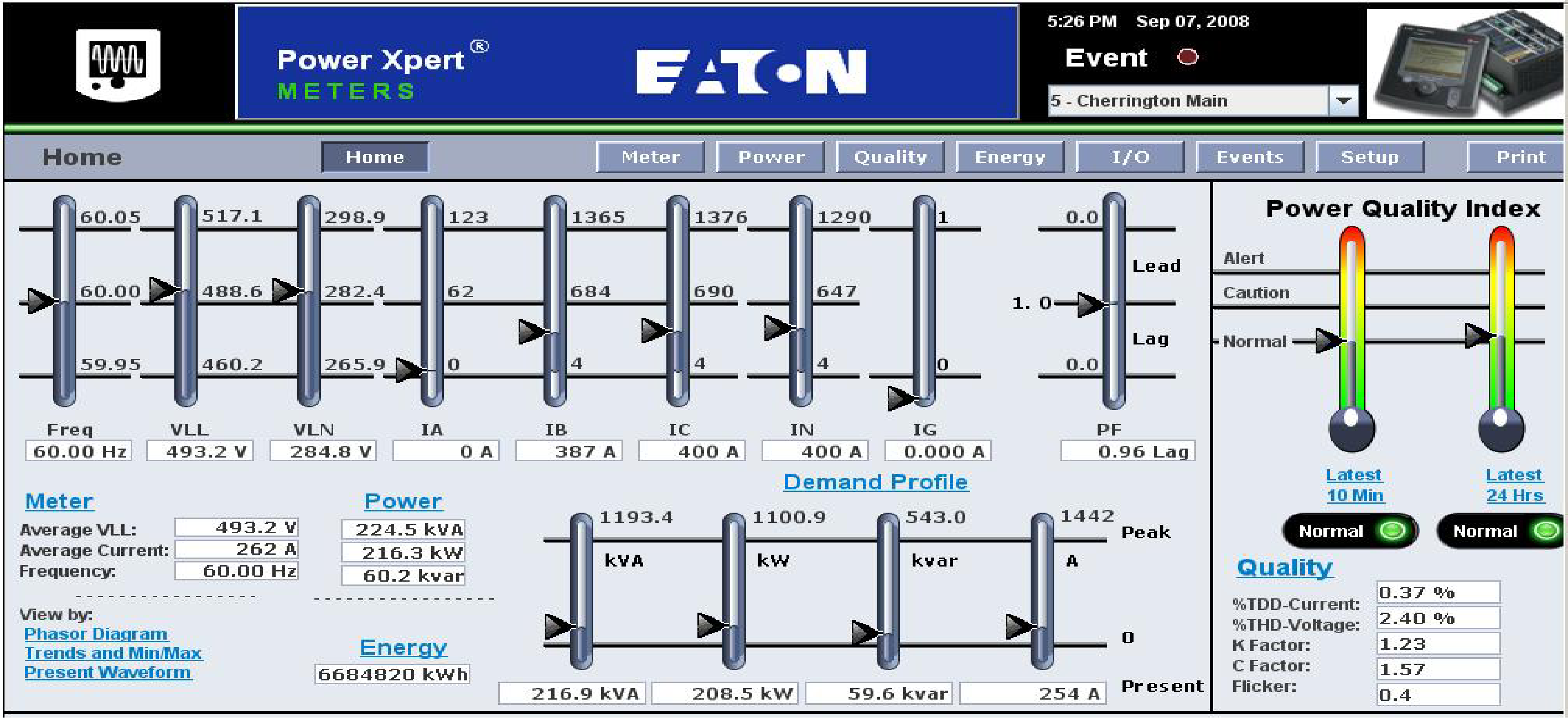

Power Factor Correction

Presented by:
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Eaton Corporation

Learning Objectives

- Define power factor (PF)
- Explore other benefits of power factor correction (PFC)
- Identify potential PF charges on your electric utility bill
- Identify solutions available to correct PF
- Summarize how harmonics effect the application of PFC capacitors
- Calculate the financial ROI for PFC
- Determine real savings versus overstated savings

What am I paying for on my bill?

Energy (kWh)

Demand (kW)

PF Charges

+ 

Taxes

TVA
SNOHOMISH COUNTY PUD PUBLIC UTILITY DISTRICT NO. 1
PECO An Exelon Company
Duquesne Light Our Energy...Your Power
Reliant Energy
ONCOR
ALABAMA POWER A SOUTHERN COMPANY
AEP
conEdison

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What is Power Factor?

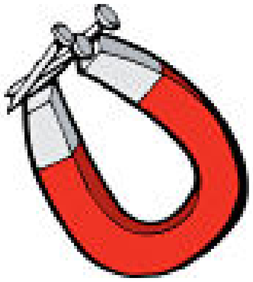
- PF is a measure of the efficient use of power or the ratio of Working Power (kW) to Apparent (or Total) Power (kVA)

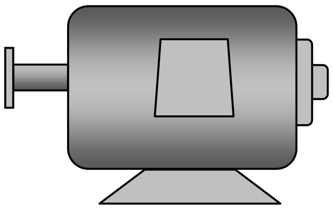
PF = kW / kVA

- Poor PF is costly for the utility and for the end user – power system capacity is used, kW losses are increased and voltage at the load is low.
- Utilities often penalize customers for low PF as an incentive to compensate for this inefficiency.

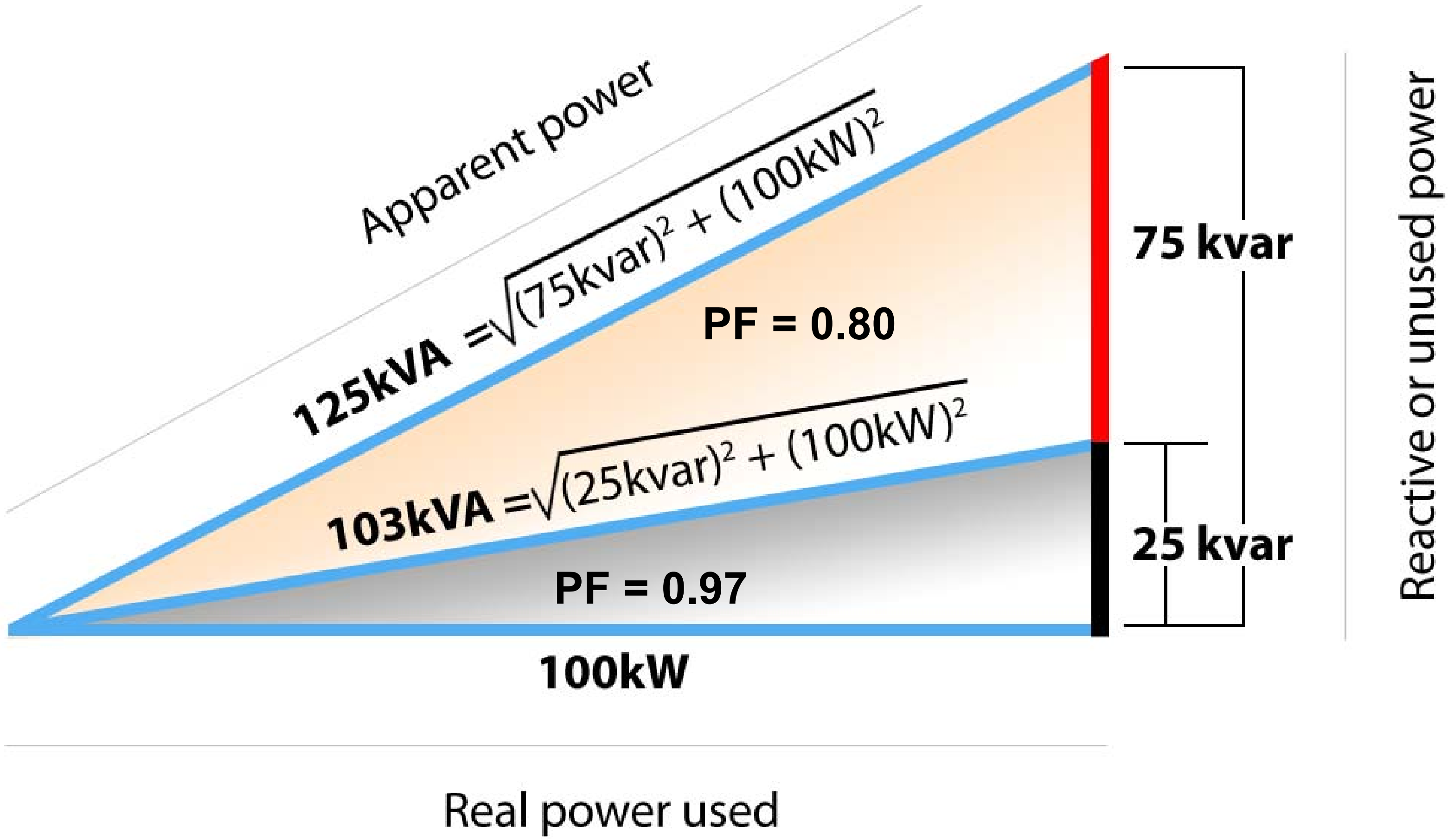
What is a VAR?

