NEPSI
Northeast Power Systems, Inc.

Medium-Voltage Metal-Enclosed Products

Power Capacitor Banks, Harmonic Filter Banks,
actiVAR™, and Surge Protection

IEEE

Houston CED Seminar

Harmonic Analysis, Harmonic Filter Design, Reactive Compensation, and Motor Starting

Presented by Paul Steciuk
Paul.Steciuk@NEPSI.com

actiVAR armorVAR armorVAR

Background of Presenter

Paul B. Steciuk is president and co-founder of **Northeast Power Systems, Inc. (NEPSI)**, the leading global supplier of medium-voltage metal-enclosed power capacitor banks and harmonic filter systems. Mr. Steciuk has grown the company and provided engineering and product support to owners and operators of small and large industrial, commercial, renewable, and utility power systems through NEPSI for over 20 years.

With over 30 technical articles and white papers to his credit, Mr. Steciuk is an expert in harmonic analysis, filter design and application, power system analysis, and manufacturing design.
Mr. Steciuk has previous experience as a power system engineer at Power Technologies, Inc. (PTI), located in Schenectady, NY where he was responsible for various power system studies including system-wide voltage sag studies, harmonic analysis and filter design studies, load-flow, short-circuit, protective coordination, and transient analysis studies.

He also worked as an application and design engineer at Commonwealth Sprague Capacitor, Inc. (CSCI), located in North Adams, MA. designing and developing low voltage automatic power factor correction equipment and harmonic filters.

Born in Troy, NY, Mr. Steciuk received his B.S. and M.E. degrees in Electric Power Engineering from Rensselaer Polytechnic Institute (RPI), Troy, NY.

Background of Presenter

Toquepala Mine, Peru, 3500 Meters, 27.256 MVAR Each (54 MVAR Total, 2 Banks), 34.5kV, 200kV BIL4-Stage Expandable to 6 Stages, All Switching, All Protection, All Control

2020

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NEPSI - Background

- Established in 1995
- Based in Queensbury, NY
- Key products designed and manufactured by NEPSI
  - Medium-voltage metal-enclosed products (2.4kV – 38kV) 200 kV BIL Max
    - Shunt Power **Capacitor Banks** (capacitive vars)
    - **Harmonic Filter Banks**
    - Shunt Reactor Banks (inductive vars)
    - Hybrid Shunt Capacitor & Shunt Reactor Banks
    - actiVAR™ – Fast Switching Capacitor Banks/Harmonic Filter Banks (2.4kV – 13.8kV) for motor start – an alternate to large VFD drives and RVSS
    - Medium Voltage Surge Protection Products
      - RC Snubbers
      - Motor Surge Protection
      - Medium-Voltage Transient Voltage Surge Protection
- Service
  - Startup | Commissioning | Maintenance
  - Power System Studies
    - Harmonic Analysis, Power Factor, Motor Start

Large Harmonic Filter Systems Designed & Manufactured by NEPSI

Large Harmonic Filter System 1 of 2 (1-line to follow)

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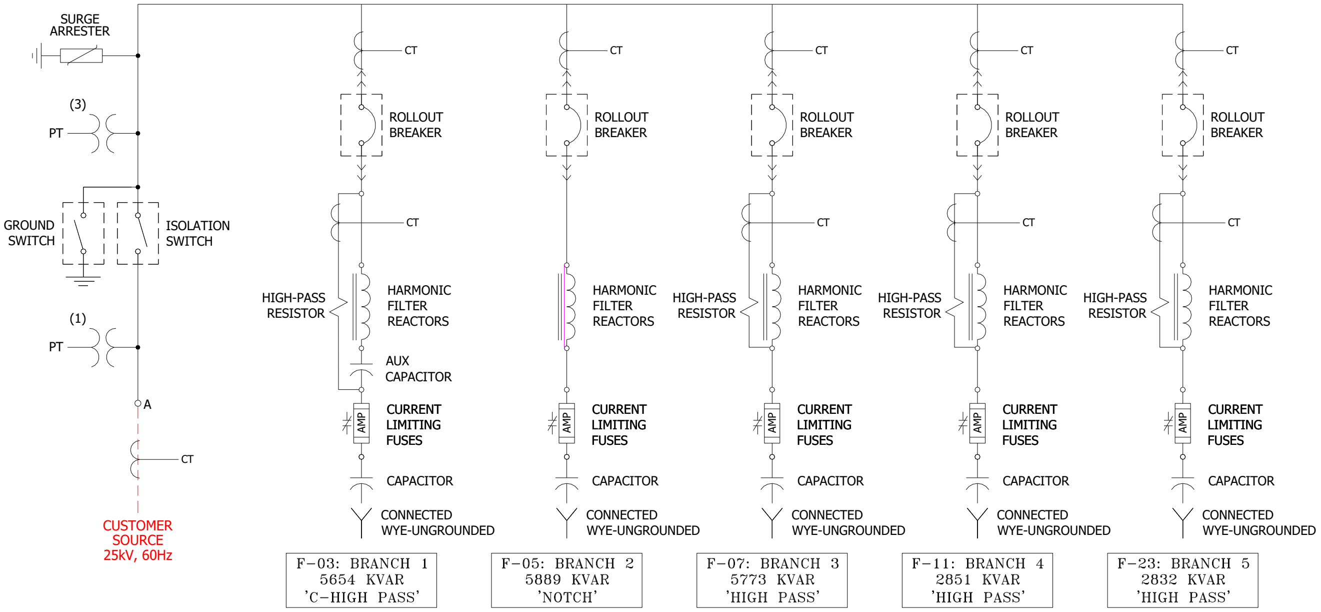
Large Harmonic Filter One-Line Diagram



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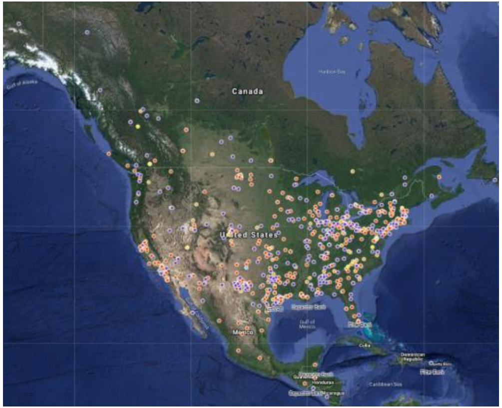
Background

NEPSI Sells Into All Major Markets

- Mining (copper, gold, diamond, oil sands, limestone, lithium, rare earth metals)
- Renewable energy (wind & solar power)
- Oil/Gas, Petro-Chemical
- Electric Utilities (large IOU's, electric cooperatives, municipalities)
- Steel
- Pulp & Paper
- Institutions (hospitals, universities, military bases, data centers, financial institutions)
- Private Label – Supplier of product to nearly all of the "majors"
- Others
    - semiconductor, scrap recycling, pharma, waste water

Largest Installed Based On The Globe



North & Central America

South America

Africa, Asia, Europe, Australia

With an installed base of over 2000 systems over the last 24 years (more than 140 in mining and 800 in Oil/Gas) **NEPSI** is the leading world supplier of medium-voltage metal-enclosed capacitor banks and harmonic filter banks

NEPSI also brand labels and Supplies to Many of the Major Electrical OEM's

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Configuration Options – Metal-Enclosed / Open-Air

Metal-Enclosed

Open-Air

When all costs are considered, including engineering & procurement, integration, site preparation, installation, commissioning, maintenance, and liability, **the Metal-Enclosed configuration provides the lowest cost of ownership**

Configuration Options – Metal-Enclosed / E-House

Metal-Enclosed Configuration

E-House Configuration

Metal-enclosed laser focused, elegant solution that avoids the complex, ancillary requirements (and associated costs) of local and national building codes inherent with the e-house configuration.

