University of Idaho
College of Engineering

# ECE 528 – Understanding Power Quality

http://www.ece.uidaho.edu/ee/power/ECE528/

Paul Ortmann
portmann@uidaho.edu
208-316-1520 (voice)

## Lecture 18

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## Today…

- Capacitors
  - – Utility and end-user capacitor applications
    - Overview
    - Capacitor sizing
    - Current reduction
    - Loss reduction
    - Location discussion
    - Power factor charges
    - Voltage rise

## Capacitors - overview

- A local reactive power source, that can improve power factor and in turn…
  - Reduce real power losses
  - Release transformer and conductor capacity
  - Reduce power factor charges
  - Boost voltage

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## Power factor:
## Displacement, True, and Distortion (review from lecture 9)

- Displacement power factor:
  - Due to <u>phase shift</u> between V and I <u>at fundamental frequency</u>

$$\mathrm{DPF} = \cos\theta$$

- True Power Factor:
  - includes harmonics

$$\mathrm{PF} = \frac{\mathrm{P}}{\mathrm{S}} = \frac{\mathrm{Active\_power}}{\mathrm{Apparent\_power}}$$

- True Power Factor may also be called “Power Factor” or “Total Power Factor”

# Power factor: Displacement, True, and Distortion (review from lecture 9)

- Distortion PF: Relates RMS of the distorted current, including the fundamental current, to RMS of the fundamental current only

$$PF_{dist} = \frac{1}{\sqrt{1 + THD_I^2}}$$

- How displacement, distortion, and true power factor are related

$$TruePF = DPF \; x \; PF_{dist}$$

- Adding capacitors only corrects Displacement Power Factor (DPF). This equation shows that the best True Power Factor we can achieve by adding capacitors is limited by the distortion power factor.

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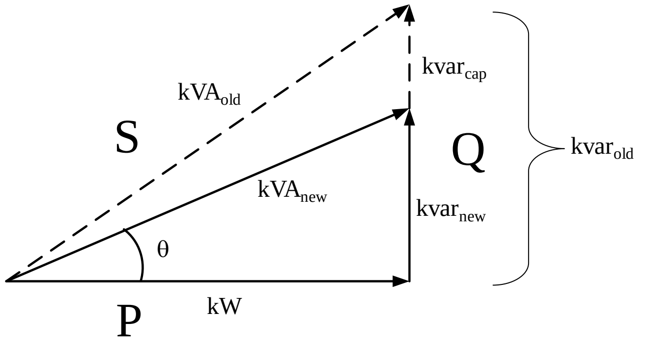
# Sizing capacitor banks

- To correct Displacement PF, analyze the power triangle

(Review from Lecture 2)



$$\cos(\theta) = DPF$$

$$P = S \cdot \cos(\theta)$$

$$Q = P \cdot \tan(\theta)$$

$$S = \sqrt{P^2 + Q^2}$$

$$S = \frac{P}{PF} \qquad PF = \frac{P}{S}$$

Reminder – the “Power Factor Teaching Tool” Excel spreadsheet is on the class website.

## Sizing capacitor banks

- Text equations: (PSQ pg. 342 has an error, see lecture 17)

$$\mathrm{kVAR} = \mathrm{kW}\cdot\left(\sqrt{\frac{1}{\mathrm{DPF_{orig}}^2} - 1} - \sqrt{\frac{1}{\mathrm{DPF_{new}}^2} - 1}\right)$$

$$\mathrm{kVAR} = \mathrm{kW}\cdot\left(\tan\left(\theta_{orig}\right) - \tan\left(\theta_{new}\right)\right)$$

Try it:
For an 80kW load with an initial DPF of 80%, how much reactive power (kVAR) is required to raise the DPF to 90%?

21.26kVAR is needed to correct the power factor to 90%.

These equations can be used if we know the real power, the existing power factor, and our target power factor.

