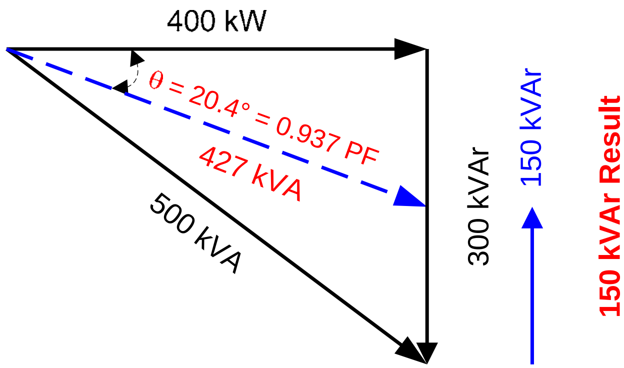
Understanding Power Factor Correction



300 kVAr required by loads

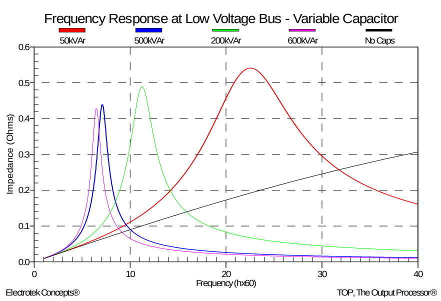
150 kVAr power factor capacitor added

150 kVAr result

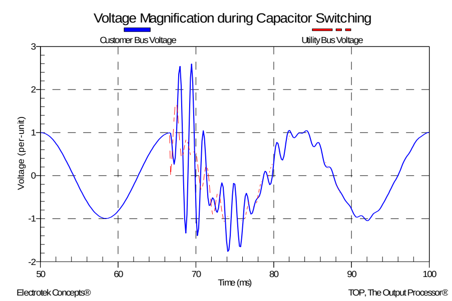
$$\text{kVA}_{\text{new}} = \sqrt{\left(400^2 + 150^2\right)} = 427\,\text{kVA}$$

$$\text{PF} = \frac{400}{427} \text{x} 100 = 93.7\%$$

$$\theta = \text{COS}^{-1}(\text{PF}) = \text{COS}^{-1}(0.937) = 20.4°$$



April 26, 2005



Thomas Grebe
Electrotek Concepts, Inc.

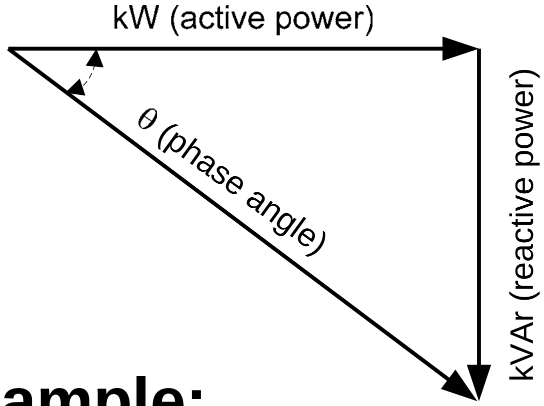
Introduction

- Definition of power factor
- Benefits of improving power factor
- Methods for improving power factor
- Determining financial savings
- Customer/utility application considerations:
  - Harmonic resonances
  - Transient overvoltages

Power Factor Definition

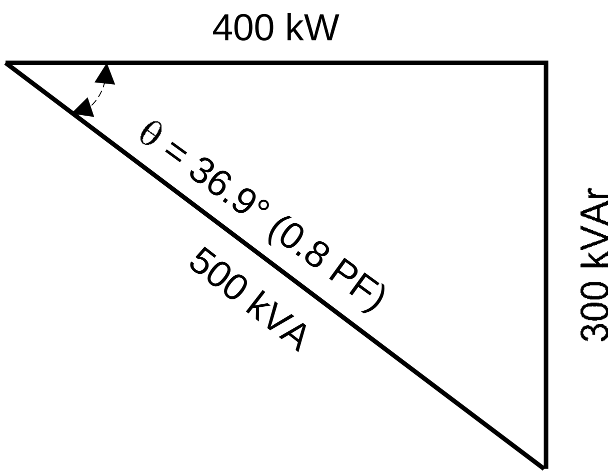
- Power factor measures how effectively electrical power capacity is being used.
- Related to power flow in electrical systems:
  - ***Real Power*** (a.k.a. active or working power) is the power that is converted into useful work for creating heat, light, and motion. Measured in kW, totalized in kWh.
  - ***Reactive Power*** (a.k.a. magnetizing power) is the power that sustains an electromagnetic field in inductive and capacitive equipment. Measured in kVAr, totalized in kVArh.
  - ***Total Power*** (a.k.a. apparent power) is the combination of real and reactive power. Measured in kVA, totalized in kVAh.

