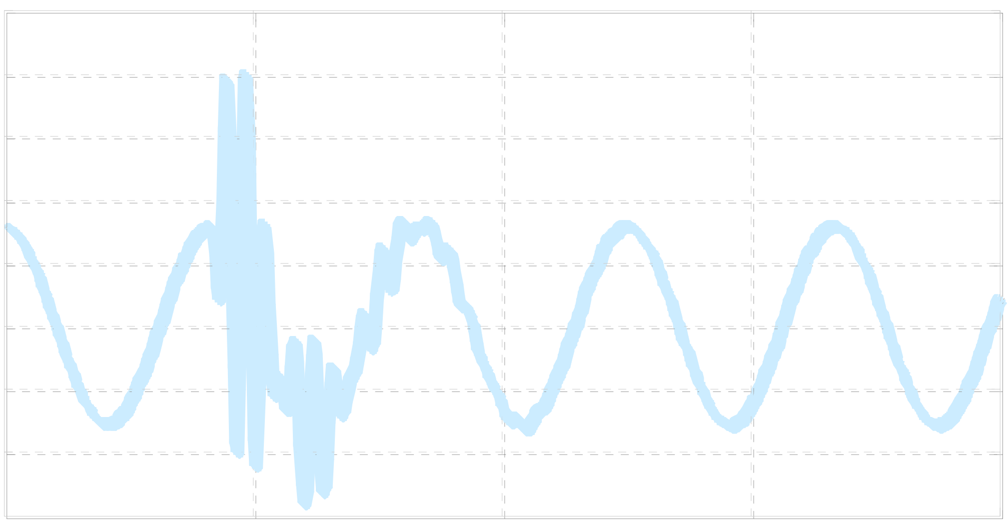
Utility Capacitor Bank Applications

Electrotek Concepts, Inc.



December 2009

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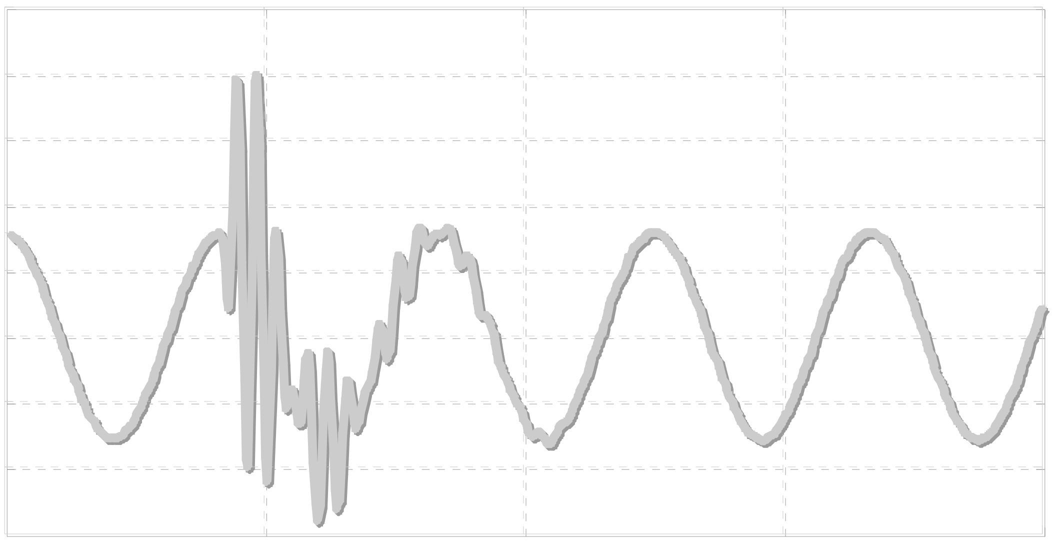
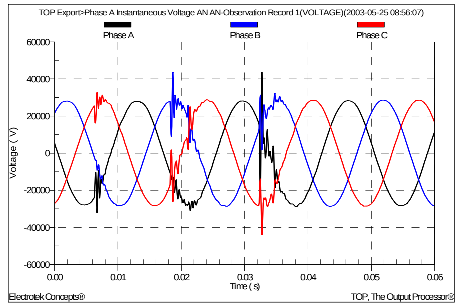
Definitions

- **Ampere** – The unit used to measure an electric current or the rate of flow of electricity in the circuit.
- **Average Power Factor** – The ratio of real energy (kWh) to apparent energy (kVAh).
- **Displacement Power Factor** – The phase displacement between the voltage and current.
- **Kilovolt-Ampere (kVA)** – The unit of apparent electric power equal to 1,000 volt-amperes. The product of volts and amperes yields volt-amperes.
- **Kilovolt-Ampere-Hour (kVAr)** – The product of apparent power in kVA and time measured in hours.
- **Kilowatt (kW)** – The unit of electric power equal to 1,000 watts. The term horsepower is equivalent to 746 watts.
- **Kilowatt-Hour (kWh)** – The product of power in kW and time measured in hours.
- **Kilovolt-Ampere-Reactive (kVAr)** – The inactive component of the apparent electric power (kW is active component). The quantity is also known as kilovar.
- **Ohm** – The unit of electrical resistance.
- **Power Factor** – The ratio of real or active power in kW to total or apparent power in kVA. Power factor is often expressed in percent and the term unity power factor is used to describe a 100% power factor.
- **Single-Phase** – Pertaining to a circuit energized single ac source.
- **Three-Phase** – Pertaining to a combination of three circuits energized by three ac sources that differ in phase by 120 .
- **True Power Factor** – the ratio of real power to total apparent power (volt-amperes). Used when voltage and current have harmonic components.
- **Volt** – The unit of electric force or pressure.
- **Watt** – The unit of electric power.
- **Watt-Hour** – The unit of electric energy. The work done in one hour at the steady rate of one watt.

INTRODUCTION



Capacitor Bank Applications Outline

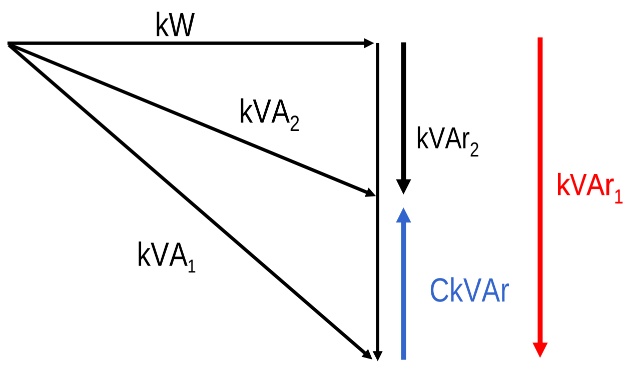


- System Benefits
- Capacitor Bank Design
- Capacitor Bank Protection
- Harmonic Concerns
- Transient Disturbances
- Impact of Capacitor Banks on Power Quality
- Example Problems
- References
- Glossary

The application of utility capacitor banks has long been accepted as a necessary step in the efficient design of utility power systems. Also, capacitor switching is generally considered a normal operation for a utility system and the transients associated with these operations are generally not a problem for utility equipment. These low frequency transients, however, can be magnified in a customer facility (if the customer has low voltage power factor correction capacitors) or result in nuisance tripping of power electronic based devices, such as adjustable-speed drives (ASDs). Capacitor energizing is just one of the many switching events that can cause transients on a utility system. However, due to their regularity and impact on power system equipment, they quite often receive special consideration.

Purpose of Shunt Capacitor Banks

- Provide leading reactive power (VArs) to an electric power system:



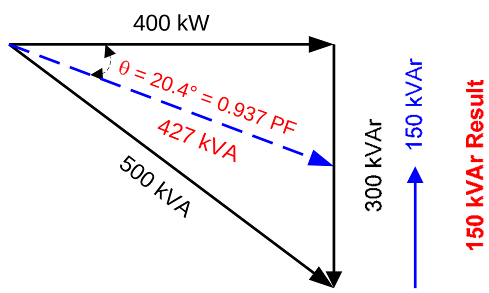
Most power system loads and delivery apparatus (e.g. lines and transformers) are inductive in nature and therefore operate at a lagging power factor. When operating at a lagging power factor, a power system requires additional var flow, which results in reduced system capacity, increased system losses, and reduced system voltage.

Var support and voltage control are the primary benefits for a transmission system while the distribution system benefits may be more varied depending upon whether the system belongs to a generating utility, a non-generating utility, or an industrial power user.

Capacitor banks are typically installed on the transmission system at major buses to provide voltage support for a large area. They are also installed at distribution buses and directly on customer delivery buses to provide voltage support to smaller areas and to individual customers. Capacitor banks installed on distribution lines support voltage along the entire length of line.

Improving Power Factor

- Power factor measures how effectively electrical power capacity is being used. Power factor is the ratio between active power (kW) and apparent power (kVA).



300 kVAr required by loads
150 kVAr power factor capacitor added
150 kVAr result

$$kVA_{new} = \sqrt{(400^2 + 150^2)} = 427\,kVA$$

$$PF = \frac{400}{427} x100 = 93.7\%$$

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

How much kVAr is required for power factor correction?

The amount of power factor correction that is required to correct a facility to a target power factor level is the difference between the amount of kVAr in the uncorrected system (required by loads) and the amount of kVAr in the corrected system. An example power factor capacitor application is shown in the power triangle shown above.

Summary of Benefits

- VAr support and voltage control are the primary benefits for transmission systems, distribution benefits may vary significantly.

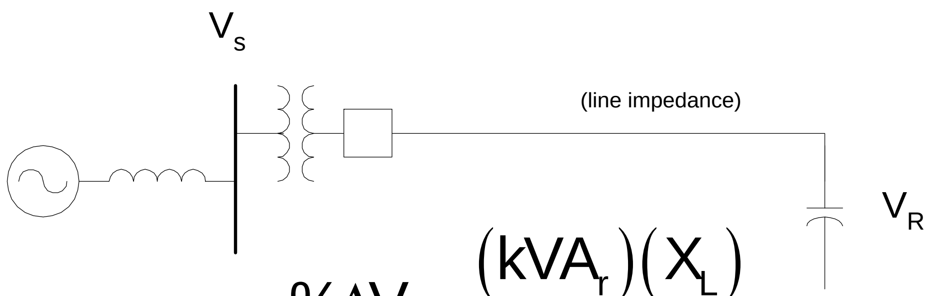
Benefits	Transmission System	Distribution System
Var Support	Primary	Secondary
Voltage Control	Primary	Primary
Increased System Capacity	Secondary	Primary
Reduced Power System Losses	Secondary	Primary
Reduced Billing Charges	N/A	Primary

VAr Support

- Voltage Control (voltage rise at the point of installation)
- Increased System Capacity (reduction in kVA load)
- Reduced System Losses (reduction in current flow)
- Reduced Billing Changes (reduction in penalty charges)

Var support encompasses many of the different benefits of shunt power capacitors, such as improved voltage control and power factor, reduced system losses and reactive power requirements at generators, and increased steady-state stability limits. Capacitive vars are rated and located at transmission and distribution substations to supply vars close to the loads or to provide midway support across heavily loaded transmission circuits.

Voltage Improvement



$$\%\Delta V_r \approx \frac{(kVA_r)(X_L)}{10 * kV^2}$$

where:

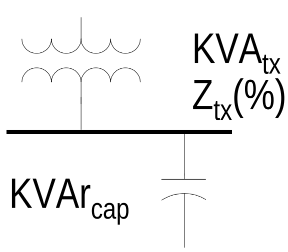
ΔV_r = % voltage rise due to the installation of (kVAr) the capacitor

kV = system line-to-line voltage

X_L = inductance reactance (@ capacitor location) of the system in Ω

Applying capacitors to a system will result in a voltage rise in the system from the point of installation back to the generation. In a system with lagging power factor, this occurs because capacitors may reduce the amount of reactive current being carried in the system, thus decreasing the amount of resistive and reactive voltage drop in the system.

Industrial application:



$$\%\Delta V = \frac{(kVAr_{cap})(\%Z_{tx})}{kVA_{tx}}$$

Loss Reduction

- On some distribution and transmission systems, a significant reduction in losses may be achieved by the installation of shunt power capacitors.
- Reduction in losses due to a reduction in current flow:

$$\text{Loss Ratio} = \frac{\text{Loss}_{\text{with caps}}}{\text{Loss}_{\text{without caps}}} = \left(\frac{\text{PF}_{\text{without caps}}}{\text{PF}_{\text{with caps}}} \right)^2$$

The installation of shunt power capacitors can reduce current flow through the system from the point of the capacitor installation back to the generation. Since power losses are directly proportional to the square of the current, a reduction of current flow results in a much greater reduction of power losses. Capacitors are often installed as close to the load as possible for this reason. This reduction in losses will reduce the generation fuel requirement to supply these losses as well as the system equipment costs to supply the losses at peak load.

$$\%\text{Loss Reduction} = 100 \left[1 - \left(\frac{\text{PF}_{\text{old}}}{\text{PF}_{\text{new}}} \right)^2 \right]$$

Increased System Capacity

- Increased system capacity is often the most important benefit from the addition of distribution capacitors.

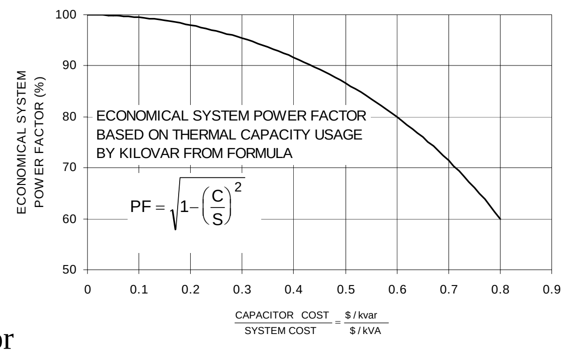
$$PF = \sqrt{1 - \left(\frac{C}{S}\right)^2}$$

where:

C = cost per kVAr of capacitor bank

S = cost per kVA of system equivalent

PF = optimum power factor



Increased system capacity is often the most important benefit justifying the addition of shunt power capacitors on a distribution system. This is particularly significant when loads supplied by the system are increasing rapidly. The addition of shunt power capacitors reduces the kilovoltampere loading on the system, thereby releasing capacity that can then be used to supply future load increases. The power factor required to release a desired amount of system kVA can be determined using:

$$PF_{new} = \frac{PF_{old}}{\left(1 - kVA_{release}\right)}$$

where:

PF_{new} = corrected power factor

PF_{old} = existing power factor

$kVA_{release}$ = kVA to be released (in pu)

Power Factor Correction (kilowatt multipliers)

Orig PF	Corrected Power Factor 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
0.54	0.809	0.861	0.913	0.965	1.019	1.074	1.133	1.196	1.267	1.356	1.559
0.56	0.729	0.781	0.834	0.886	0.940	0.995	1.053	1.116	1.188	1.276	1.479
0.58	0.655	0.707	0.759	0.811	0.865	0.920	0.979	1.042	1.113	1.201	1.405
0.60	0.583	0.635	0.687	0.740	0.794	0.849	0.907	0.970	1.042	1.130	1.333
0.62	0.515	0.567	0.620	0.672	0.726	0.781	0.839	0.903	0.974	1.062	1.265
0.64	0.451	0.503	0.555	0.607	0.661	0.716	0.775	0.838	0.909	0.998	1.201
0.66	0.388	0.440	0.492	0.545	0.599	0.654	0.712	0.775	0.847	0.935	1.138
0.68	0.328	0.380	0.432	0.485	0.539	0.594	0.652	0.715	0.787	0.875	1.078
0.70	0.270	0.322	0.374	0.427	0.480	0.536	0.594	0.657	0.729	0.817	1.020
0.72	0.214	0.266	0.318	0.370	0.424	0.480	0.538	0.601	0.672	0.761	0.964
0.74	0.159	0.211	0.263	0.316	0.369	0.425	0.483	0.546	0.617	0.706	0.909
0.76	0.105	0.157	0.209	0.262	0.315	0.371	0.429	0.492	0.563	0.652	0.855
0.78	0.052	0.104	0.156	0.209	0.263	0.318	0.376	0.439	0.511	0.599	0.802
0.80	0.000	0.052	0.104	0.157	0.210	0.266	0.324	0.387	0.458	0.547	0.750
0.82		0.000	0.052	0.105	0.158	0.214	0.272	0.335	0.406	0.495	0.698
0.84			0.000	0.053	0.106	0.162	0.220	0.283	0.354	0.443	0.646
0.86				0.000	0.054	0.109	0.167	0.230	0.302	0.390	0.593
0.88					0.000	0.055	0.114	0.177	0.248	0.337	0.540
0.90						0.000	0.058	0.121	0.193	0.281	0.484
0.92							0.000	0.063	0.134	0.223	0.426
0.94								0.000	0.071	0.160	0.363
0.96									0.000	0.089	0.292
0.98										0.000	0.203
1.00											0.000

$$kVAr_{required} = kW * \left(\tan\left(\cos^{-1}\phi_{original}\right) - \tan\left(\cos^{-1}\phi_{desired}\right)\right)$$

$$kVAr_{required} = multiplier * kW$$

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:

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

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

This relationship is commonly provided in tabular form, as shown above. As an example, the data provided in table may be used to find the capacitor rating required to improve the power factor of a 400 kW load from 0.80 to 0.94:

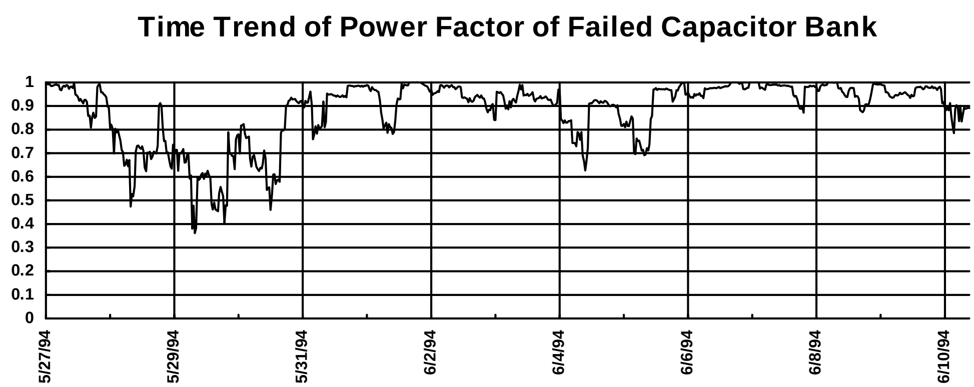
kVAr = kW * multiplier
kVAr = 400 * 0.387 = 155 kVAr

Reduced Billing Charges

- A number of utilities use some form of kVA billing for their larger customers (e.g. utilities and large industrial customers).

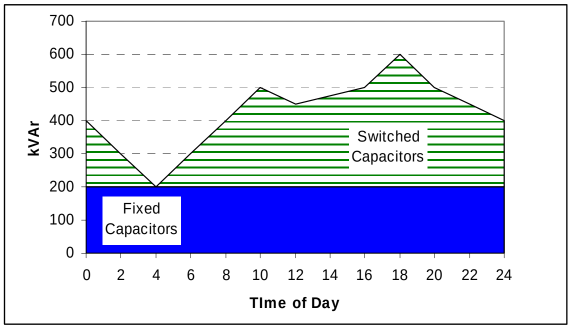
- kVA billing charge may be calculated many different ways:
  - a fixed dollar amount for each kW plus a fixed dollar amount for each kVAr.
  - a certain dollar amount for each kW at or above a certain power factor, with additional charges made for each kVAr in excess of that required by a minimum power factor.
  - a charge per kW demand multiplied by a factor which increases with decreasing power factor.
  - a fixed charge per peak kVA

Example power factor trend:



Control of Capacitor Banks

- Capacitor banks are generally switched based on:
  - Voltage (voltage regulation improvement)
  - Current (current related to VAr demand)
  - VArs (VAr demand major consideration)
  - Time (VAr demand regular with respect to time)
  - Temperature (VAr demand regular with respect to temp)



Switched capacitors give added flexibility to control system voltage, power factor, and losses. Switched capacitors are usually applied with some type of automatic switch control. The control senses a particular condition. If the condition is within a preset level, the control's output level will initiate a close or trip signal to the switches that will either connect or disconnect the capacitor bank from the distribution line.

Fixed capacitor banks are usually left energized on a continuing basis. However, in areas with significant seasonal demand changes, select banks may be manually switched on a seasonal basis. Remote switching of capacitor banks is being used in some areas. This requires a specific capacitor bank or group of banks to have controls capable of receiving a signal and initiating a close or open operation on the capacitor switches. The computer algorithm or manually entered command originates at a remote location.

Application Considerations

- Protection
  - Overcurrent
    - Fusing
    - Inrush/Outrush Reactors
  - Overvoltage
    - Arresters
  - Unbalance
    - Relaying Alternatives
- Harmonic distortion / resonance
- Transient disturbances caused by capacitor bank switching
- Power quality aspects of capacitor bank applications

Capacitor Application Studies:

- Overvoltages associated with normal energizing.
- Open line/cable end transient voltages.
- Phase-to-phase transients at transformer terminations.
- Voltage magnification at lower voltage capacitors.
- Arrester duty requirements.
- Analysis of current limiting reactor requirements.
- System frequency response and harmonic injection.
- Impacts on sensitive customer loads.
- Analysis of ferroresonance possibilities.

Capacitor-Related Standards

- ANSI/IEEE Std. 18
  Shunt Power Capacitors
- IEEE Std. 824
  Series Capacitor Banks
- IEEE Std. 1036
  Guide for Application of Shunt Capacitor Banks
- ANSI/IEEE Std. C37.99
  Guide for Protection of Shunt Capacitor Banks
- ANSI/IEEE Std. C37.012
  Guide for Capacitor Switching Breakers
- IEEE Std. 1531
  Guide for Application and Specification of Harmonic Filters
- IEEE Std. 519
  Recommended Practice for Harmonic Control

IEEE Standards Collection - Power Capacitors, 1994 Edition
SH17228 ISBN 1-55937-416-0, July 22, 1994

Includes:

IEEE Std. 18
IEEE Std. 824 (series capacitors)
IEEE Std. 1036
ANSI/IEEE Std. C37.012
ANSI/IEEE Std. C37.99
Bibliography on Shunt Power Capacitors 1975-1991
Bibliography on Series Power Capacitors 1975-1991

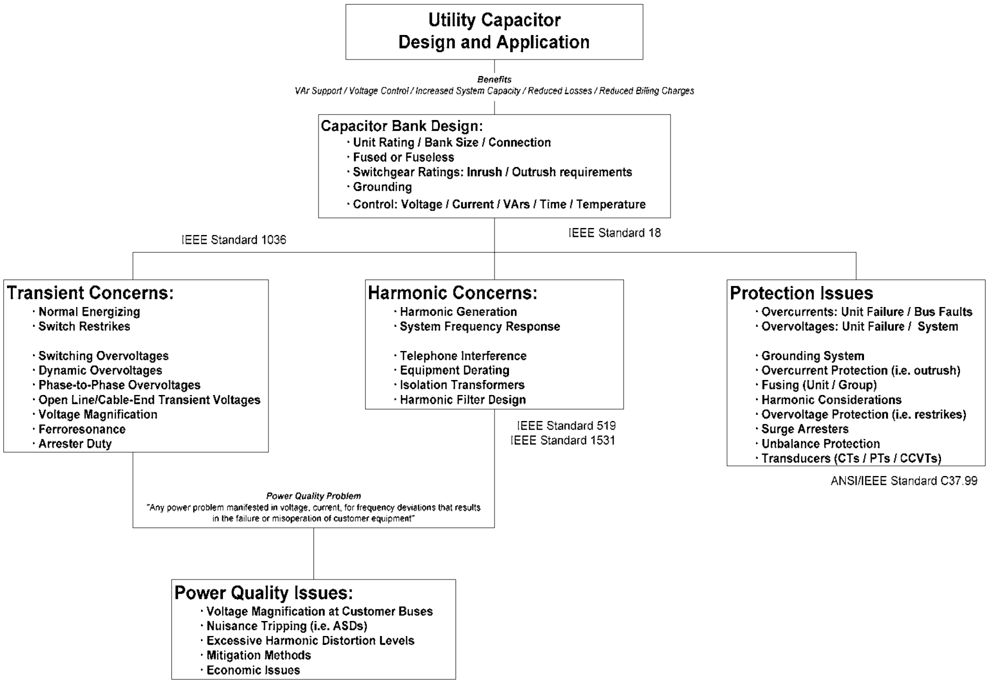
IEEE Capacitor Subcommittee

- Capacitor Subcommittee:
  - Treatment of all shunt and series capacitor matters related to economics, technical design, theoretical and experimental performance, installation, application and service operation for use in power circuits of 60 Hertz and below for the purpose of affecting the performance or operating characteristics of the circuit.
- Working Groups/Task Forces:
  - Thyristor Controlled Series Capacitor Working Group
  - Shunt Capacitor Standard Working Group
  - Series Capacitor Standard Working Group
  - Series Capacitor Application Guide Working Group
  - Shunt Capacitor Application Guide Working Group
  - Harmonic Filter Working Group
  - Capacitor Technical Paper Working Group
  - Capacitor Bibliography Working Group

Website:

http://grouper.ieee.org/groups/td/cap/

Capacitor Design and Application

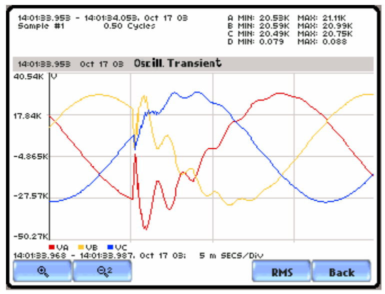


The analysis of utility transmission and distribution capacitor banks often includes measurements and computer simulations. Application considerations include capacitor bank configurations, insulation withstand levels, switchgear capabilities, grounding, overcurrent protection, overvoltage protection, energy duties of protective devices, and unbalance detection. In addition, the concern for harmonic and transients concerns for the utility and its customers should be evaluated.

