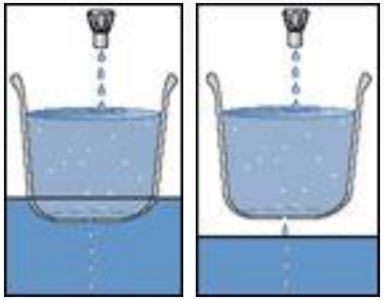


Image source: Daniel M. Short

CAPACITANCE



Electrical Concepts

- Power versus Energy
  - Kilowatt (kW) is a measure of **power**/demand.
    - A measure of the rate at which work is done

1 HP = 746 watts = 33,000 lb-ft/min = 550 lb-ft/sec

Source: stock.xchng

Power (kW) = HP x 0.746/eff

- Example: What is electrical power for a 200 HP motor?

Power (kW) = 200 HP x 0.746/0.90 = 166 kW

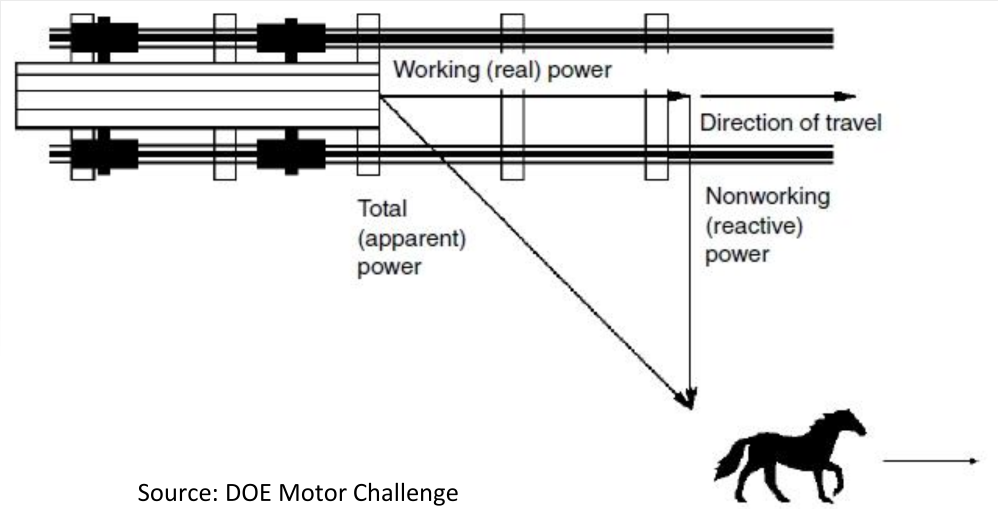
Electrical Concepts

- Power versus Energy
  - Kilowatt-hour (kWh) is a measure of **energy/load** consumption.
  - Energy (kWh) = Power (kW) x time (hrs)

Source: Commonwealth of Kentucky

What is Power Factor?

- Power Factor
  - Real/active power (kW) does real work.
  - Reactive power (kVAR) bound up in magnetic fields.
  - Apparent power (kVA) must be supplied by the utility to accommodate the reactive component.



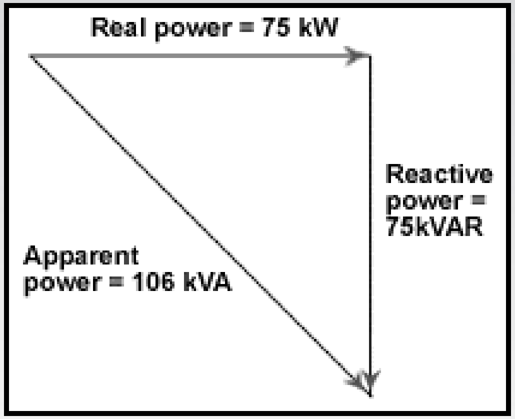
Source: DOE Motor Challenge

What is Power Factor?

- Power Factor

Method #1

PF = Real/Apparent Power
= kW/kVA
= 75 kW/106 KVA
= 0.70 or 70%



What is Power Factor?