Illustrated using Power Triangle



$$\text{Power Factor} = \frac{\text{Active Power (kW)}}{\text{Apparent Power (kVA)}}$$

Example:



$$\text{kVA} = \sqrt{\left(\text{kW}^2 + \text{kVAr}^2\right)} = \sqrt{\left(400^2 + 300^2\right)} = 500\text{kVA}$$

$$\text{PF} = \frac{\text{kW}}{\text{kVA}}(\text{x100 for percent}) = \frac{400}{500}\text{x100} = 80\%$$

$$\theta = \text{COS}^{-1}(\text{PF}) = \text{COS}^{-1}(0.80) = 36.9°$$

Displacement vs. True Power Factor

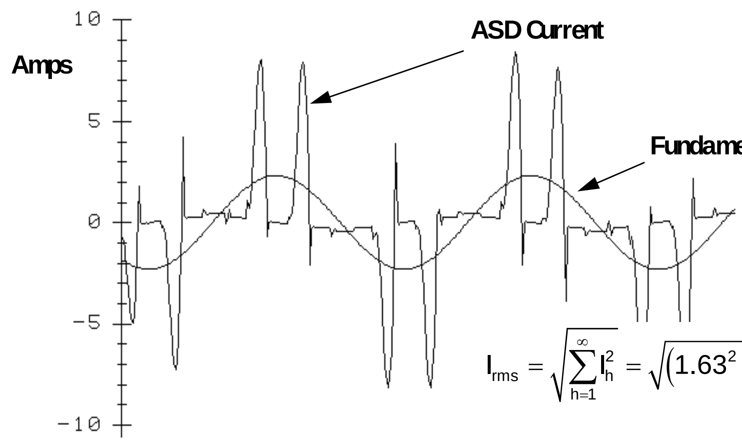
- Harmonic distortion in the voltage and/or current changes the way power factor should be calculated.
- True power factor (TPF) is defined as the ratio of real power to the total volt-amperes in the circuit:

$$DPF = Cos\theta = \frac{kW}{kVA}$$

$$TPF = \frac{Power_{real}}{Voltamperes_{total}} = \frac{P}{V_{RMS} * I_{RMS}} \approx \sqrt{\frac{1}{\left(1 + THD_{current}{}^{2}\right)}}$$

True Power Factor Example

- Sample ASD current waveform:



$$DPF \approx 1.00$$

$$I_{rms} = \sqrt{\sum_{h=1}^{\infty} I_h^2} = \sqrt{\left(1.63^2 + 1.50^2 + 1.30^2 + 0.94^2 + 0.78^2 + 0.42^2 + \ldots\right)} = 2.913\,\text{amps}$$

$$P = V_1 * I_i * \cos\theta = (480V)(1.63A)(1) = 782.4W$$

$$TPF = \frac{Power_{real}}{Voltamperes_{total}} = \frac{P}{V_{RMS} * I_{RMS}} = \frac{782.4W}{(480V)(2.913A)} = 0.559 \approx 56\%$$

$$TPF \approx \sqrt{\frac{1}{\left(1 + 1.48^2\right)}} = 0.559 \approx 56\%$$

Typical Equipment Power Factor

Equipment Description	Typical Displacement Power Factor (%)
Induction Motors	70-80
Diode Rectifiers (small ASDs)	95-90
Fluorescent Lighting: Standard Ballast (also HID)	70
Electronic Ballast	90
Phase Controlled Rectifier (dc & large ac drives)	40-90
Arc Furnaces	75-90
Arc Welding	35-60
Resistance Welding	40-60

Benefits of Improving Power Factor

- The principle benefit is usually lower monthly electric bills.
- Additional benefits:
  - More efficient use of the electrical system
  - Improved voltage regulation due to reduced line voltage drop
  - Increased load carrying capabilities in existing circuits
  - Possible reduction in size of transformers, cables, and switchgear for new installations
  - Reduced power system losses

Methods for Improving Power Factor

- Improving power factor by reducing reactive power requires equipment that operates at a leading power factor.
- Options include:
  - Static capacitors – devices without moving parts that provide magnetizing current to the load.
  - Synchronous motors – either over-excited or under-loaded motors with full excitation will supply kilovars to the system.
  - Power electronic devices – (e.g., SVC) that can provide reactive power and harmonic compensation.
  - Capacitors are generally the most economical option for reactive compensation.

Applying Capacitors

- Capacitors are generally the most economical source of reactive compensation. Other advantages include:
  - low losses (less than ¼ watt/kVAr)
  - essentially no maintenance
  - light, compact units which can be combined as needed, make capacitors relatively easy to install and modify as reactive compensation needs change

Capacitor Bank Sizing

- The rating of the power factor correction capacitor required to correct a load to a desired power factor is often approximated using the following approach:

$$\text{kVAr} = \text{kW} * \left(\tan\phi_{\text{original}} - \tan\phi_{\text{desired}}\right)$$

where:

- kVAr = required compensation in kVAr
- kW = real power in kW
- $\tan\phi_{original}$ = original power factor phase angle
- $\tan\phi_{desired}$ = desired power factor phase angle

	Corrected Power Factor										
Orig PF	**0.80**	**0.82**	**0.84**	**0.86**	**0.88**	**0.90**	**0.92**	**0.94**	**0.96**	**0.98**	**1.00**
0.50	0.982	1.034	1.086	1.139	1.192	1.248	1.306	1.369	1.440	1.529	1.732
0.52	0.893	0.945	0.997	1.049	1.103	1.158	1.217	1.280	1.351	1.440	1.643

Illustrated using Power Triangle

- Power factor correction capacitors supply the necessary reactive portion of power (kVAr) for inductive devices. By supplying its own source of reactive power, a facility frees the utility from having to supply it.