There are a number of important transient related concerns when transmission and distribution voltage level capacitor banks are applied. The transmission system concerns include insulation withstand level, switchgear capabilities, energy duties of protective devices, and system harmonic considerations. The considerations must also be extended to include distribution systems and power quality evaluations (sensitive customer equipment).

Impact of Capacitor Banks on Power Quality

- Introduction to Power Quality
- Harmonic Resonance Conditions
- Voltage Magnification at Customer Buses
- Controlling Transients with Harmonic Filters
- Nuisance Tripping of Adjustable-Speed Drives (ASDs)
- Effect of Reactors (chokes) and Isolation Transformers



Power Quality is an issue driven by end users.

Power Quality is a collection of various subjects which utilities have traditionally dealt with individually:

Interruptions / Sags / Flicker / Voltage Regulation / Harmonics

Capacitor Switching / Lightning Surges / Reliability

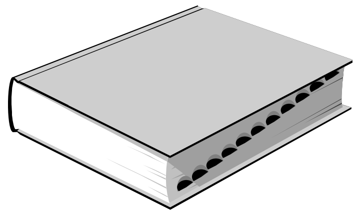
Power Quality requires looking at the whole picture.

The application of transmission and distribution system capacitor banks has long been accepted as a necessary step in the design of utility power systems. Design considerations often include traditional factors such as voltage and var support, power factor, and released capacity. However, as customer systems evolve through the use of power electronics, the capacitor bank system design of the future will also include power quality as a consideration.

What is a Power Quality Problem?

- A power quality problem is:

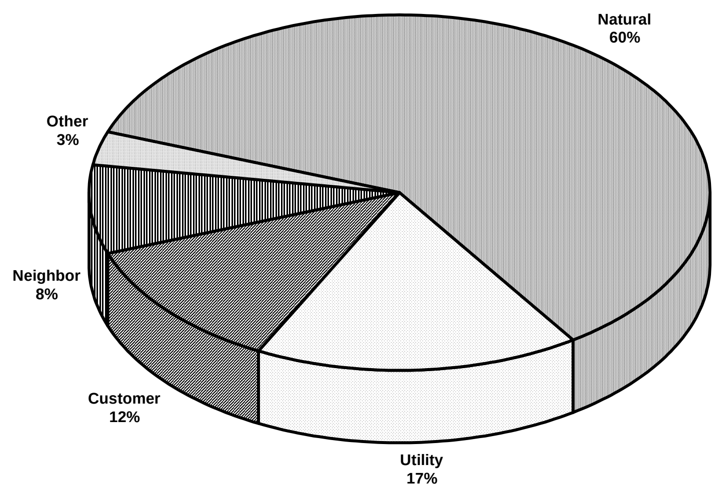
"Any occurrence manifested in voltage, current, or frequency deviations which results in failure or misoperation of end-use equipment"



The term power quality has many different meanings, perhaps as many as attempt to describe its impact on system operation. The electric utility may describe power quality as reliability and quote statistics stating that the system is 99.95% reliable. The equipment manufacturer often defines power quality as the characteristics of the power supply, which may vary drastically for different vendors. However, customers are the group ultimately affected by power quality related problems, and the best definition should include their perspective.

Whose Problem Is It?

Customer Perception

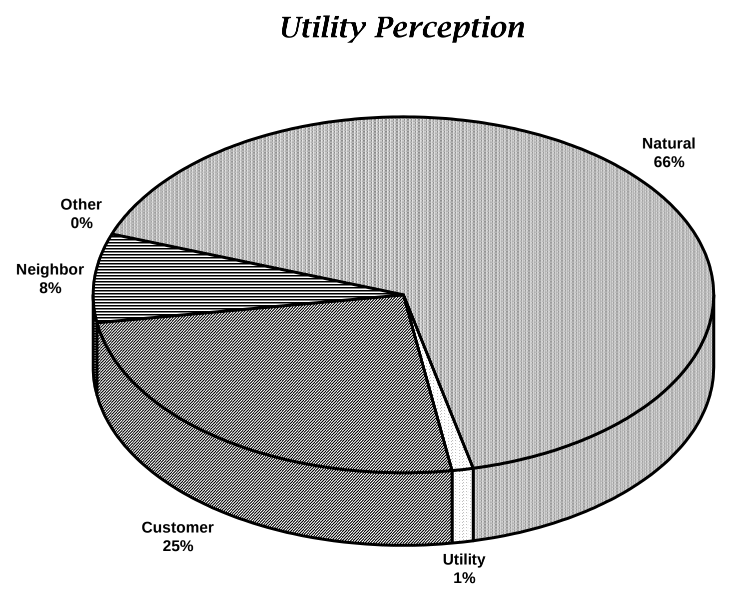


* From Georgia Power Survey

Results of one survey conducted by the Georgia Power Company in which both utility and customer personnel were polled about what causes power quality problems. While surveys of other market sectors might indicate different splits among the categories, one common theme that arises repeatedly in such surveys: the utility and customer perspectives are often much different.

There are standards for voltage and other technical criteria that may be measured, but the ultimate measure of power quality is determined by the performance and productivity of end-user equipment. If the electric power is inadequate for those needs, then “quality” is lacking. In response to this growing concern for power quality, electric utilities are developing programs that can help them respond to customer concerns. The philosophy behind these programs ranges from reactive, where the utility responds to customer complaints, to proactive, where the utility is involved in educating the customer and promoting services that can help develop solutions to power quality problems.

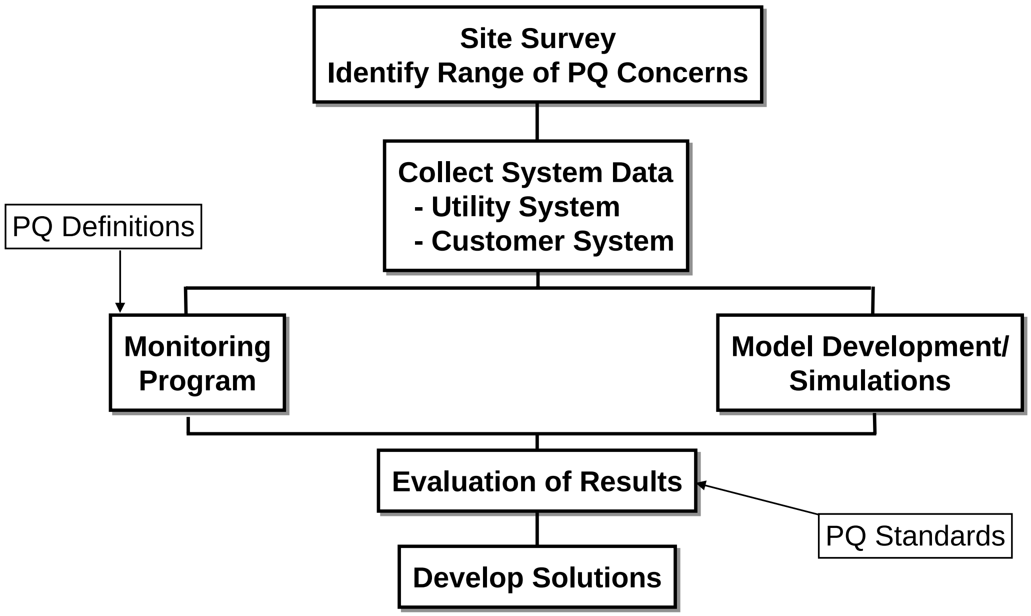
Whose Problem Is It? – continued



* From Georgia Power Survey

In addition to real power quality problems, there are also perceived power quality problems that may actually be related to hardware, software, or control system malfunctions. Electronic components can degrade over time as a result of repeated transient voltages and eventually fail due to a relatively low-magnitude event. Thus, it is sometimes difficult to associate a failure with a specific cause. Control software may not have anticipated a particular occurrence. There are standards for voltage and other technical criteria that may be measured, but the ultimate measure of power quality is determined by the performance and productivity of end-user equipment. If the electric power is inadequate for those needs, then "quality" is lacking.

PQ Investigation – Methodology



Power Quality Investigation Process:

Inventory sensitive equipment in the customer facility.

Determine equipment sensitivity to power quality variations.

Determine power quality characteristics for utility supply to facility.

Characterize power quality variations within the facility

- Caused by utility disturbances
- Caused by internal operations

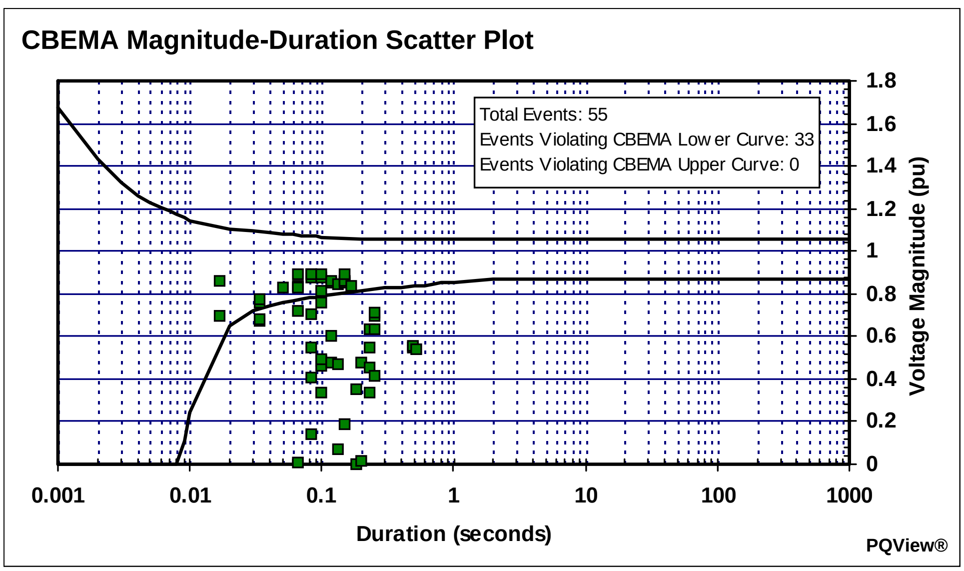
Propose range of solutions to improve equipment performance.

- Utility system power quality improvement
- Customer system power quality improvement
- Equipment design considerations

PQ Categories (IEEE Std. 1159)

	Frequency	Duration	Magnitude
Transients			
▪ Impulsive	> 5kHz	< 200µs	
▪ Oscillatory			
▪ Low Frequency	< 5kHz	0.3 – 50ms	0-4 pu
▪ Medium Frequency	5 - 500kHz	20µs	0-8 pu
▪ High Frequency	> 500kHz	5µs	0-4 pu
Short Duration Variations			
▪ Voltage Sags			
▪ Instantaneous		0.5 - 30 cycles	0.1-0.9 pu
▪ Momentary		30 cycles - 3 sec	0.1-0.9 pu
▪ Temporary		3 sec - 1 min	0.1-0.9 pu
▪ Voltage Swells			
▪ Instantaneous		0.5 - 30 cycles	1.1-1.8 pu
▪ Momentary		30 cycles - 3 sec	1.1-1.4 pu
▪ Temporary		3 sec - 1 min	1.1-1.2 pu

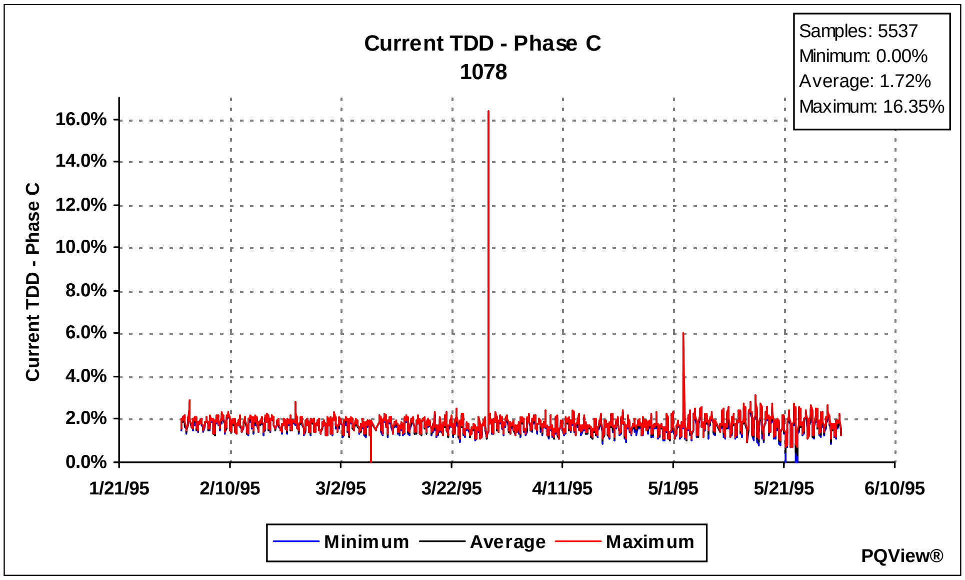
Example display of power quality voltage variation measurement data:



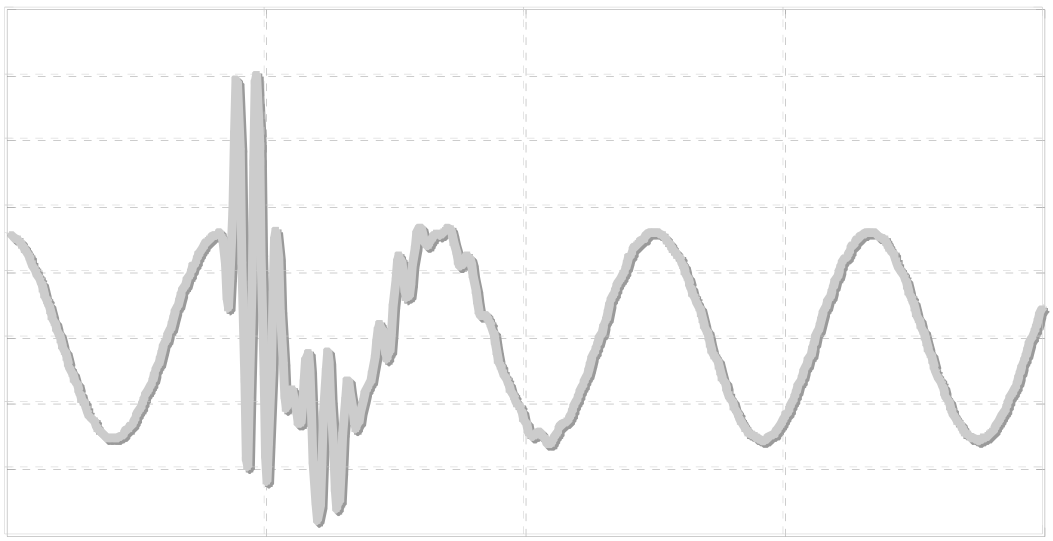
Power Quality Categories – continued

	Frequency	Duration	Magnitude
Long Duration Variations			
▪ Undervoltages		> 1 min	0.8-0.9 pu
▪ Overvoltages		> 1 min	1.0-1.2 pu
Interruptions			
▪ Momentary		< 3 sec	< 0.1 pu
▪ Temporary		3 sec - 1 min	< 0.1 pu
▪ Sustained (Outage)		> 1 min	0.0 pu
Waveform Distortion (Harmonics)			
▪ Voltage	0-50th harmonic	steady state	0-20%
▪ Current	0-50th harmonic	steady state	0-20%
Voltage Fluctuations (Flicker)	< 25 Hz	intermittent	0.1-7%
Voltage Notching	20-200kHz	steady state	

Example display of power quality waveform distortion measurement data:



CAPACITOR BANK DESIGN AND PROTECTION



Capacitor Bank Design and Protection

- Capacitor bank equipment ratings
- Capacitor bank connections
  - Grounded vs. ungrounded
- Capacitor bank sizing
- Locations for capacitor banks
- Calculations
  - Full load current
  - Impedance
  - etc.

Refer to IEEE Std. C37.99 (capacitor bank protection) and IEEE Std. C37.48 (external capacitor fuses) for information regarding the protection of shunt power capacitor banks.

Occasional failures should be anticipated and a protective scheme should be provided that will reliably detect and clear a faulted capacitor before

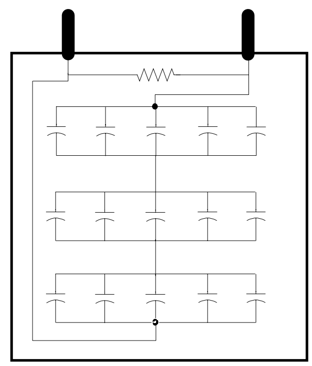
a) A major fault develops that jeopardizes the circuit.

b) Gas pressure inside the faulted capacitor increases to the point where it becomes hazardous to personnel, adjacent capacitors, or other equipment

c) The remaining capacitors are damaged by overvoltage (in ungrounded Y banks or in banks with more than one series group per phase).

Typical Capacitor Unit Configuration

- Individual pack
- Series group of parallel-connected packs
- Internal discharge resistor
- Case



Typical Capacitor Unit

Capacitor ratings are based on maximum ambients with an allowance for heat dissipation by radiation and convection. The arrangement and mounting of capacitors and the conditions of installations will affect the heat dissipation and thereby limit the ambient temperature in which capacitors may be operated. Capacitors and capacitor equipment operating outdoors in direct sunlight and with unrestricted ventilation will normally operate with lower temperature rise than those operating indoors in still air.

The life of a capacitor is shortened by overstressing, overheating, chemical change, physical damage, or repeated temperature changes. Life to 90% survival should exceed 20 years when capacitors are applied according to the guidelines of this standard application guide. Shunt capacitors cause a voltage rise at the point where they are located and are therefore more likely to operate at overvoltages than other types of equipment.

Typical Voltage & Reactive Power Ratings

Volts, rms (terminal-to-terminal)	kvar	Number of phases	BIL kV
216	5, 7 1/2, 13 1/3, 20, and 25	1 and 3	30
240	2.5, 5, 7 1/2, 10, 15, 20, 25, and 50	1 and 3	30
480, 600	5, 10, 15, 20, 25, 35, 50, 60, and 100	1 and 3	30
2400	50, 100, 150, 200, 300 and 400	1 and 3	75, 95, 125, 150 and 200
2770	50, 100, 150, 200, 300, 400 and 500	1 and 3	75, 95, 125, 150 and 200
4160, 4800	50, 100, 150 200,300, 400, 500, 600, 700 and 800	1 and 3	75, 95, 125, 150 and 200
6640,7200,7620,7960, 8320, 9540, 9960, 11 400, 12 470, 13 280, 13 800, 14 400	50, 100, 150, 200, 300, 400, 500, 600, 700 and 800	1	95, 125, 150 and 200
15 125	50, 100, 150, 200, 300, 400, 500, 600, 700 and 800	1	125, 150 and 200
19 920	100, 150, 200, 300, 400, 500, 600, 700 and 800	1	125, 150 and 200
20 800, 21 600, 22 800, 23 800, 24940	100, 150, 200, 300, 400, 500, 600, 700 and 800	1	150 and 200

Capacitors may be used on circuits of higher voltage than the terminal-to-case insulation class, provided the cases are supported on external insulation suitable for the circuit voltage and provided the terminal-to-terminal voltage limits are not exceeded.

ref: IEEE Std. 18

Power capacitors are designed for operation at the device's rated nominal frequency of either 50 Hz or 60 Hz. When capacitors are operated at frequencies lower than rated, both the reactive power and the capacitive current are reduced in direct proportion to the operating frequency as shown in the following equations:

$$k\,\text{var}_{OP} = k\,\text{var}_{R}\left(\frac{f_{OP}}{f_{R}}\right)$$

$$I_{OP} = I_{NOM}\left(\frac{f_{OP}}{f_{R}}\right)$$

Capacitor Unit/Bank Ratings

- Nameplate information includes V_{rms}, BIL, kVAr, and frequency (ref: IEEE Std. 18):
  - 110% of rated rms voltage
  - 120% of rated crest voltage, i.e. crest voltage not exceeding 1.2 x (square root of two) x rated rms voltage, including harmonics, but excluding transients
  - 135% of nominal rms current based on rated kVAr and voltage
  - 135% of rated kVAr

Tolerance:
-0% to +10% of rated capacitance

Common Unit Ratings:

50,100,150,200,300,400 kVAr

Internal Discharge (down to 50 V)

< 600 Volts - 1 min

> 600 Volts - 5 min

Unit ratings:

Tolerances

Discharge voltage

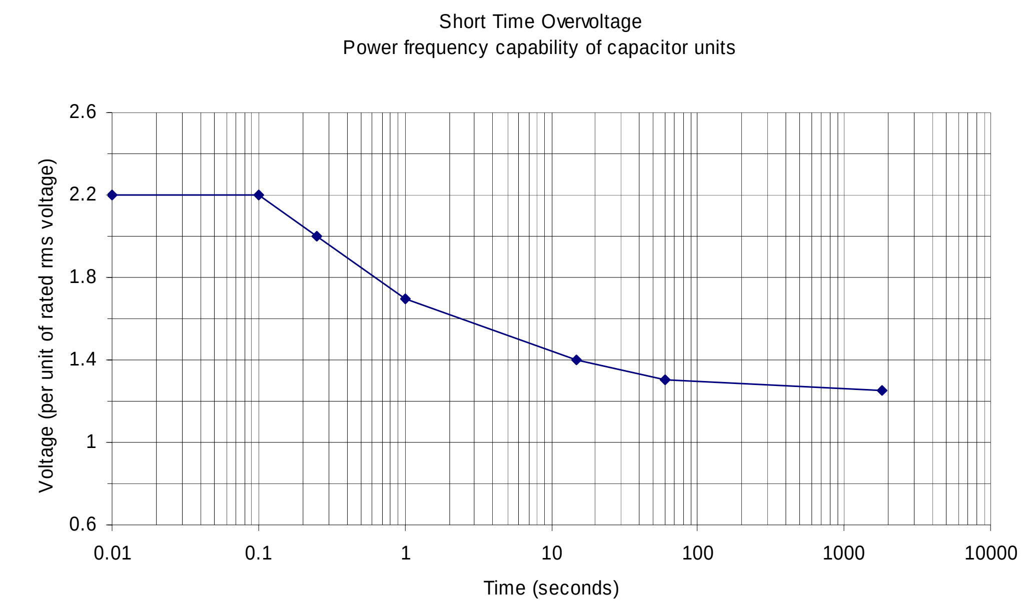
Short duration overvoltages:

Time to failure

Short duration overvoltages

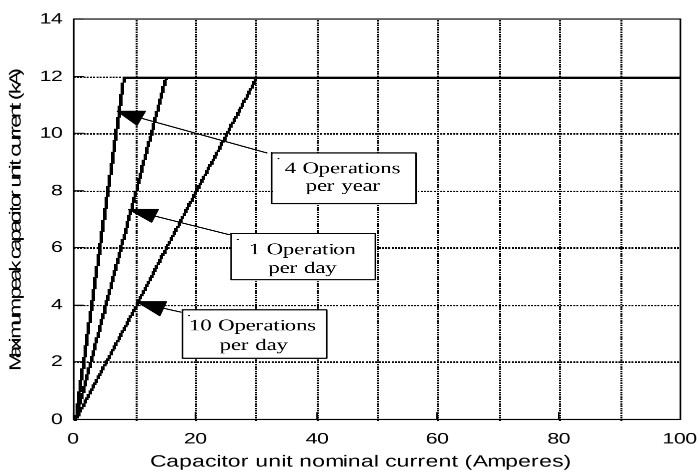
Standard Ratings:
Voltage, RMS (terminal-to-terminal)
Terminal-to-case insulation class
Reactive power
Number of phases
Frequency