The streamlined approach to power-factor correction and harmonic filtering.

Houston CED Seminar – Topics Covered

Major Topics Covered

- Power Factor
- Harmonic Analysis
- Harmonic Filter Design
- Starting Motors With Capacitor Banks
- More…

Please Ask Questions

Any Question Related To Medium- and Low-Voltage Reactive Compensation, Associated Equipment, Control, Protection, and Related Studies

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Medium-Voltage Metal-Enclosed Products

Power Capacitor Banks, Harmonic Filter Banks,
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Power Factor and Power Factor Correction
Knowing It and Understanding Why We Should Care About It

Presented by Paul Steciuk
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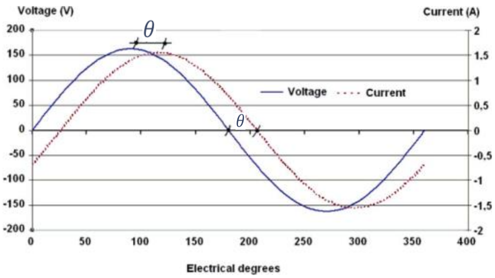
actiVAR armorVAR armorVAR

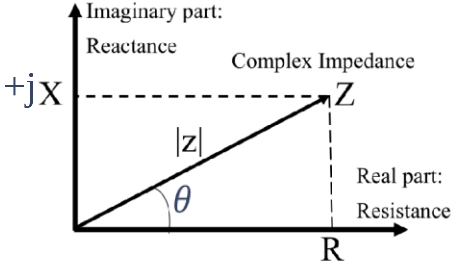
Definition of Power Factor (PF)

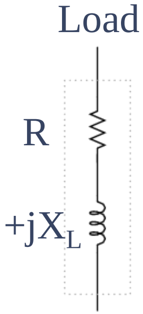
- Power Factor is the ratio of *real power (P)* to *apparent power (S)*

$$Power\ Factor\ (PF) = \frac{Power\ (kW)}{Apparent\ Power\ (kVA)} = \cos\theta$$

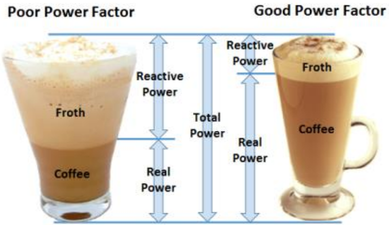
- Power Factor is the cosine of the phase angle (θ) between current and voltage
- Power Factor is the cosine of the impedance angle (θ)

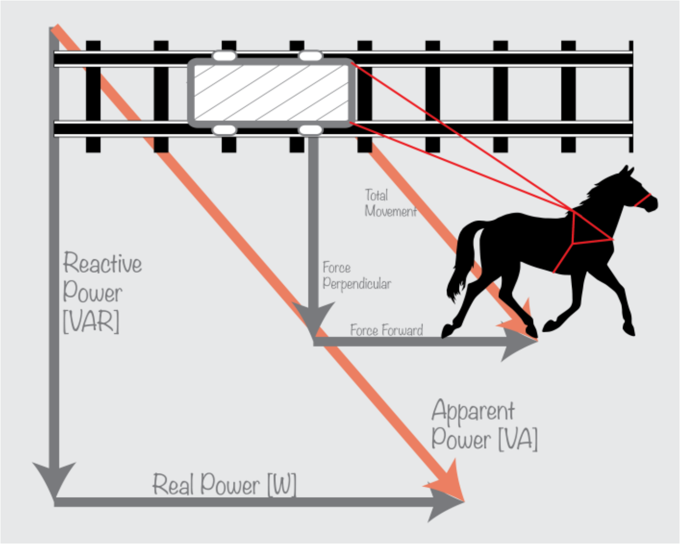






Power Factor – Common Analogies





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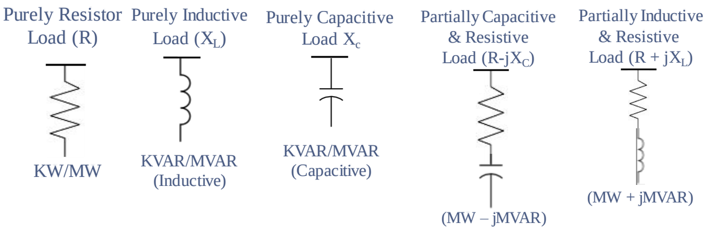
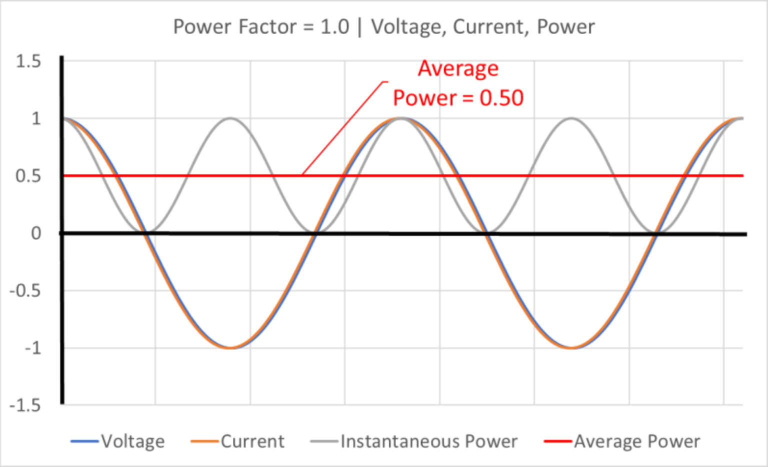
Electric Power and Power Factor Basics

- Electric Power = Voltage X Current

  $P_{INST} = V_{INST} \times I_{INST}$ (WATTS)

- Current is in phase with voltage in a resistor
- Current lags voltage in an inductor by 90º
- Current leads voltage in a capacitor by 90º
- ELI the ICE man





The phase shift between voltage and current and the impact on power delivery is the basis of power factor

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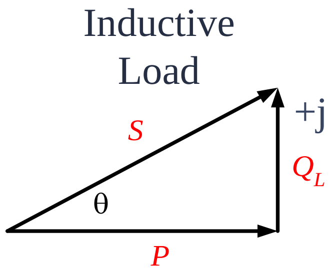
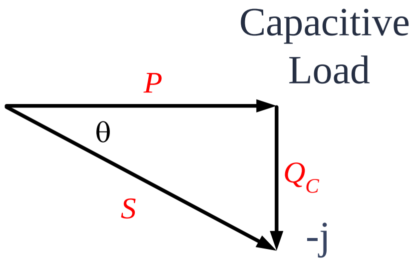
Complex Power – The Power Triangle