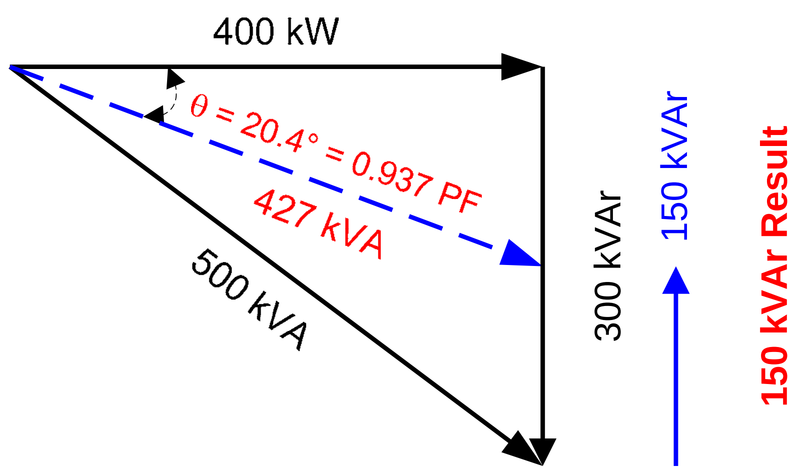


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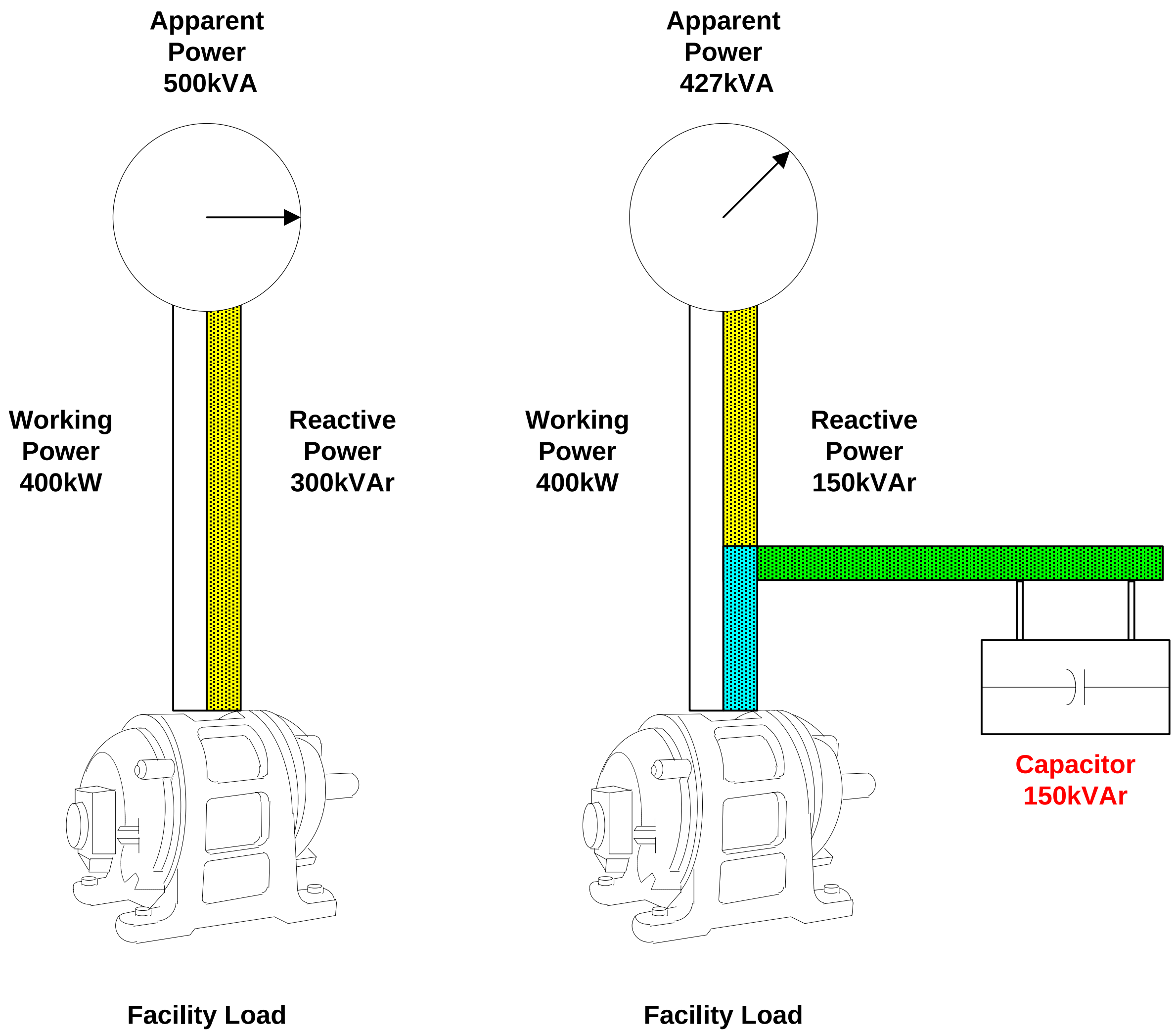
Illustration of Power Factor Correction