- **Active power,** also called **real power,** is measured in **Watts or kW** and performs **Useful Work**
- Electrical equipment like motors and transformers require **reactive power** create a **Magnetic Field** and allow work to be performed.
- This reactive power is called **volt-amperes-reactive or VAR's**
- **Reactive power** is measured in **vars or kvars**
- **Total apparent power** is called **volt-amperes** and is measured in **VA or kVA**



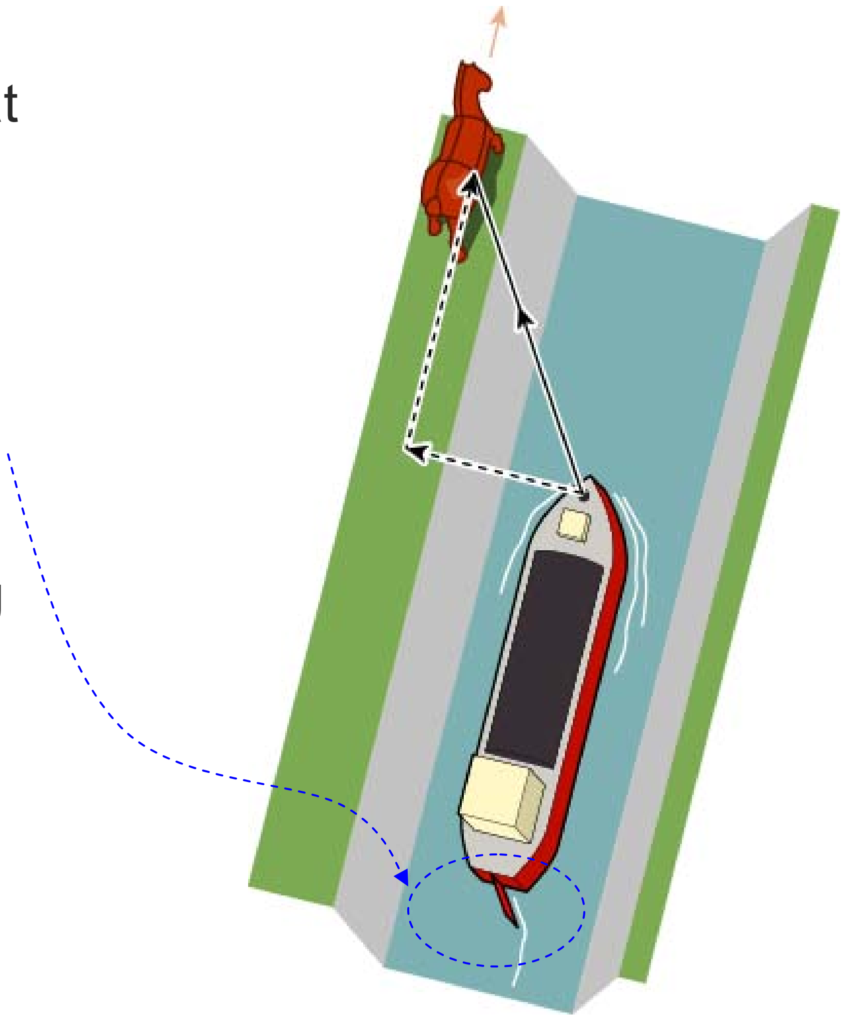


Example: Power Factor



Power Factor Analogy

- Consider a horse pulling a boat on a canal.
- The boat turns it's rudder to stop from running onto the bank.
- The turned rudder creates drag so less of the horse's power is going toward moving the boat forward.



Source: Con Ed

Somebody has to pay for capacity and losses

Wasted Capacity
(VAR's)

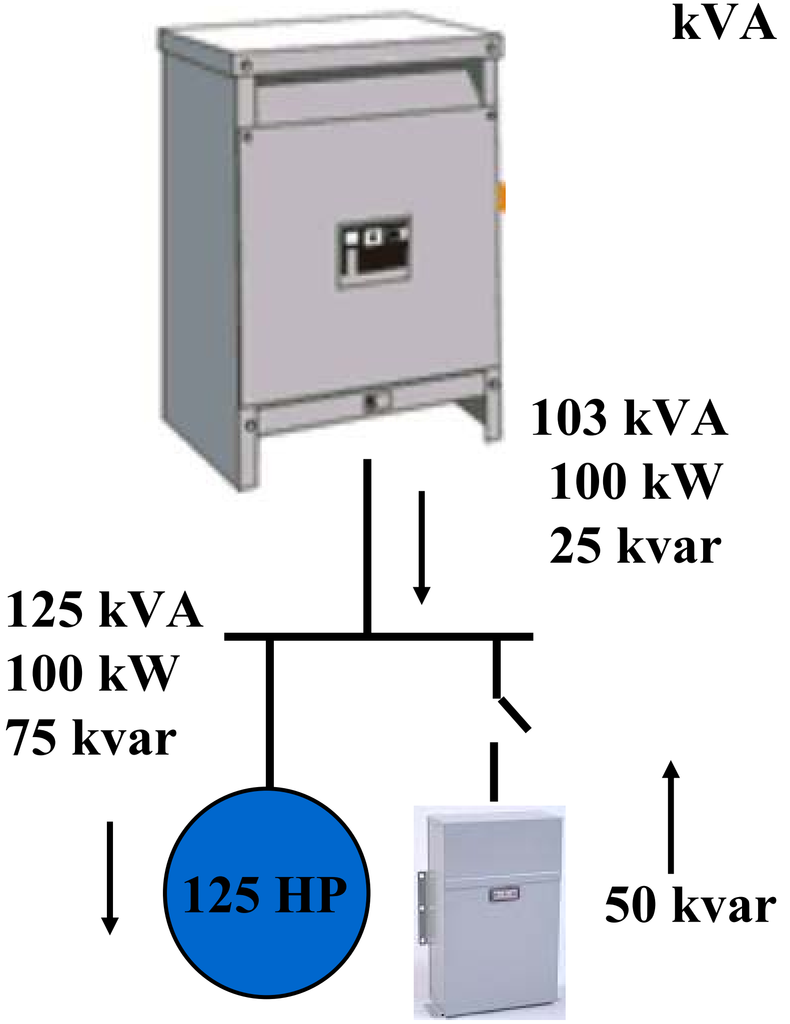
Useful Work
(Watts)

Capacity
(kVA)