Momentary Power Frequency Overvoltage



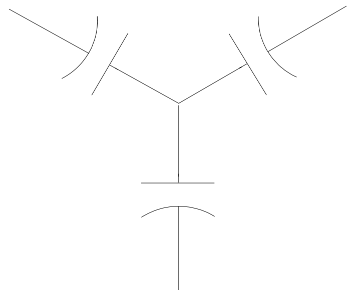
ref: IEEE Std. 1036

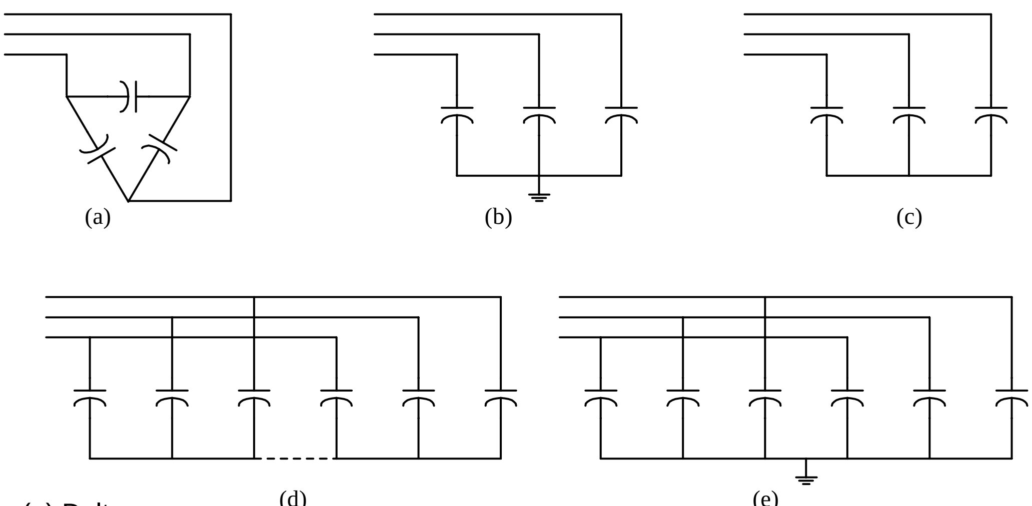
Transient overcurrents:



Capacitor Bank Connections

- Grounded Wye
  - low impedance path for lightning current (also triplen harmonics)
- Ungrounded Wye
  - avoid fuses for faults ($I_f = 3*I_{FL}$)
- Grounded Double-Wye
- Ungrounded Double-Wye
- Delta
  - generally distribution, industrial (single series group), e.g., 2400V

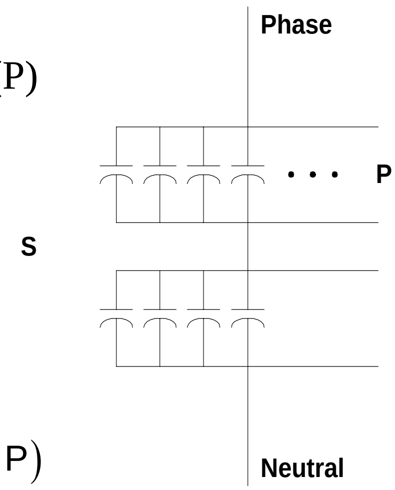




(a) Delta
(b) Grounded Wye
(c) Ungrounded Wye
(d) Ungrounded Double Wye -Neutrals (may or may not be tied)
(e) Grounded, Double Wye

Typical Capacitor Bank Configuration

- Number of phases
- Number of series groups (S)
- Number of parallel units in group (P)
- Unit ratings ($kVAr_{unit}$ & kV_{unit})
- Neutral connection



Bank Rating:

$$Rating_{bank_{3\phi}} = 3 * (kVAr_{unit} * S * P)$$

Example:

300kVAr units

13 parallel units per group

10 series groups

$$Rating_{bank_{3\phi}} = 3 * (300kVAr * 10 * 13) = 117MVAr$$

Capacitor Bank Grounding

- Severity of recovery voltage important consideration
  - (generally grounded > 100kV)
- Concern for high frequency current flowing in ground grid
- Single point grounding
  - All capacitor bank (same voltage level) neutrals are tied together and connected to the substation grid at only one point. This method eliminates high frequency currents from flowing in the grid during back-to-back switching
- Peninsula grounding
  - Capacitor bank neutrals and equipment grounds tied together and connected to grid at one point, neutral leads routed beneath phase conductors

One of the main advantages associated with neutral grounding concerns the severity of the recovery voltage across the first pole to clear of a switch interrupting the charging current of a capacitor bank. The recovery voltage across the first pole to open consists of trapped charges on the capacitors and the variation in the 60 Hz system voltage.

Due to system parameters and capacitor bank rating, the recovery voltage can be approximately 2.0 per-unit when the bank is grounded. On an ungrounded bank, the magnitude of the first peak of the recovery voltage can be high as 3.0 per-unit.

Pro's and Con's of Capacitor Grounding

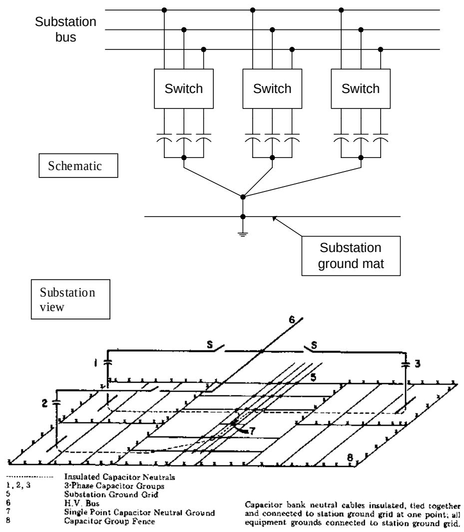
- The advantages of grounding include:
  - Phases are isolated from each other. When single phase sectionalizing (fusing or reclosing) is used on a multigrounded system, grounding the neutral of the capacitor bank avoids problems associated with disconnected phases being energized through an ungrounded capacitor bank.
  - Initial cost of the bank may be lower since the neutral does not have to be insulated from ground at full system BIL, as in the case with floating neutral arrangements.
  - Capacitor switch recovery voltages are reduced.
  - When compared to ungrounded wye, no overvoltage on unfaulted units during fuse operation for a faulted capacitor on another phase.
- The disadvantages of the grounded-wye configuration include:
  - Grounded neutral may draw zero-sequence harmonic currents and cause telephone interference.
  - The grounded-wye arrangement provides a low-impedance fault path to ground and may require resetting of ground relays on the system. This is one reason why grounded-wye banks are not generally applied to ungrounded systems.
  - High inrush currents may occur in station grounds and structures.

It is generally recommended that the neutral of capacitor banks be grounded only to systems that are effectively grounded.

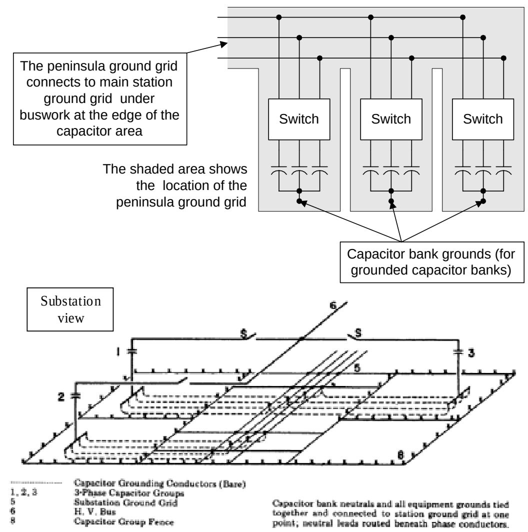
Where two or more grounded-wye capacitor banks are at the same location, the neutrals should be directly connected, with a single connection to ground. Improper grounding can result in neutral current transformer, voltage transformer, or control cable failures. If single point grounding is used, there will be substantial voltages (tens of kV) between the ends of the neutral bus and the single point ground during switching. Primary to secondary insulation of neutral current transformers will be subjected to this voltage, increasing the probability of failure. Two bushing voltage transformers should be used with the primary connected to the capacitor bank neutral. With peninsula grounding, all equipment at the neutral tends to rise to the same potential. Peninsula grounding, coordinated with control cable shielding and grounding, will hold common mode voltages appearing on control cables to safe levels. Single point grounding and peninsula grounding are not compatible.

Single Point and Peninsula Grounding

Single Point Grounding



Peninsula Grounding



ref: IEEE Std. 1036

With single point grounding, the neutrals of all capacitor banks of a given voltage are connected together with insulated cable, or an isolated bus, and tied to the substation ground grid at only one point. This arrangement prevents high frequency currents that flow between banks during back-to-back switching from flowing in the ground grid. In the event of a nearby ground fault, however, this arrangement does not eliminate those high frequency currents that flow back into the power system via the substation ground grid.

With peninsula grounding, the ground grid in the capacitor area is built under the capacitor banks and buswork, in a form resembling a series of peninsulas. One or more ground grid conductor(s) is carried underneath the capacitor rack of each phase of each group and tied to the main station ground grid at one point at the edge of the capacitor area. All capacitor bank neutral connections are made to this isolated peninsula ground grid conductor(s) only.

Capacitor Bank Sizing

- Wye-Connected Capacitor Bank - Number of Series Groups:

VLL	VLN	Available Capacitor Unit Voltages (kV)												
kV	**kV**	**21.6**	**19.92**	**14.4**	**13.8**	**13.28**	**12.47**	**9.96**	**9.54**	**8.32**	**7.96**	**7.62**	**7.2**	**6.64**
500.0	288.68	14	15	20	21	22		29	30	35	36	38		
345.0	199.19		10			15	16	20	21	24	25	27		
230.0	132.79					10			14	16	17	18		20
161.0	92.95					7							13	14
138.0	79.67		4	6	6	6		8			10		11	12
115.0	66.40					5			7	8	9	9		10
69.0	39.84		2		3	3		4			5			6
46.0	26.56					2								4
34.5	19.92		1					2						3
24.9	14.38			1									2	
23.9	13.80				1									
23.0	13.28					1								2
14.4	8.31									1				
13.8	7.97										1			
13.2	7.62											1		
12.5	7.20												1	

Use of capacitors with the highest possible voltage rating will result in a capacitor bank with the fewest number of series groups. This generally provides the simplest and most economical rack structure and the greatest sensitivity for unbalance detection schemes.

Capacitor Bank Sizing – continued

- Maximum bank rating influenced by:
  - change in system voltage with bank in service
  - switchgear continuous current limitations (125% - 135%)

$$\Delta V = \left(\frac{MVAr}{MVA_{sc}} \right) * 100\%$$

- Minimum bank rating influenced by:
  - capacitor bank unbalance considerations
  - fuse coordination

Minimum recommended number of units to limit voltage to 110% with one unit out:

Series Groups	Wye-Gnd	Ungnd-Wye	Split Ungnd-Wye
1	-	4	2
2	6	8	7
3	8	9	8
4	9	10	9
5	9	10	10
6	10	10	10
7	10	10	10
8	10	11	10
9	10	11	10
10	10	11	11

Fuseless Capacitor Banks – Introduction

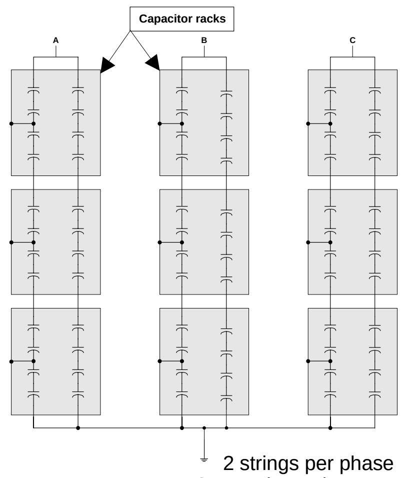
- A capacitor bank without any fuses, internal or external, protecting individual capacitor units which is constructed of (parallel) strings of capacitor units.
- Use of polypropylene films significantly reduces likelihood of gassing and case rupture.
- Principal purpose of fuse, in present data design, is to disconnect a faulted unit so the installation may remain in service.
- Testing that occurred on fuseless design:
  - Continuous current
  - Capacitor switching
  - Capacitor losses

ref: Fuseless Capacitor Banks - ABB (Harder)

A fuseless bank is not simply removing fuses from conventional fused capacitor banks, but a completely different bank arrangement that does not use fuses. When an all film capacitor has a dielectric short, the film burns away, resulting in a weld between the foils. This type of short creates a low resistant short, which should not generate large amounts of heat or gas, as long as the current is limited through the short, allowing the capacitor to continue in operation indefinitely. Fuseless bank designs were not commonly used with paper/film or all paper capacitors because dielectric shorts were more likely to have localized heating and gassing with an increased probability of case rupture.

Fuseless Capacitor Banks – continued

- A fuseless capacitor bank is arranged with individual capacitors in series (called a "series string") connected between the phase terminals and ground or neutral.
- Protection considerations:
  - Protection schemes / time delays
  - Locating a defective unit
- Design guidelines:
  - String current
  - Maximum voltage to frame
  - Establishing frame potential
  - Unit rating (kV / kVAr)
  - Protection
  - Overvoltage protection (MOVs)



2 strings per phase
12 capacitor units per string

The sum of the individual unit voltages in a string should equal or exceed the normal phase to ground or phase to neutral voltage of the bank. The desired 3-phase kVAr of the capacitor bank is accomplished by putting series strings of capacitor units in parallel.

Once the desired phase to ground or phase to neutral rating of the capacitor bank is determined then a unit voltage rating can be chosen to determine the number of units in the series string.

In determining the kVAr rating of the capacitor units keep in mind the continuous current capability of the available capacitor units. The string current should be limited to this value, as well as the value that is not likely to create gassing through the fault (consult the manufacturer). A good starting point in the design of a bank is to divide the total phase current, calculated from the desired 3-phase kVAr rating of the bank, by the continuous current capability of the unit to find the minimum number of strings required.

Fuseless Capacitor Banks – continued

- Field experience:
  - All-film capacitors that short remain shorted without arcing or case rupture.
  - Fuses will not always operate with a short in a capacitor.
  - Observing the number of blown fuses in a capacitor bank may not be a reliable indicator of the bank condition.
- Characteristics of fuseless capacitor banks:
  - Simplicity - no requirement for fuse rails and insulators, fuses and flippers (and fuse clearance space).
  - Protection (animal and contamination)
  - Size (about 1/3 of volume for standard design)
  - Easier field assembly
  - Losses / minimum bank rating / parallel energy

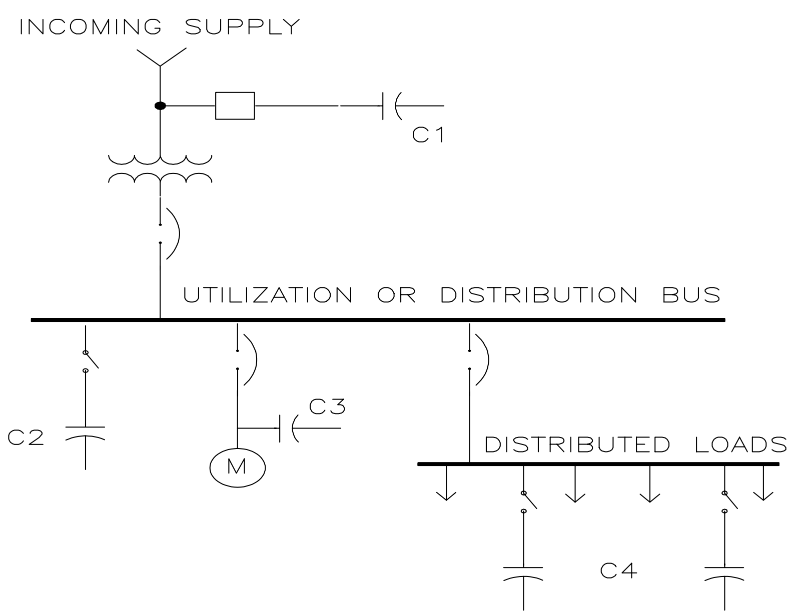
Fuseless capacitors usually have two bushings in order to keep the individual strings isolated from each other. A standard externally fused unit may not have adequate bushings or internal case insulation for a fuseless application. The BIL of the bushings and the internal insulation of the unit is determined by the maximum voltage to the rack. All of the units in a series string will probably not be in the same rack, but will be connected together in different racks. These things should be considered in determining the stacking arrangement of the capacitor bank.

The higher external and internal insulation requirements for the units in the example above might not be preferred, therefore requiring consideration of another unit voltage rating or a different stacking arrangement. Changing the voltage rating on the unit could require a change in the kVAr rating of the unit or the number of series strings in the bank. Changing the stacking arrangement to only have two units from the same series string in the same rack would make the voltage from the rack to the outside bushings only 9.96 kV, equal to the rating of the units, and would allow use of 9.96-kV units with bushings and internal insulation rated for 9.96-kV and 95-kV BIL.

Location of Capacitor Banks

- Distribution systems:
  - Fixed capacitor banks are rated for minimum load conditions
  - Switched capacitor banks are designed for load levels above the minimum condition up to peak load

- Rules of thumb for capacitor location:
  - For uniformly distributed loads: capacitor should be placed 2/3 of the distance from the substation
  - For uniformly decreasing loads: capacitor should be placed 1/2 of the distance from the substation
  - For maximum voltage rise: capacitor should be placed near the end of the feeder



Capacitor Bank Calculations

- Rated capacitor unit current:

$$I_{unit_{rated}} = \frac{kVAr_{unit_{rated}}}{kV_{unit_{rated}}}$$

- Adjusted unit rating:

$$kVAr_{unit_{actual}} = kVAr_{unit_{rated}} * \left(\frac{kV_{unit_{applied}}}{kV_{unit_{rated}}} \right)^2$$

Example:

400 kVAr, 21.6 kV Capacitor Unit:

$$I_{can_{rated}} = \frac{400kVAr}{21.6kV} = 18.5Amps$$

Applied on a 34.5 bus (wye-ground)

$$kVAr_{can_{actual}} = 400 * \left(\frac{19.92}{21.60} \right)^2 = 340kVAr$$

Capacitor Bank Calculations – continued

- Rated capacitor bank current:

$$I_{bank_{rated}} = \frac{MVAr_{rated}}{\sqrt{3}\left(\sqrt{3} * S * kV_{can_{rated}}\right)}$$

- Adjusted bank rating:

$$MVAr_{bank_{actual}} = MVAr_{rated} * \frac{kV^2{}_{operating}}{\left(S * kV_{can_{rated}}\right)^2}$$

where:
S = number of series groups

Example:

117 MVAr, 14.4 kV Unit, 10 Series Groups

$$I_{bank_{rated}} = \frac{117E6}{\sqrt{3}\left(\sqrt{3} * 10 * 14.4E3\right)} = 270.8 Amps$$

Applied on a 230kV bus (wye-ground)

$$MVAr_{bank_{actual}} = 117 * \frac{\left(230/\sqrt{3}\right)^2}{\left(10 * 14.4\right)^2} = 99.5 MVAr$$

Capacitor Bank Calculations – continued

- Capacitive reactance (equivalent wye):

$$X_{c_{ratedY}} = \frac{kV^2_{rated}}{MVAr_{rated}} = \frac{\left(\sqrt{3} * S * kV_{can_{rated}}\right)^2}{MVAr_{rated}}$$

- Capacitance (equivalent wye):

$$C_Y = \frac{1}{\omega X_C} = \frac{1}{\left(2 * \pi * f_{sys}\right) * X_C}$$

Example:

117 MVAr, 14.4 kV Unit, 10 Series Groups

$$X_{c_{ratedY}} = \frac{kV^2_{rated}}{MVAr_{rated}} = \frac{\left(\sqrt{3} * 10 * 14.4\right)^2}{117} = 531.7\Omega$$

$$C_Y = \frac{1}{\omega X_C} = \frac{1}{(2 * \pi * 60) * 531.7} = 4.99\mu F$$

Summary of Protection Methods

Condition	Type of Protection and Prevention Methods	Remarks
Bus faults	Breaker with overcurrent relays, fuses	Conventional methods apply
System surge voltages	Surge arresters	Grounded bank reduces OVs, check arrester rating
Overcurrents due to unit failure	Cap unit fusing / expulsion or current limiting	Coordination provided by manufacturer
Continuous unit overvoltages	Unbalance protection, fuse inspection	Some limitations, many options
Discharge currents	Fusing (CL), reactors, proper design	Limit # of parallel units
Inrush currents	Reactors	Back-to-back switching
Rack faults	Relaying / unbalance	Relay speed to limit damage

[bank vs. system protection]

- Overcurrents due to capacitor bank bus faults
- System surge voltages
- Overcurrents due to individual capacitor unit failure
- Continuous capacitor unit overvoltages
- Discharge currents from parallel capacitor units
- Inrush currents due to switching
- Arc-over within the capacitor bank

Often the protection of capacitor banks includes the following components:

- Individual capacitor unit fusing
- Unbalance relaying
- Overcurrent relaying
- Surge arresters
- Phase voltage relays
- Periodic visual inspection

Individual Capacitor Unit Fusing

- First line of protection - designed to operate in response to the failure of a single capacitor unit.
- Needs to operate fast enough to prevent case rupture and damage to adjacent units.
- Energy discharge into faulted unit an important quantity (this limits the number of parallel units in a group).
- Maximum continuous current - including harmonics, tolerances, and overvoltages.
- Needs to withstand transient outrush currents.

The function of the capacitor fuse is to sense and indicate the failure of a single capacitor unit and remove the unit from service fast enough to prevent case rupture and damage to other units. At the same time, it is desirable that the fuse withstand the normal capacitor bank conditions without spurious operations. To withstand normal conditions, it is desirable that the fuse be rated to withstand the following conditions:

a) Maximum continuous current. This includes allowances for harmonics, capacitor unit tolerance, and overvoltage.

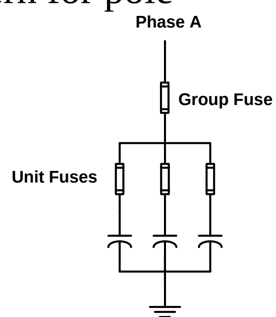
b) Switching inrush current. This is a concern for back-to-back capacitor switching. Current-limiting reactors may be used to change the magnitude and frequency of the inrush current to an acceptable level, while switch closing resistors may be used to damp the current to acceptable levels.

c) Lightning surge currents. This is more of a concern for pole-mounted racks and is seldom a problem for substation banks.

d) Discharge current into a failing unit. When a capacitor unit fails, i.e. shorts, the adjacent capacitors discharge into it.

Group Fusing

- Group fuses are generally used to protect pole mounted distribution capacitor banks.
- Maximum continuous current - including harmonics, tolerances, and overvoltages (125% - 135% of I_{FL}).
- Switching inrush current - back-to-back switching most important (I^2t is important quantity).
- Lightning surge currents - more of a concern for pole mounted banks.
- Rated fuse voltage:
  - phase-to-phase for ungrounded banks
  - phase-to-ground for grounded banks



The function of the group fuse is to detect the escalating failure of a single capacitor and remove the capacitor group from service fast enough to prevent case rupture and damage to other units. At the same time, it is desirable that the group fuse withstand the normal capacitor bank operating conditions without spurious fuse operations. To withstand normal conditions, it is necessary that the group fuse be rated to withstand the following conditions:

a) Continuous current. This includes consideration for a harmonic component, capacitance tolerance (maximum of +10% to + 15%), and overvoltage (+10%). Historically, the continuous current capability of the fuse has been a minimum of 125% to 135% of the capacitor nominal current.

b) Switching inrush current.

c) Surge current.

d) Rated fuse voltage.

Protection for Rack Faults

- Begins as an arc-over of a single series group.
- Low fault current - unbalance protection needed to detect condition.
- If the protection fails to operate, the fault may cause excessive damage to the capacitor bank, including blown fuses and ruptured capacitor units.
- Instantaneous overcurrent relays are not effective for rack faults.
- Most effective protection is fast timing of an unbalance protection scheme (e.g., 0.05 seconds).

ref: IEEE Std. C37.99

One series group shorted:

- Ungrounded

$$V_n = \frac{1}{3S-2} * V_{LG}$$

- Grounded

$$I_n = \frac{1}{S-1} * I_\phi$$

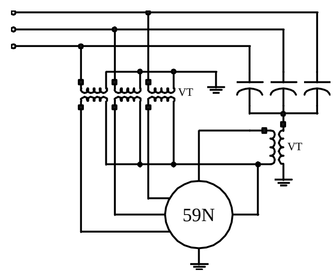
where S = number of series groups

V_{LG} = system phase-to-ground voltage

I_ϕ = full load phase current

Unbalance Protection Schemes

- Removal of a failed unit results in an increase in voltage across the remaining units within the group.
- Failure to remove the bank from service may result in:
  - Excessive damage to the capacitor bank
  - Adverse system effects
  - Spread of damage to adjacent equipment
  - Possible undesirable discharge of dielectric liquid
- Factors include:
  - Inherent unbalance
  - System voltage unbalance
  - Harmonic voltages / currents
  - Sensing device tolerances, etc.



C37.99....

[capacitor unbalance protection]

Unbalance protection normally provides the primary protection against arcing faults within a capacitor bank and other abnormalities that may damage capacitor units and/or fuses.

Most installations will require an individual engineering analysis to determine the most appropriate protection scheme. Selection of the bank configuration and design should include an analysis of the amount of inherent unbalance that can be expected and tolerated by the protection.