- The **power triangle** shows the relationship between real *(P)*, reactive *(Q)*, and apparent (S) power.
- Complex power or apparent power (S) – Units of Volt-Amps or KVA, MVA
  - Real Power (P) – Units of Watts, KW, MW, HP
    - Real component of complex power
  - Reactive Power (Q) - Volt Amperes Reactive (VARs, KVAR, MVAR)
    - Imaginary component "j" of complex power





Power Factor (PF) – Some Trigonometry

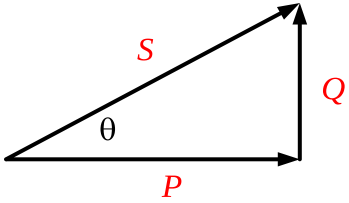
- From the power triangle it can be seen that

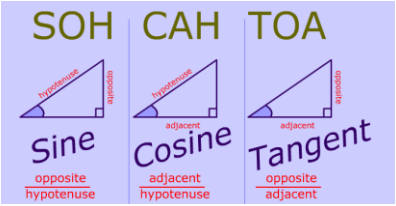
$$PF = P / S = \cos\theta$$

- **Power factor angle** is thus given by

$$\theta = \cos^{-1}(P / S)$$

- For a pure resistance, $\theta = 0^{o}$
- For a pure inductance, $\theta = 90^{o}$
- For a pure capacitance, $\theta = -90^{o}$





$$\cos\theta = \frac{P}{S} \qquad \sin\theta = \frac{Q}{S} \qquad \tan\theta = \frac{Q}{P} \qquad S^2 = P^2 + Q^2$$

Power Factor (PF) – More Terminology

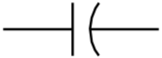
- Power factor is expressed as a number between 0 to 1.0 (or as a percent from 0% to 100%)
- Power factor is also said to be "LAGGING" or "LEADING" (i.e. 0.8 lag, or 80% lag)
- Power factor is also said to be "INDUCTIVE" or "CAPACITIVE"

The Same

Inductance (L)

+jX_L Associated With Inductance

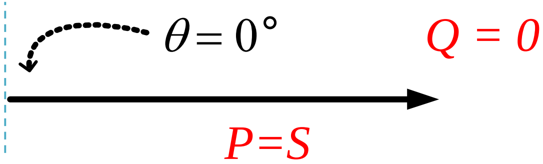
Capacitance (C)



-jX_C Associated With Capacitance

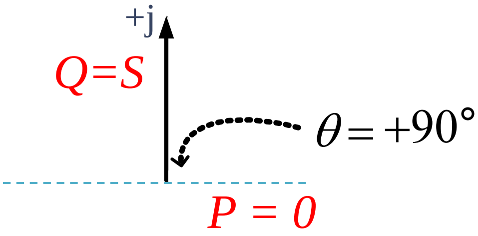
(PF=1), Unity Power Factor

- If PF = 1, then θ = 0º and Q = 0
- The load is purely resistive
- The circuit is not Lagging or Leading



(PF = 0), Lagging, Purely Inductive Load

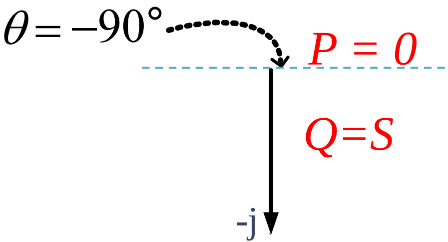
- If PF = 0, and circuit is Lagging, then $\theta = +90^{o}$ and P = 0
- The load is purely inductive



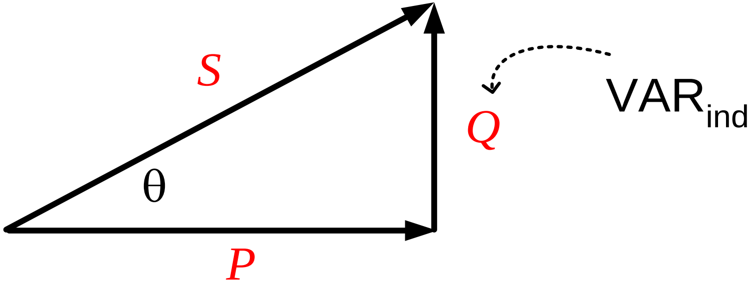
Shunt Reactors

(PF = 0), Leading, Purely Capacitive Load

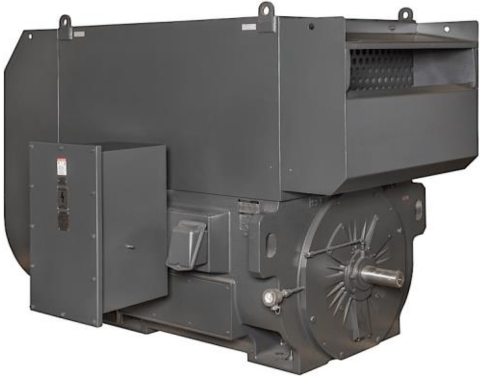
- If PF = 0, and circuit is leading, then θ = -90º and P = 0
- The load is purely capacitive



Typical Lagging Power Factor of Industrial Plant



$(\theta > 0^o)$



Induction Motor Load

Power Equations – Real, Reactive & Apparent

Three-Phase Formulas

$$P_{3\emptyset} = \sqrt{3}\, V_{LL} I \cos\theta \ = S cos\theta \text{ (W)}$$

$$Q_{3\emptyset} = \sqrt{3}\, V_{LL} I \sin\theta \ = S sin\theta \ (VAR)$$

$$S_{3\emptyset} = \sqrt{3}\, V_{LL} I \text{ (VA)}$$

Single-Phase Formulas

$$P_{1\emptyset} = V_{LN} I \cos\theta \ = S cos\theta \text{ (W)}$$

$$Q_{1\emptyset} = \ V_{LN} I \sin\theta \ = S sin\theta \ (VAR)$$

$$S_{1\emptyset} = \ V_{LN} I \text{ (VA)}$$

Why Should We Care About Power Factor?

Industrial | Commercial Customer

- Potential Savings $$$$$$$
- Improved Voltage Regulation (Power Quality)
- Increased System Capacity Issues

Independent Power Producer

- To Meet Interconnect Requirement

Electric Utility (Transmission | Distribution Provider)

- Loss Reduction $$$
- Voltage Regulation (Voltage Support)
- System Capacity / Power Transfer

Increased System Capacity / Power Transfer

Power Factor Correction

- The process of adding reactive compensation, or VARS to a system to improve the system power factor.