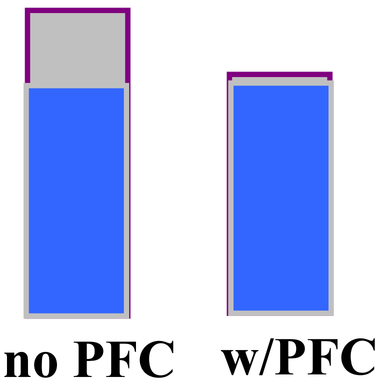
Cost savings due to increased capacity

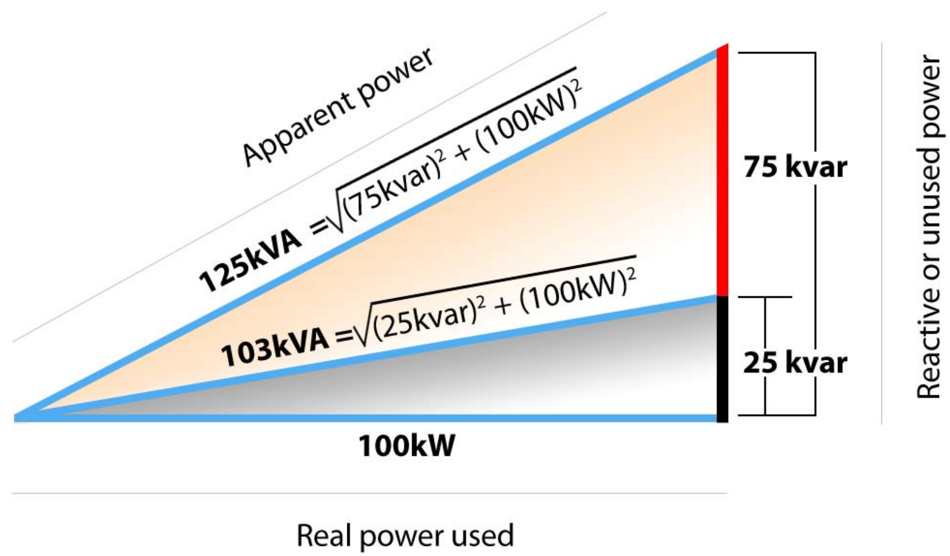
- Correcting poor power factor can significantly reduce the load on transformers and conductors and allow for facility expansion
  - Transformers are rated by kVA and must be sized accordingly

Example: Improving PF Cont.



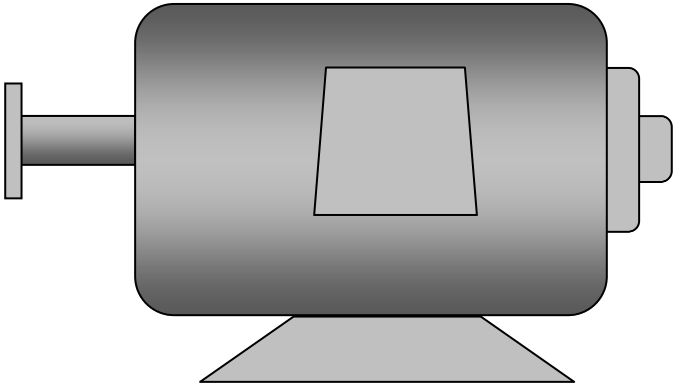
kVA (and Amp) Reduction





Loads with Low PF

- Air Handling/HVAC
- Pumps
- Elevators
- Compressors
- Computers
- Process Machinery



Typical Uncorrected Power Factor

Industry	Percent Uncorrected PF
Brewery	76-80
Cement	80-85
Chemical	65-75
Coal Mine	65-80
Clothing	35-60
Electroplating	65-70
Foundry	75-80
Forge	70-80
Hospital	75-80
Machine manufacturing	60-65
Metal working	65-70
Office building	80-90
Oil-field pumping	40-60
Paint manufacturing	55-65
Plastic	75-80
Stamping	60-70
Steelworks	65-80
Textile	65-75

Source: *IEEE Std 141-1993 (IEEE Red Book)*

Low PF typically results from unloaded or lightly loaded motors

Unloaded motor – PF = .1 to .20
Loaded motor – "rated PF" = .85

Demonstration

Break

Why Consider PFC?

PF correction provides many benefits:

- Primary Benefit:
  - Reduced electric utility bill if there is a penalty (a typical payback 1-5 years)
- Other Benefits:
  - Increased system capacity (generators, cables, transformers)
  - Improved voltage regulation
  - Reduced losses in transformers and cables
  - May reduce harmonics on the power system (with harmonic filters)
  - Greening the power system

How Can I Justify PFC Equipment?

- If you know the penalty and you know the cost of the corrective equipment, you can calculate the (ROI)

- So…let's just **calculate the penalty** – all you have to do is go to the utility company's website and read the tariff for your rate structure…

- Then we'll just **calculate the size and cost** of equipment…

Sounds easy, doesn't it?

How do Utility Companies Bill?

- Always measure energy usage in Watt-hours (kWh) – **typical charges are 5¢ -15¢ per kWh**
- For larger customers like hospitals and universities - kW or kVA demand (i.e. - 15 minute demand) **typical charges are $5-$15 per kW or kVA**
- PF penalties may be part of demand charges, separate charges and sometimes kWh charges are affected
- Many times, if a penalty is imposed, a minimum PF is required (i.e. 85%, 95%, etc.)

Con Ed Tariff

$1.10/kvar

@ peak kW demand to maintain **0.95 lagging** PF

Step 1 – determine peak kW demand per month

Step 2 – determine kvar demand at same interval

Step 3 – determine kvar at 0.95 PF

Step 4 – determine excessive kvar (i.e. compare step 2 to step 3)

Step 5 – multiply step 4 by $1.10 to determine penalty per month

Con Ed Tariff: Example (estimated)

Billed kvar = measured kvar – (1/3) kw   [at peak]

@ 0.95 p.f. , kvar ≈ 0.33 *kW

1,800kW @ 0.85 p.f. => 1,115.5 kvar measured

515.5 kvar billed   (1,115.5 - 600)

1200kW @ 0.85 p.f. => 743.6 kvar measured

343.6 kvar billed   (743.6 - 400)

Source: Con Ed

Con Ed Tariff: Example

Assuming a 1,800kW peak load for 4 months and 1200kW for 8 months at 0.85 p.f.

1800kW @ 0.85 p.f. => 1115.5 kvar for 4 months, the customer is charged for 515.5kvar

1200kW @ 0.85 p.f. => 743.6 kvar for 8 months, the customer is charged for 343.6kvar.

Assume the installation of 300kvar at a cost of $50/kvar.

- capital cost = $15,000
- avoided kvar charges = $4,724.8 per year
- $3,027 in energy savings annually
- simple payback: $15,000/($4,724.8+$3,027) = **1.9 years.**

Assuming $30/kvar: simple payback = $9,000/$7,751.8 = **1.2years**

Assuming $70/kvar: simple payback = $21,000/($7,751.8) = 2.7 **years**

Assuming $50/kvar, ignoring loss savings: simple payback = $15,000/$4,724.8= 3.2 **years**

Source: Con Ed

How Can I Justify PFC Equipment?