Unbalance Protection Schemes – continued

- Unbalance relay should coordinate with the unit fuses.
- Alarm at loss of one unit and trip @ voltage > 110%.
- Time delay short enough to prevent internal damage.
- Time delay long enough to prevent false tripping due to inrush current, non-simultaneous closing (~0.5 sec).
- Protect against transient voltages on control wiring.
- Immune to harmonic voltages / currents.
- Lock-out protection to prevent automatic reclosing.
- System / internal unbalance compensation.

C37.99....

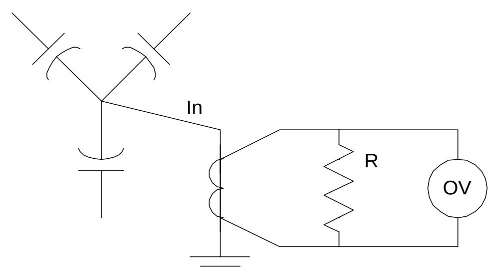
[unbalance relay methods]

All neutral unbalance schemes detect an unbalance in the three phases. Overvoltage caused by the loss of an equal number of capacitor units in one or more groups in each phase will not be detected. In practice, this is not a significant limitation.

In an internally fused capacitor bank, the unbalance detection gives an indication of the total number of failed capacitor elements. The actual number of failed elements will be determined by the settings of the relay.

Neutral Current Method

- Unbalance in bank (failed unit) will cause a neutral current (I_n) to flow.
- Current transformer loaded with a resistance (typically 10-25 ohms).
- Voltage relay (with harmonic filter) used - alarm and trip should be available.
- Concern for CT failure due to inrush (energizing) currents.



$$\%I_n = \left[\frac{100F}{S(P-F)+F}\right]$$ (neutral current)

Where:

S = number of series groups

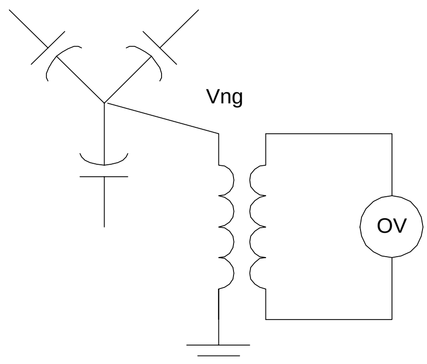
P = number of units in group

F = number of failed units

$$\%V = \left[\frac{100F}{S(P-F)+F}\right] * \left[\frac{V_{terminal}}{S * V_{unit}}\right]$$ (voltage on remaining units)

Neutral Voltage Method

- Unbalance in bank (failed unit) will cause a neutral voltage (V_{ng}) to shift.
- Voltage relay (with harmonic filter) used - alarm and trip should be available.
- Concern for PT overvoltages during switching (rated for system voltage).
- PT can be replaced by a capacitor string.



$$\%V_{ng} = \left[\frac{100F}{3S(P-F)+2F}\right]$$ (neutral-to-ground voltage)

Where:

S = number of series groups

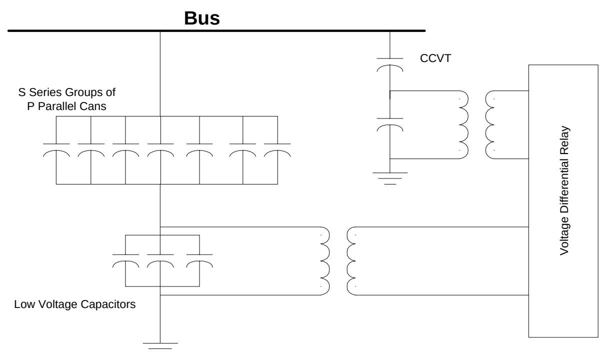
P = number of units in group

F = number of failed units

$$\%V = \left[\frac{300F}{3S(P-F)+2F}\right] * \left[\frac{V_{terminal}}{S * V_{unit}}\right]$$ (voltage on remaining units)

Voltage Differential Method

- Unbalance in bank (failed unit) will cause a voltage difference between the low voltage capacitors and the bus.
- Compensation for system unbalance.
- Voltage relay used - alarm and trip should be available.



Fuseless capacitor bank protection :

Bank protection works best if all units have the same rating. Mixing capacitors of different ratings in a bank will usually result in more complex considerations in setting the unbalance protection. Each individual capacitor unit consists of many elements connected in series and parallel within the unit to give the proper voltage and kVAr rating. If one of these capacitor elements fails, the capacitor bank may normally stay in service. A puncture or failure of one capacitor element results in a weld between the aluminum foils in that section. This is a stable weld which unit carry more than the rated current of the string, along with capacitor switching transients, without causing gassing or swelling of the unit. The losses in the weld are low so that localized heating does not lead to deterioration in the vicinity of the weld. As a result, a shorted element may be left in service indefinitely.

Capacitor Bank Switching Devices

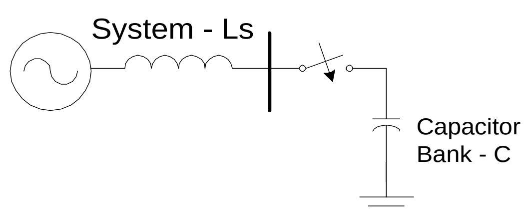
- Capacitor switching requires special attention due to the severe equipment duties.
- Devices used for capacitor switching include:
  - Circuit breakers (SF_6, vacuum, oil, air)
  - Circuit switchers (SF_6)
  - Interrupter switches (oil, SF_6, vacuum, Thyristor)
- References: IEEE Std. C37.06 and Std. C37.012.
- Current ratings should include effects of system overvoltages, capacitor unit tolerances, and harmonics.
- Transient inrush and outrush currents should also be evaluated.
- Recovery voltages, including duties during restrikes, should be considered.

Switchgear applied to a capacitor bank should be rated for that specific duty. The key considerations are maximum service voltage, available short circuit current, maximum continuous capacitive current, transient inrush current during energization, nominal system voltage, and transient recovery voltage during de-energization. These parameters are defined in more detail for circuit breakers in IEEE Std. C37.06 and IEEE Std. C37.012.

These standards suggest using a continuous current rating for the breaker that is 1.25 times the nominal capacitor current at rated capacitor voltage for ungrounded neutral operation and 1.35 times the nominal current for grounded neutral operation. Inrush current duties are defined in terms of peak magnitude and frequency.

Inrush Control

- Energizing of a capacitor bank results in a transient inrush current.
- Magnitude and frequency of inrush current is a function of:
  - applied voltage
  - source inductance and capacitor bank capacitance
  - inrush reactor (or pre-insertion reactor/resistor rating)
- Circuit breaker (switch) inrush capability, I_{pk} and f should be evaluated with respect to IEEE Std. C37.06.

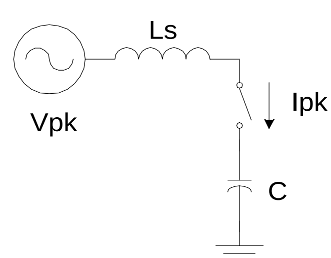


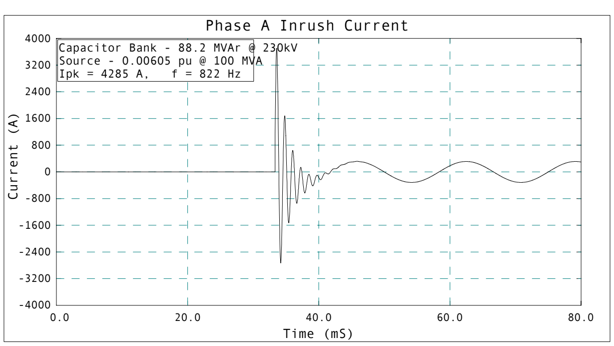
Where:

Vpk is the peak line-to-ground system voltage

Ls is the system inductance

C is the capacitance of the bank



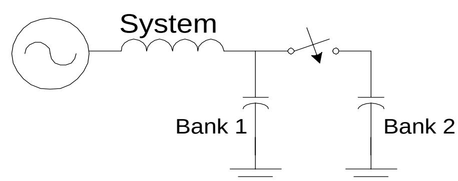


$$I_{pk} = \frac{Vpk}{\sqrt{\left(L_s/C\right)}}$$

$$f = \frac{1}{2\pi\sqrt{(L_s C)}}$$

Back-to-Back Switching

- Energizing a shunt capacitor bank, with an adjacent bank already in service, can result in high-magnitude, high-frequency inrush currents.
- This operation is known as “back-to-back switching.”
- Reactors or pre-insertion devices may be required to limit the inrush current during energization of the second bank.
- Circuit breaker (switch) inrush capability, I_{pk} and f should be evaluated with respect to IEEE Std. C37.06.



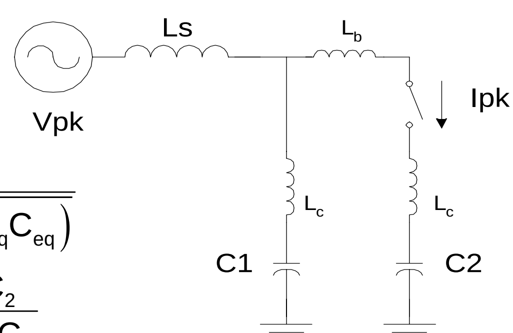
Where:

V_o is the initial voltage on bank number 1
L_b is the bus inductance between banks
L_c is the self inductance of capacitor bank
C_1 is the capacitance of the first bank
C_2 is the capacitance of the second bank

$$I_{pk} = \frac{Vo}{Z_s}$$

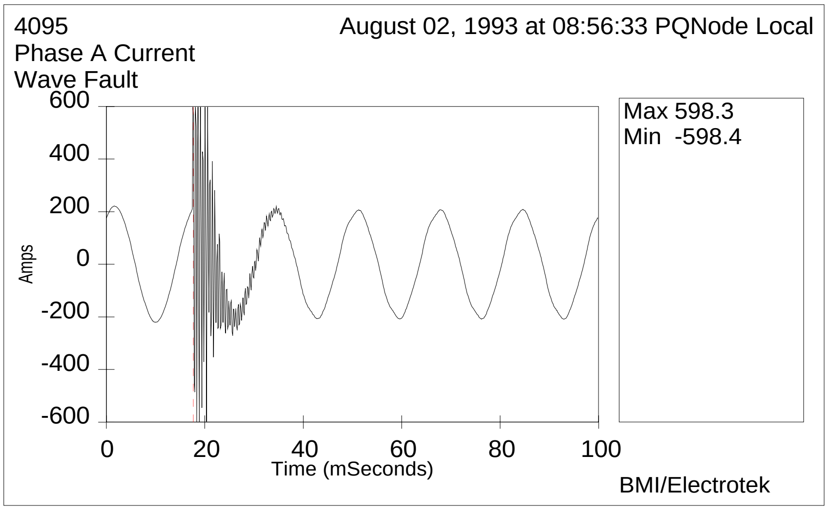
$$Z_s = \sqrt{\frac{L_{eq}}{C_{eq}}} \qquad f = \frac{1}{2\pi\sqrt{\left(L_{eq}C_{eq}\right)}}$$

$$L_{eq} = L_c + L_c + L_b \qquad C_{eq} = \frac{C_1C_2}{C_1 + C_2}$$



Back-to-Back Switching Snapshot #1

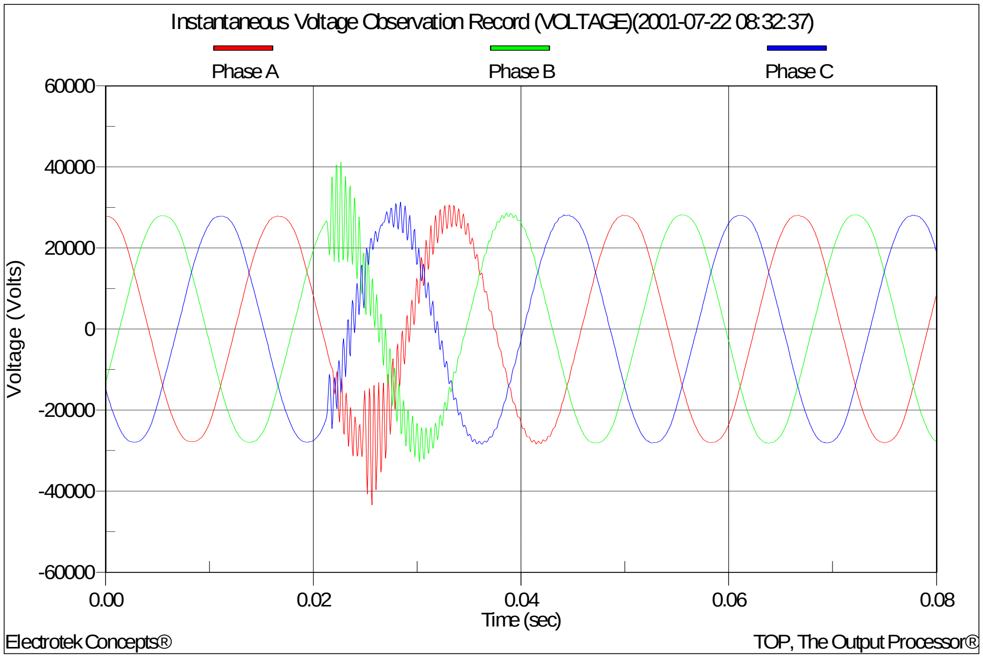
- High frequency back-to-back switching current waveform for a distribution system event:



Energizing a shunt capacitor bank with an adjacent capacitor bank already in service is known as "back-to-back" switching. High magnitude and frequency currents, illustrated above, will flow between the banks when the second bank is energized. This current must be limited to acceptable levels for switching devices and current transformer burdens. Generally, series reactors are used with each bank to limit the current magnitude and frequency, although pre-insertion resistors/inductors may be used with some types of switches.

The frequency and magnitude of the inrush current during back-to-back switching depends upon the rating of the discharging capacitor bank, the impedance of the discharging loop, and the instantaneous capacitor bank terminal voltage at the time of contact closure. The impedance of the discharging loop is determined by the inductance between the banks rather than the system inductance (Ls). The magnitude of the inrush current is therefore much higher than for the isolated bank energization (Ipk). Typically, the inrush current lasts for only a fraction a power frequency cycle.

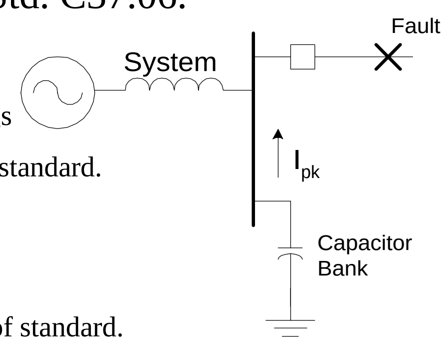
Back-to-Back Switching Snapshot #2



The waveform above shows the bus voltage during energization of a utility 34.5kV capacitor bank with another bank on the same bus. The resulting transient voltage and voltage rise were 1.5 per-unit (150%) and 1%.

Outrush Control

- Outrush current from a capacitor bank into a nearby fault can be a concern.
- The close and latch rating of the circuit breaker is the important factor.
- Circuit breaker capabilities (I_{pk}, f, & I_{pk}*f) should be evaluated with respect to IEEE Std. C37.06.
  - Definite Purpose (Class C1 & C2)
    - Not to exceed close and latch ratings
    - Refer to notes in current version of standard.
  - General Purpose (Class C0):
    - $I_{pk} < 50\text{kA}$, $I_{pk} * f < 20$ kAkHz[1]
    - [1]Refer to notes in current version of standard.



Where:

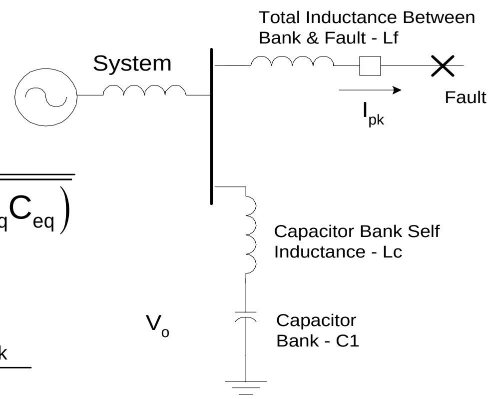
V_o is the initial voltage on the bank
L_c is the self inductance of capacitor bank
L_f is the total inductance between the bank and the fault
C_1 is the capacitance of the bank

$$I_{pk} = \frac{Vo}{Z_s}$$

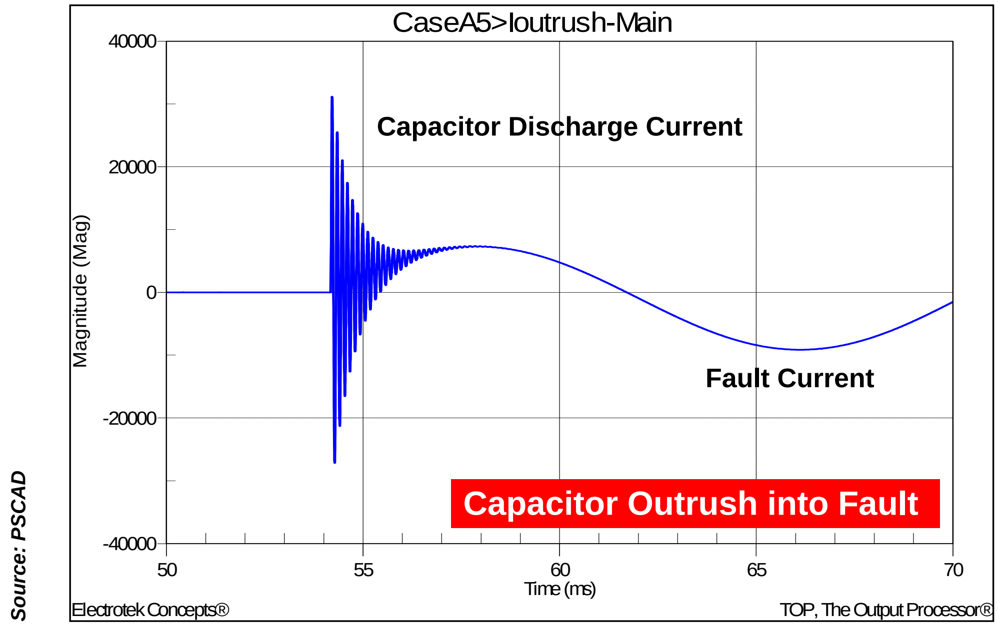
$$Z_s = \sqrt{\frac{L_{eq}}{C_{eq}}} \qquad f = \frac{1}{2\pi\sqrt{\left(L_{eq}C_{eq}\right)}}$$

$$L_{eq} = L_c + L_f \quad C_{eq} = C_1$$

$$\text{assuming } V_o = V_{pk} : \ I_{pk} * f = \frac{V_{pk}}{2\pi L_{eq}}$$

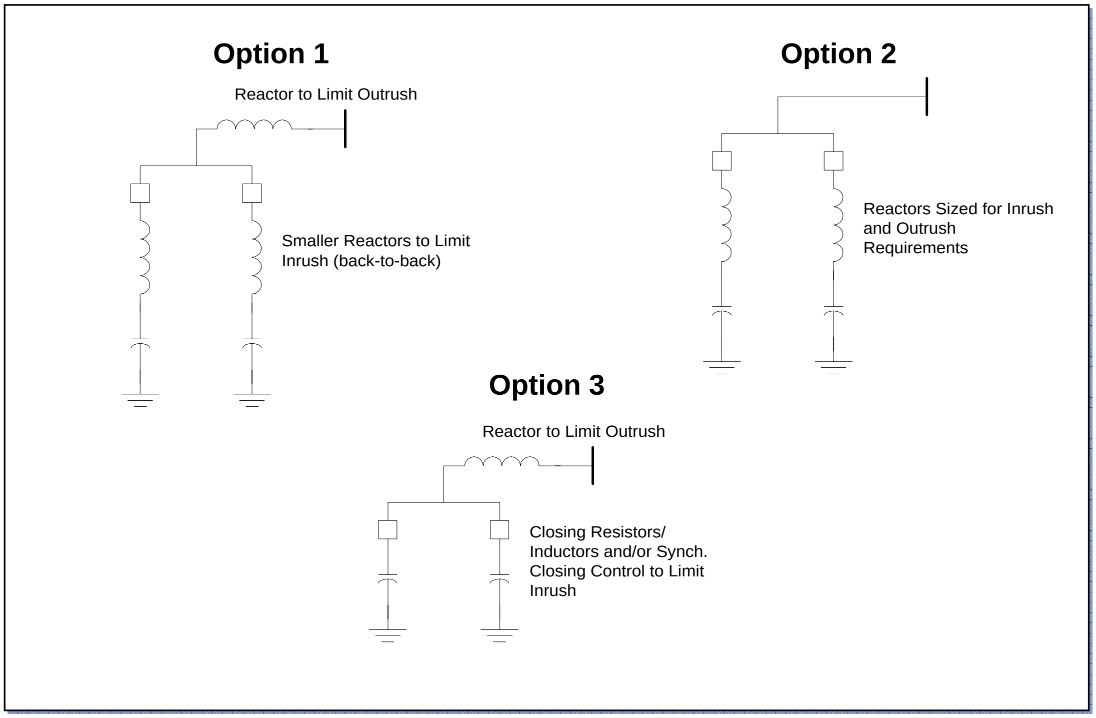


Outrush Current Snapshot #1



The waveform above shows a simulated high frequency transient outrush current from a utility transmission capacitor bank into a nearby three-phase fault. The peak magnitude of the outrush current was approximately 16.7kA.

Inrush / Outrush Options – Multiple Banks



Any of the three options illustrated above are suitable for limiting both inrush and outrush currents. The optimum configuration will depend on breaker capabilities, site considerations, and economic analysis. It is also worthwhile to consider the likelihood of very close-in faults, which are the basis of the outrush calculations.

Bank Overvoltages – Surge Arresters

- Lightning and capacitor switching transients can cause significant overvoltages.
- Prestrike / restrike events in the capacitor bank switch may cause the highest overvoltages (and most severe arrester duties).
- Voltage magnification can cause severe duties for arresters (lower voltage locations).
- MOVs generally better, with higher energy duty for same rating (vs. SiC).
- Arrester coordination/location should be evaluated.

The energy duty requirements for arresters at capacitor bank locations depends on the rating of the capacitor bank(s), and on existing arresters located at the substation. In general, the most severe duty for an arrester near a capacitor bank occurs during a switch restrike. This is due to the trapped charge on the capacitor at the instant the restrike occurs, resulting in a greater magnitude of the voltage oscillation.

Voltage Sensing Devices

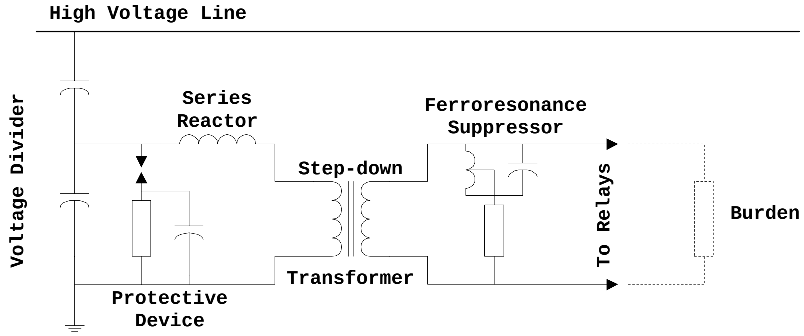
- PTs, CCVTs, or other potential devices should be able to withstand switching surges or several per-unit.
  - 0.5 to 2.4 x phase-to-ground voltage w/o saturation.
- Conventional high voltage magnetic type voltage transformers often have primary winding self resonant frequencies in the range 500 to 2000 Hz.
  - There is a concern for relays, etc. being subjected to magnified secondary overvoltage levels.
- Low voltage capacitor units provide an alternative for unbalance protection.
- Meter or relay accuracy CCVTs can be used for to provide input to voltage differential schemes.

Coupling Capacitance Voltage Transformers:

generally stand-alone single-phase units.

successfully used as inputs to electromechanical relays.

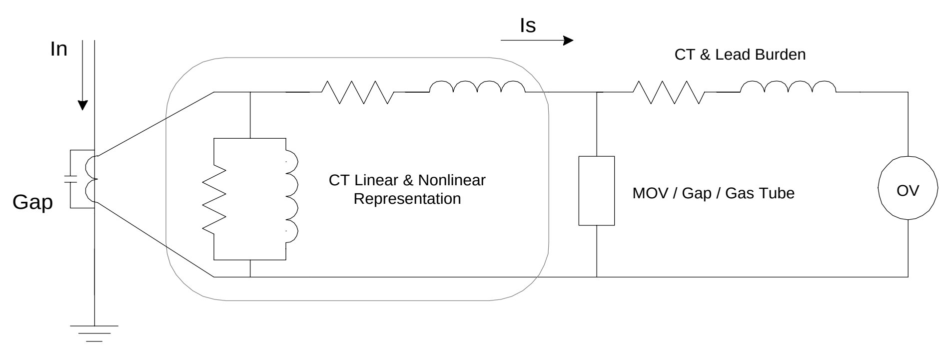
concern for the impact of transient response on the performance high-speed solid-state relays.