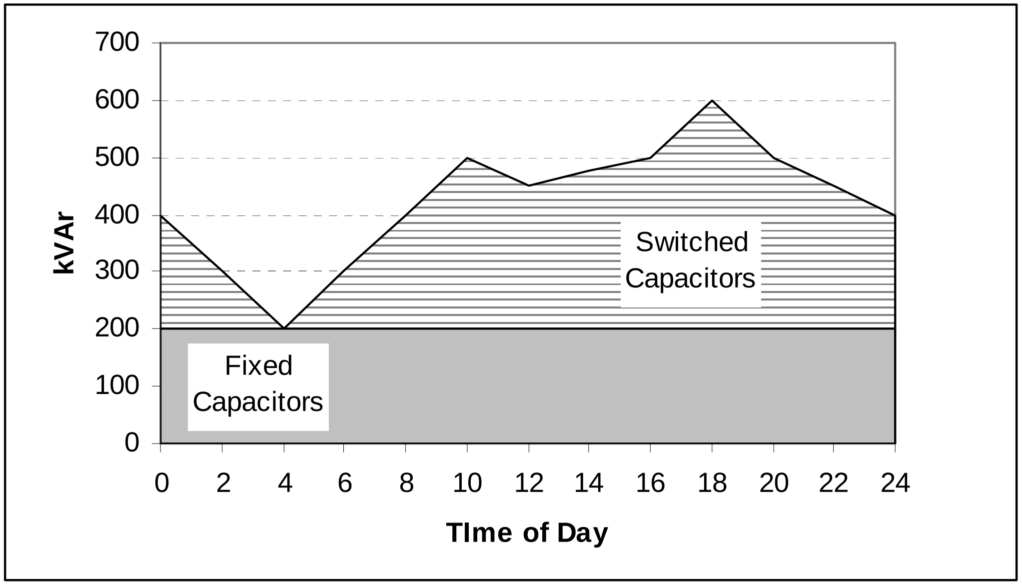


Capacitor Bank Control

- Power factor correction capacitor banks are either switched or fixed. Generally, in determining the type of capacitor bank required, the following guidelines should be considered:
  - Fixed capacitor banks are sized for the minimum load conditions.
  - Switched capacitor banks are designed for load levels above the minimum condition up to peak load.

Switching based on:

- Voltage
- Current
- Var or reactive current
- Time
- Temperature



Utility Power Factor Rates

- Each utility has their own method and related rates for determining power factor penalties.
- Number of methods for charging for poor power factor, including:
  - Charges for kVArh
  - Charges for kVAr demand
  - Charges for kVA demand
  - Charges for adjusted kW demand
  - Charges based on a percentage of the demand or base charge

Determining Payback

- Electric bills will include an additional surcharge if the rate schedule has a power factor penalty.
- This penalty can be reduced or eliminated with the proper application of power factor correction capacitors.
- The savings realized needs be weighed against the equipment, installation, and maintenance costs to determine if the payback time is acceptable.
- Payback times can vary significantly due to wide range of utility power factor penalties and equipment costs.
- A reasonable range for payback period might be between 6 months and 2 years.

Example Payback Case

- A facility with an **800 kW** load has a demand of **1000 kVA**. The utility has a demand charge of **$2.50/kVA** for customers with power factors below **95%**.
- The present power factor may be determined using:

  Power Factor = kW/kVA = 800kW/1000kVA = 0.80 or 80%

- The amount of power factor correction capacitors that are required to improve the power factor to **95%** may be determined using:

$$\text{kVAr} = \text{kW} * \left(\tan\phi_{\text{original}} - \tan\phi_{\text{desired}}\right)$$

$$= 800\text{kW} * \left(\tan\left(\cos^{-1}0.80\right) - \tan\left(\cos^{-1}0.95\right)\right) = 337\text{kVAr (use 360kVAr)}$$

Payback Case - continued

- The new kVA demand after the capacitors have been installed may be determined using:

  kVA = kW/power factor = 800/0.95 = 842 kVA

- The annual savings may be determined using:

  (1000 kVA – 842 kVA) * $2.50/kVA = $395/month * 12 months = $4,740

- The cost to purchase and install 360 kVAr of capacitors (cost assumed to be $15/kVAr):

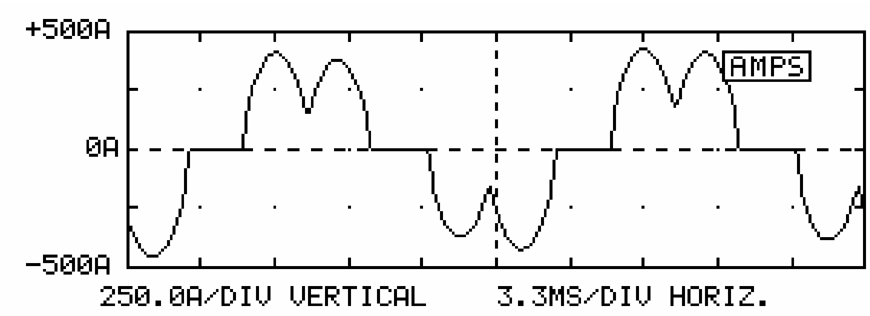
  360 kVAr * $15/kVAr = $5,400

- The payback period for the capacitor installation may be determined using:

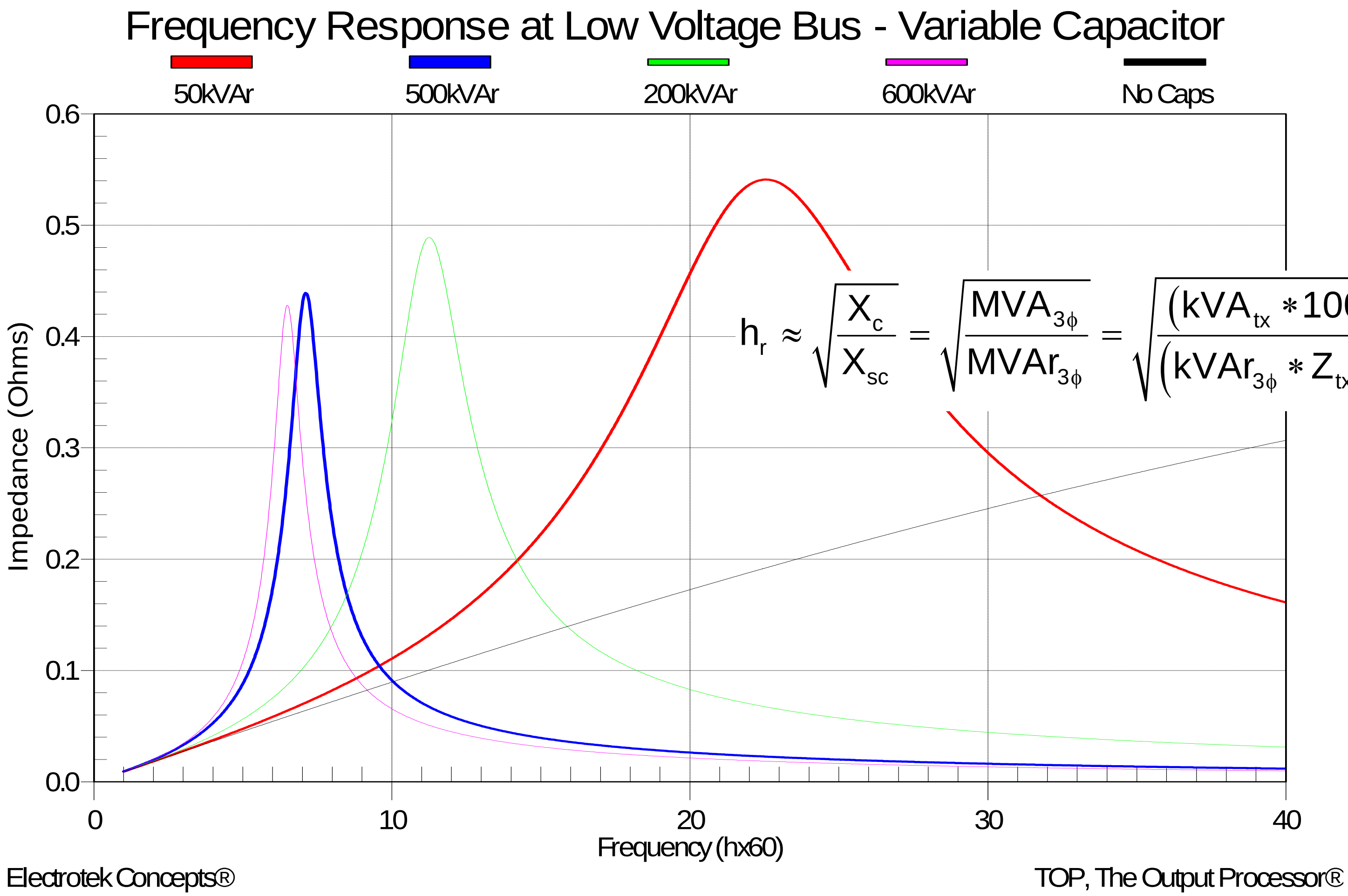
  $5,400/$4,740 = 1.14 (or about 14 months)

Harmonic Problems

- Harmonics can cause equipment to misoperate, capacitor banks to fail, transformers to overheat, or breakers to trip mysteriously.
- Capacitors create resonances that can increase distortion levels significantly.



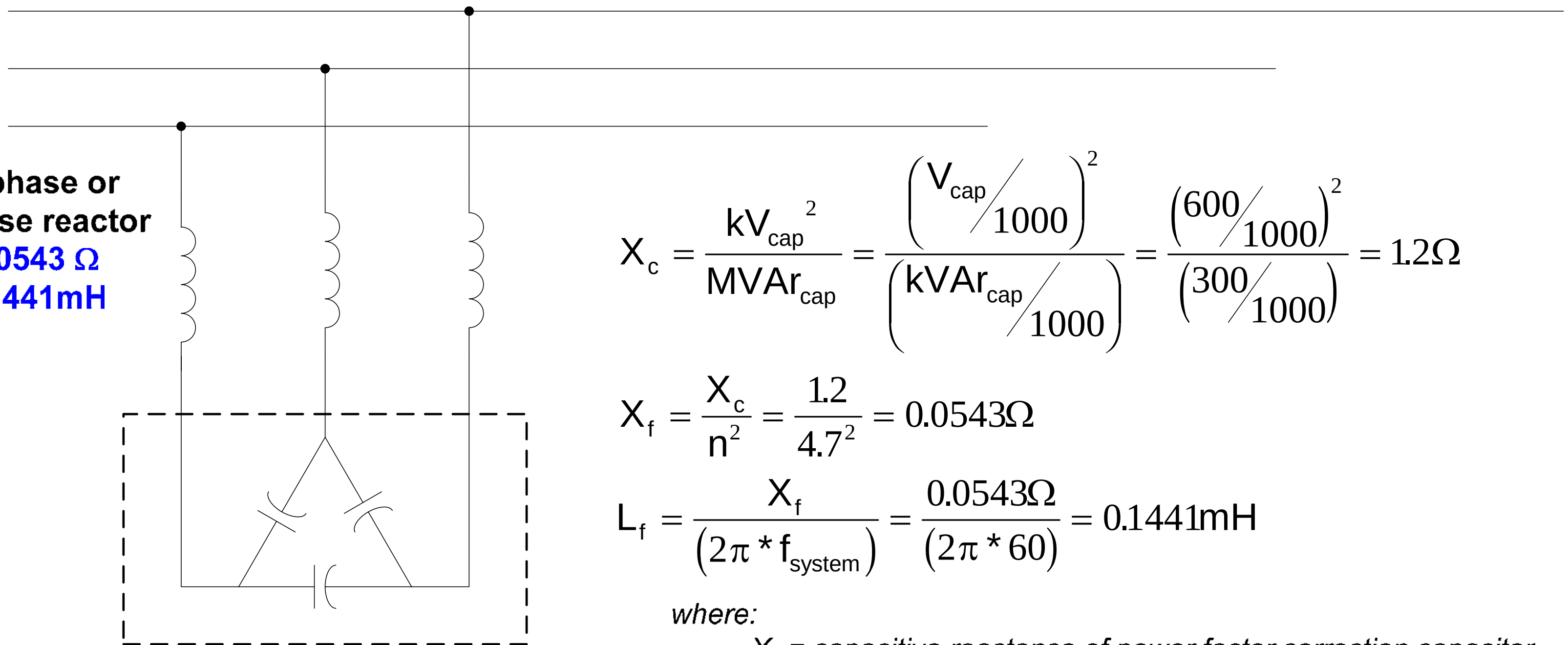
Frequency Response – Resonance



$$h_r \approx \sqrt{\frac{X_c}{X_{sc}}} = \sqrt{\frac{MVA_{3\phi}}{MVAr_{3\phi}}} = \sqrt{\frac{(kVA_{tx} * 100)}{(kVAr_{3\phi} * Z_{tx_{\%}})}}$$