PF Penalty

Loss Savings

0-2%

Green Benefit

System/Societal Benefit

PF Calculator

- Eaton Power Factor Correction Tool™ - PF Penalty Page
- Calculator to identify potential PF savings
- Example: $5366/year

Customer Name	Eaton				Location	NYC
2003	MONTHLY Demand (kW)	MONTHLY Demand (kvar)	PF	Maximum kvar to avoid penalty	Required kvar compensation	Potential PF Savings
JAN	1,200	750	0.848	394	356	$ 391
FEB	1,200	750	0.848	394	356	$ 391
MAR	1,200	750	0.848	394	356	$ 391
APR	1,200	750	0.848	394	356	$ 391
MAY	1,800	1,100	0.853	592	508	$ 559
JUN	1,800	1,100	0.853	592	508	$ 559
JUL	1,800	1,100	0.853	592	508	$ 559
AUG	1,800	1,100	0.853	592	508	$ 559
SEP	1,200	750	0.848	394	356	$ 391
OCT	1,200	750	0.848	394	356	$ 391
NOV	1,200	750	0.848	394	356	$ 391
DEC	1,200	750	0.848	394	356	$ 391
Average PF			0.850			
Total PF Penalty						**$ 5,366**

Select Service Type Schedule 1 - kvar charge

First Demand Block $ 1.10 per kvar

Enter Quantities in Blue

Quantities in Orange are Calculated

PF Penalty for < 0.95

Average PF 0.850

Total Months of Data Entered 12 months

Total PF Penalty/Year **$ 5,366** Potenti[illegible] Savings Per Year (E[illegible]r in B17 of PF Calculator Worksheet)

Next step – select the proper size and type of PFC…

How do you select the correct PFC?

What size of PFC?

What type of PFC?

Where do you install them?

Sizing PFC Equipment

1. Determine the target PF **(> 0.95 for Con Ed)**
2. Determine (tables or software) the size of PFC required
3. Select PFC size to avoid penalty, minimize negative effects (overvoltage, harmonic resonance, losses)
4. Consider installation location to determine low voltage or medium voltage installation, fixed or switched

Capacitor Sizing

"kvar needed" calculation

- Gather past utility bills, if possible
- Do multiple monthly calculations
  - Easy to do many calculations quickly with a spreadsheet
  - Examples shown in the capacitor application paper
  - kvar demand on Con Ed bill will be **at peak kW demand** (i.e. don't average kvar levels) – will likely be higher in summer than winter (HVAC loads)

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Capacitor Selection

Consideration (after kvar size is chosen)

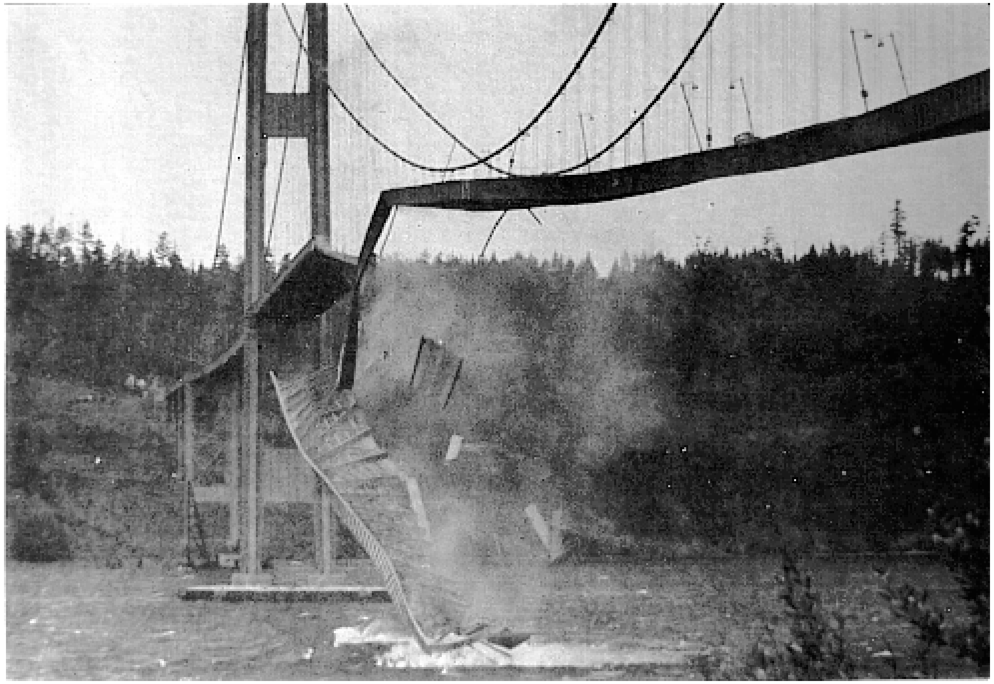
- Utility penalties (take care of whole penalty?)
- Installed cost and payback of equipment
- Load variability (fixed or switched)
- kW losses (location)

Capacitor Selection

What can cause major problems

- Harmonic resonance
- Switching transients and voltage magnification
- Voltage regulation (especially high voltage)
- Leading PF on generators
- Self excitation of motors
- Load requirements (flicker requirements) – speed of switching device

Harmonic Resonance

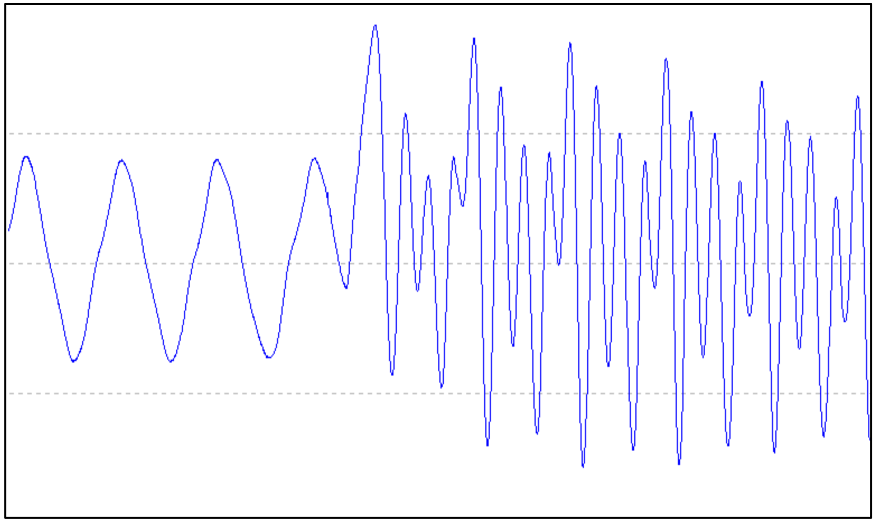


On November 7, 1940, at approximately 11:00 AM, the Tacoma Narrows suspension bridge collapsed due to **wind-induced vibrations**…the bridge had only been open for traffic **a few months**.

Harmonic Resonance

The "Self Correcting" Problem

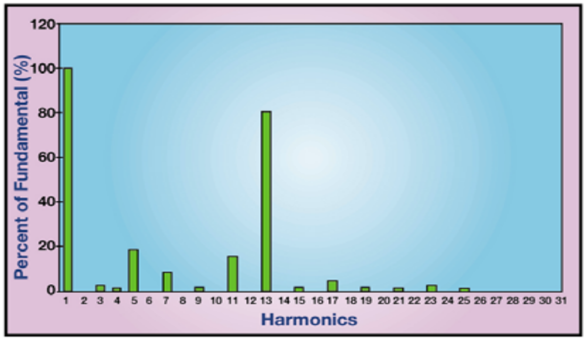
- Blown Fuses
- Failed Capacitors
- Damaged Transformer