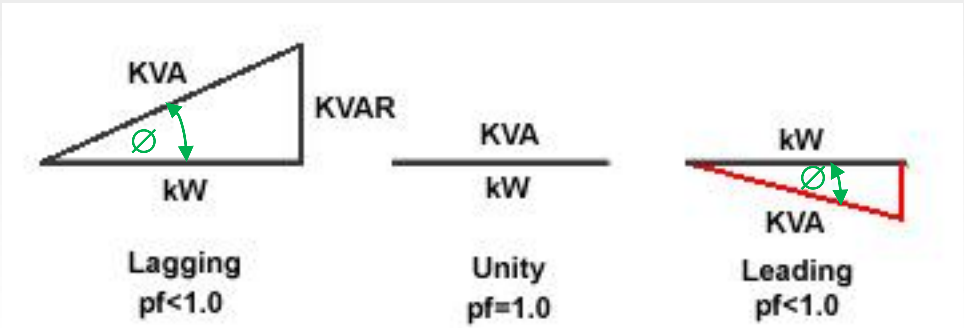
- Displacement Power Factor

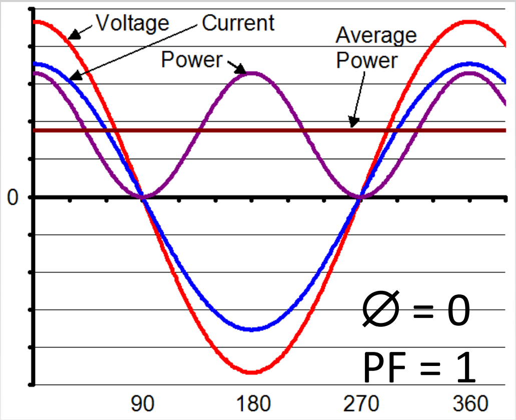
Method #2

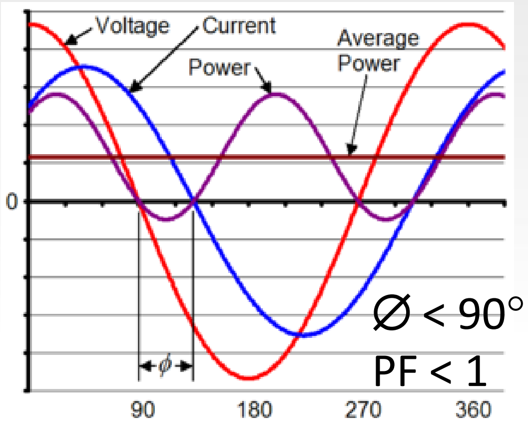
Power Factor = |cos ø |

ELI ~ current (I) lags voltage (E); inductive (L)

ICE ~ current leads voltage; capacitive (C)







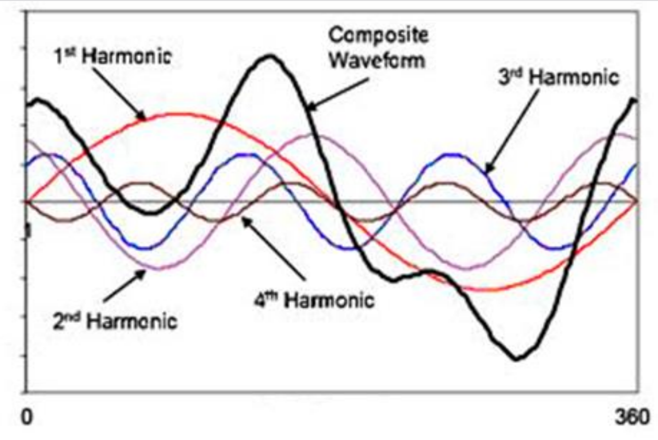
Source: Wikimedia Commons

What is Power Factor?

- Distortion Power Factor (non-linear loads)