## Sizing capacitor banks

- Some other useful equations

$$Q_{old} = P\cdot\tan\left(\mathrm{acos}\left(\mathrm{DPF_{old}}\right)\right)$$

$$Q_{old} - Q_{cap} = Q_{new}$$

$$\mathrm{DPF_{new}} = \cos\left(\mathrm{atan}\left(\frac{Q_{new}}{P}\right)\right)$$

These equations can be used to find the reactive power for a given power factor and the new power factor when a capacitor is installed.

## Line current reduction

- Line current reduction is approximately*:

$$\%\Delta I = 100\left[1 - \left(\frac{\cos\theta_{before}}{\cos\theta_{after}}\right)\right] \qquad \%\Delta I = 100\left[1 - \left(\frac{DPF_{original}}{DPF_{corrected}}\right)\right]$$

Apparent power can also be used to calculate current:

$$\mathrm{I} = \frac{\mathrm{S_{3\_phase}}}{\mathrm{V_{LL}}\cdot\sqrt{3}}$$

A *change* in S can be used to calculate a change in current.

*assumes voltage at the load doesn't change.

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## Loss reduction

- The reduction in system losses is approximately:

$$\%loss_{reduction} = 100\left[1 - \left(\frac{DPF_{original}}{DPF_{corrected}}\right)^2\right]$$

- The portion of the original losses remaining after power factor correction is approximately:

$$\%\,power\ loss \propto 100\left(\frac{DPF_{original}}{DPF_{corrected}}\right)^2$$

# Voltage improvement – Primary system (FPQ pg 148)

$$\Delta V = \frac{Qcap\_3\phi}{MVAsc\_3\phi} = \frac{Xs}{Xc}$$

Q is in MVAr or kVAr

$$\frac{kV_{LL}^{\;2}}{X_s(\Omega)} = MVA_{sc\_3\phi}$$

(in MVA)

Given a capacitor bank size in kVAr and the system short circuit MVA or the system voltage and upstream impedance in ohms at the capacitor's location, we can calculate the per-unit or percent voltage rise.

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# Example calculation: Voltage improvement - Primary system

- Example system:
  - 1,200kVAr capacitor (400kVAr/phase)
  - 12.47kV L-L distribution line
  - Short circuit duty: 20MVA – assume entirely inductive

Calculated voltage rise:

$$\Delta V := \frac{Qcap\_3\phi}{MVAsc\_3\phi} \qquad \frac{1.2\ MVAR}{20 \cdot MVA} = 0.06 \qquad \Delta V = 6\%$$

## Voltage improvement – Secondary system (PSQ pg. 339)

- Voltage rise is approximately:

$$\%\Delta V = \frac{kvar_{cap}\, x\, Z_{tx}(\%)}{kVA_{tx}}$$

  - Assumes system impedance is dominated by the service transformer
    - Example:

      Capacitor: 300kvar

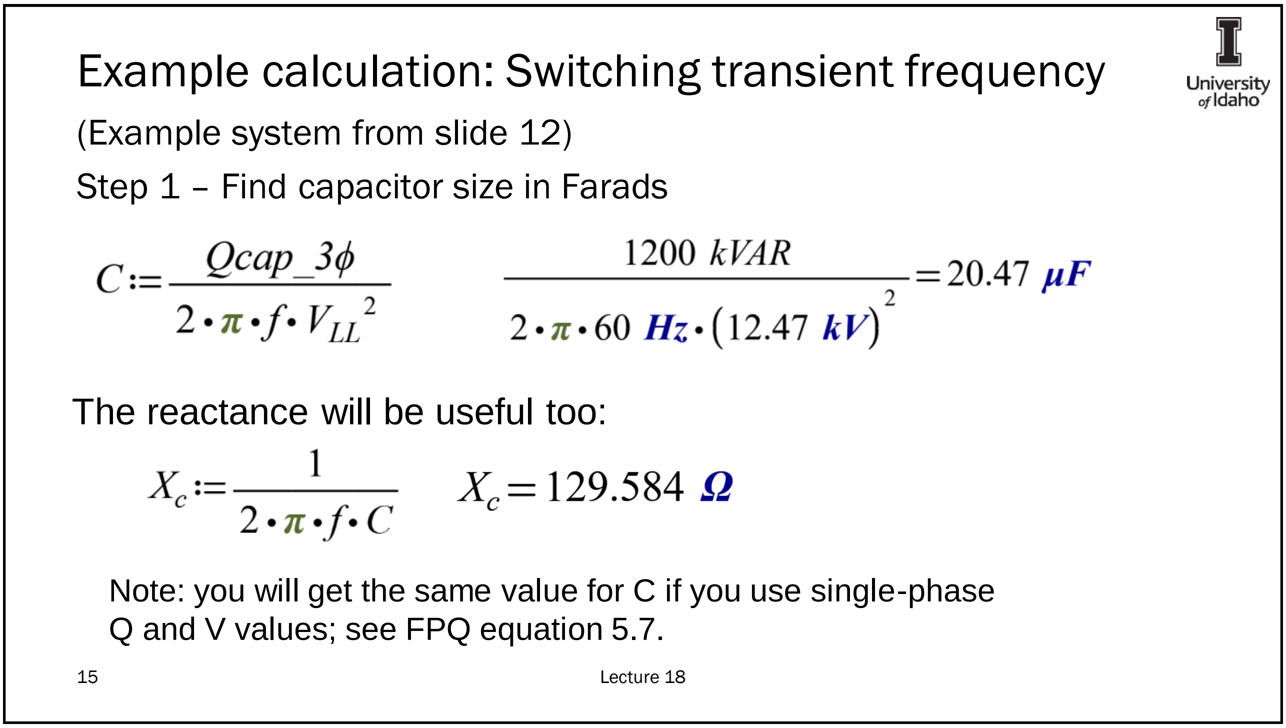
      Transformer: 1000kVA, 6% impedance

      Voltage rise (%)?

## Switching transient frequency (FPQ pg. 153)

- The frequency of the oscillatory switching transient is given by the resonant frequency calculation for an L-C circuit, using the system's inductance and the capacitor's capacitance.

$$f_{transient} := \frac{1}{2 \cdot \pi \cdot \sqrt{Ls \cdot C}}$$



# Example calculation: Switching transient frequency

(Example system from slide 12)