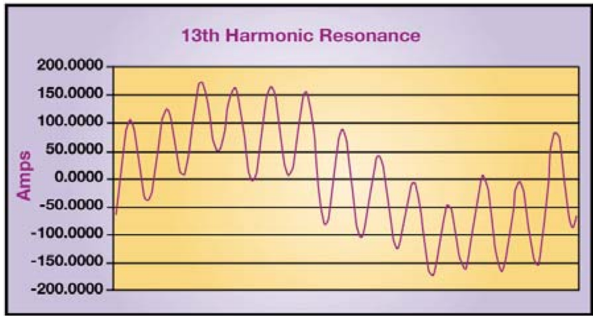


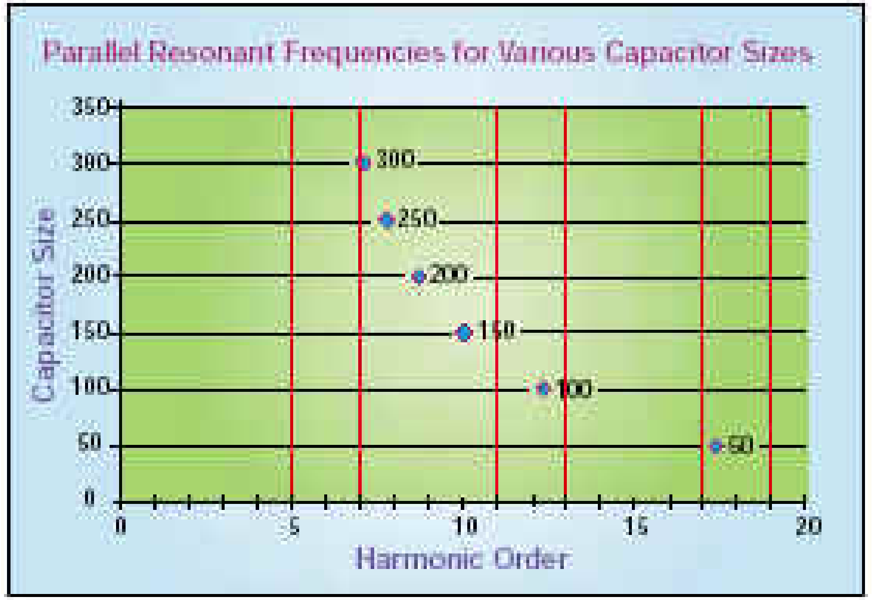
Harmonics = Wind (Excites Resonance)

Harmonic Resonance - Solutions

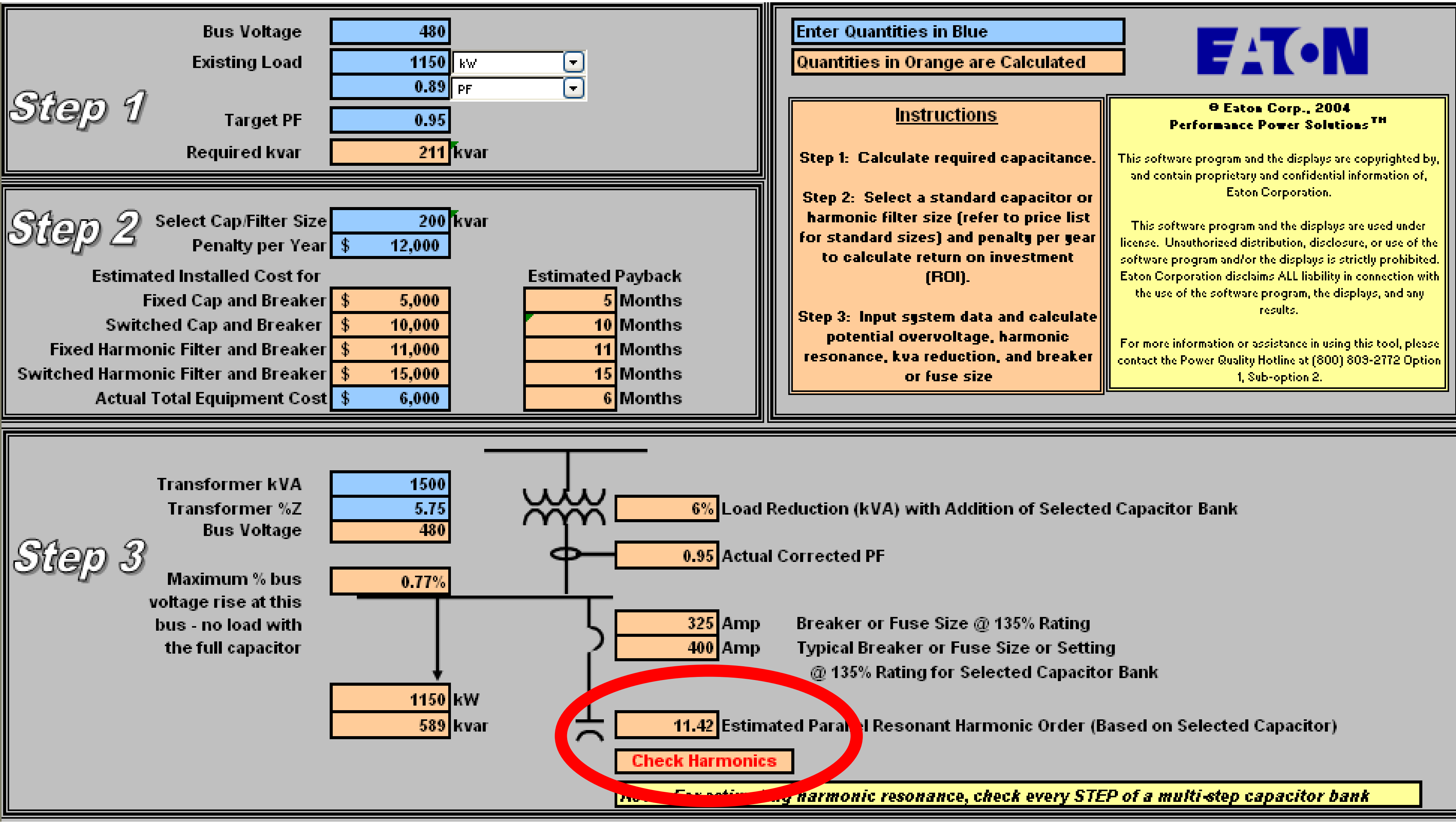
1. **Change the method** of kvar compensation (harmonic filter, active filter, etc.)
2. **Change the size** of the capacitor bank to over-compensate or under-compensate for the required kvar and live with the ramifications (i.e. overvoltage or PF