- Reactive compensation (VAR Sources).
  - Capacitor banks, tuned (or harmonic filters) and de-tuned
  - Static var compensators (SVCs)
  - STATCOM
  - Synchronous Motors
  - Synchronous Generators
  - Synchronous Condensers

Primary Reasons For Improving Power Factor

- **Industrial | Commercial Customer**
  - Potential Savings $$$$$$$
    - PF Penalties
    - KVA Billing
  - System Capacity Issues
  - Improved Voltage Regulation (Power Quality)
- **Electric Utility** (Transmission/Distribution Provider)
  - Voltage Regulation (Voltage Support)
  - Loss Reduction $$$

Payback periods as low as 6-Months. They, vary significantly throughout the country.

Released System Capacity From Power Factor Improvement

- Industrials sometimes cost justify power factor correction on the basis of released system capacity

$ $ $ $ $ $ $ $ $ $

Avoided cost associated with buying a new, larger transformer

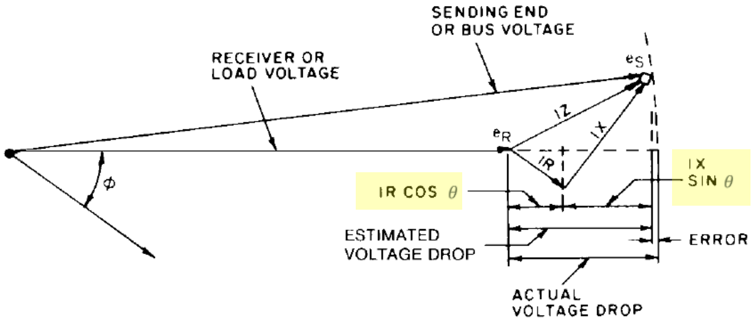
$$KVA_{RELEASED} = \left(1 - \frac{PF_{INITIAL}}{PF_{CORRECTED}}\right) KVA_{INITIAL}$$

For Example: Correcting a plant with a 0.8 lagging power factor to unity would release 20% of the plant's KVA.

Improved Voltage Regulation (Voltage Drop)

- Reduce voltage drop across impedance of network
  - Transmission system
  - Distribution system
  - Service transformers
- The flow of reactive power through the network's inductive reactance contributes significantly to the voltage drop.

- $V_{drop} \approx IR\cos\theta + IX\sin\theta$



Loss Reduction From Power Factor Correction

- **Electric Utilities** often cost justify power factor correction on the basis of loss reduction.

- **Industrials** rarely justify power factor correction on the basis of loss reduction.

$$P_{LOSSES} = 3I^2R \text{ (3-phase watts)}$$

$$\%\ Loss\ Reduction\ (\%) = 100 - \left(\frac{PF_{INITIAL}}{PF_{CORRECTED}}\right)^2 X\ 100$$

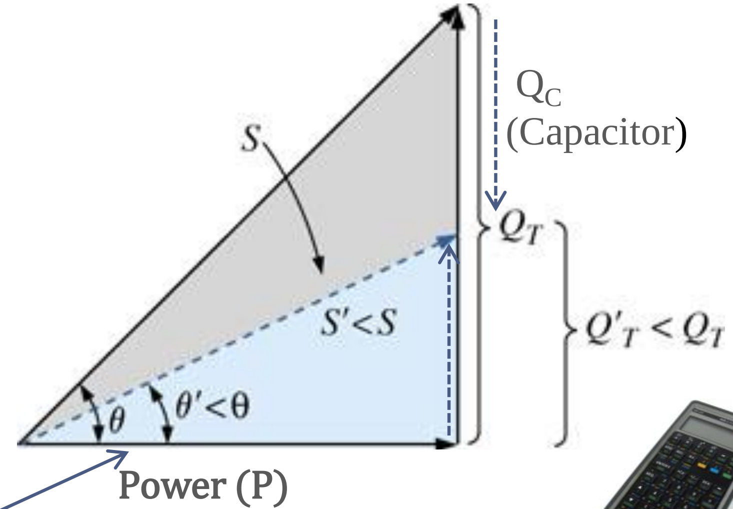
Power Factor Correction Illustrated With Power Triangle

$$Q_c = \mathrm{P}(\tan\theta - \tan\theta')$$

Where:

$$\theta = \cos^{-1}\frac{P}{S} = \cos^{-1} PF_{initial}$$

$$\theta' = \cos^{-1}\frac{P}{S'} = \cos^{-1} PF_{desired}$$



Note: “**P**” remains constant

If You Don't Like Trigonometry – Use Popular Table

1. Determine KW of load. If on plant-wide bases, normally this is based on maximum demand.
2. Determine desired power factor and horizontal row.
3. Determine initial power factor and enter vertical column.
4. Obtain "KW" multiplier at intersection and multiply by kW of load determined in 1 above.
5. The resulting value is the 3-phase reactive power rating of capacitor bank required to correct power factor to desired value.