Current Sensing Devices

- Conservative voltage rating for neutral CTs is 0.2 of system voltage.
- CT protection:
  - Primary - rod gap (3/64 - 1/16 inch)
  - Secondary - low voltage arrester or equivalent
- Secondary current < 10 amps for full load current in primary (stuck pole).
- Failures have been observed during energizing (primary side turn-to-turn short).

Neutral CT Primary & Secondary Protection:



Inspection and Maintenance

- Visual inspections
  - Check for blown capacitor fuses, capacitor case leaks, bulged cases, discolored cases, and ruptured cases.
  - Check the ground for spilled dielectric fluid.
  - Check for dirty insulating surfaces and cracked bushings.
  - Check for signs of overheated electrical joints.
  - Check for open switches and "tripped" protective devices.
  - Check for vandalism and damage due to gunfire.
  - On metal-housed and pad-mounted banks, verify that any required locking device is in place, and inspect the exterior for corrosion, oil leaks, (around structure) and ensure that any required warning sign (e.g., "High Voltage") is properly installed and legible.

Substation and distribution banks should be inspected and electrical measurements made periodically, or as required, throughout their service life. The frequency of inspections should be determined by local conditions and requirements (i.e., environmental conditions, percent of time the capacitor bank is switched "on," and number of "on" and "off" switching operations). Physical inspections and measurements should include the following items:

Check for loose connections, frayed leads, faulty fuse tubes, and faulty ejector spring assemblies.

Fuses should be inspected for evidence of overheating or other damage.

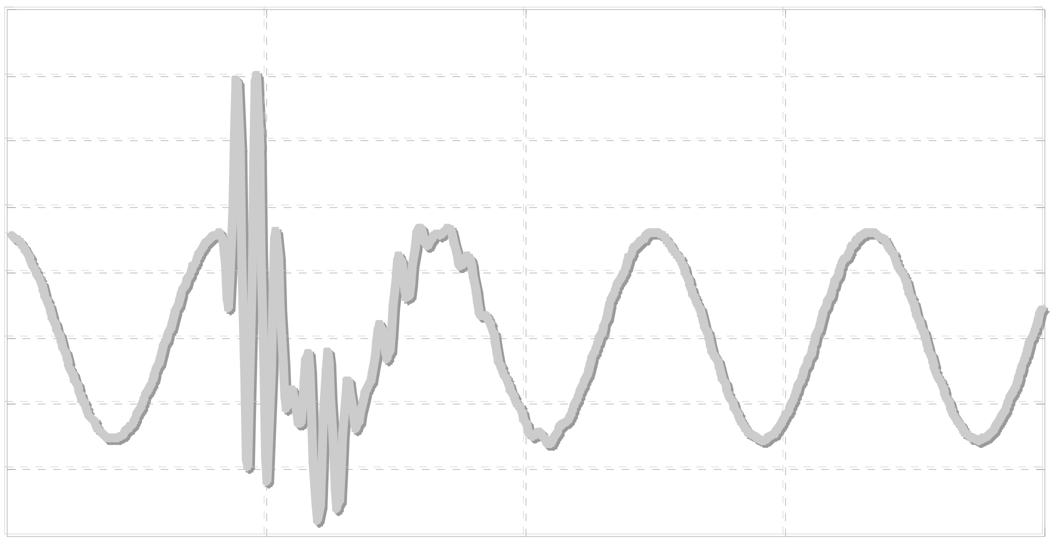
Verify proper settings and operation of protective and/or control devices, switches, and potential and/or current transformers.

Equipment exposed to weathering should be repainted, if necessary, to prevent corrosion.

The capacitance of the individual units or groups of units should be measured and compared with their previous reading (see 7.5).

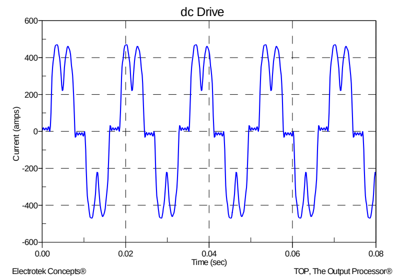
Any other maintenance operations suggested in the manufacturer's instructions.

HARMONIC CONCERNS



Harmonic Distortion Concerns – Outline

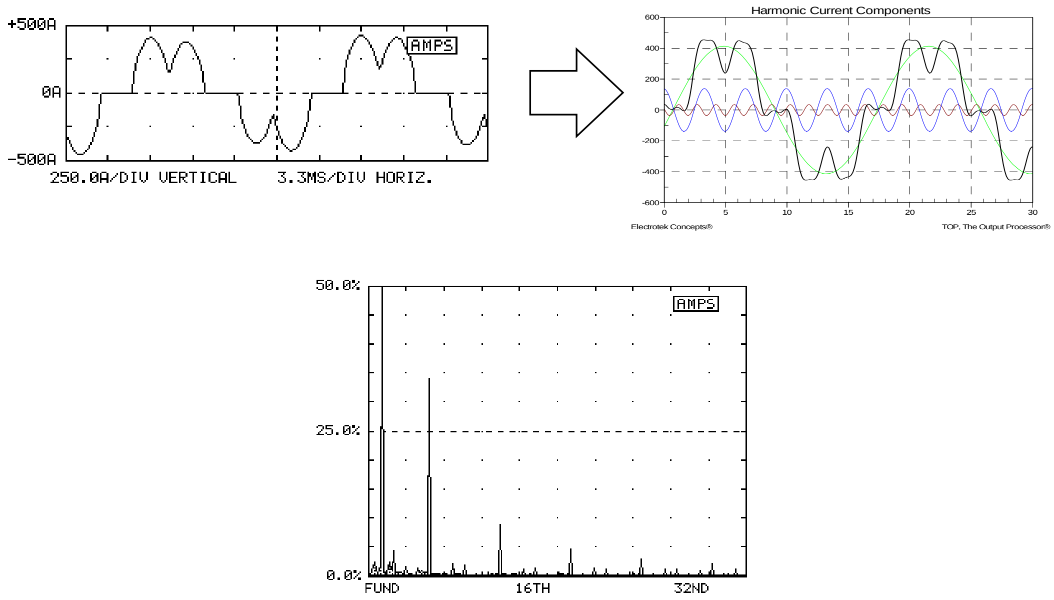
- Definitions
- Standards
- Symptoms of Harmonic Problems
- Sources of Harmonics
- System Response Characteristics
- Effect of Capacitors
  - Power Factor Correction
- Basic Harmonic Filter Design
  - Effects of Harmonics on Equipment
- Distribution System Considerations



A fundamental objective of electric utility operations is to supply each electric customer with a constant sinusoidal voltage. The voltage signal at any point within the power system is ideally a constant sinusoidal signal that repeats at a rate of precisely 60 times per second, or 60 Hz. Although not perfect, the voltage signal produced by power system generators approximates a perfect sinusoid with a rather high degree of accuracy.

Almost all load equipment connected to the electric power system has been designed to operate from a sinusoidal voltage source.Some load equipment, however, does not draw a sinusoidal current from a perfectly sinusoidal voltage source. This equipment is said to be “nonlinear”; that is, the relationship between voltage and current at every instant of time is not constant.

Harmonic Distortion – Definition



Fourier Transformation:

> A periodic, complex waveform may be expressed as the sum of an infinite series of sinusoidal signals
>
> Harmonic components will be at a frequency which is an integer multiple of the frequency of the original signal

Although harmonic levels may vary with time, just as the system load and fundamental voltage magnitude vary with time, they can be analyzed using steady-state techniques. Any steady-state signal, no matter how complex, can be described as a summation of an infinite number of sinusoidal signals as long as it is periodic. All of the signals in the infinite series are integer multiples of the lowest, or fundamental, frequency in the series, and are known as harmonics. Decomposition of a complex, repetitive waveform into its harmonic components permits analysis of each harmonic component individually in the same way that 60 Hz voltages and currents are analyzed.

Why are Harmonics Important?

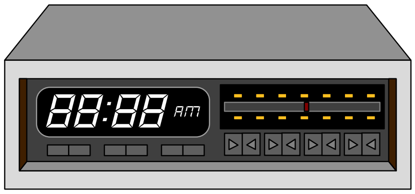
- Fundamental objective of electric utility operations is to supply each electric customer with a fairly constant sinusoidal voltage.
- Present trends in the electric power industry have placed an increased emphasis on the impact of nonlinear equipment. These include:
  - The increasing ratings and application of nonlinear equipment
  - Increased application of capacitors
  - Modern architectural/construction practices
- Load equipment sensitivity (microprocessor-based).

A fundamental objective of electric utility operations is to supply each electric customer with a fairly constant sinusoidal voltage. The voltage signal at any point within the power system is ideally a constant sinusoidal signal which repeats at a rate of precisely 60 times per second, or 60 Hz. Although not perfect, the voltage signal produced by power system generators approximates a perfect sinusoid with a rather high degree of accuracy.

Almost all load equipment connected to the electric power system has been designed to operate from a sinusoidal voltage source.

Symptoms of Harmonic Problems

- Capacitor fuse blowing
- Motor overheating
- Equipment misoperating
- Circuit breakers tripping mysteriously
- Transformer overheating at less than full load
- Customer capacitor or transformer failure
- Clocks running fast
- High neutral currents
- Telephone interference



Harmonics have existed on electric power systems for many years. Recently, however, much more attention has been given to monitoring and analyzing the presence and effects of harmonics on utility and customer devices than in the past.

This new concern is the result of significant increases in harmonic distortion on many electric power systems in the last fifteen years. Two factors contributing greatly to this trend are:

- The increasing size and application of nonlinear equipment.
- Increased application of utility and industrial capacitors to increase the utilization of existing distribution system infrastructures.

Sources of Harmonics

- Saturable devices
  - Transformers
  - Nonlinear inductors/reactors
- Arcing devices:
  - Arc furnaces and welders
  - Fluorescent lighting (magnetic ballast)
- Power electronics equipment:
  - Adjustable-speed motor drives
  - DC motor drives
  - Power-electronic devices
  - Electronic power supplies (SMPS)
  - Fluorescent lighting (electronic ballast)

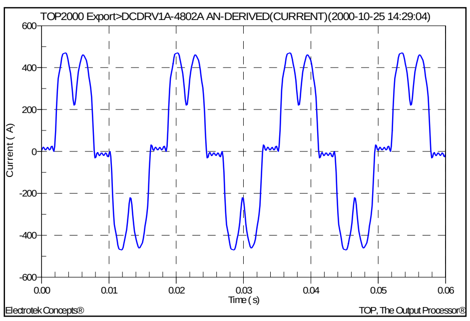
The three classifications of harmonic sources - power electronics, saturable devices, and arcing devices - all present nonlinear voltage/current characteristics to the power system. Arcing and saturable devices are passive, and the nonlinearities are a result of the physical characteristics of the electric arc and of the iron core. In power electronics equipment, semiconductor device switching which occurs within a single cycle of the power system fundamental frequency is responsible for the nonlinear characteristic.

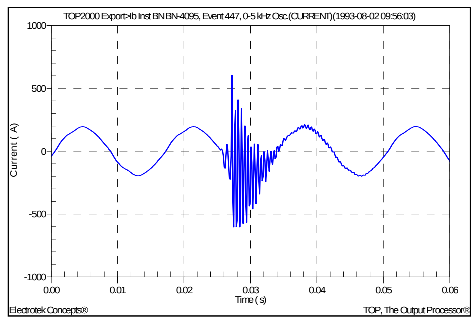
Distortion of power system voltages is a result of the interaction between harmonic currents drawn by nonlinear loads and the impedance of the power system itself. If the magnitude and frequency of harmonic currents are known, voltage distortion at a harmonic frequency can be calculated as the product of the corresponding harmonic current and system impedance at that frequency. Performing this computation at each harmonic frequency will yield an estimate of voltage total harmonic distortion.

Harmonics vs. Transients

- Steady-state distortion of the waveform.
- Periodic and continuous in nature.

- Sudden changes in the power system.
- Classified by peak magnitude, frequency, and duration.

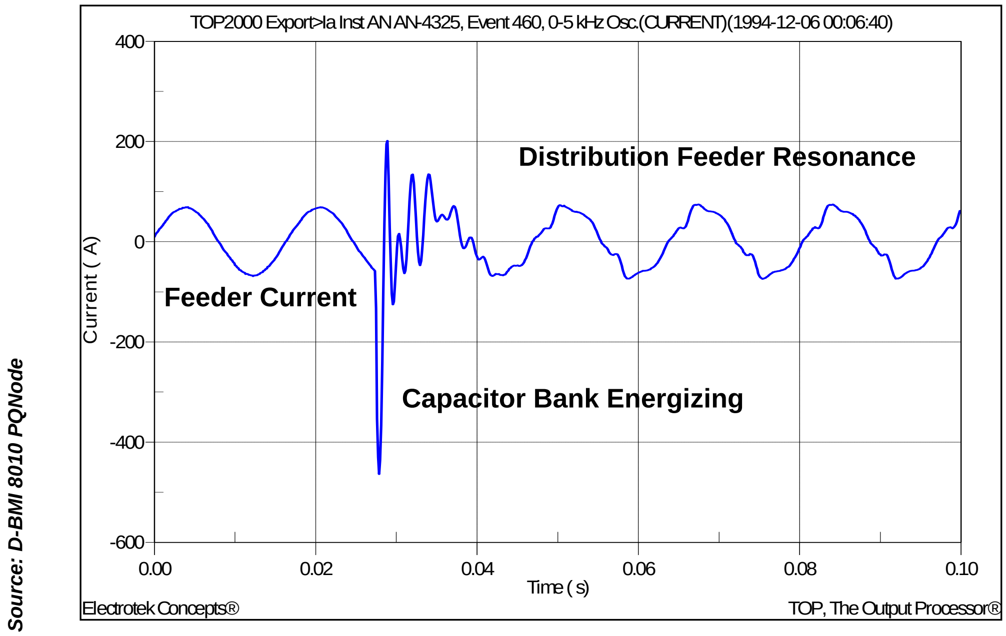




Harmonic distortion is blamed for many power quality disturbances that are actually transients. A measurement of the event may show a distorted waveform with obvious high-frequency components. Although transient disturbances contain high-frequency components, transients and harmonics are distinctly different phenomena and are analyzed differently. Transient waveforms exhibit the high frequencies only briefly after there has been an abrupt change in the power system. These frequencies are not necessarily harmonics; they are the natural frequencies of the system at the time of the switching operation, and are not related to the system fundamental frequency.

The figures above illustrate two examples of harmonic vs. transient waveforms. The figure on the left shows a customer steady-state dc drive harmonic current waveform and the figure on the right shows a utility feeder transient current waveform during a capacitor bank switching event.

Harmonics vs. Transients – continued

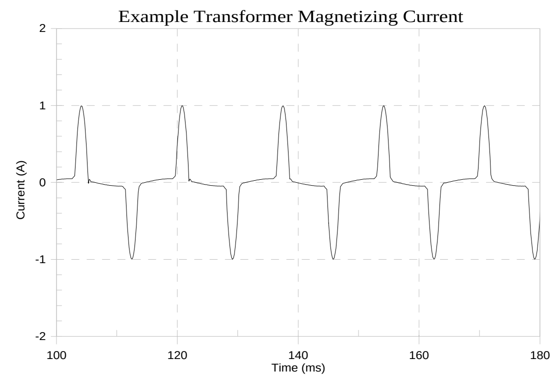


Harmonics, by definition, occur in the steady state, and are integer multiples of the fundamental frequency of the supply system. The waveform distortion that produces the harmonics is continually present, or at least for several seconds. Transients, which are classified by peak magnitude, frequency, and duration, are due to sudden changes in the power system and are usually dissipated within a few cycles. Transients are associated with changes in the power system, such as switching a utility capacitor bank. Harmonics are generally associated with the continuous operation of a customer load (e.g., adjustable-speed drive).

The figure above shows a measured 13.8kV feeder current waveform, before and after energizing a pole-mounted 900 kVAr capacitor bank. Insertion of the capacitor bank creates a resonance that results in higher levels (13% THD) of current distortion.

Saturable Loads

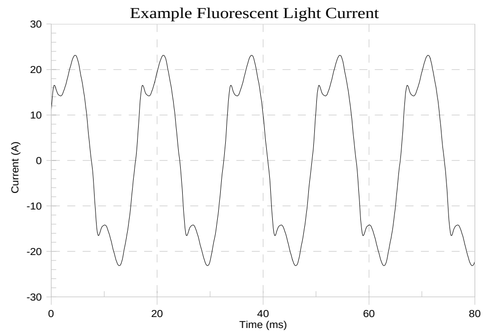
- Transformers and Reactors
- Small, harmonic rich magnetizing currents from normal operation are usually not a problem, but will contribute to background voltage distortion.



Equipment in this category includes transformers and nonlinear inductors. Harmonics are generated due to the nonlinear magnetizing characteristics. Power transformers are designed to normally operate just below the "knee point" of the iron core saturation characteristic (the point where the slope changes dramatically). A higher knee point would require additional steel (increased cost) and lowering the knee point would result in unacceptable magnetizing current losses and heating. Although transformer exciting current is rich in harmonics at normal operating voltage, it is typically less than 2% of rated full load current.

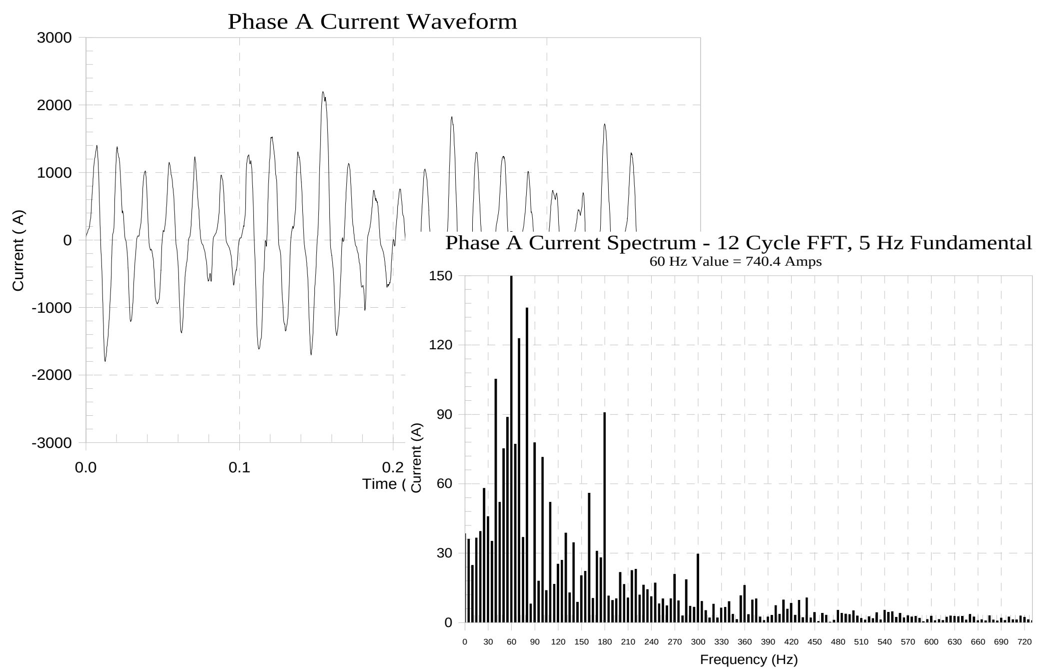
Arcing Loads

- Welding loads, arc furnaces, fluorescent lighting (without electronic ballasts)
- Distorted voltage, current due to non-linear nature of electric arc
- The electric arc itself is actually a source of voltage harmonics, but when auxiliary circuit elements such as ballasts or arc furnace leads are considered, the current source approximation is quite valid.



This category includes arc furnaces, arc welders, and fluorescent lighting (without electronic ballasts). Voltage/current characteristics of electric arcs are nonlinear. Following arc ignition, the voltage decreases as the arc current increases, limited only by the impedance of the power system. This negative resistance characteristic makes the arc by itself a very unstable circuit element. In fluorescent lighting applications, additional "ballasting" impedance is necessary to stabilize operation within the capabilities of the fluorescent tube. In electric arc furnace applications, where high currents are desirable, it is the impedance of the power system, furnace transformer and cabling which stabilize operation.

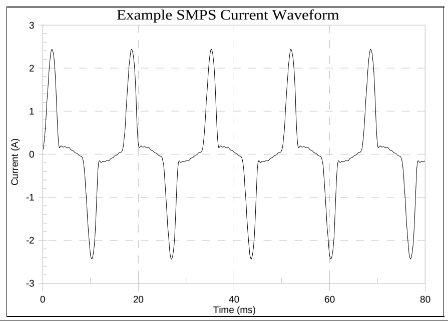
Example Arc Furnace Snapshot



Name	Frequency	Magnitude	Angle
5530 DATA CHANNEL A	0	38.4315	0
5530 DATA CHANNEL A	5	36.07	115.948
5530 DATA CHANNEL A	10	24.7951	116.884
5530 DATA CHANNEL A	15	36.6261	-125.905
5530 DATA CHANNEL A	20	39.434	-29.6126
5530 DATA CHANNEL A	25	58.0282	23.6471
5530 DATA CHANNEL A	30	45.8772	101.223
5530 DATA CHANNEL A	35	35.204	-153.026
5530 DATA CHANNEL A	40	105.25	-33.9617
5530 DATA CHANNEL A	45	52.0254	-43.6144
5530 DATA CHANNEL A	50	75.2055	28.6136
5530 DATA CHANNEL A	55	88.7641	148.137
5530 DATA CHANNEL A	60	740.401	-106.8

Power Electronic Loads

- Power supplies for electronic equipment, adjustable-speed motor drives (ASDs), dc motor drives, fluorescent lighting (electronic ballasts), battery chargers, and power converters for many industrial applications.
- Power electronics devices produce harmonics by the switching action of diodes, SCRs, or other switching devices that can switch current on and off within a cycle of the fundamental frequency.

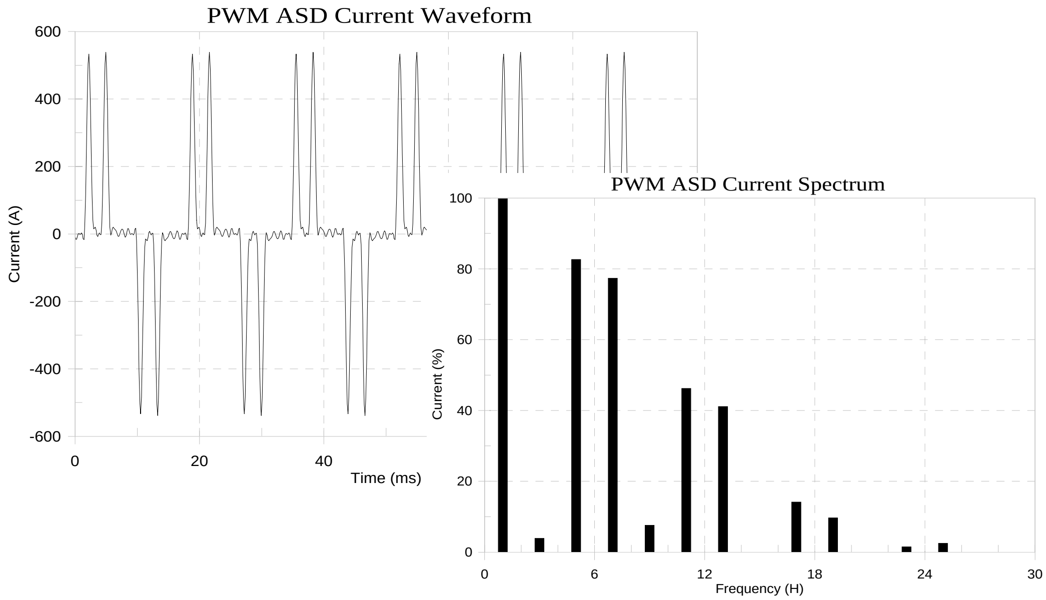


Advances in semiconductor device technology have fueled a revolution in power electronics over the past decade, and there is every indication that this trend will continue. Equipment includes adjustable speed motor drives, electronic power supplies, dc motor drives, battery chargers, electronic ballasts, and many other rectifier/inverter applications.

Two major types of power supplies are utilized in most electronic equipment. The older-technology is based on a diode bridge rectifier, but utilizes ac-side voltage control methods, such as transformers, for regulation of the dc bus voltage. The inductance of the transformer smoothed the input current waveform, reducing harmonic content. Newer technology, switch-mode power supplies use dc/dc conversion techniques for maintaining constant dc voltage output. In the absence of a large ac-side inductance, input current to the power supply becomes positive and negative current "pulses", characterized by high crest factors (peak to rms ratio) and high harmonic content.