  Power Factor = $\sqrt{[1 / (1 + THD^2)]}$

  where THD = Total Harmonic Distortion



- Total Power Factor
  - Product of distortion and displacement power factors

$$\text{Total Power Factor} = \sqrt{[1 / (1 + THD^2)]} \bullet |\cos ø|$$

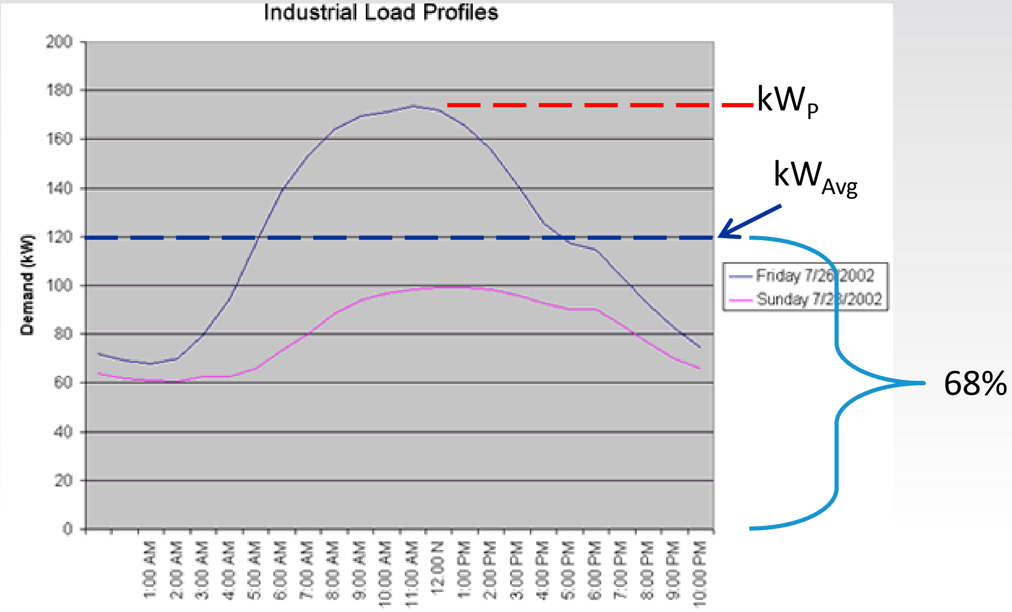
What is load factor?

- Load Factor
  - Ratio of average load over peak load
  - LF = kW_{Avg}/kW_P = kWh/hrs ÷ kW_P
  - Example calculation assumptions
    - 30-day billing (30 x 24 hrs = 720 hrs)
    - 86,400 kWh load
    - 175 kW peak

LF = 86,400/720 ÷ 175 kW

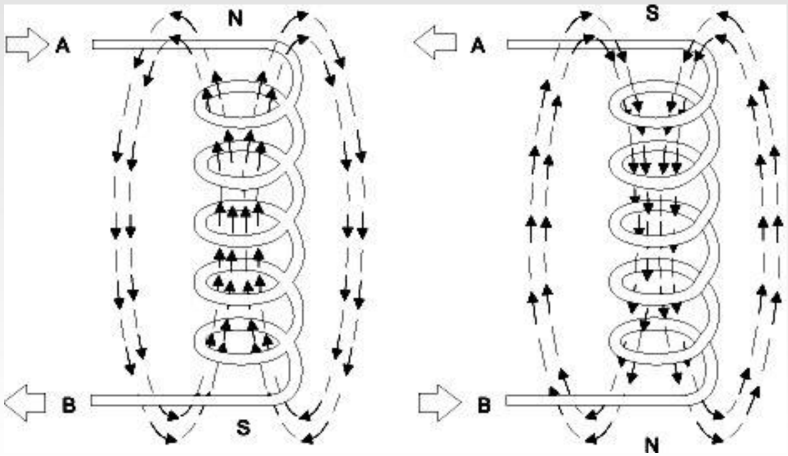
= 120 ÷ 175 kW

= 68%

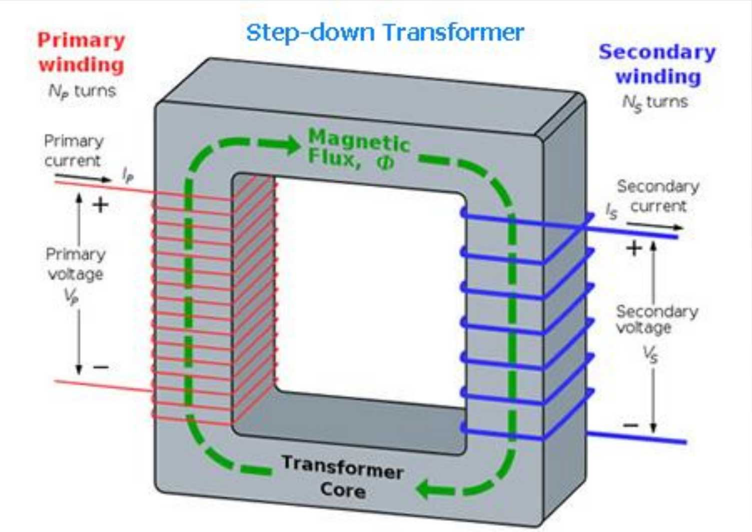


What causes power factor?