Final power factor		Capacitor power in kVAr to be installed per kW of load to increase the power factor to:										
cosφ		0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1
	tg φ	0.48	0.46	0.43	0.40	0.36	0.33	0.29	0.25	0.20	0.14	0.0
0.40	2.29	1.805	1.832	1.861	1.895	1.924	1.959	1.998	2.037	2.085	2.146	2.288
0.41	2.22	1.742	1.769	1.798	1.831	1.840	1.896	1.935	1.973	2.021	2.082	2.225
0.42	2.16	1.681	1.709	1.738	1.771	1.800	1.836	1.874	1.913	1.961	2.002	2.164
0.43	2.10	1.624	1.651	1.680	1.713	1.742	1.778	1.816	1.855	1.903	1.964	2.107
0.44	2.04	1.558	1.585	1.614	1.647	1.677	1.712	1.751	1.790	1.837	1.899	2.041
0.45	1.98	1.501	1.532	1.561	1.592	1.626	1.659	1.695	1.737	1.784	1.846	1.988
0.46	1.93	1.446	1.473	1.502	1.533	1.567	1.600	1.636	1.677	1.725	1.786	1.929
0.47	1.88	1.397	1.425	1.454	1.485	1.519	1.532	1.588	1.629	1.677	1.758	1.881
0.48	1.83	1.343	1.730	1.400	1.430	1.464	1.467	1.534	1.575	1.623	1.684	1.826
0.49	1.78	1.297	1.326	1.355	1.386	1.420	1.453	1.489	1.530	1.578	1.639	1.782
0.50	1.73	1.248	1.276	1.303	1.337	1.369	1.403	1.441	1.481	1.529	1.590	1.732
0.51	1.69	1.202	1.230	1.257	1.291	1.323	1.357	1.395	1.435	1.483	1.544	1.686
0.52	1.64	1.160	1.188	1.215	1.249	1.281	1.315	1.353	1.393	1.441	1.502	1.644
0.53	1.60	1.116	1.144	1.171	1.205	1.237	1.271	1.309	1.349	1.397	1.458	1.600
0.54	1.56	1.075	1.103	1.130	1.164	1.196	1.230	1.268	1.308	1.356	1.417	1.559
0.55	1.52	1.035	1.063	1.090	1.124	1.156	1.190	1.228	1.268	1.316	1.377	1.519
0.56	1.48	0.996	1.024	1.051	1.085	1.117	1.151	1.189	1.229	1.277	1.338	1.480
0.57	1.44	0.958	0.986	1.013	1.047	1.079	1.113	1.151	1.191	1.239	1.300	1.442
0.58	1.40	0.921	0.949	0.976	1.010	1.042	1.073	1.114	1.154	1.202	1.263	1.405
0.59	1.37	0.884	0.912	0.939	0.973	1.005	1.039	1.077	1.117	1.165	1.226	1.368
0.60	1.33	0.849	0.878	0.905	0.939	0.971	1.005	1.043	1.083	1.131	1.192	1.334
0.61	1.30	0.815	0.843	0.870	0.904	0.936	0.970	1.008	1.048	1.096	1.157	1.299
0.62	1.27	0.781	0.809	0.836	0.870	0.902	0.936	0.974	1.014	1.062	1.123	1.265
0.63	1.23	0.749	0.777	0.804	0.838	0.870	0.904	0.942	0.982	1.030	1.091	1.233
0.64	1.20	0.716	0.744	0.771	0.805	0.837	0.871	0.909	0.949	0.997	1.058	1.200
0.65	1.17	0.685	0.713	0.740	0.774	0.806	0.840	0.878	0.918	0.966	1.007	1.169
0.66	1.14	0.654	0.682	0.709	0.743	0.775	0.809	0.847	0.887	0.935	0.996	1.138
0.67	1.11	0.624	0.652	0.679	0.713	0.745	0.779	0.817	0.857	0.905	0.966	1.108
0.68	1.08	0.595	0.623	0.650	0.684	0.716	0.750	0.788	0.828	0.876	0.937	1.079
0.69	1.05	0.565	0.593	0.620	0.654	0.686	0.720	0.758	0.798	0.840	0.907	1.049
0.70	1.02	0.536	0.564	0.591	0.625	0.657	0.691	0.729	0.796	0.811	0.878	1.020
0.71	0.99	0.508	0.536	0.563	0.597	0.629	0.663	0.701	0.741	0.783	0.850	0.992
0.72	0.96	0.479	0.507	0.534	0.568	0.600	0.634	0.672	0.721	0.754	0.821	0.963
0.73	0.94	0.452	0.480	0.507	0.541	0.573	0.607	0.645	0.685	0.727	0.794	0.936
0.74	0.91	0.425	0.453	0.480	0.514	0.546	0.580	0.618	0.658	0.700	0.767	0.909
0.75	0.88	0.398	0.426	0.453	0.487	0.519	0.553	0.591	0.631	0.673	0.740	0.882
0.76	0.86	0.371	0.399	0.426	0.460	0.492	0.526	0.564	0.604	0.652	0.713	0.855
0.77	0.83	0.345	0.373	0.400	0.434	0.466	0.500	0.538	0.578	0.620	0.687	0.829
0.78	0.80	0.319	0.347	0.374	0.408	0.440	0.474	0.512	0.552	0.594	0.661	0.803
0.79	0.78	0.292	0.320	0.347	0.381	0.413	0.447	0.485	0.525	0.567	0.634	0.776
0.80	0.75	0.266	0.294	0.321	0.355	0.387	0.421	0.459	0.499	0.541	0.608	0.750
0.81	0.72	0.240	0.268	0.295	0.329	0.361	0.395	0.433	0.473	0.515	0.582	0.724
0.82	0.70	0.214	0.242	0.269	0.303	0.335	0.369	0.407	0.447	0.489	0.556	0.698
0.83	0.67	0.188	0.216	0.243	0.277	0.309	0.343	0.381	0.421	0.463	0.530	0.672
0.84	0.65	0.162	0.190	0.217	0.251	0.283	0.317	0.355	0.395	0.437	0.504	0.645
0.85	0.62	0.136	0.164	0.191	0.225	0.257	0.291	0.329	0.369	0.417	0.478	0.602
0.86	0.59	0.109	0.140	0.167	0.198	0.230	0.264	0.301	0.343	0.390	0.450	0.593
0.87	0.57	0.083	0.114	0.141	0.172	0.204	0.238	0.275	0.317	0.364	0.424	0.567
0.88	0.54	0.054	0.085	0.112	0.143	0.175	0.209	0.246	0.288	0.335	0.395	0.538
0.89	0.51	0.028	0.059	0.086	0.117	0.149	0.183	0.230	0.262	0.309	0.369	0.512
0.90	0.48		0.031	0.058	0.089	0.121	0.155	0.192	0.234	0.281	0.341	0.484

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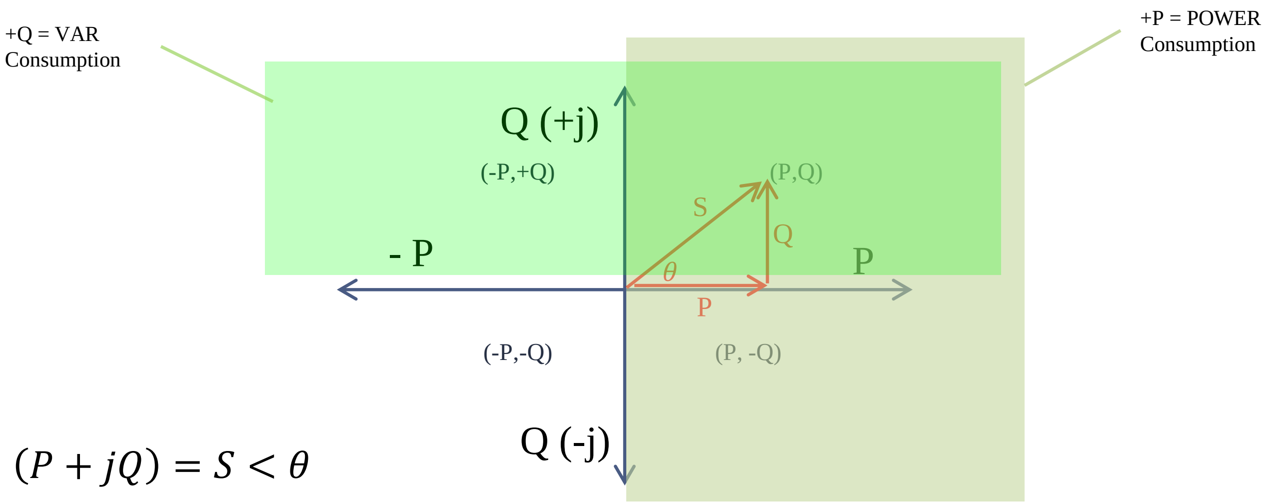
Power Triangle on PQ Load Diagram



$$S = (P + jQ) = S < \theta$$

Power Factor Correction – Application / Solution Steps

Determine Reactive Power Of Load
- From Electric Utility Bills
- Switchboard Meters / PQ Metering
- Loadflow Studies / Load Studies

Calculate Reactive Power Rating of Capacitor Bank
- Consider Rate Tariff Structure (Desired PF)
- Consider Interconnect Requirements
- Determine Step Size To Meet PQ Requirements and Tariff
- Calculate Payback Period