Applying Capacitors as Filters

480 Volt Bus



single-phase or
three-phase reactor
$X_f = 0.0543\ \Omega$
$L_f = 0.1441\text{mH}$

three-phase (delta connected)
low voltage capacitor bank
(300 kVAr @ 600 V, $X_c = 1.2\Omega$)

$$X_c = \frac{kV_{cap}^{\ 2}}{MVAr_{cap}} = \frac{\left(V_{cap}/1000\right)^2}{\left(kVAr_{cap}/1000\right)} = \frac{\left(600/1000\right)^2}{\left(300/1000\right)} = 1.2\Omega$$

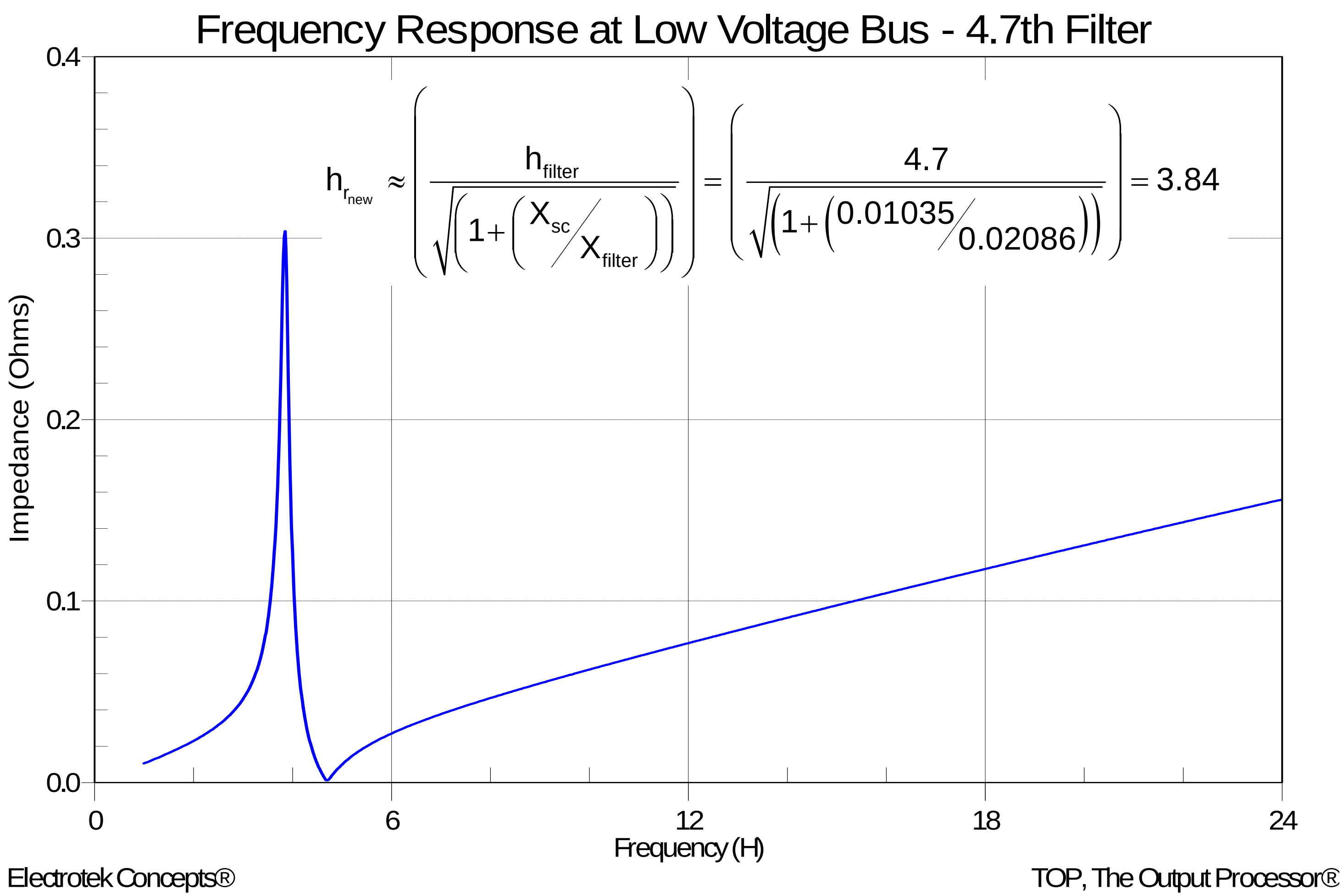
$$X_f = \frac{X_c}{n^2} = \frac{1.2}{4.7^2} = 0.0543\Omega$$

$$L_f = \frac{X_f}{\left(2\pi * f_{system}\right)} = \frac{0.0543\Omega}{\left(2\pi * 60\right)} = 0.1441\text{mH}$$

where:

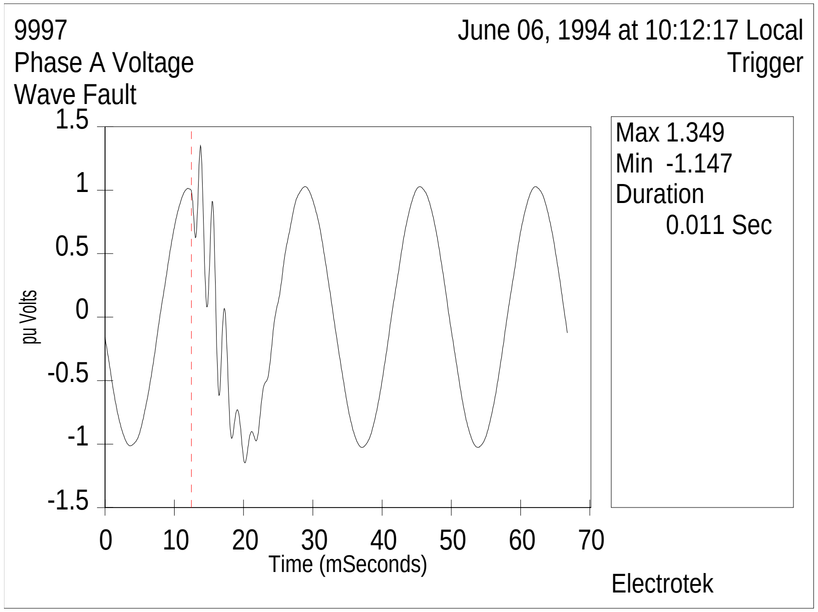
X_c = capacitive reactance of power factor correction capacitor
X_f = inductive reactance of series reactor
L_f = inductance of series reactor
n = tuning harmonic (multiple of f_{system})
f_{system} = system frequency

Solution to Resonance Problem – Filters

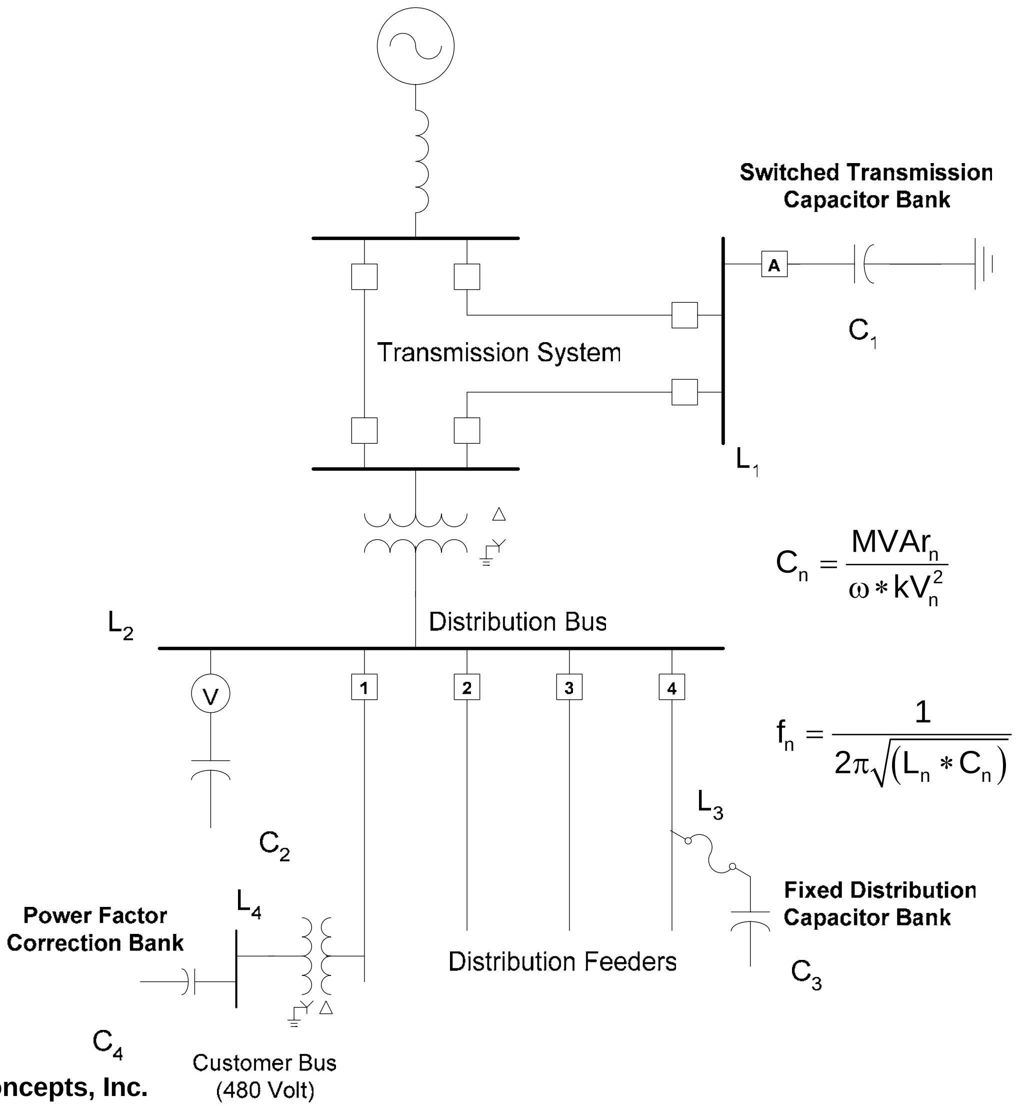


Transient Problems

- Utility capacitor switching produces transient voltages that:
  - can be magnified in a customer facility that has power factor correction capacitors (*voltage magnification*)
  - can cause nuisance tripping of power electronic-based devices (e.g., ASDs).