- Electric motors, transformers and inductors/chokes
  - Current flow in coil creates magnetic fields.
    - Reactive power (kVAR)



Source: Baldor Electric Company



Source: CA Air Resources Board

What causes power factor?

- Impedance Z can be split into two parts

  $$Z = R + X = R + X_L - X_C$$

  - Resistance R (the part which is constant regardless of frequency)
  - Reactance X (the part which varies with frequency due to capacitance and inductance)
    - Capacitive reactance (X_C)

      $X_C = \frac{1}{2 \pi fC}$ = reactance in ohms ()

      where f = frequency in hertz (Hz)

      C = capacitance in farads (F)
    - Inductive reactance (X_L)

      $X_L = 2\pi fL$ where L = inductance in henrys (H)
    - The total reactance (X) is the difference between the two

      $$X = X_L - X_C$$

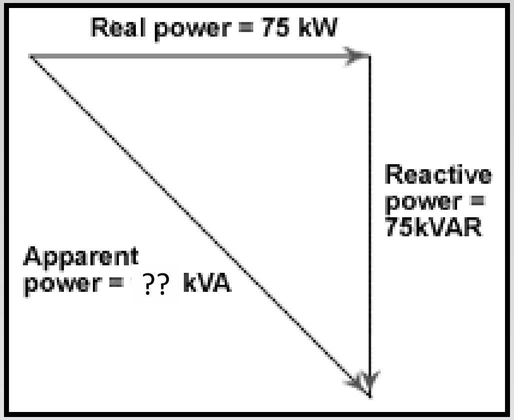
Source: The Electronics Club; John Hewes

Calculating Power Factor

- Power Factor
  - Given kW and kVAR, what is PF?

    PF = Real/Apparent Power

    = kW/kVA



  - Knowing 2 of 3 legs, you can calculate the other

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

$$(kVA)^2 = (75)^2 + (75)^2 = 11{,}250$$

$$\text{Apparent Power (kVA)} = \sqrt{11{,}250}$$

$$= 106\ \text{kVA}$$

Then: Power Factor = kW/kVA = 75/106 = 70.8%

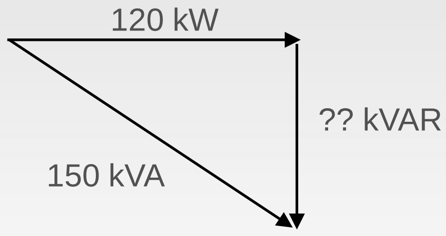
Calculating Power Factor

- What is power factor and kVAR for a circuit with 150 kVA and 120 kW?

PF = Real (kW)/Apparent (kVA)

= 120 kW / 150 kVA

= 0.80



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

$kVAR = \text{sqrt}\ (kVA^2 - kW^2)$

$= \text{sqrt}\ (150^2 – 120^2)$

= 90 kVAR

Calculations

- Real Power (inductive circuits)

  - P (1 ∅, kW) = (I x V x PF) / 1,000

    Power (kW) = 223 A x 480 V x 0.7/1000
    = 75 kW

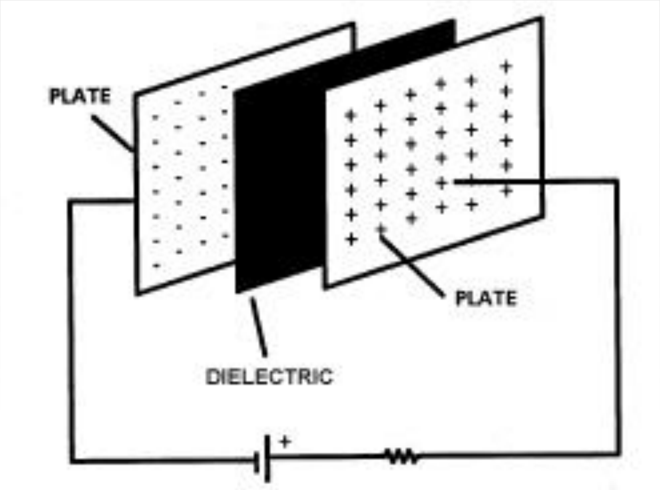
  - P (3 ∅, kW) = (I x V x PF x 1.73) / 1,000