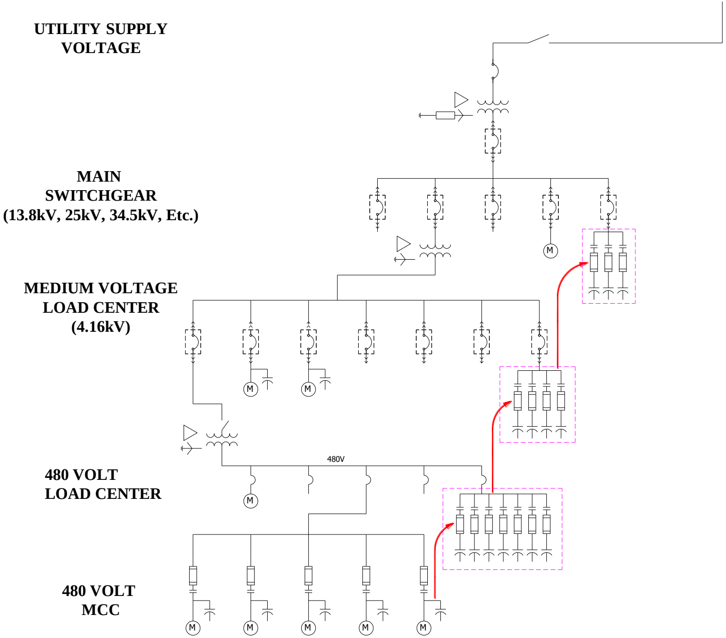
Determine Location
- Service Entrance
- Medium-Voltage Load Centers
- Low Voltage
- At Load Terminals

Resonance Concerns?
- Determine Resonance Frequencies
- Determine Sensitivity of System to Change
- Filter / De-Tuned Capacitor Bank / Standard Capacitor Banks

Develop Specifications
- **Equipment Spec** Open Air/Metal-Enclosed; Filter / De-Tuned Capacitor / Standard Capacitor
- Switching Requirements
- Protection / Control Requirements
- Site Requirements

Bid Evaluation
- Commercial Review
- Technical Review

Voltage Level & Location for Power Factor Correction



- NEPSI recommends plant wide power factor correction over correction at individual loads
- Low voltage systems are typically “off-the-shelf” standard designs below 800 kvar.
  - Systems greater than 800 kvar are custom and cost much more.
  - Consider medium voltage at and above this reactive power rating.
- Low voltage banks are more complicated
  - More current
  - More stages
  - Higher probability for resonance issues
  - Higher probability for transient (PQ Problems) due to proximity to load.

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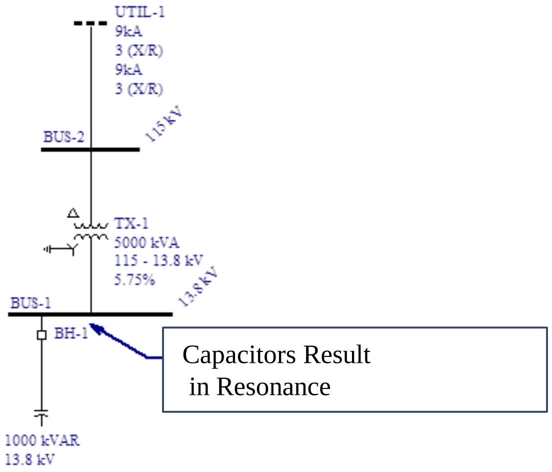
Primary Concerns When Adding Capacitors To A Network

- Over-Compensation ??? – Going Leading
  - High-Voltage Concerns
- Harmonic Resonance
- Voltage Rise/Drop During Switching
- Switching Transients (Voltage Transients)
- Switching transients (Back-to-Back Switching)
- Outrush current for near-in substation faults
  - Breaker rating
- Motor Self Excitation

System Resonance Concerns When Adding Capacitors To A Network



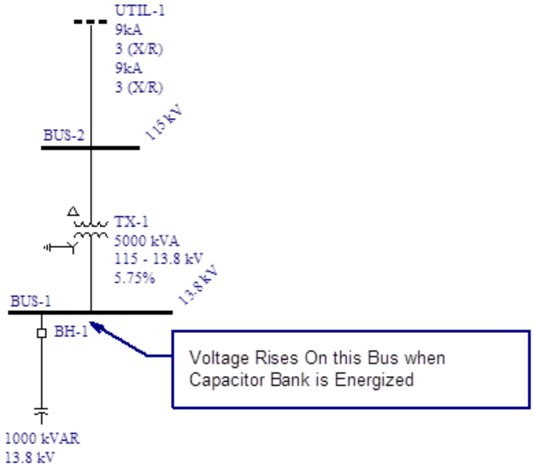
- Capacitor banks cause resonance which may or may not result in high voltage and high current distortion
- Capacitors do not produce harmonics

$$Resonance\ Harmonic \approx \sqrt{\frac{kvar}{KVA_{SC}}}$$

$$KVA_{SC} \approx \frac{Transformer\ KVA\ Rating}{Transformer\ Per\ Unit\ Impedance}$$

$$KVA_{SC} = A_{SC} x kV_{LL}\ x\ 1.73$$

Voltage Rise/Drop When Switching Capacitor Banks



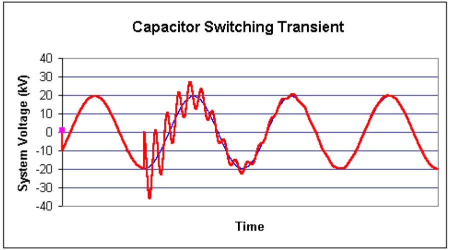
- Capacitor banks & harmonic filter banks result in voltage rise
- Voltage rise/drop should be limited to 1.5% to 3% per switching step

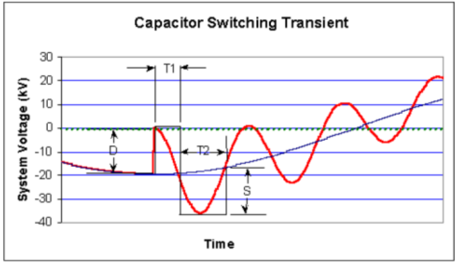
$$Voltage\ Rise/Drop\ (\%) \approx \frac{kvar}{KVA_{SC}}\ X\ 100$$

$$KVA_{SC} \approx \frac{Transformer\ KVA\ Rating}{Transformer\ Per\ Unit\ Impedance}$$

$$KVA_{SC} = A_{SC} X\ kV_{LL}\ x\ 1.73$$

Switching Transients (Voltage)





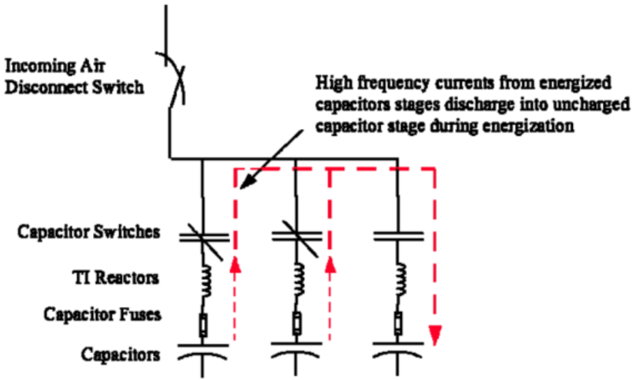
Power Quality Concerns

- Initial voltage depression, loss of voltage magnitude "D" and duration "T1"
- The recovering system voltage will result in an initial transient over-voltage of magnitude "S" and Duration "T2".
- Multiple zero-crossings. For the transient in figure 4, a total of three zero crossings occur before the natural system voltage zero crossing.