Example PWM Drive – Snapshot

- PWM ASD with small (or no) input choke:



Name	Frequency	Magnitude	Angle
PWM1A	1	99.8283	11.5159
PWM1A	3	3.8933	-117.452
PWM1A	5	82.6578	-117.421
PWM1A	7	77.3669	89.6112
PWM1A	9	7.58695	-66.3571
PWM1A	11	46.2205	-35.3253
PWM1A	13	41.1293	168.706
PWM1A	15	0	0
PWM1A	17	14.1756	44.7699
PWM1A	19	9.68334	-116.198
PWM1A	23	1.49742	-113.135
PWM1A	25	2.49571	145.897

Harmonic Standards – IEEE Std. 519

- Harmonic Current Limits - Customer Responsibility

SCR =I_{sc}/I_L	<11	11<h<17	17<h<23	23<h<35	35<h	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20 - 50	7.0	3.5	2.5	1.0	0.5	8.0
50 - 100	10.0	4.5	4.0	1.5	0.7	12.0
100 - 1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Values shown are in percent of rated load current

SCR = short circuit ration (utility short circuit current at point of common coupling divided by customer "rated" load current

- Harmonic Voltage Limits - Utility Responsibility

Bus Voltage	Maximum Individual Harmonic Component (%)	Maximum THD (%)
69 kV and below	3.0%	5.0%
115 kV to 161 kV	1.5%	2.5%
Above 161 kV	1.0%	1.5%

In general, there are two types of harmonic simulations:

1 Frequency Scans: The frequency scan is the simplest and most commonly used technique for harmonic analysis. A scan calculates the frequency response characteristic at a particular bus or node. Usually, this is accomplished by injecting one amp into the bus over a range of frequencies and then observing the resultant voltage. The resultant voltage is directly related to the system impedance in ohms. Frequency scan analysis is the best method for identifying resonance conditions.

2 Distortion Simulations: Harmonic distortion simulations use harmonic source characteristics of nonlinear loads to determine current and voltage distortion levels at various points in the system. Distortion simulations are useful for evaluating component duty and determining harmonic limit compliance (i.e. IEEE Std 519).

IEEE Std. 519.1 – Application Guide

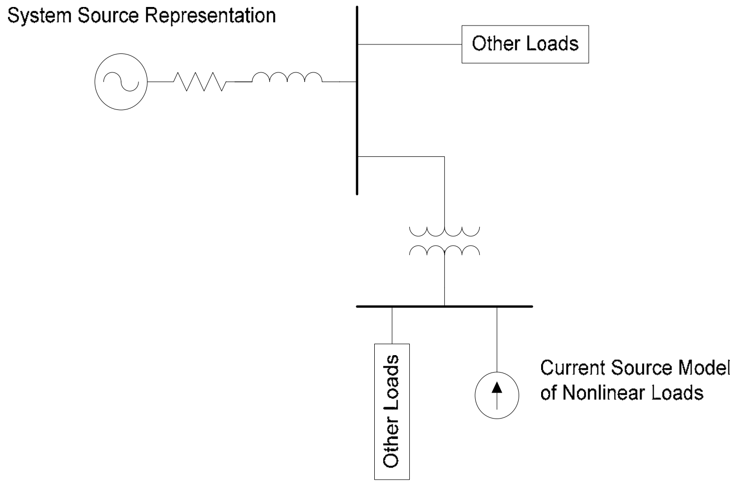
- IEEE Harmonics Working Group - ongoing development
  - Introduction and Scope
  - References / Background
  - General Procedure for Applying Harmonic Limits
    - General Evaluation Procedure
      - Stage 1 - Automatic Acceptance
      - Stage 2 - Evaluation According to the Current Limits
    - Evaluating the Time Varying Characteristics of Harmonics
      - Probability Distributions
      - Magnitude / Duration Limits for Short Duration Harmonic Levels
    - Measurement Considerations
  - Applying Harmonic Limits:
    - Industrial / Commercial / Residential Customers
  - Utility System Considerations

For more information:

http://grouper.ieee.org/groups/harmonic/p519a/

Representation of Nonlinear Loads

- In general, a nonlinear load can be represented as a source of harmonic currents:

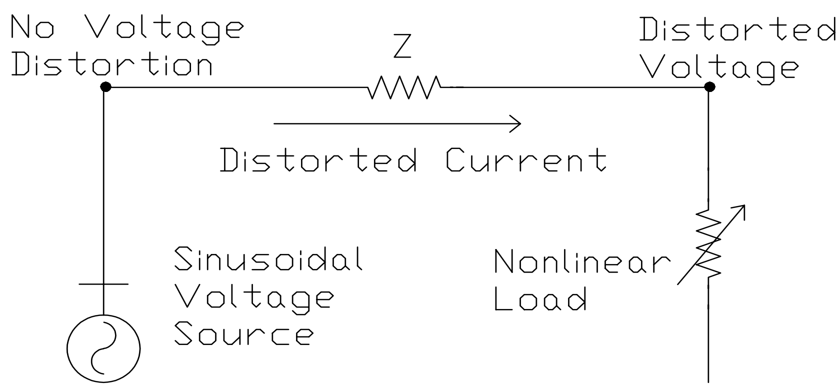


For the most part, nonlinear devices inject harmonic current components into the distribution system. The constant current source model is valid for Zsource << Zload. Often a voltage distortion level of 10% is used as a cut-off point.

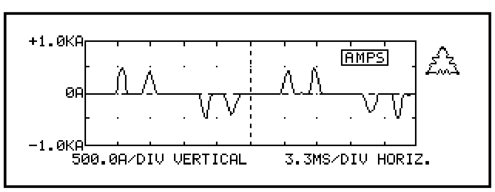
Distortion of power system voltages is a result of the interaction between harmonic currents drawn by nonlinear loads and the impedance of the power system itself. If the magnitude and frequency of harmonic currents are known, voltage distortion at a harmonic frequency can be calculated as the product of the corresponding harmonic current and system impedance at that frequency. Performing this computation at each harmonic frequency will yield an estimate of voltage total harmonic distortion.

Voltage Distortion vs. Current Distortion

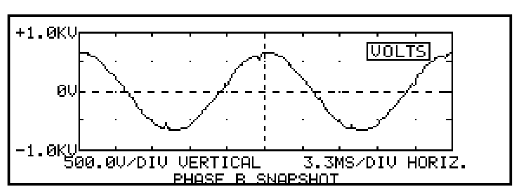
- Nonlinear loads inject harmonic current components onto the system.
- The system <u>impedance vs. frequency</u> characteristics determine the harmonic voltage distortion levels.



Current Waveform - 130% THD



Voltage Waveform - 2.4% THD



System Response Characteristic

- Voltage distortion is a result of the voltage drop created across the equivalent power system impedance.
- At 60 Hz, power systems are primarily inductive. The equivalent inductance can be calculated:

$$L_{eq} = \frac{X_{sc}}{2\pi * f}$$

X_{sc} = system short circuit reactance

f = power system fundamental frequency (60 Hz)

At utilization voltages, the equivalent system reactance is usually dominated by local impedances (the step-down transformer).

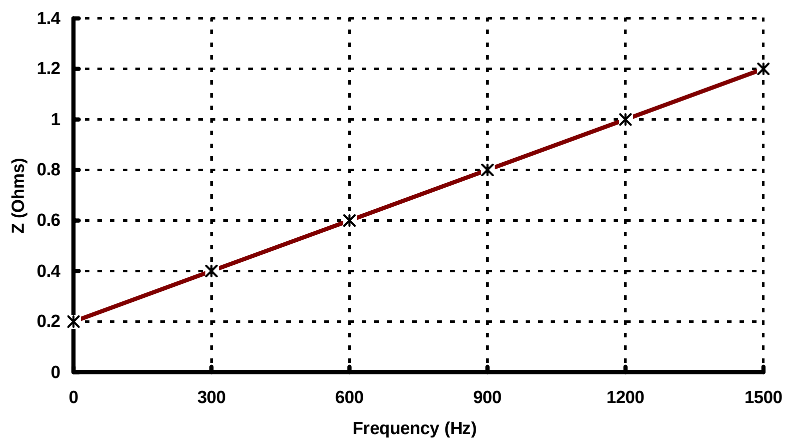
In general: $X_{sc} » X_{transformer}$

$$X_t = \frac{\left(kV_{LV}{}^2\right) * Z_{pu}}{MVA}\,\Omega$$

Impedance vs. Frequency

- At harmonic frequencies, the impedance of the equivalent inductance is:

$$X_h = 2*\pi*f_h*L_{eq} = 2*\pi*60*h*L_{eq}$$



For example: 1500kVA, Z_{tx} = 6%

h	f	X_s
1	60	0.0092Ω
5	300	0.0460Ω
7	420	0.0644Ω
11	660	0.1012Ω
13	780	0.1196Ω

$$X_s = h * X_{tx}$$

Voltage Distortion Calculation

$$V_{THD} = \sqrt{\frac{\sum V_h^2}{V_1^2}}$$

500 HP Drive, 1500 kVA, 6% Transformer

Harmonic Number h	Harmonic Current (Amps) Ih	System Impedance (Ohms) Xh	Harmonic Voltage (Volts) Vh
5	186	0.046	8.55
7	38	0.064	2.43
11	61	0.101	6.16
13	28	0.119	3.33
			4.09%

$$V_{THD} = \sqrt{\frac{\left(8.55^2 + 2.43^2 + 6.16^2 + 3.33^2\right)}{\left(480/\sqrt{3}\right)^2}} = 4.09\%$$

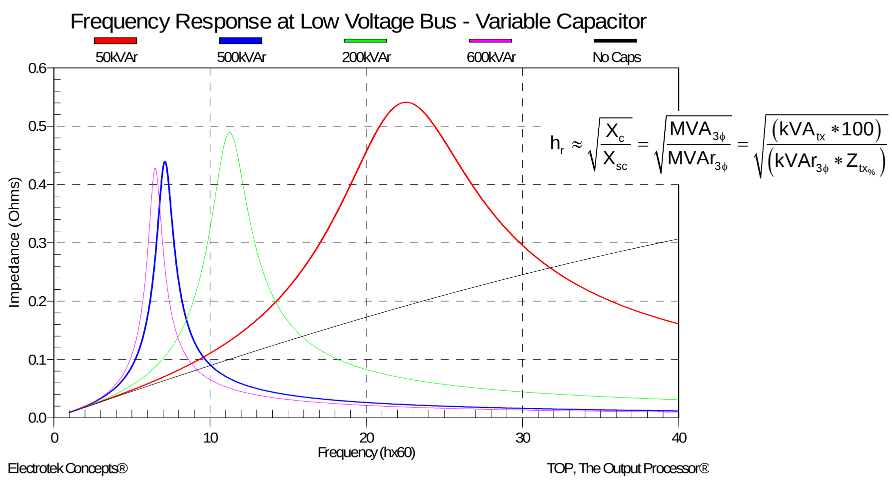
Note: No capacitors in service

Harmonic voltage distortion is a result of the voltage drop created across the equivalent power system impedance by harmonic currents from nonlinear loads. Once the characteristics of the harmonic sources have been identified, the response of the power system at each harmonic frequency must be developed to determine the impact of the nonlinear load on harmonic voltage distortion.

$$X_{tx} = \left(\frac{kV_{\phi\phi}^{\ 2}}{MVA_{3\phi}}\right) * Z_{tx}(\%) = \left(\frac{0.480^2}{15}\right) * 0.06 = 0.0092\Omega$$

Effect of Shunt Capacitors

- Shunt capacitors can dramatically alter the system frequency response. They create a parallel resonance that can magnify harmonic currents and cause increased voltage distortion levels.



Shunt capacitors in the power system dramatically alter the system impedance variation with frequency. Capacitors are one of the most linear elements of the power system and do not create harmonics themselves. However, severe harmonic distortion can sometimes be attributed to their presence. While the reactance of inductive components increases proportionately to frequency, capacitive reactance, Xc, decreases proportionately.

At harmonic frequencies, shunt capacitors appear to nonlinear loads as being in parallel with the equivalent system inductance. At the frequency where X_C and X_{SC} are equal, the parallel impedance (combination of inductance and capacitance), as seen by the nonlinear load, becomes very high. This frequency (f_r) is known as the resonant frequency for that particular circuit configurations.

Resonant Frequency

- At the frequency where the capacitive reactance (X_C) and the inductive reactance (X_L) are equal, the impedance seen by the nonlinear load becomes very large.
- This is known as the parallel resonant frequency and can be calculated from:

$$f_r = \frac{1}{2\pi\sqrt{L*C}} = \sqrt{\frac{MVA_{sc}}{MVAr_c}} * 60$$

If the **calculated frequency** corresponds to one of the **characteristic harmonic frequencies** of a nonlinear load, **high distortion** might be expected.

$$h \approx \sqrt{\frac{kVA_{tx} * 100}{kVAr_{cap} * Z_{tx}(\%)}}$$

where: h = parallel resonance frequency (x 60 Hz)

MVA_{sc} = short circuit duty in MVA

$MVAr_{cap}$ = capacitor bank rating in MVAr

I_{cap} = capacitor bank load current in amps

X_c = shunt capacitive reactance Ω (C - capacitance)

X_{sc} = short circuit reactance Ω (Ls - inductance)

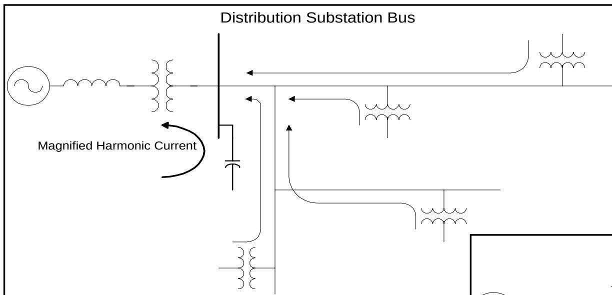
kVA_{tx} = step-down transformer rating in kVA

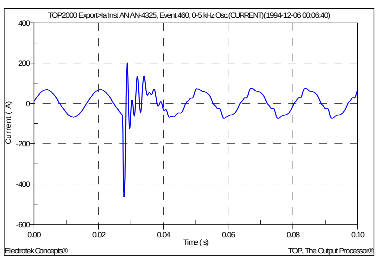
Z_{tx} = step-down transformer impedance in percent

$kVAr_{cap}$ = capacitor bank rating in kVAr

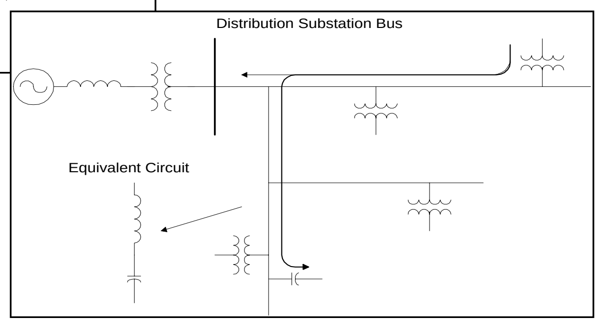
Distribution Feeder Resonances

Parallel Resonance

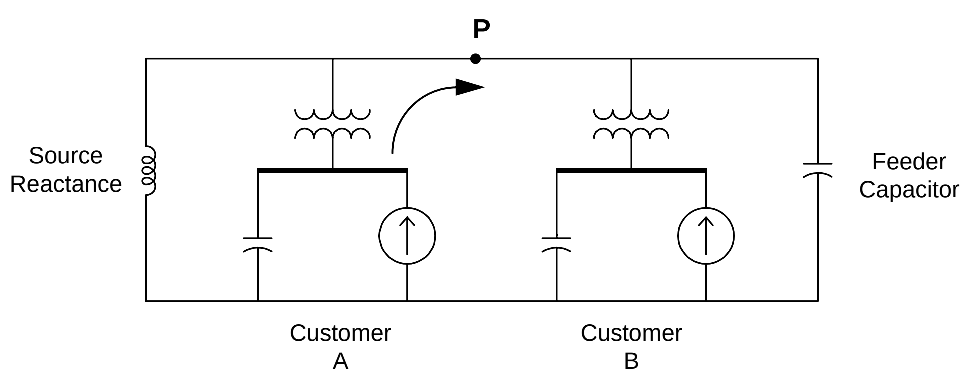




Series Resonance



Altered flow of harmonic currents due to series resonance:



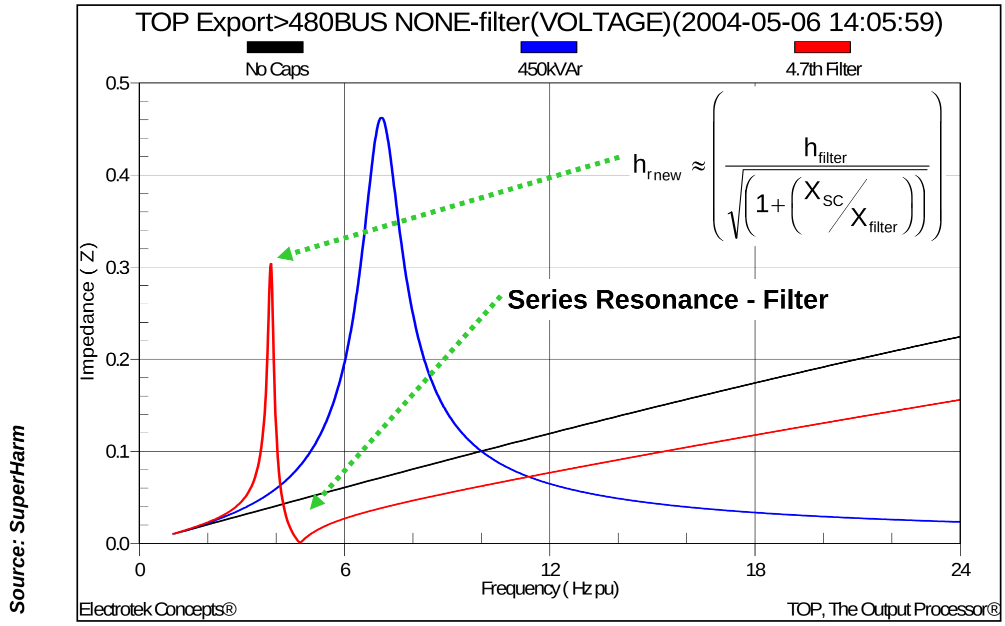
Reduction Methods – Basic Filter Design

- The general method for applying filters is as follows:
  - Apply one single tuned filter first, and design it for the lowest generated frequency (i.e. 5^{th} harmonic - 4.7^{th} filter).
  - Determine the voltage distortion at the low voltage bus, 5% is the commonly applied limit.
  - Vary filter elements (tolerances) and check its effectiveness.
  - Check the frequency response characteristic to verify that the newly created parallel resonance is not close to a harmonic frequency.
  - If necessary, investigate the need for several filters, such as 5^{th} and 7^{th}.

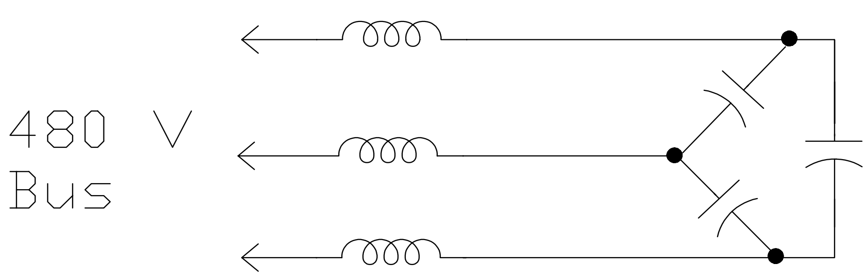
Passive filters are made of inductive, capacitive and resistive elements. They are relatively inexpensive compared with other means for eliminating harmonic distortion, but they have the disadvantage of potentially adverse interactions with the power system. They are employed either to shunt the harmonic currents off the line or to block their flow between parts of the system by tuning the elements to create a resonance at a selected harmonic frequency.

The most common type of passive filter is the single-tuned "notch" filter. This is the most economical type and is frequently sufficient for the application. The notch filter is series-tuned to present a low impedance to a particular harmonic current. It is connected in shunt with the power system. Thus, harmonic currents are diverted from their normal flow path on the line into the filter. Notch filters can provide power factor correction in addition to harmonic suppression.

Effect of Filter on Frequency Response



Typical Low Voltage Filter Configuration:



$$h_{notch} = \sqrt{\frac{X_{C_Y}}{X_f}} = \sqrt{\frac{\left(kV^2_{\phi\phi}/MVAr_{3\phi}\right)}{X_f}} \qquad h_{r\,new} \approx \left(\frac{h_{filter}}{\sqrt{\left(1+\left(X_{SC}/X_{filter}\right)\right)}}\right)$$

Effects of Harmonics on Equipment

- In general, harmonics increase heating and losses in almost every piece of equipment in the electric power system.
  - Capacitor banks - usually cause the resonant condition where the highest distortion levels occur
  - Resistive loads - will absorb slightly more power
  - Motor loads - harmonic fluxes within the motor
  - Power transformers - hot spots within the windings
  - Electronic controls - operate improperly
  - Communication circuits - can cause interference

References:

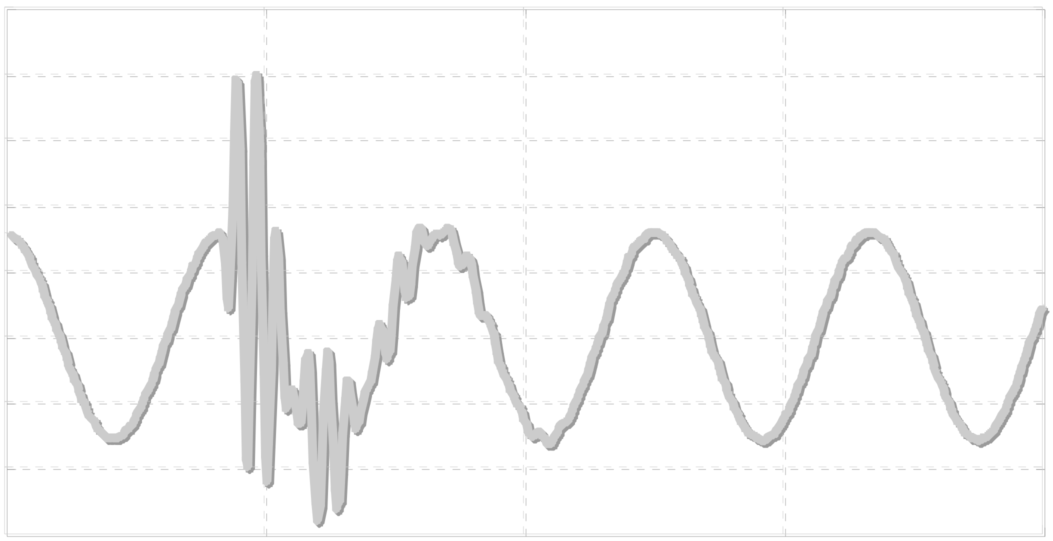
Transformers: ANSI C57.110

Capacitors: ANSI/IEEE Std. 18

Effect of Harmonics on Equipment - IEEE Task Force Report (Harmonics Working Group)

"*Adjustable Speed Drives Drive and Power Rectifier Harmonics and Their Effect on Power System Components*", David E. Rice (GE)

TRANSIENT DISTURBANCES



Power System Transients

- Sudden changes in the electric power system are called transients.
- All transients are caused by one of two actions:
  - Connection or disconnection of elements within the electric circuit.
  - Injection of energy due to a direct or indirect lightning stroke or static discharge.

Transient overvoltages and overcurrents are classified by peak magnitude, frequency, and duration.

Transient voltages and currents are a result of sudden changes within the electric power system. Opening or closing of a switch or circuit breaker causes a change in circuit configuration and the associated voltages and currents. A finite amount of time is required before a new stable operating point is reached. A principal effect of these events is a temporary departure of power system voltage and current from the normal steady-state sinusoidal waveforms. Opening or closing of switches is a very common occurrence, whether it be normal cycling of loads at the utilization level, or utility operations on the transmission and distribution system.

Transient characteristics are dependent on the combination of initiating mechanism and the electric circuit characteristics at the source of the transient. Circuit inductances and capacitances are responsible for the oscillatory nature of transients.

How do Transients Propagate?

- High frequency transients do not propagate over long distances:
  - this is a good reason for separating sensitive loads and disturbing loads
- Local resonances can cause oscillations remote from the transient source:
  - can be particularly important for transients caused by utility capacitor switching
- Lower frequency transients will appear throughout the facility:
  - capacitor switching transients are usually less than 1 kHz

Transient characteristics are dependent on the combination of initiating mechanism and the electric circuit characteristics at the source of the transient. Circuit inductances and capacitances - either discrete components such as shunt capacitance of power factor correction banks or inductances in transformer windings, or stray inductance or capacitance because of proximity to other current carrying conductors or voltages - are responsible for the oscillatory nature of transients.

If the dominant circuit elements are known, transient frequencies can be easily calculated, as with the case of utility capacitor switching. In many instances, where small inductances and capacitances associated with circuit conductors may predominate, transient frequencies are more difficult to calculate.