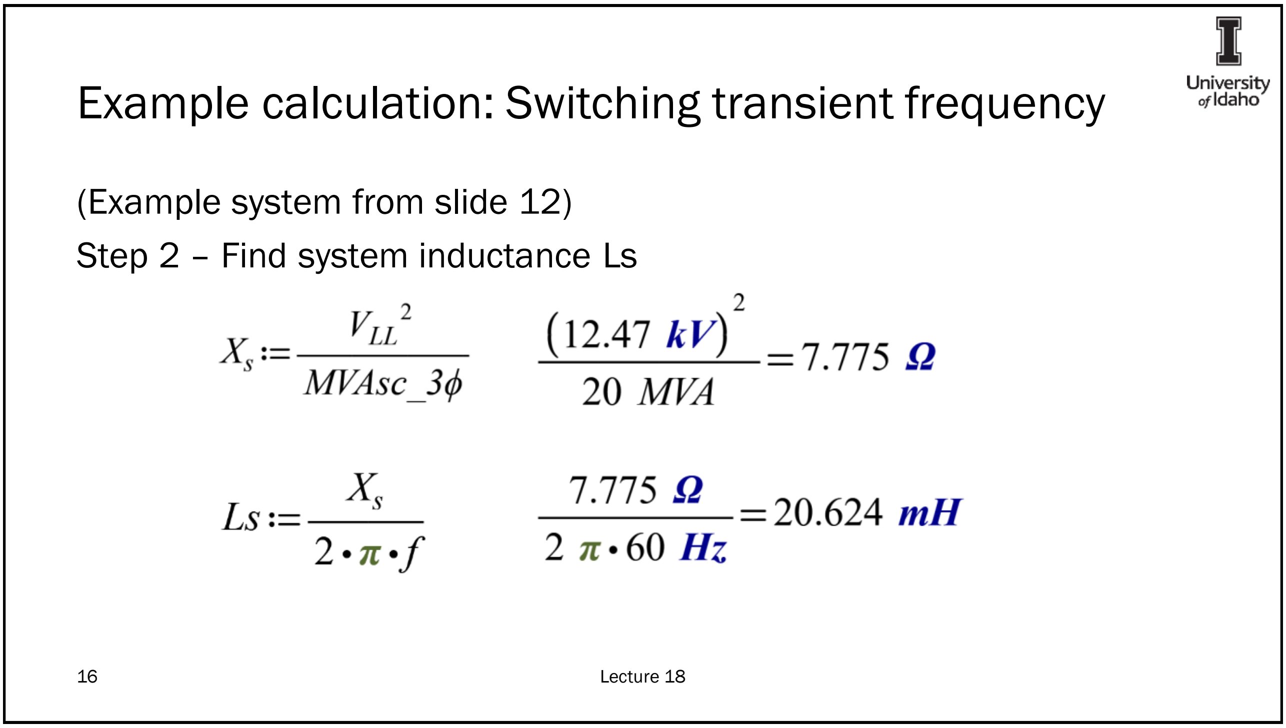
Step 1 – Find capacitor size in Farads

$$C := \frac{Qcap\_3\phi}{2 \cdot \pi \cdot f \cdot V_{LL}^{2}} \qquad \frac{1200\ kVAR}{2 \cdot \pi \cdot 60\ \mathbf{Hz} \cdot (12.47\ \mathbf{kV})^{2}} = 20.47\ \boldsymbol{\mu F}$$

The reactance will be useful too:

$$X_c := \frac{1}{2 \cdot \pi \cdot f \cdot C} \qquad X_c = 129.584\ \boldsymbol{\Omega}$$

Note: you will get the same value for C if you use single-phase Q and V values; see FPQ equation 5.7.



# Example calculation: Switching transient frequency

(Example system from slide 12)

Step 2 – Find system inductance Ls

$$X_s := \frac{V_{LL}^{2}}{MVAsc\_3\phi} \qquad \frac{(12.47\ \mathbf{kV})^{2}}{20\ MVA} = 7.775\ \boldsymbol{\Omega}$$

$$Ls := \frac{X_s}{2 \cdot \pi \cdot f} \qquad \frac{7.775\ \boldsymbol{\Omega}}{2\ \pi \cdot 60\ \mathbf{Hz}} = 20.624\ \mathbf{mH}$$

## Pause to check our work:

- With Xs and Xc we can calculate the voltage rise again to check our work (see equation on slide 11).

$$\Delta Vcheck := \frac{X_s}{X_c} \qquad \Delta Vcheck = 6\%$$

- This agrees with the earlier result, so C and Ls values should be correct.

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## Example calculation: Switching transient frequency

(Example system from slide 12)

Step 3 – Use capacitance and inductance to calculate resonant frequency:

$$f_{transient} := \frac{1}{2 \cdot \pi \cdot \sqrt{Ls \cdot C}} \qquad \frac{1}{2\ \pi\ \sqrt{Ls \cdot C}} = 244.949\ \boldsymbol{Hz}$$

# Inrush current amplitude (FPQ pg. 153)

- We will use Ohm's law to calculate the peak inrush current with the capacitor bank switches on:
- System surge impedance: $Z_o := \sqrt{\frac{Ls}{C}}$
- Ohm's Law: $Ipk = \frac{Vm}{Z_o}$

*Vm* is the peak (not RMS) line-to-neutral voltage, and this will give us the peak line current.