    Power (kW) = 128 A x 480 V x 0.7 x 1.73/1000
    = 75 kW

Correcting Power Factor

- Power factor (PF)
  - PF correction capacitors are generally the most economical solution.

$$Z = R + X = R + X_L - X_C$$



Source: Alibaba

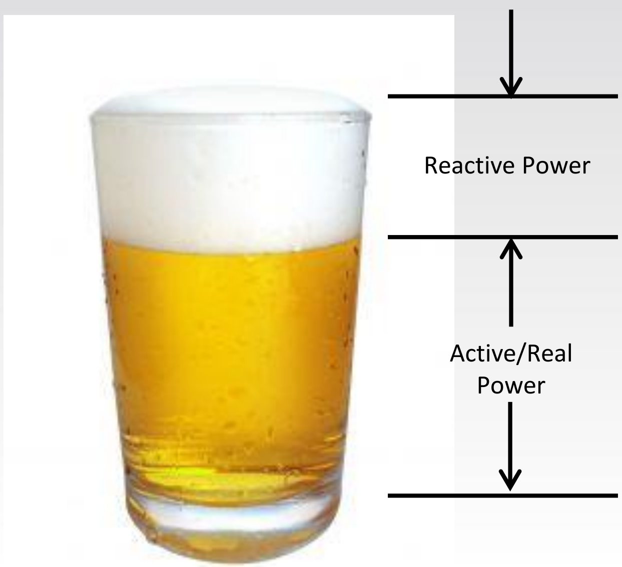
Correcting Power Factor

- Fixed capacitor bank
  - Single value of capacitance (KVAR)
  - Motors mainly operate at rated speed
- Automatic/switched capacitor bank
  - Varying value of capacitance
  - Best for large swings in load
  - Time delay between switching can vary from 5 seconds to 20 minutes
  - More expensive
  - Can lead to more transient and harmonic concerns for the system

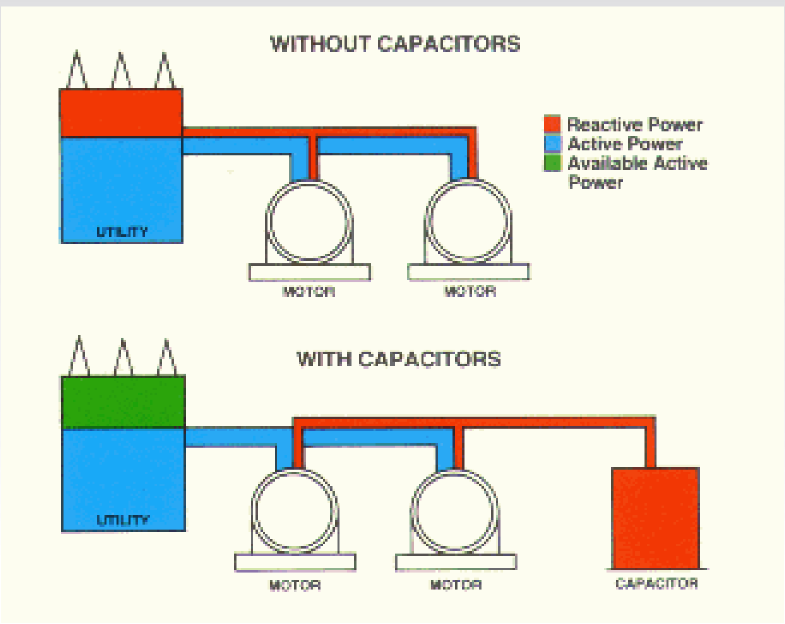
Source: LANL

Correcting Power Factor

- Power Factor Correction
  - Add capacitance to correct power factor.
  - Does not change demand (kW) or save much energy (kWh).