Utility Capacitor Switching

- Capacitor Bank Energizing Transient:
  - The voltage across a capacitor cannot change instantaneously.
  - The step change in voltage when a capacitor bank is energized results in an oscillation between the capacitance and the system inductance.
- Typical Magnitudes: 1.2 – 1.7 per-unit (x normal)
- Typical Frequencies: 250 – 1000 Hz

$$f_s = \frac{1}{2\pi\sqrt{L_s C}} \approx f_{system} * \sqrt{\left(\frac{X_c}{X_s}\right)} \approx f_{system} * \sqrt{\left(\frac{MVA_{sc}}{MVA_r}\right)} \approx f_{system} * \sqrt{\left(\frac{1}{\Delta V}\right)}$$

Capacitor switching is considered to be a normal event on a utility system and the transients associated with these operations are generally not a problem for utility equipment. However, the transients can be magnified in a customer facility if the customer has low voltage power factor correction capacitors. In addition, nuisance tripping of adjustable-speed drives can occur, even if the customer does not have capacitors.

Because capacitor voltage cannot change instantaneously, energization of a capacitor bank results in an immediate drop in system voltage toward zero, followed by a fast voltage recovery (overshoot) and finally an oscillating transient voltage superimposed on the 60 Hz fundamental waveform. The peak voltage magnitude depends on the instantaneous system voltage at the moment of energization, and can reach 2.0 times the normal system peak voltage (per-unit) under worst-case conditions. The magnitude is usually less than this due to system loads and damping (resistive elements). Typical distribution system overvoltage levels range from 1.1 to 1.6 per unit.

Energizing Transient – Example

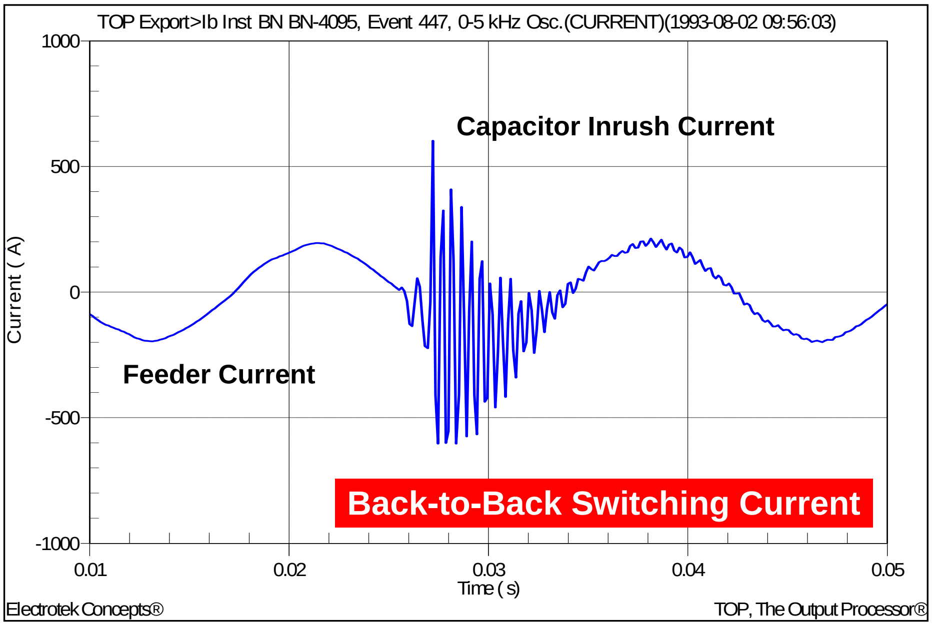
$$f_s = \frac{1}{2\pi\sqrt{L_s C}} \approx f_{system} * \sqrt{\left(\frac{X_c}{X_s}\right)} \approx f_{system} * \sqrt{\left(\frac{MVA_{sc}}{MVA_r}\right)} \approx f_{system} * \sqrt{\left(\frac{1}{\Delta V}\right)}$$

MVA_{sc} = three-phase short circuit capacity (MVA)	[2000 MVA]
MVA_r = three-phase capacitor bank rating (MVAr)	[50 MVAr]
f_{system} = system frequency (50 or 60 Hz)	[60 Hz]
X_s = positive sequence source impedance (Ω)	[6.61 Ω]
X_c = capacitive reactance of bank (Ω)	[264.50 Ω]
L_s = positive sequence source inductance (H)	[17.53mH]
C = capacitance of bank (F)	[10.03μF]
ΔV = steady-state voltage rise (per-unit)	[2.5%]
V_{pk} = peak line-to-ground bus voltage (V)	[93897.11 V]
Z_s = surge impedance (Ω)	[39.35 Ω]
f_s = characteristic frequency (Hz)	**[379 Hz]**

Relating the characteristic frequency of the capacitor energizing transient (f_s) to a steady-state voltage rise (ΔV) design range provides a simple way of quickly determining the expected frequency range for utility capacitor switching.

For example, a 60 Hz system with a design range of 1.0% to 2.5% would correspond to characteristic frequency range of 380 to 600 Hz. For a shunt capacitor bank on a high voltage bus, transmission line capacitance and other nearby capacitor banks cause the energizing transient to have more than one natural frequency. However, for the first order approximation, the equation above (1) can still be used to determine the dominant frequency.

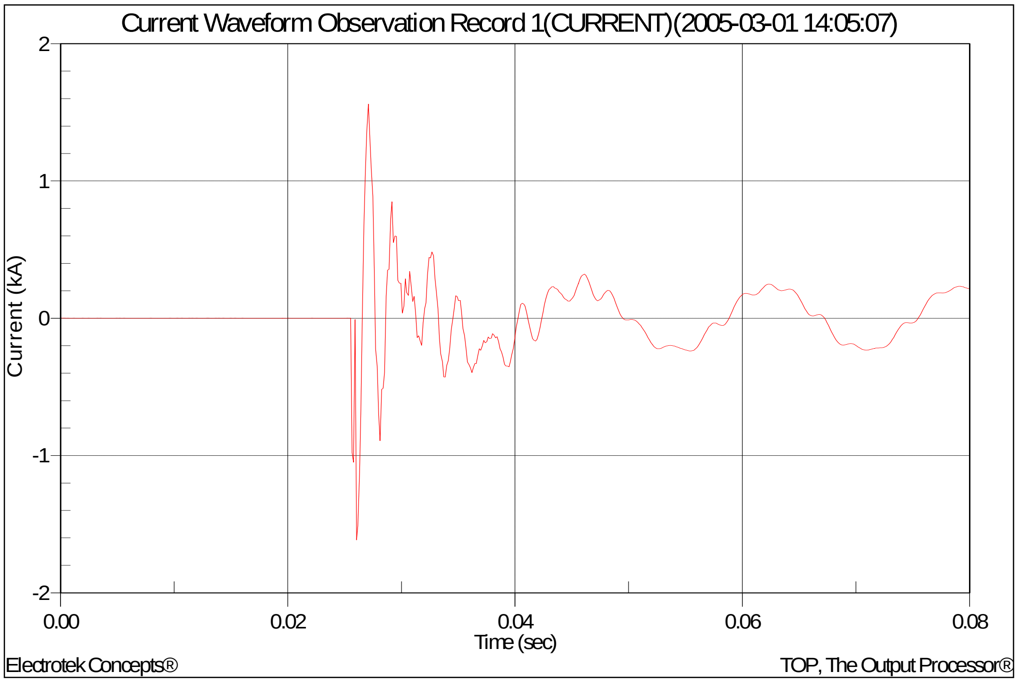
Measured Capacitor Energizing Current



Source: D-BMI 8010 PQNode

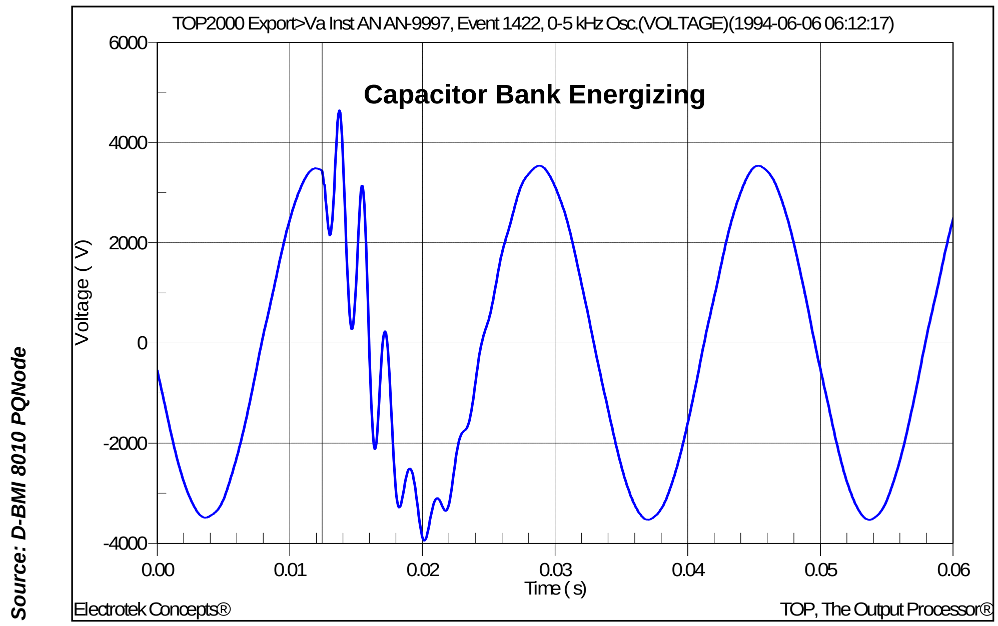
Transient overvoltages and overcurrents related to capacitor switching are classified by peak magnitude, frequency, and duration. These parameters are useful indices for evaluating potential impacts of these transients on power system equipment. The absolute peak voltage, which is dependent on the transient magnitude and the point on the fundamental frequency voltage waveform at which the event occurs, is important for dielectric breakdown evaluation. Some equipment and types of insulation, however, may also be sensitive to rates of change in voltage or current. The transient frequency, combined with the peak magnitude, can be used to estimate the rate of change.

Simulated Capacitor Energizing Current



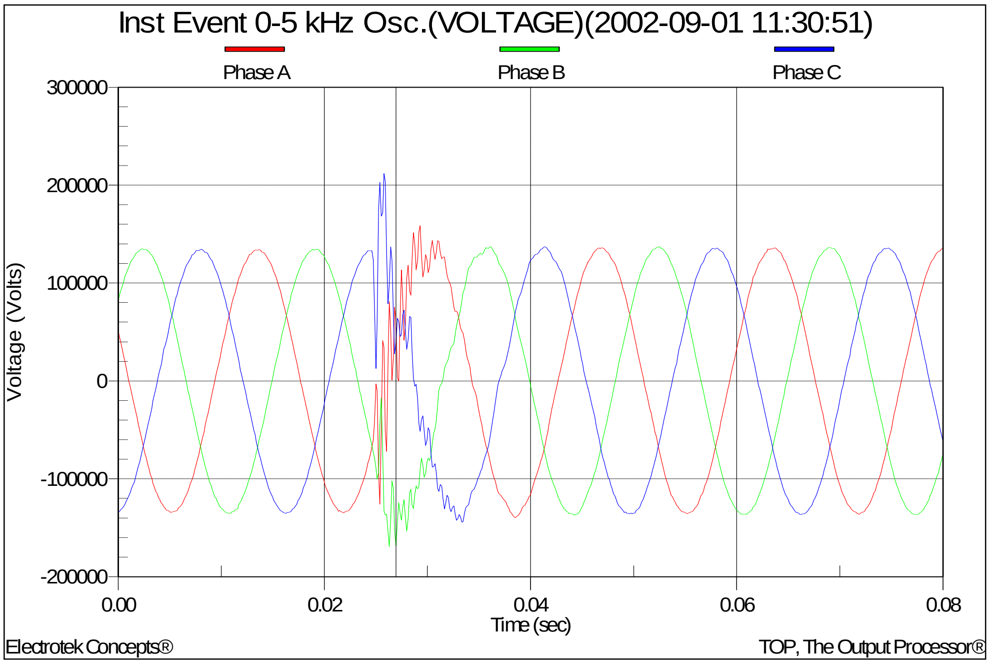
This waveform shows the inrush current during energization of a 138kV transmission capacitor bank. The characteristics of the peak transient inrush current were approximately 1.6kA and 440 Hz.

Measured Capacitor Energizing Voltage



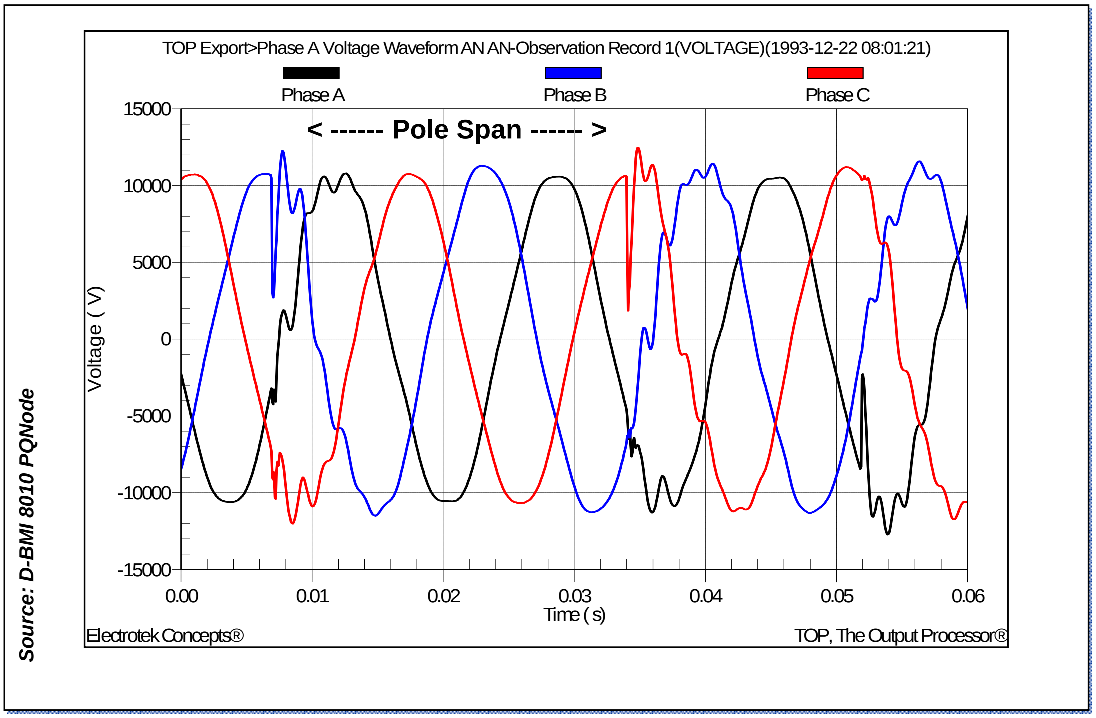
For a shunt capacitor bank on a high voltage bus, transmission line capacitance and other nearby capacitor banks cause the energizing transient to have more than one natural frequency. However, for the first order approximation, this equation can still be used to determine the dominant frequency.

Measured Capacitor Energizing Voltage



The waveform above shows the bus voltage during energization of a utility transmission (161kV) capacitor bank. The resulting transient voltage was 1.6 per-unit (160%) and steady-state voltage rise was approximately 1%.

Measured Capacitor Energizing Voltage



The following factors affect the transient magnitude and characteristics:

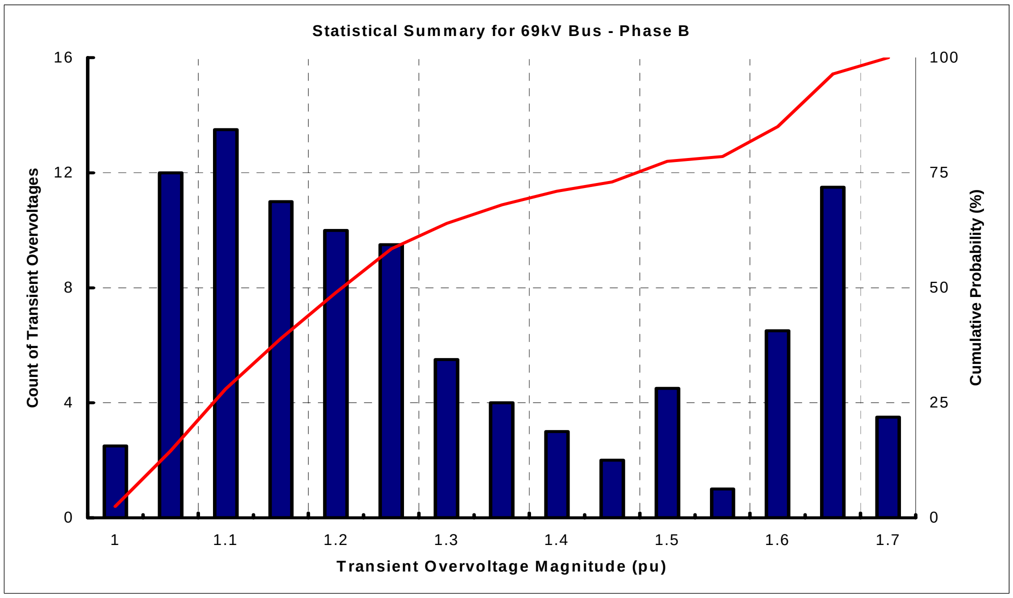
Source strength: In general, the transient becomes more severe as the source strength is reduced.

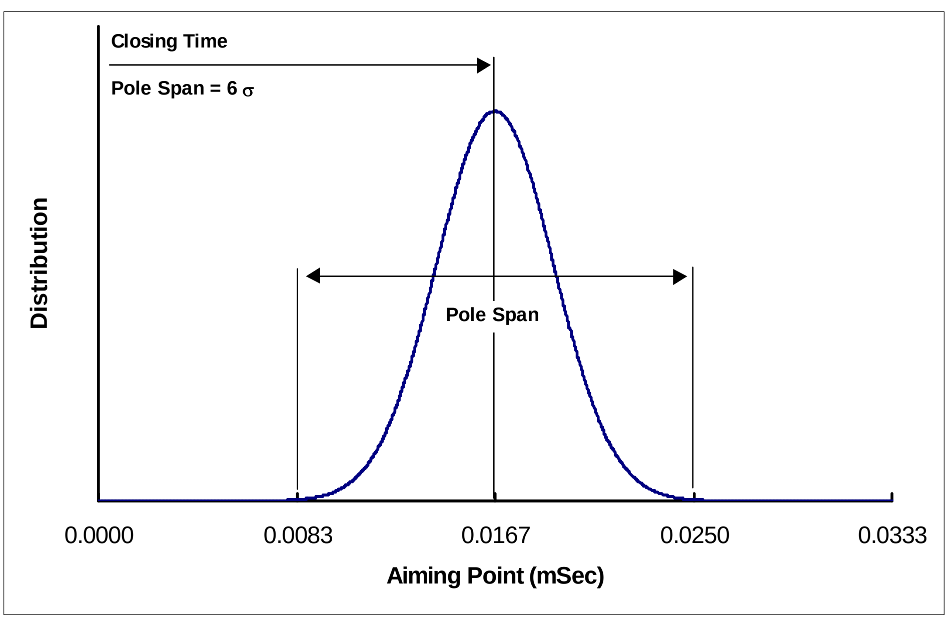
Transmission lines: Transmission lines and their associated capacitance reduce the capacitor bank energizing transient. The transmission line capacitance effectively makes the system stronger for the energizing operation.

Other transmission system capacitor banks: Other shunt capacitor banks in the vicinity of the switched capacitor bank reduce the system surge impedance and make the equivalent short circuit capacity of the source stronger.

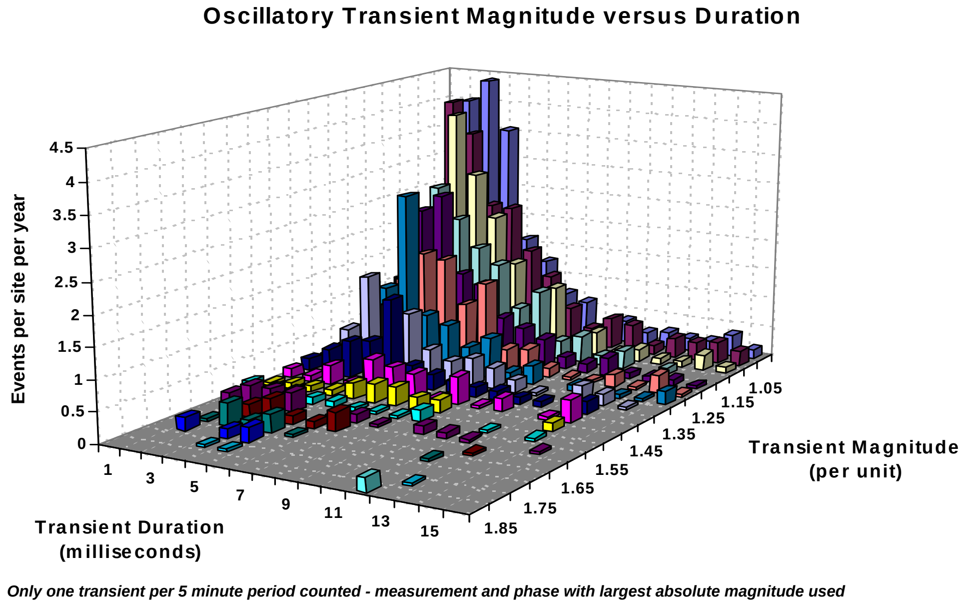
Switching device: The energizing transient can be controlled by using pre-insertion devices such as pre-insertion resistors or pre-insertion reactors. It can also be controlled by applying phase angle control techniques, known as synchronous closing. A typical connection time of a pre-insertion device is a half power frequency cycle.

Capacitor Energizing – Statistical Analysis





Capacitor Energizing – Characteristics



The capacitor energizing transient is important because it is one of the most frequent system switching operations. It can produce high phase-to-phase overvoltages on a terminating transformer, excite circuit resonances resulting in transient voltage magnification in secondary voltage networks, or cause problems with sensitive electronic equipment in customer facilities. Power quality symptoms related to utility capacitor switching include: customer equipment damage or failure (due to excessive overvoltage); nuisance tripping of adjustable-speed drives or other process equipment shutdown (due to dc bus overvoltage); transient voltage surge suppressors (TVSS) failure; and computer network problems (e.g., UPS cycling).

Overvoltage Control Methods

- Uncontrolled
  - No preventative means applied (always simulation basecase for comparison of effectiveness of other methods).
- Synchronous closing control
  - Method for controlling overvoltage by switching when the voltage across the switch at the closing instant is equal to zero (zero voltage on capacitor - zero voltage on bus).
- Pre-insertion device
  - Method for controlling overvoltage by inserting an impedance (usually inductance or resistance in series with the component to be energized voltage.
- Arresters
  - Method for controlling overvoltage by “clipping” at a specified protective level.

Each of the above technologies has been utilized in the field with varying degrees of success. The criteria by which these devices are evaluated, however, is changing significantly. For example, design requirements often state that protection of utility equipment is the primary factor. However, the recent concern for customer systems has prompted a number of utilities to seek a "transient-free" solution. This fact is best illustrated by reviewing the concern for nuisance tripping of ASDs (i.e. dc bus trip setting for small VSI drives may be as low as 117% of nominal). In addition to the overvoltage design limits, there are a number of other factors that have delayed the widespread application of mitigation technologies. One obvious obstacle is cost, however, an equally important reason has been reliability.