Eaton Power Factor Correction Tool™ - Resonance



Capacitor Switching Transients

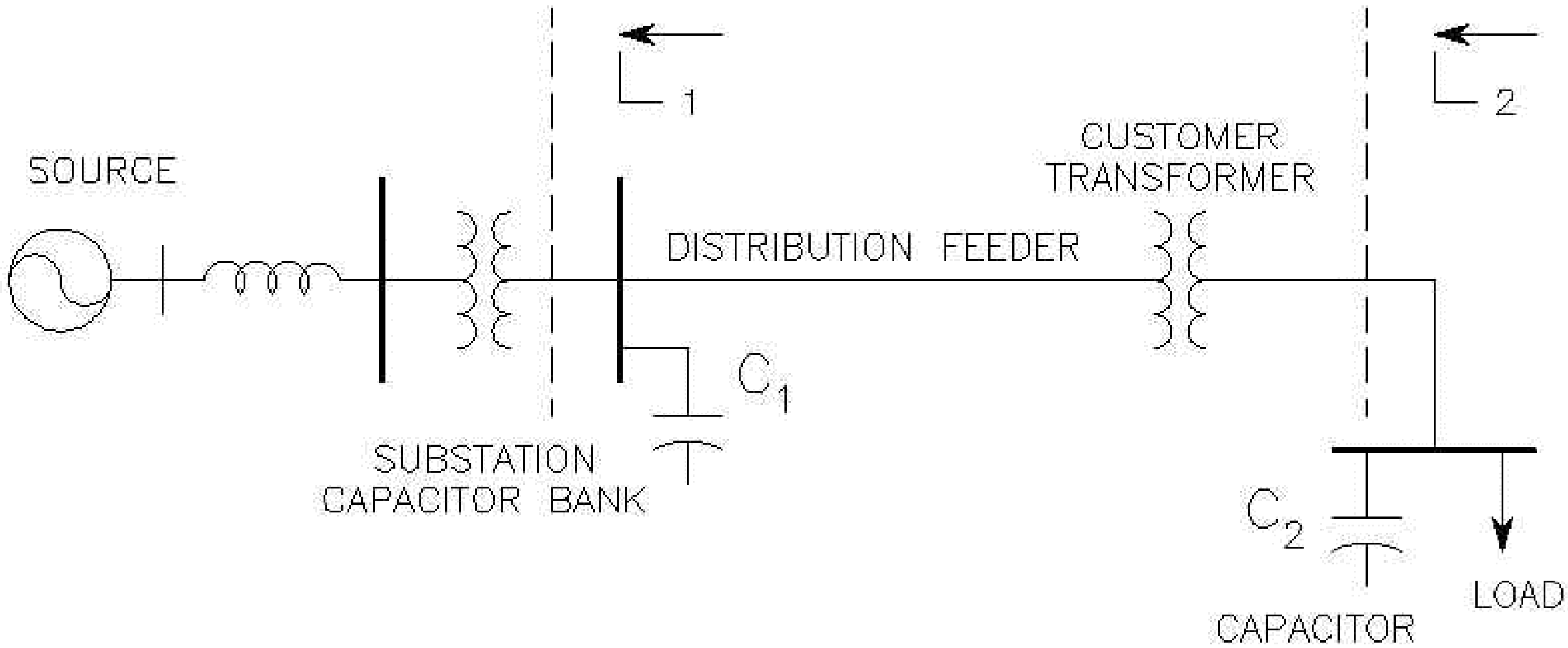


Figure 8. Voltage Magnification Circuit

Capacitor Switching Transients

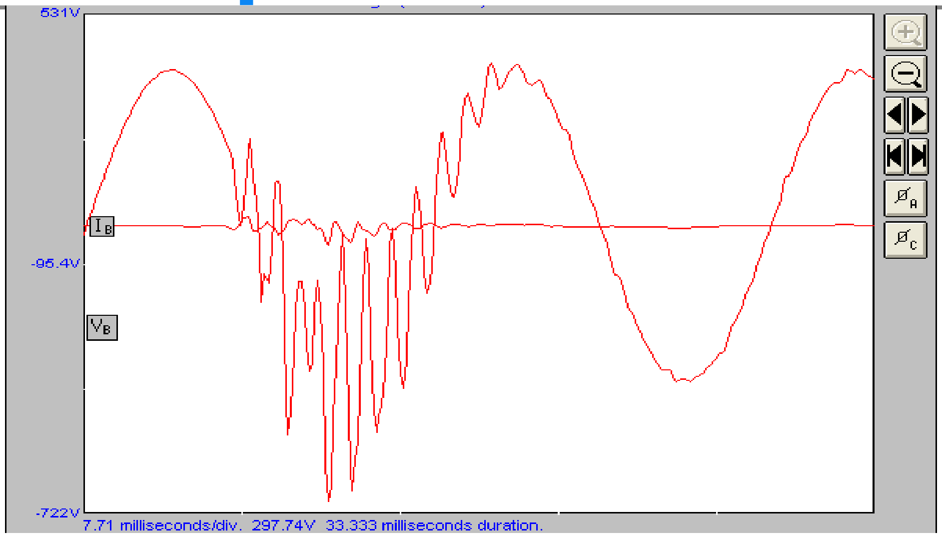


FIGURE 9. UTILITY CAPACITOR ENERGIZED WITH LV CAPACITOR ENERGIZED: VOLTAGE MAGNIFICATION AT 480 V BUS

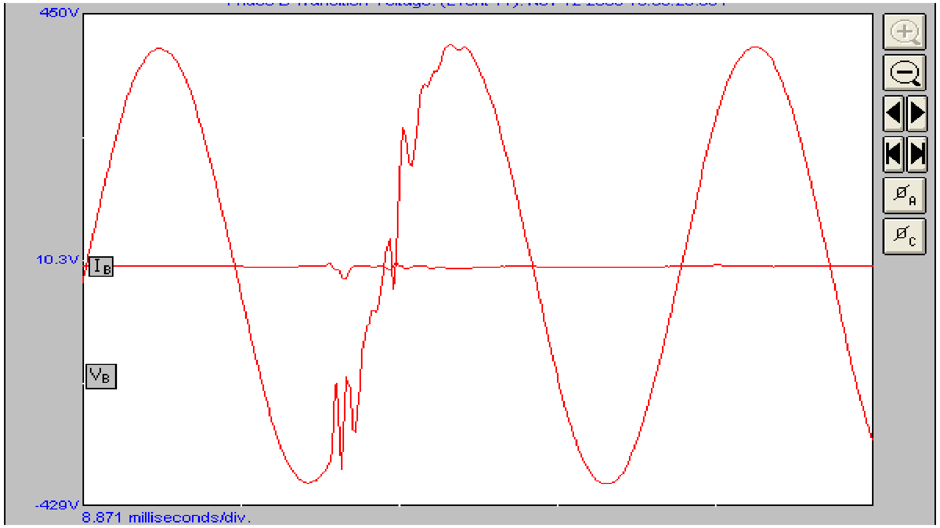


FIGURE 10. UTILITY CAPACITOR ENERGIZED WITHOUT LV CAPACITOR ENERGIZED: NO VOLTAGE MAGNIFICATION

Applying PF Capacitors

Where to apply?

- When applied close to the load (i.e. motor) transformer and cable losses are reduced
- Lower installation cost when applied in a central location
- Commonly applied at the utility metering point

So, what is the right answer?

- Depends on the application, budget, physical space and preference of the customer

Capacitor Placement – Physical Location

Utility Penalty – If needed for PF penalty

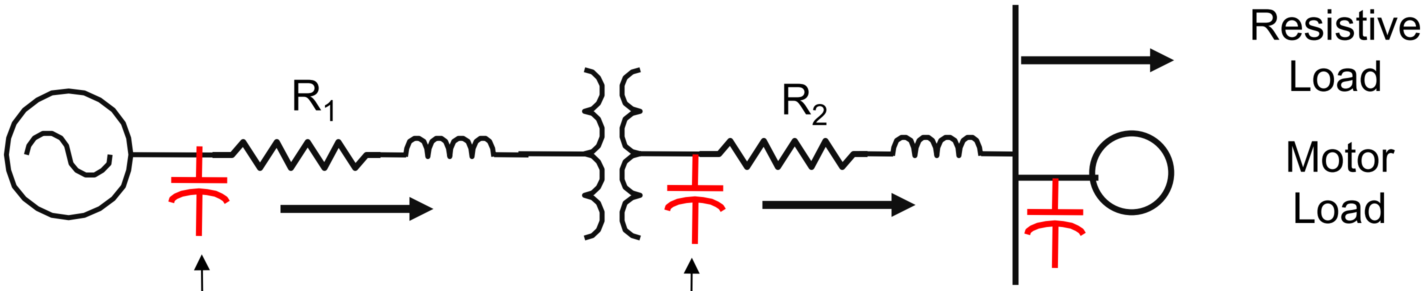
- Apply anywhere downstream of the meter

Capacity Improvement – if needed to improve the capacity of a transformer or cable, it must be placed downstream of the component

Loss Reduction – If needed for kVA or loss reduction

- Apply at or near the loads for I^2R loss reduction
- 1-2% of overall kW is possible with distributed capacitor (some may *claim* more)
- Payback is generally 10 years or more (Typically not enough alone to justify cost to add capacitor