Transient Mitigation Techniques

- Pre-insertion resistor switching
- 0-Voltage closing vacuum switches (synchronous closing)
- ABB DS1 Switch

Switching Transients - Inrush Current From Back-To-Back Switching



Key Points:

- Charge from parallel connected capacitors discharge into stage being switched on.
  - Amplitude and frequency of inrush current can be very high resulting in breaker/switch failure
  - Capacitor bank design must mitigate for it.

Mitigation technologies

- Inrush reactors
  - For multi-stage banks or banks on the same bus, inductance of transient inrush reactor decreases magnitude and frequency (rate of rise) of inrush current.
- Pre-insertion resistor switching
- 0-Voltage closing vacuum switches (synchronous closing)
- ABB DS1 Switch
- Filter Reactors (tuning reactors)

Inrush Current and Inductance Calculation

Table 1 *Typical Inductance Requirements for Medium Voltage Capacitor Banks*	
L-L Voltage KV	Leq* (µH)
2.4 4.16	8.6 14.9
4.8 6.9	17.1 24.6
8.32 12	29.7 42.9
12.47 13.2	44.5 47.1
13.8 20.78	49.3 74.2
22.8 23	81.6 82.1
24.94 34.5	89.1 123.2

Calculation Method

- NEPSI's Website provides calculator on resource page
- IEEE C37.012-2005, *Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers*

Formulas

$$I_{i\,peak}(A) = 13{,}500\sqrt{\frac{U_r I_1 I_2}{f_s L_{eq}(I_1+I_2)}}$$

$$f_i(kHz) = 9.5\sqrt{\frac{U_r f_s (I_1+I_2)}{L_{eq}(I_1+I_2)}}$$

$$L' = \frac{1}{\frac{1}{L_1}+\frac{1}{L_2}+\frac{1}{L_3}+\cdots\frac{1}{L_n}}$$

$$L_{eq} = L' + L_{n+1}$$

Inrush Current Calculator

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66 Carey Road Queensbury, NY 12804
Ph: (518) 792-4776 Fax: (518) 792-5767
www.nepsi.com sales@nepsi.com

CALCULATION OF PEAK INRUSH CURRENT FOR ISOLATED AND BACK-TO-BACK CAPACITOR BANK SWITCHING

The following calculator computes the expected transient inrush current associated with isolated and back-to-back capacitor bank switching. Input the stage reactive power rating, stage inductance, capacitor bank voltage rating, system frequency, and the short circuit level at the capacitor bank. The calculator provides the expected single stage inrush current as well as back-to-back inrush current and frequency for multi-stage capacitor banks.

The calculations are based on IEEE C37.012-2005, Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers.

Calculator-1

Known variables: Stage Reactive Power Rating, Stage Inductance, System Voltage, Short Circuit Level at Capacitor Bank, and System Frequency

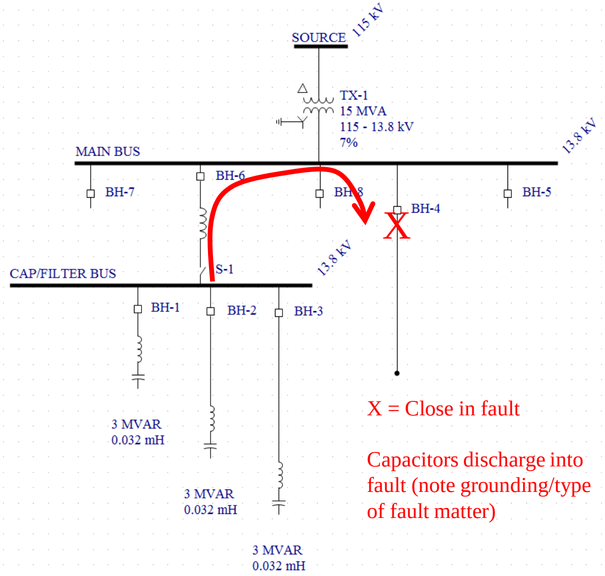
Input Capacitor Bank Voltage (kV_{LL}): 13.80
Input Short Circuit Current Level at Capacitor Bank (kA): 4.358
Input System Frequency (Hz): 60

Stage #	Reactive Power Rating (kvar)	Stage Inductance (µH)	Stage Current (amps)	Single Stage Inrush Current (amps-peak)	Single Stage Inrush Frequency (Hz)	Back-to-Back Inrush Current (amps-peak)	Back-to-Back Inrush Frequency (kHz)	Product I x f kAHz
Stage 1	2000	47	83.8	854.5	432.8	n/a	n/a	370
Stage 2	2000	47	83.8	n/a	n/a	4321.9	4.356	18828
Stage 3	2000	47	83.8	n/a	n/a	5762.5	4.356	25104
Stage 4	2000	47	83.8	n/a	n/a	6482.8	4.356	28242
Stage 5	2000	47	83.8	n/a	n/a	6915.0	4.356	30125
Stage 6	2000	47	83.8	n/a	n/a	7203.1	4.356	31380

Calculation Tool

- Located at nepsi.com/resources
- Requires system voltage, stage kvar, stage inductance
- Also calculates single bank inrush current when short circuit kA is known at the capacitor bank

Transient Outrush Current Concerns



Calculation Method

- Determine inductance between capacitor bank and fault (include transient inrush reactors if they exist).
- Calculate initial current peak I_O and compare to breaker rating (See ANSI/IEEE C37.06)
- Add necessary inductance or increase rating of feeder breaker as required.

Formulas

$$i(t) = \frac{V_{\max(PEAK)}}{Z_o} Sin(\omega_o t) \text{ (amps)} \qquad \omega_o = 2\pi f = \sqrt{\frac{1}{C_{total} L_S}} \text{ (rad/s)}$$

$$I_o = \frac{V_{\max(PEAK)}}{Z_o} \text{ (amps peak)} \qquad Z_o = \sqrt{\frac{L_S}{C_{total}}} \text{ (ohms)}$$

Z_o = Surge Impedance of circuit

C_{total} = Total capacitance of capacitor bank

$V_{max(peak)}$ = Maximum peak line-to-neutral voltage

L_S=Total inductance to fault

i(t)=instantaneous current

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Transient Outrush Calculation Tool

Northeast Power Systems, Inc.