Source: Stock Exchange

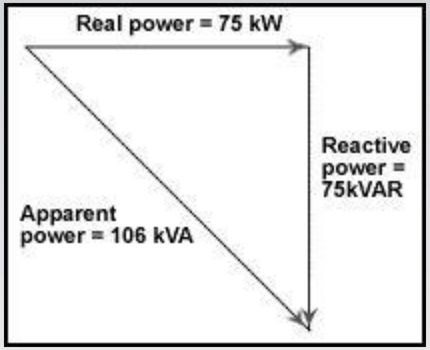


Source: Van Rijn Electric

Correcting Power Factor

- [Power Factor Correction]()
  - PF = Real (kW)/Apparent (kVA)

Present Power Factor = 75 kW / 106 kVA
= 70%



Correcting Power Factor

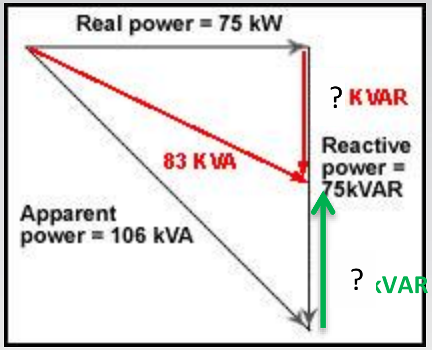
- Power Factor Correction
  - PF = Real (kW)/Apparent (kVA)

Present Power Factor = 75 kW / 106 kVA
= 70%

  - What kVAR is needed to correct to 90% PF given PF and kW?

New Power Factor = 90% = 75 kW / ?? kVA

New KVA = 75 kW/0.90
= 83 KVA



Correcting Power Factor

- Power Factor Correction
  - PF = Real (kW)/Apparent (kVA)

  Present Power Factor = 75 kW / 106 kVA = 70%

  - What kVAR is needed to correct to 90% PF given PF and kW?

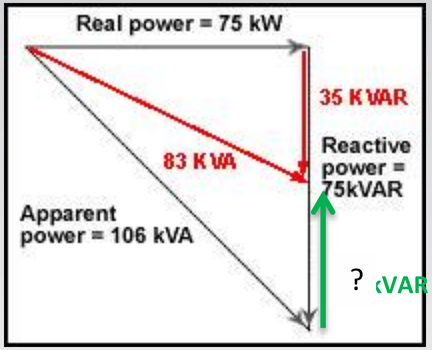
New KVA = 83 KVA

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

New kVAR = sqrt $(kVA^2 - kW^2)$

= sqrt $[(83^2) - (75^2)]$

= 35 kVAR



Correcting Power Factor

- Power Factor Correction
  - PF = Real (kW)/Apparent (kVA)

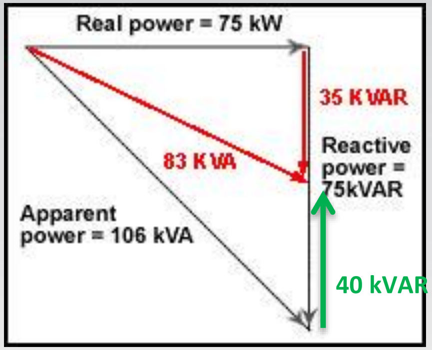
Present Power Factor = 75 kW / 106 kVA = 70%

  - What kVAR is needed to correct to 90% PF given PF and kW?

New KVA = 83 KVA

New kVAR = 35 kVAR

kVAR correction = Old - New
= 75 – 35 kVAR
= 40 kVAR



Correcting Power Factor

- kVAR contribution of a capacitor is proportional to the square of rated voltage and the capacitive rating

$$C(\mu f) = (kVAR \times 1{,}000)/[(2\pi f) \times kV^2]$$

$$kVAR = \frac{(2\pi fC) \times (kV)^2}{1{,}000} = \frac{(kV)^2}{1{,}000\ [1/(2\pi fC)]} = \frac{(kV)^2}{1{,}000\ (X_C)}$$

  - Capacitance size decreases by the inverse square of the voltage
    - If the capacitor bank is upstream (higher voltage), the capacitive rating (size) can be decreased and achieve the same kVAR impact.
    - If you double voltage, capacitance is reduced to one-fourth as much.