PF Correction – Loss Reduction



Place here for line loss reduction and voltage improvement

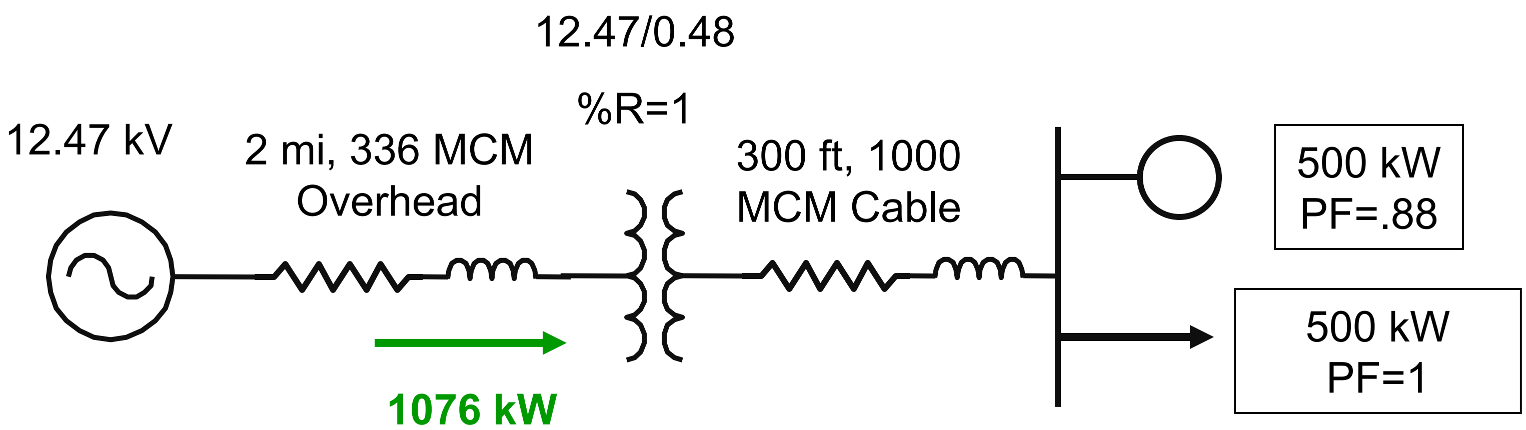
Place here for utility PF penalty

Place here for utility PF penalty (utility owned transformer)

or

Place here to reduce losses in transformer or free capacity

Example – PF Correction Savings



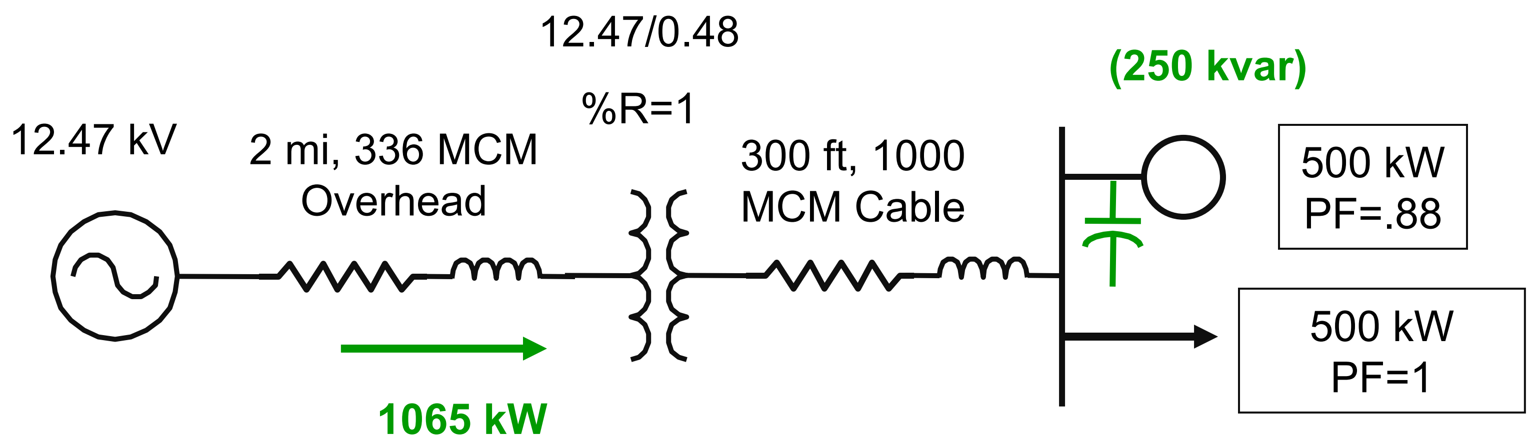
LOSSES:

4.73 kW	**5.1 kW**	**71.2 kW**
0.44%	**0.47%**	**6.65%**

Total Circuit Losses: 81 kW / 8.1%

Source: EPRI

Example, Capacitor at Load



LOSSES:

4.03 kW	4.32 kW	60.6 kW
0.38%	0.40%	6.23%

Total Circuit Losses: 68.9 kW / 6.89%

End User Loss Savings: 76 kW - 65 kW = 11 kW

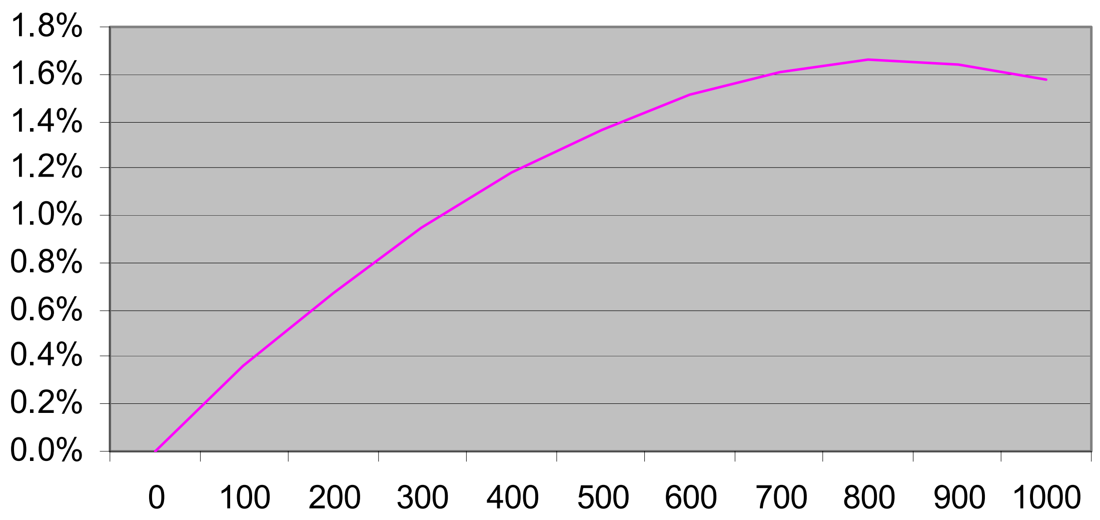
This is nearly 15% savings in <u>losses,</u> but net power into load decreases only 11 kW or 1.1% of load

Source: EPRI

Computer Simulation – Loss Savings

PF	kW	kvar	kvar added	% kW Savings
0.58	615	870	0	0.0%
0.62	612.8	771	100	0.4%
0.67	610.9	671	200	0.7%
0.73	609.2	568.8	300	0.9%
0.79	607.7	466	400	1.2%
0.86	606.6	361	500	1.4%
0.92	605.7	255	600	1.5%
0.97	605.1	147	700	1.6%
1.00	604.8	38	800	1.7%
0.99	604.9	-72	900	1.6%
0.96	605.3	-184	1000	1.6%

% Loss Improvement



Losses vs. kvar Added

What type of PFC solution?