# Example calculation: Inrush current magnitude

(Example system from slide 12)

$$Z_o := \sqrt{\frac{Ls}{C}} \qquad \sqrt{\frac{20.624\ \boldsymbol{mH}}{20.47\ \boldsymbol{\mu F}}} = 31.742\ \boldsymbol{\Omega}$$

$$Ipk = \frac{Vm}{Z_o} \qquad Ipk := \frac{\frac{\sqrt{2}\cdot 12.47\cdot \boldsymbol{kV}}{\sqrt{3}}}{Z_o} = 320.77\ \boldsymbol{A}$$

## Capacitor size based on voltage rise

- Voltage rise is determined from capacitor size and system short circuit duty (see slide 11), so:

$$Max\_MVAR = \Delta V\_limit\_pu \cdot MVAsc\_3\phi$$

The maximum 3-phase MVAR of the capacitor bank is the per-unit voltage rise x the 3-phase short circuit MVA.

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## Example calculation: limit the voltage rise to 2.5%

(Example system from slide 12)

$$Max\_MVAR = \Delta V\_limit\_pu \cdot MVAsc\_3\phi$$

$$Max\_MVAR := 0.025 \cdot 20\ \mathbf{MVA} = 0.5\ \mathbf{MVAR}$$

This is the maximum 3-phase capacitor bank size. We then must select available capacitors to assemble the capacitor bank. For example, 150kVAr/phase using 3 x 50kVAr/phase for a 450kVAr capacitor bank.

## Why install capacitors

- Release conductor and transformer capacity
  - Reducing current in conductors and transformers makes additional capacity available in those conductors and transformers
- Reduce real-power losses
  - Reducing reactive power flow *through* conductors and transformers reduces real power losses ($I^2R$ losses) *in* conductors and transformers

## Capacitor location considerations

- Capacitors do NOT change the power factor of the original load
- They are a local source of reactive power for inductive loads
- This distinction is important and can be used as a guide when deciding where to install capacitors
- It is the load + capacitor combination that has a better power factor than the load alone

## Capacitor location considerations

- Current and the associated losses are only reduced upstream of the capacitor
- Installing a capacitor near, but downstream of the service meter reduces power factor charges if there are any, but does not address losses inside the facility

## Capacitor location considerations

- Ideally, capacitors should be placed as close as possible to the location where reactive power is needed
  - May be switched with specific motors*
- Trade-offs
  - Multiple small capacitors may be more expensive than one larger one
  - It may be easier to control harmonics in one location

*Beware of self-excitation risk

## Capacitor location considerations - Self-excitation

- If a motor with terminal-connected capacitors is isolated, the capacitors can provide a path for reactive power flow back and forth between the motor and capacitor.
- Voltage at motor terminals can increase to damaging levels.
- If motor and capacitor are reconnected to system, phase shift may be large, resulting in transients in voltage, current, and torque.
- To reduce likelihood of self-excitation:
  - Limit capacitor bank to 20 to 30% of motor kVA [1]
  - Limit capacitor bank to motor's magnetizing kVA[1,2]

$$Q_c \le 0.9 \cdot I_{no\_load} \cdot V_{LL} \cdot \sqrt{3}$$ [2]

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## Capacitors and power factor charges

- Power factor charges

A popular method of charging for poor power factor is to adjust the customer's demand charge based on the difference between a target DPF and the customer's actual DPF when the customer's DPF is below the target

Examples: (Both increase the billing demand for DPF<90%)

$$AdjustedDemand = Demand((0.90 - DPF) + 1)$$

$$AdjustedDemand = Demand\left(\frac{0.90}{DPF}\right)$$

Note: Adjustment is only applied if DPF is below the target.

# More on capacitor size and location

- It’s important to understand the applicable rate schedule before installing capacitors
  - You cannot save money that you are not spending to begin with
- A large capacitor bank may cause large voltage changes when switched on or off

# Next time…

- Flicker
- More examples

References for self excitation:
[1] EPRI Power Plant Electrical Reference Series, Volume 6 – “Motors”
[2] Wiki-Electrical Installation Guide, “Power Factor Correction of Induction Motors”
https://www.electrical-installation.org/enwiki/Power_factor_correction_of_induction_motors