The Cost of Power Factor Correction

- Power factor penalty
  - Energy charge - metered versus billed kWh
  - Power charge - power factor penalty charge ($/kW or $/kVAR)
  - Target is typically 85% to 95% PF
- Cost per kVAR factors (typically $20 to $90/kVAR)
  - Voltage level of bank
  - Number of switched stages
  - Control requirements
  - Filter bank rating requirements and tuning point
  - Individual Capacitor kVAR rating

Disadvantages of PF Correction

- Concerns to be addressed
  - Voltage rise (delta V)
  - Harmonic resonance
  - Capacitor switching transients
  - Leading power factor

Disadvantages of PF Correction

- Voltage rise (delta V)
  - Never exceed 2% voltage rise from PF correction
  - Estimate voltage rise in a No Load situation

$$\%\ \text{Voltage Rise} = \frac{\text{Capacitor KVAR}}{\text{Transformer short circuit capacity}}$$

$$= \frac{\text{Capacitor KVAR}}{\text{Transformer KVA/ \%Impedance}}$$

  - Example, a 1500 KVA transformer (assume 5.0% impedance) is serving a load that has 500 KVAR on the system.

$$\%\ \text{Voltage Rise} = \frac{\text{500 KVAR}}{\text{1500 KVA/ 0.05}} = \frac{500}{30{,}000} = 1.67\%$$

Disadvantages of PF Correction

- Harmonic Resonance
  - Large amounts of capacitance in parallel with inductance.
    - Harmonic producing loads are operating on the power system.
    - Capacitor(s) and the source impedance have the same reactance (impedance) at one of the load characteristic frequencies.

$X_L = X_C$ and, therefore $X = X_L - X_C = 0$

  - Two possible solutions
    - Apply another method of KVAR compensation
      - Harmonic filter, active filter, condenser, etc)

OR

    - Change the size of the capacitor bank
      - Over-compensate or under-compensate for the required KVAR and live with the ramifications.

Source: Eaton Performance Power Solutions

Disadvantages of PF Correction

- Harmonic Resonance
  - Estimate the closest harmonic order for parallel resonance

    $H_r = \sqrt{(T_r /(Z * C_r)}$

    H_r is the parallel resonant harmonic (for example, 5th or 7th)

    T_r is the transformer rating, kVA

    Z is the transformer impedance, %

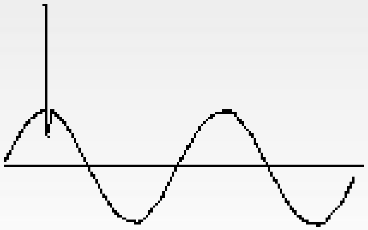
    C_r is the three-phase load of the capacitor bank in kVA
  - Example, a 1500 KVA transformer (assume 5.75% impedance) is serving a load that has a 600 KVA capacitor load on the system.

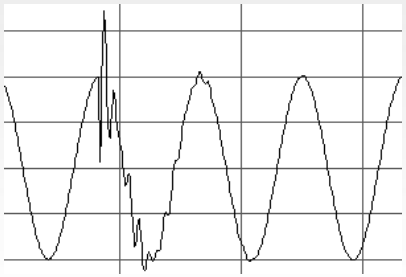
    $H_r = \sqrt{(T_r /(Z * C_r)} = \sqrt{1500/(0.0575 * 600)} = 6.59$

    - Therefore, if any magnitude of 7th harmonic current flows on the power system at that bus, the effect could be catastrophic.

Disadvantages of PF Correction

- Capacitor switching transients
  - The problem occurs when the power factor correction capacitors are switched on, first causing the voltage on the line to fall, followed by a sudden rise in voltage.

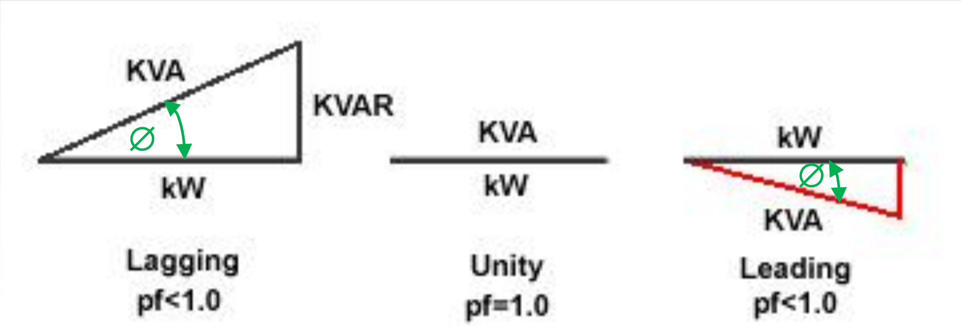




Disadvantages of PF Correction

- Leading Power Factor
  - Impedance is total resistance to current flow

    $Z = R + X_L - X_C$
  - Too much capacitance cancels inductance
    - Excessive current draw
    - Voltage rise



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