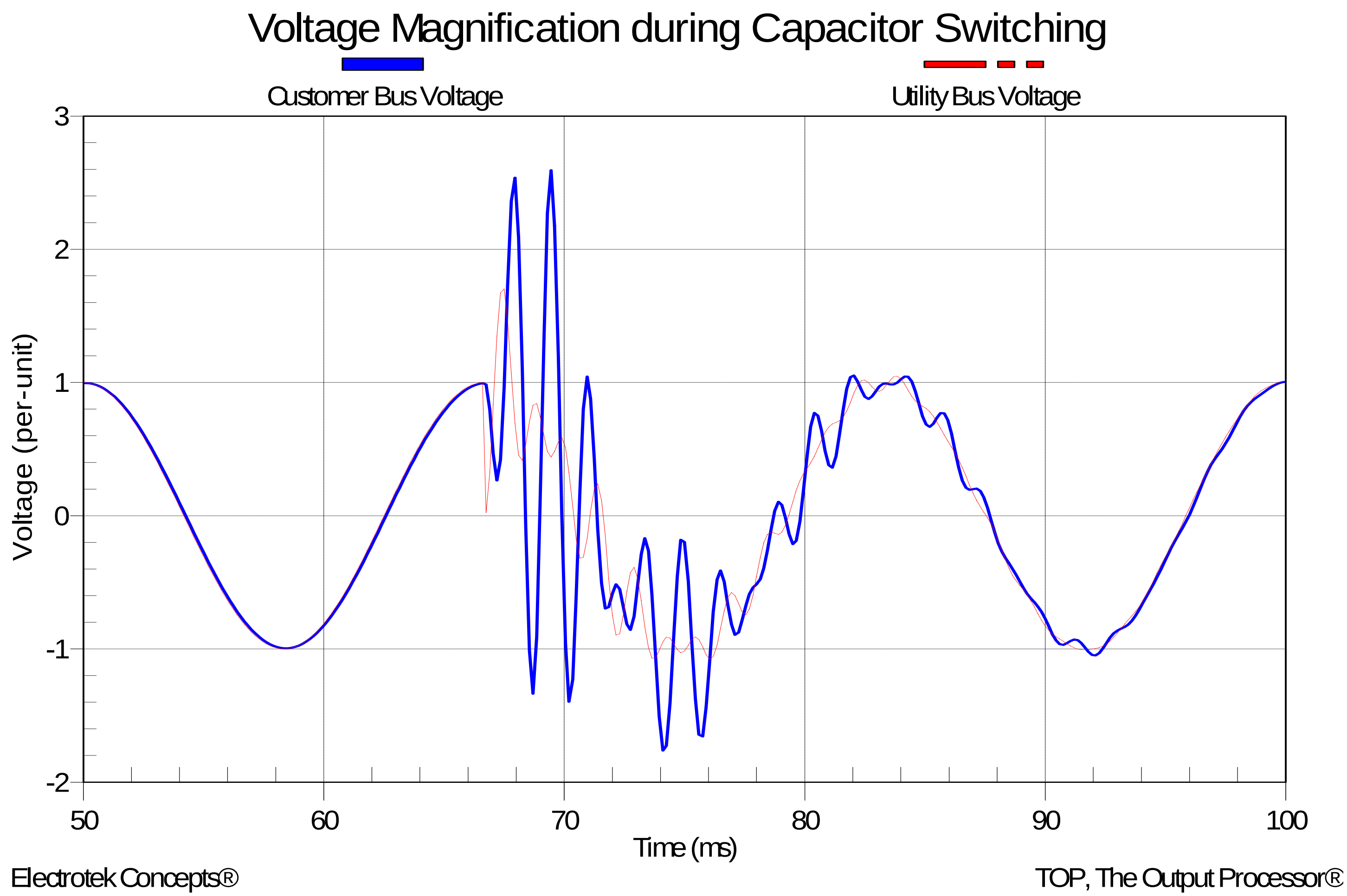
Voltage Magnification Circuit



$$C_n = \frac{MVAr_n}{\omega * kV_n^2} \qquad L_n = \frac{kV_n^2}{\omega * MVA_{sc_n}}$$

$$f_n = \frac{1}{2\pi\sqrt{(L_n * C_n)}} \approx f_{system} * \sqrt{\frac{MVA_{sc_n}}{MVAr_n}} = f_{system} * \sqrt{\left(\frac{\sqrt{3} * kV_n^2 * kA_{sc_n}}{MVAr_n}\right)}$$

Example Transient Voltage Waveform



Solutions to Transient Problems

- Solutions to the voltage magnification and nuisance tripping generally involve:
  - Using an overvoltage control method, such as pre-insertion resistors or synchronous closing control.
  - Detuning the circuit by changing capacitor bank sizes, moving banks, and/or removing banks from service.
  - Switching large banks in more than one section.
  - Applying surge arresters (MOVs) at the remote location.
  - Converting the customer's power factor correction banks into harmonic filters.
  - Adding series inductors (chokes) on the input of adjustable speed drives.

Additional Information

- Electrotek provides consulting services related to power factor, transient, and harmonic studies using tools such as PSCAD, and SuperHarm.
- Additional Information:
  - Electrotek (studies, training, and seminars): http://www.electrotek.com/
  - PQSoft (simulation and analysis tools and support): http://www.pqsoft.com/
  - Monitoring service: http://www.powermonitoring.com/