66 Carey Road, Queensbury, NY

Phone: (518) 792-4776 Fax: (518) 792-5767 www.nepsi.com

CAPACITOR BANK OUT RUSH CURRENT CALCULATION

Project Information

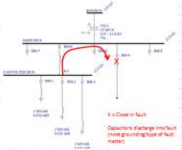
Customer Name:	Customer Name	Project Name:	Project Name
Equipment Tag:	Tag Name		

Background Information

This spreadsheet provides calculation assistance for calculating peak outrush current and frequency associated with a capacitor bank and nearby feeder circuit breaker that may close into a nearby fault (see figure to right). In such a scenario, depending on the grounding of the capacitor bank and the type of fault, the discharge current could exceed the breakers rating. The magnitude and frequency of the outrush current is dependent upon the total equivalent inductance between the capacitor bank and the fault, the capacitor bank rating, and the point on the voltage waveform where the breaker closes into the fault. This spreadsheet calculates the worst case current magnitude, assuming the fault occurs at peak voltage with no dampening due to resistance in the circuit.

The spreadsheet allows for entry of inductance associated with transient inrush reactors, commonly put on each stage of the capacitor bank, inductance associated with an outrush reactor, commonly put in the incoming compartment of the capacitor bank or in series with the capacitor bank feeder cables supplying the capacitor bank, and the total inductance of the cable length and assocaited buswork between the capacitor bank and the close in feeder fault.

Note: For ungrounded banks, cable faults do not contribute to outrush current as these are line-to-ground faults and there is not a complete circuit for the out rush current to flow.



Information and formulas used in the spreadsheet were obtained from IEEE Standard 1036-2010 - *Guide for the Application of Shunt Capacitors* and IEEE PES technical report PES-TR16 - *Transient Limiting Inductor Applications in Shunt Capacitor Banks.*

Formulas

$i(t) = \frac{V_{max(PEAK)}}{Z_s} Sin(\omega_o t)$ (amps) $\omega_o = 2\pi f = \sqrt{\frac{1}{C_{total} L_s}}$ (rad/s) $Z_o = \sqrt{\frac{L_s}{C_{total}}}$ (ohms) $I_o = \frac{V_{max(PEAK)}}{Z_o}$ (amps peak)

Where

- $i(t)$ = Instantaneous Current
- I_0 = Maximum Peak Current
- ω_0 = Angular frequency

- L_s = Total inductance to fault
- $V_{max(peak)}$ = Maximum peak line-to-neutral voltage
- C_{total} = Total phase capacitance of capacitor bank
- Z_0 = Surge Impedance of circuit

$$L_{eq} = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \dots \frac{1}{L_n}}$$

$$L_s = L_{eq} + L_{outrush} + L_{capacitor-to-fault}$$

Capacitor Bank & System Data

Incoming outrush reactor Inductance (μH)	0	(outrush reactor inductance on capacitor bank main or feeder cables)
Total inductance between capacitor bank and fault (μH)	20	(inductance of cables - assume 0.2 μH/Foot if not known)
Bank Voltage Rating (kV)	13.8	(a 10% over-voltage may be considered for worst case condition)
Frequency Rating of Bank (HZ)	60	

	Stage Rating (kvar)	Stage Inrush/Outrush Inductance (μH)	Capacitance (μF)	Current Rating (amps)
Stage 1	3000	80	41.79	125.66
Stage 2	3000	80	41.79	125.66
Stage 3	3000	80	41.79	125.66

Internal Inductance associated with the capacitor bank itself or internal bus work.

IEEE Std. C37.012-2005 - *Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers* provides the following basic approximatations for capacitor bank inductance:

Out Rush Current Calculation | C37.06 - 2009 | IEEE Std. 1036-

- Located at nepsi.com/resources
- Requires system voltage, stage kvar, stage inductances, inductance of feeder cable, inductance to fault
- Can be used to determine requirement for out rush reactor.
- Sites relevant standards, C37.06-2009, IEEE Std. 1036-2010, PES-TR16

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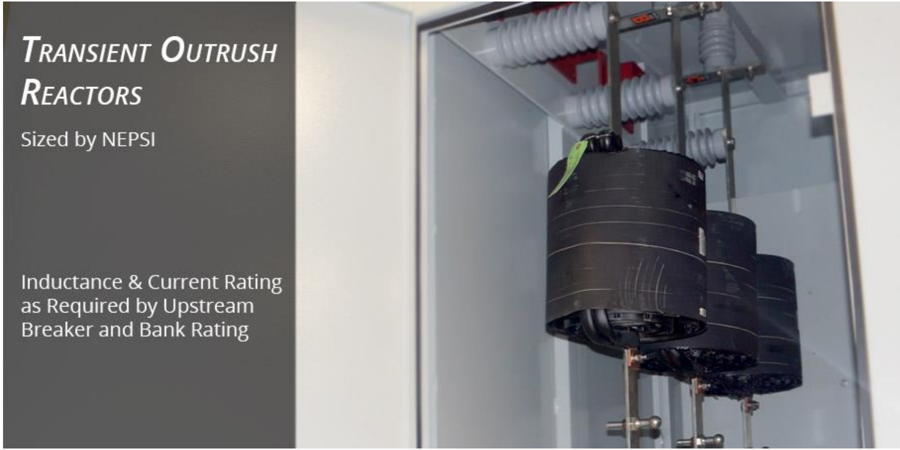
One-Line

Typical Transient Outrush Reactor



- Fixed inductors used to limit transient outrush current for close in faults.
- Inductance is chosen to limit outrush current to breaker rating (See C37.06).
- Current rating based on capacitor bank current rating.
- Usually not necessary at voltages below 34.5kV.
- Can be costly in large banks due to high current rating
- Sometimes located on top of enclosure
- Calculations are simple

Typical Transient Outrush Reactor

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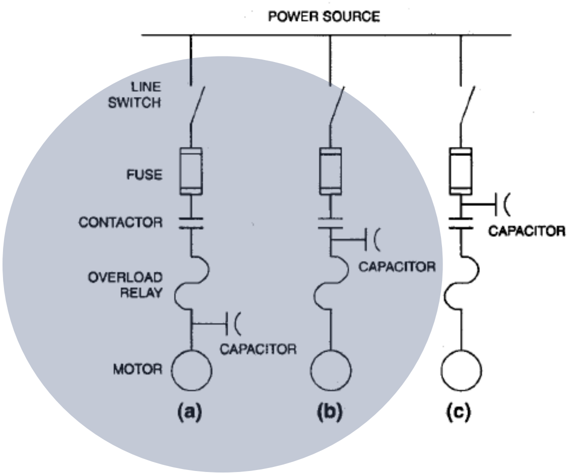
When large, are typically located on roof of enclosure

Motor Self Excitation Concerns



Power Factor Correction At The Motor

Notes:

- If capacitors are over-sized and placed on motor terminals, a condition known as self excitation can occur.
- Such a condition can cause over-voltages at the motor terminals during opening of the motor starter. This over-voltage can damage the motor.

Never:

- Over size PF capacitors at the motor. The capacitor rating should not exceed the no-load reactive power requirement of the motor.
- Check the motor datasheets for recommended size.

NEPSI Resources To Help With
Power Factor Correction and Filter Design and More

- Website: www.nepsi.com
  - Filter design spreadsheet tools (indispensable tool) + others
  - Power system calculators
  - Guide form specifications (by industry)
  - Common component cut sheets/instructions for MV filter banks and capacitor banks
  - NEPSI product literature
  - Technical notes
  - Case studies
  - How-to-videos

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