- Capacitors (standard/harmonically hardened)
- Harmonic Filters (Tuned or De-tuned)
- Active Filters
- LV or MV
- Fixed or Switched (contactor or thyristor)
- Active harmonic filter (PF and harmonic control)

Estimated Cost of Power Factor Correction

INSTALLED COST COMPARISON
OF POWER FACTOR CORRECTION EQUIPMENT

TYPE OF CORRECTION	INSTALLED COST, $/KVAR
Fixed (LV – motor applied)	$15
Fixed (LV)	$25
Fixed (MV)	$30
Switched (LV)	$50
Switched (MV)	$50
Static Switched (LV)	$75
Switched Harmonic Filter (LV)	$75
Switched Harmonic Filter (MV)	$60
Active Harmonic Filter (LV)	$150

What else should be included?

- Breaker/Fused Disconnect
- Installation Costs (labor, cables, shutdown required?, etc)

These are very important to understand the “total cost” – this ***could easily triple the cost*** of the project for low voltage applications

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Applying PF Capacitors

Special NYC considerations

- If applied at main service
  - 6 circuit tap rule
  - NYC Advisory Board if modifying incoming service
- Applied on 208 V network system
  - 130-180kA of available fault current!
  - Excessive 3rd harmonics on 120/208 V service

Fixed capacitor banks

Advantages

- Simplest to install
- Lowest cost per kVAR
- Longest life, least maintenance (no moving parts)

When to Use

- Facility load is relatively constant – 24/7/365
- Few anticipated changes to plant system and loads

Considerations

- Possibility of “overcorrecting” (utilities really don’t like that) if load fluctuates
- Overvoltage can occur if load drops

LV Fixed Capacitor Banks

- Designed for industrial and commercial power systems
- var Range: 1 kvar to 400 kvar
- 208 Volts through 600 Volts AC
- Must be harmonic free environment

Individually mounted capacitors

Advantages

- Auto-regulating, comes on and off with load
- Capacitor matched with load – reduces concern of overcorrection
- Relatively small in size – easy to locate, no additional distribution equipment required

When to Use

- Facility load fluctuates
- Many anticipated changes to plant system and loads

Considerations

- Higher installation cost – each capacitor must be individually installed
- Higher cost per kVA than a single large fixed bank
  - i.e. 1 – 100kVAR bank is less expensive than 10 – 10kVAR individual units
- Need to adjust motor overloads to compensate for lower currents

Automatically switched capacitor banks

Advantages

- Single installation
- System is monitored and brings in and out individual capacitors as required

When to Use

- When ultimate system flexibility is required
- When future or final facility load is unknown or expected to change

Considerations

- Highest purchase expense compared to fixed and individual capacitors
- Some maintenance required for contactors switching capacitors
- Consider how many steps are desired

LV Switched (Automatic) PFC Capacitors Banks

- Automatically sense changes in load
  - Automatic Controller
  - Steps of 50 kvar standard

Smaller wall mounted units are available, and can be a real cost savings

LV Harmonic Filtering Equipment

- Provides similar PF correction (as caps)
- Avoid harmonic capacitor interaction problems
- "Filter" harmonics to reduce voltage and current distortion

MV Capacitors

- Pole Mounted
  - These banks have exposed live parts and are typically supported on a wood power pole.
- Rack Mounted
  - These banks have exposed live parts and are supported on a steel structure. These banks are usually located in fenced-in substations.
- Metal Enclosed or Pad Mounted
  - These banks are typically enclosed in a steel enclosure and are usually located within a fenced-in substation or switchgear room.

Medium Voltage Metal Enclosed Bank

1500 kvar + 1500 kvar

Careful!!! PF Correction and Energy Savings

- Well known benefit: kW Loss Reduction (real savings)
- Problem: Overstated
- Reality: 1-4% overall savings typical
- Claim: 11-30% savings
- Selling technique: sell to unknowing residential and commercial customers with little or no knowledge of kW vs. kVA (look…current reduced from 10 to 5 Amps, that results in 50% energy savings!)
- Open the “black box” – it’s full of capacitors… If it looks like a duck and swims like a duck and quacks like a duck….

It Happens to the Best of Us….

- 2007 – Eaton Fluid Power Plant
- Applied Three (3) Energy Savers ($65k)
- Claimed 11-30%
- Actual Savings (Year/Year) – 15%?
  - What????? (Plant lighting was changed to energy efficient lighting three months prior to application of Energy Saver!)
- Actual Savings <1%!

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It Happens to the Best of Us….

	kWh	kW	Excess rKVA	Cost	kW savings over previous year	Cost savings over previous year
N-07	346,811	664.3	198.5	$28,856.55	4.3%	4.1%
Oct-07	329,366	628.5	150.1	$27,351.46	3.9%	3.2%
S-07	297,597	571	106.5	$24,879.59	13.1%	11.5%
Aug-07	312,736	605.02	22.8	$26,120.39	15.9%	15.4%
J-07	331,227	637.5[illegible]	64.1	$27,100.99	10.5%	10.4%
Jun-07	308,103	616.[illegible]	[illegible]	[illegible],607.99	12.2%	9.2%
M-07	319,200	630	529.7	$26,920.13	6.3%	5.6%
Apr-07	369,870	643	439.5	$28,231.73	16.6%	9.5%
M-07	354,678	664	[illegible]	[illegible]663.34	-4.5%	-4.5%
Feb-07	400,302	704.4	506.2	$30,757.42	16.2%	11.7%
J-07	395,049	708.7	533.6	$30,808.96	-18.0%	-21.5%
Dec-06	357,737	718.6	564.6	$30,444.10		
N-06	384,850	693.9	546.7	$30,099.75		
Oct-06	354,128	653.9	455.7	$28,255.68		
S-06	339,933	656.9	560	$28,109.33		
Aug-06	382,376	719.2	579.4	$30,869.79		
J-06	361,292	712.5	558.4	$30,259.63		
Jun-06	345,645	702.44	508.4	$29,315.43		
M-06	352,918	672	493.8	$28,505.66		
Apr-06	337,043	771.2	534.1	$31,194.23		
M-06	347,956	635.3	468.1	$27,432.08		
Feb-06	387,728	840.9	527.1	$34,813.36		
J-06	289,015	600.7	458.5	$25,364.67		

Caps installed here

Lights changed here

Power Systems Experience Center

Purpose: to demonstrate and test PQ problems and solutions

- Full-scale power system
- Demystify solutions
- "Seeing is Believing"
- Technical vs. Economic Solutions

www.eaton.com/experience

Equipment (PF/Harmonic Related)

- Fixed capacitors
- Switched capacitors
- Static switched capacitor
- Broadband Filters
- Passive (Fixed) Filters
- Passive (Switched) Filters
- Active Filters
- Reactors
- 3rd Harmonic Filter
- HMT Transformers
- K-Rated Transformers
- Phase shifting transformers

Learning Objectives

- Define power factor (PF)
- Explore other benefits of power factor correction (PFC)
- Identify potential PF charges on your electric utility bill
- Identify solutions available to correct PF
- Summarize how harmonics effect the application of PFC capacitors
- Calculate the financial ROI for PFC
- Determine real savings versus overstated savings

What should you do?

Step 1: Gather 12 months of utility bills.

Step 2: Examine the bills and evaluate the need for PF correction based on your PF

Step 3: Discuss your penalty with your Con Ed rep

Step 4: Size the corrective equipment

Step 5: Determine the type of PF equipment

Step 6: Calculate your ROI

Step 7: Install the PF equipment and start saving!

…. Eaton is here to HELP!

Reference Information

Reference Papers and Presentations:

1. Blooming/Carnovale – “Capacitor Application Issues” (IEEE IAS)
2. Carnovale/Hronek, “Power Quality Solutions and Energy Savings” (AEE Magazine, EC&M)
3. EPRI – “Energy Savings: You Can Only Save Energy That Is Wasted”
4. PFC Calculator Link
   http://www1.eatonelectrical.com/calculators/PowerFactorROI/index.html

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Thank You!

Questions?

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