Overvoltage Control Methods – continued

Mitigation Technique	Local Overvoltages	Remote Overvoltages	Customer-Side PQ Considerations	Estimated Relative Cost	Install & Maintain
Distribution Level:					
No control	Moderate - High	Moderate - High	Moderate - High	---	---
Pre-insertion resistor	Low	Low	Low - Moderate	Low - Moderate	Moderate
Synchronous closing	Low	Low - Moderate	Low - Moderate	Moderate - High	High
Fixed Inductors	Moderate - High	High - Very High	High - Very High	Low - Moderate	Low
Arresters (MOV & SiC)	Moderate - High	Moderate - High	Moderate - High	Moderate	Minimal
Transmission Level:					
No control	Moderate - High	High - Very High	High - Very High	---	---
Standard pre-insertion inductor	Low - Moderate	Moderate - Very High	Moderate - High	Moderate	Minimal
High-loss pre-insertion inductor	Low	Low - Moderate	Low - Moderate	Moderate - High	Moderate
Pre-insertion resistor	Low - Moderate	Low - Moderate	Low - Moderate	Moderate	Moderate
Synchronous closing (analog)	Low	Low - Moderate	Low - Moderate	Moderate	High
Fixed inductors	Moderate - High	High - Very High	High - Very High	High	Low
Arresters (MOV & SiC)	Moderate - High	Moderate - High	Moderate - High	Moderate	Minimal

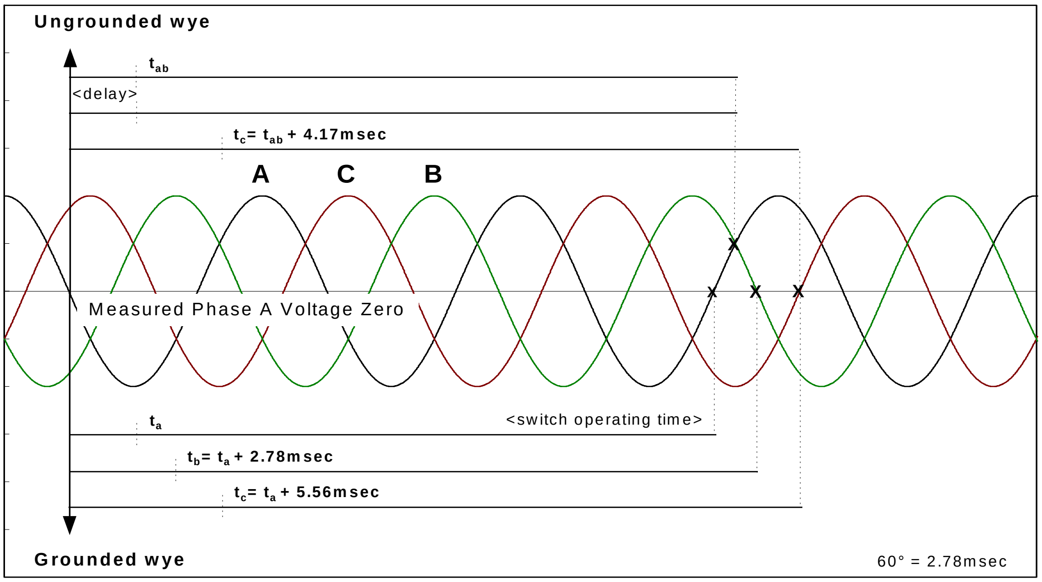
Previous studies (digital simulation and TNA) have suggested that the effectiveness of these control methods is system dependent, and that detailed analysis is required to select the optimum control scheme. Each of these methods has various advantages and disadvantages in terms of transient overvoltage reduction, cost, installation requirements, operating/maintenance requirements, and reliability.

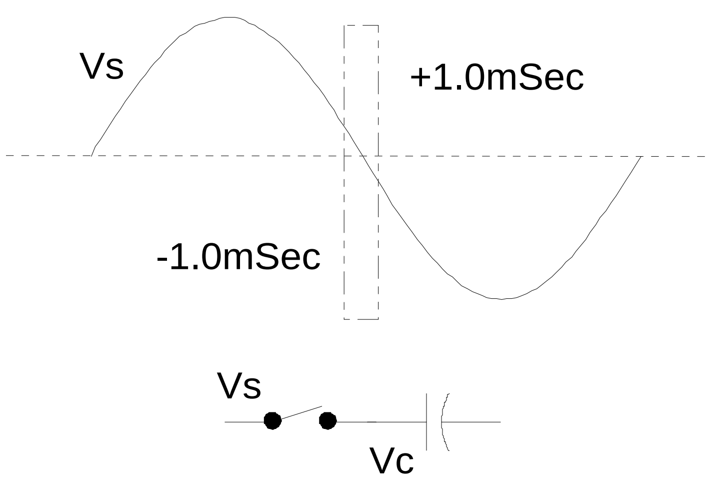
Synchronous Closing Control

- Several manufacturers now have synchronous closing available at T&D voltage levels.
- Methods include analog and microprocessor controls.
- Can be used in combination with pre-insertion device for added protection.
- **Does not provide protection during restrike.**
- May be a cost effective method when considering overvoltages at lower voltages (including customers).
- Power electronics (switches) will make concept very successful as switch voltage ratings increase.

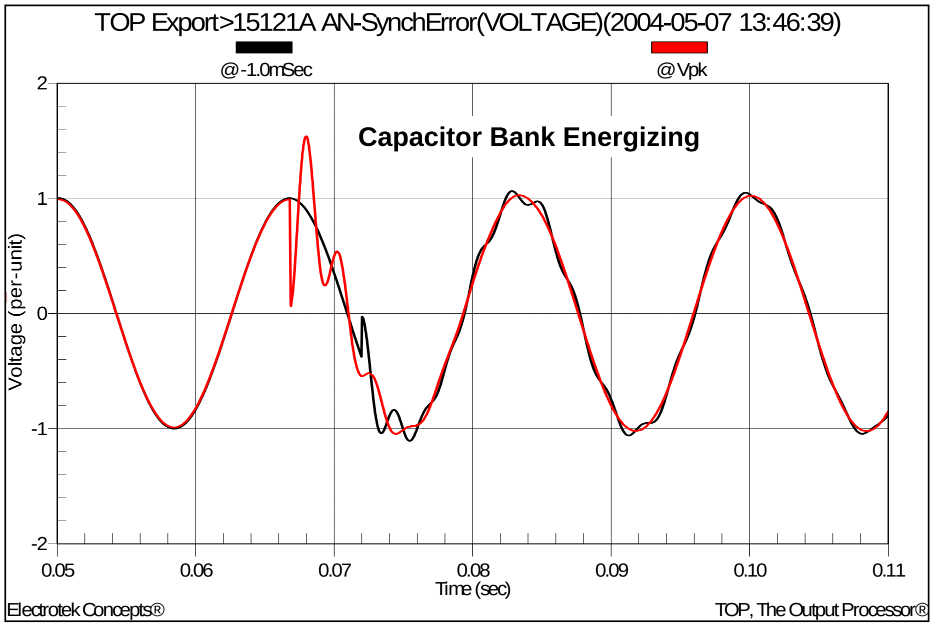
Synchronous closing is independent contact closing of each phase near a voltage zero. To accomplish closing at or near a voltage zero (avoiding high prestrike voltages), it is necessary to apply a switching device that maintains a dielectric strength sufficient to withstand system voltages until its contacts touch. Although this level of precision is difficult to achieve, closing consistency of ±0.5 milliseconds should be possible.

Illustration of Controlled Switch Closing





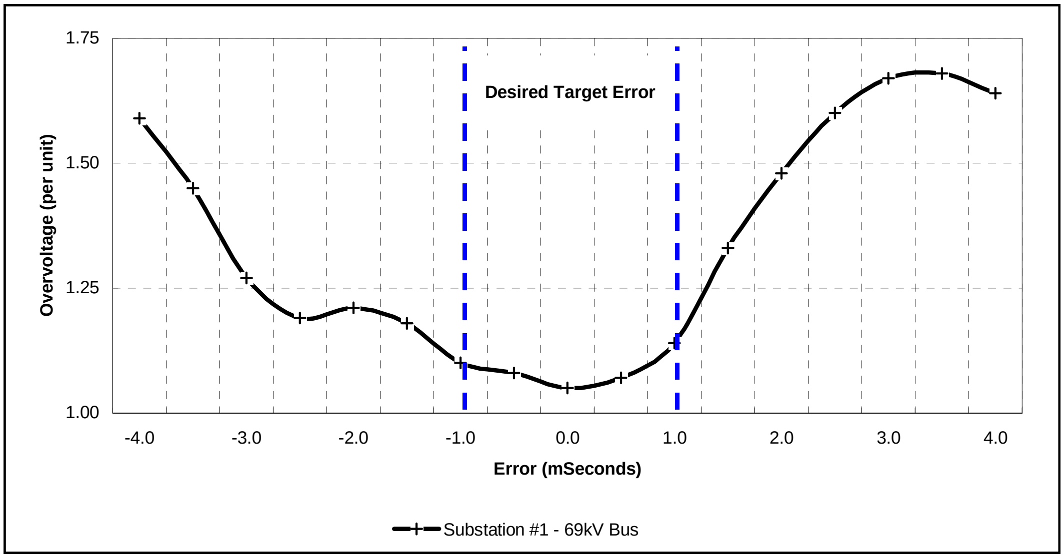
Effectiveness of Closing Control



Source: EMTP

Previous studies have indicated that a closing consistency of ±1.0 millisecond provides overvoltage control comparable to properly rated pre-insertion resistors. The success of a synchronous closing scheme is often determined by the ability to repeat the process under various (system and climate) conditions.

Synchronous Closing – Timing Error



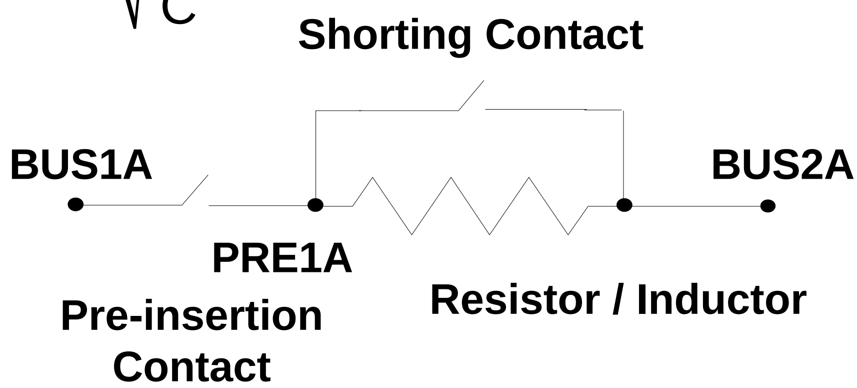
Evaluation using EMTP simulation requires the ability to vary a closing error about an ideal voltage zero. Both deterministic and statistical switches may be used to perform the necessary simulations. Results are often illustrated as overvoltage versus timing error with particular attention given to the tolerance window (e.g. ±1.0millisecond) provided by the switch/control manufacturer. Grounded capacitor banks are controlled by closing the three phases at three successive phase-to-ground voltage zeros (60° separation). Ungrounded banks are controlled by closing the first two phases at a phase-to-phase voltage zero and then delaying the third phase 90 degrees (phase-to-ground voltage zero).

Pre-insertion Devices

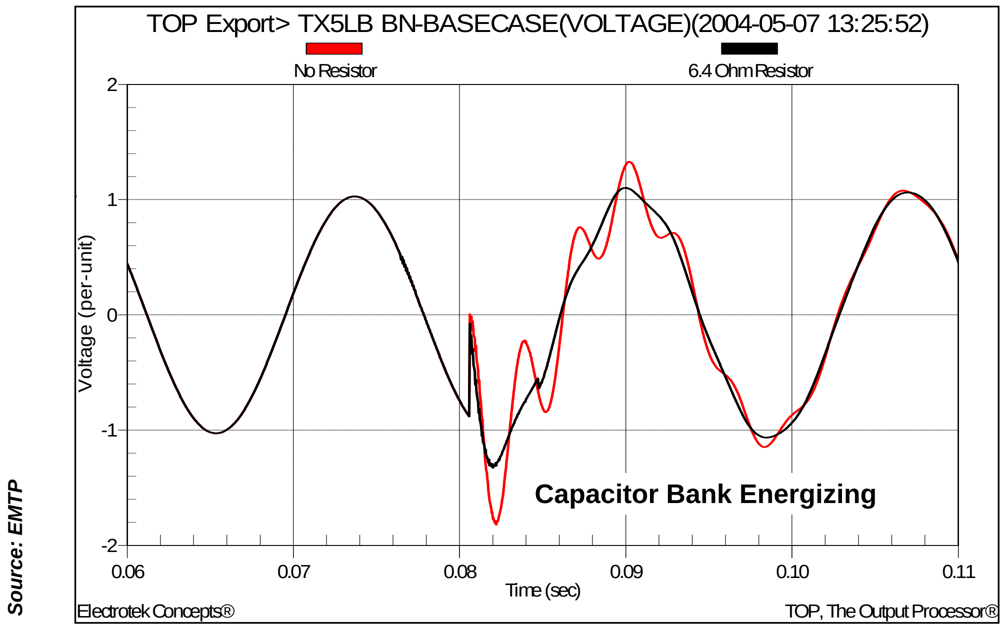
- Many options available available at T&D voltage levels.
- Devices typically include resistors and/or inductors.
- In general, resistors provide better overvoltage control and inductors provide better overcurrent control.
- Can be used in combination with synchronous closing control for added protection.
- **Does not provide protection during restrike.**
- May be a cost effective method when considering overvoltages at lower voltages (including customers).

Optimum resistor is approximately equal to the surge impedance formed by the bank and the system:

$$R_{optimum} = \sqrt{\frac{L_s}{C}}$$



Effectiveness of Pre-insertion Resistor



The optimum resistor value for controlling capacitor energizing transients depends primarily on the capacitor rating and the source strength. One particular distribution overvoltage control method, the Cooper VCR switch, includes two 3.2Ω pre-insertion resistors (6.4Ω total), which are shorted ¼ cycle after energization. The VCR switch provides capacitor switching capability for three-phase banks in ratings up to 7200 kVAr at 14.4kV. Ratings for the switch include:

Rated maximum voltage, kV rms:	15.5 kV
Nominal system voltage, kV rms:	2.4 to 14.4 kV
Rated continuous current, amps rms:	400 A
Rated capacitive switching current, amps rms:	400 A*
Rated asymmetrical making current, amps rms:	20000 A
Rated impulse withstand voltage, kV rms:	110 kV

Prestrike / Restrike Transients

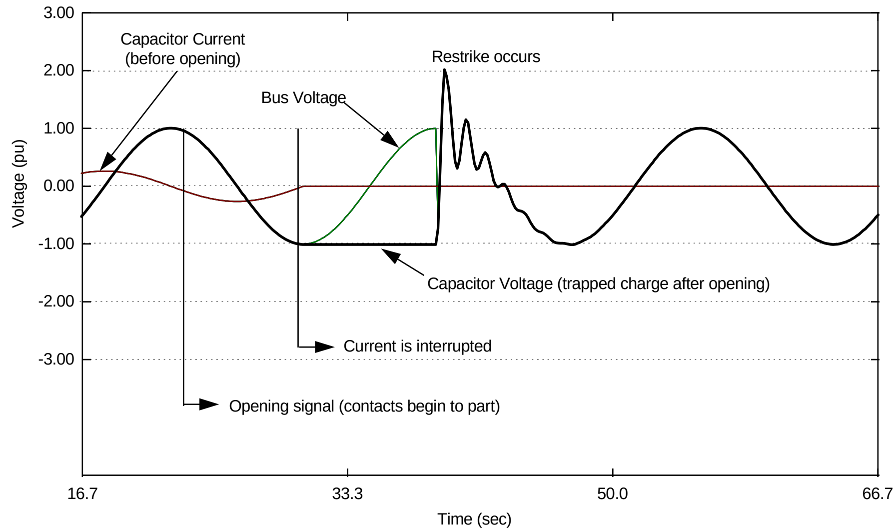
- Prestriking occurs during switch closing - high frequency inrush current is interrupted as the contacts close.
- Restriking occurs during switch opening - high frequency inrush current (and transient overvoltages) occur when the recovery voltage exceeds the dielectric strength of the switch.
- The worst case restrike occurs approximately one-half cycle after current interruption - when the recovery voltage is maximum (about 2 per-unit).
- The restrike transient generally results in the highest arrester duty.

Prestrike: Tendency for the intercontact gap to breakdown and establish current before the contacts physically touch (because of the voltage stress between them).

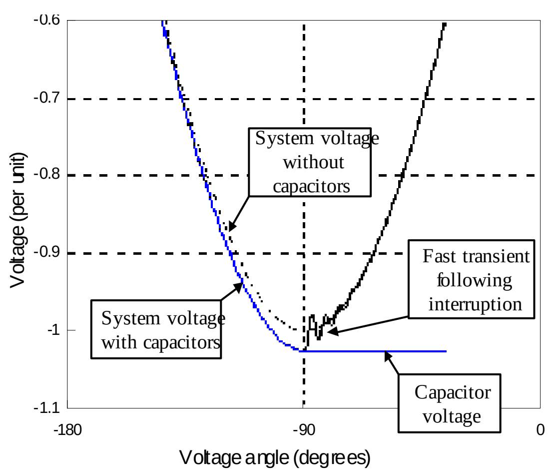
Restrike/reignition: The event is termed a reignition if the switch breaks down and current conduction is re-established with half a cycle of current interruption. If the breakdown occurs later it is called a restrike.

The Restrike Event

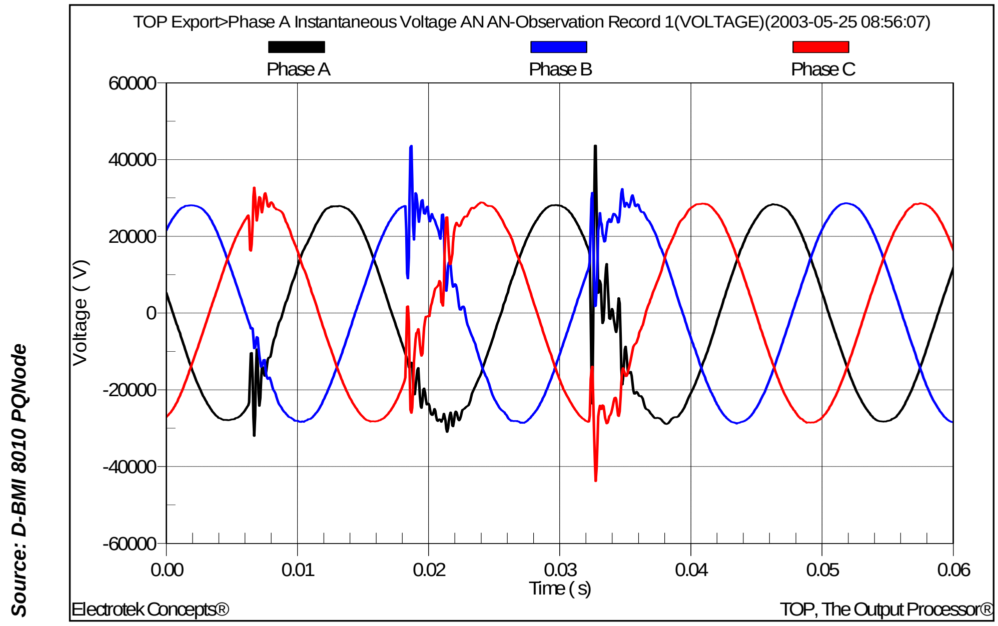
- A capacitor switching device de-energizes a capacitor bank at a current zero. Since the current is capacitive, the voltage at the time of current interruption is at a peak.



Successful interruption depends on whether the switch can develop sufficient dielectric strength to withstand the rate of rise and the peak recovery voltage. For a grounded-wye capacitor bank, two times (2 per-unit) the system voltage will appear across the switch contracts one-half cycle after interruption. If the switch cannot withstand this recovery voltage, the switch will restrike.



Measured Capacitor Switch Restrikes



Ungrounded-wye capacitor banks may expose the capacitor switch to recovery voltages greater than 2.0 per-unit. Recovery voltages may reach 2.5 per-unit on the first phase to open when the other phases open at the next current zero. If two of the phases delay opening, the recovery voltage may reach 3.0 per-unit on the first phase to open. Finally, if one of the other phases delays, the transient recovery voltage would be 4.1 per-unit. If a restrike occurs on the first phase to open at 2.5 per-unit, a recovery voltage of 6.4 per-unit can occur on one of the other two phases because of the voltage that builds up across the neutral capacitance. The high recovery voltage on another phase can cause a second restrike, resulting in a two-phase restrike.

Theoretical Arrester Duty Calculations

Restrike on Grounded-Wye Capacitor Bank

$$I_m = \frac{\left(\sqrt{(V_s - V_c)^2 - (V_p - V_s)^2}\right)}{\sqrt{\frac{L_s}{C}}} \text{ amps}$$

$$t = \frac{L_s I_m}{V_p - V_s} \text{ sec}$$

$$\text{Energy} = \frac{1}{2} I_m t V_p$$
$$= \left(\frac{1}{2}\right) * \frac{L_s I_m^2}{(V_p - V_s)} V_p \text{ Joules}$$

- For First Restrike:
  - V_s = peak line-to-neutral voltage
  - V_p = arrester protective level
  - $V_c = -V_s$
- For Worst Subsequent Restrike:
  - Same as first except $V_c = -V_p$

Two Phase Restrike on Ungrounded-Wye Capacitor Bank

$$I_m = \frac{\left(\sqrt{(V_{LL} - V_c)^2 - (2V_p - V_{LL})^2}\right)}{2\sqrt{\frac{L_s}{C}}} \text{ amps}$$

$$t = \frac{2 L_s I_m}{2V_p - V_{LL}} \text{ sec}$$

$$\text{Energy} = \frac{1}{2} I_m t V_p$$
$$= \frac{L_s I_m^2}{2V_p - V_{LL}} V_p \text{ Joules}$$

For First Restrike:

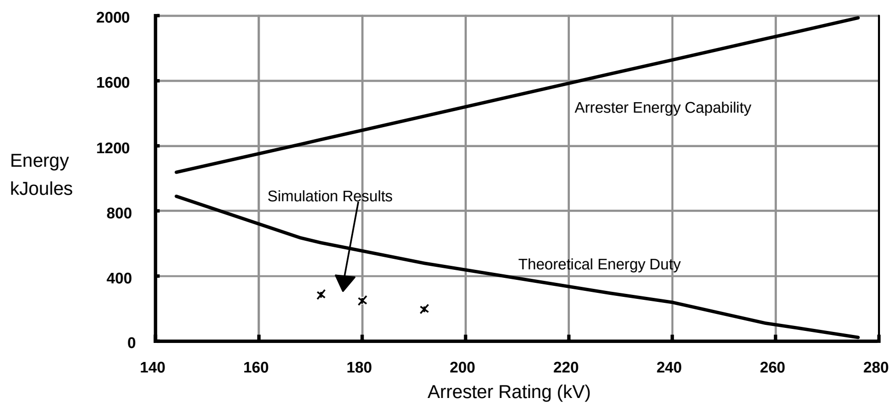
V_{LL} = peak line-to-line voltage
V_p = arrester protective level
V_c = -2.37 x peak line-to-neutral voltage

For Worst Subsequent Restrike:

Same as first except
$V_c = -2V_p$

Arrester Duties During a Restrike

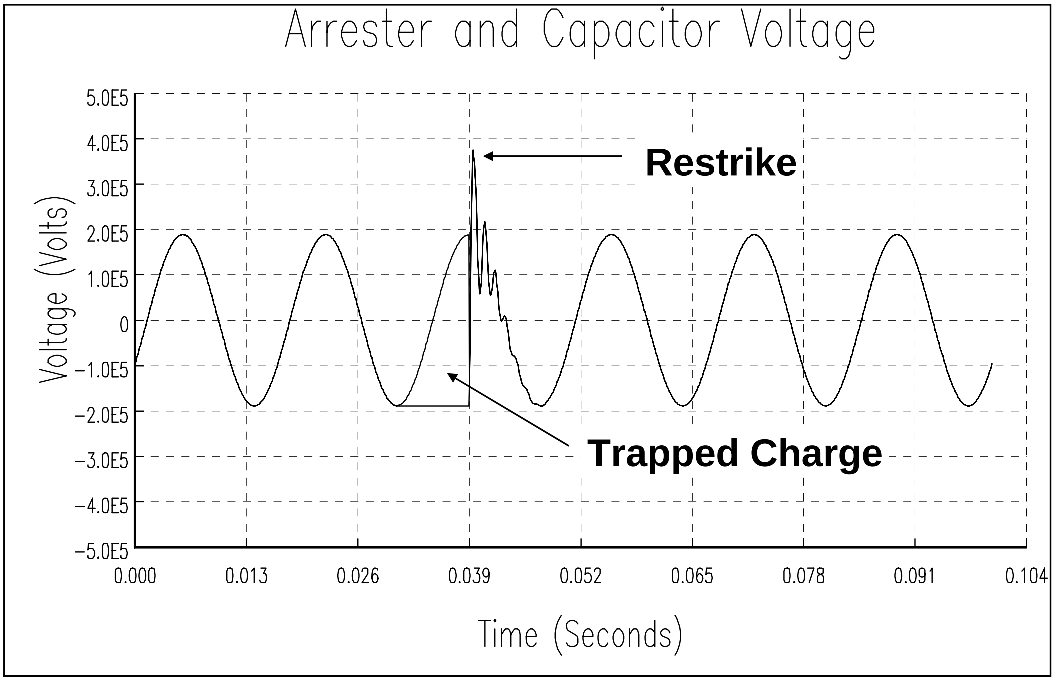
- Theoretical arrester energy duty during a capacitor restrike, arrester energy capability, and simulation results as a function of MOV arrester protective level.



The energy duty requirements for arresters at capacitor bank locations depends on the rating of the capacitor and on existing arresters located at the substation. In general, the most severe duty for an arrester near a capacitor bank occurs during a switch restrike. This is due to the trapped charge on the capacitor at the instant the restrike occurs, and results in a greater magnitude of the voltage oscillation.

It is also important to consider the coordination of MOV arresters (at the capacitor location) with any conventional gapped type arresters in the substation. It is important that the protective level of the MOV arresters be low enough to prevent operation of the gapped arresters.

Example Restrike Waveforms – Simulated

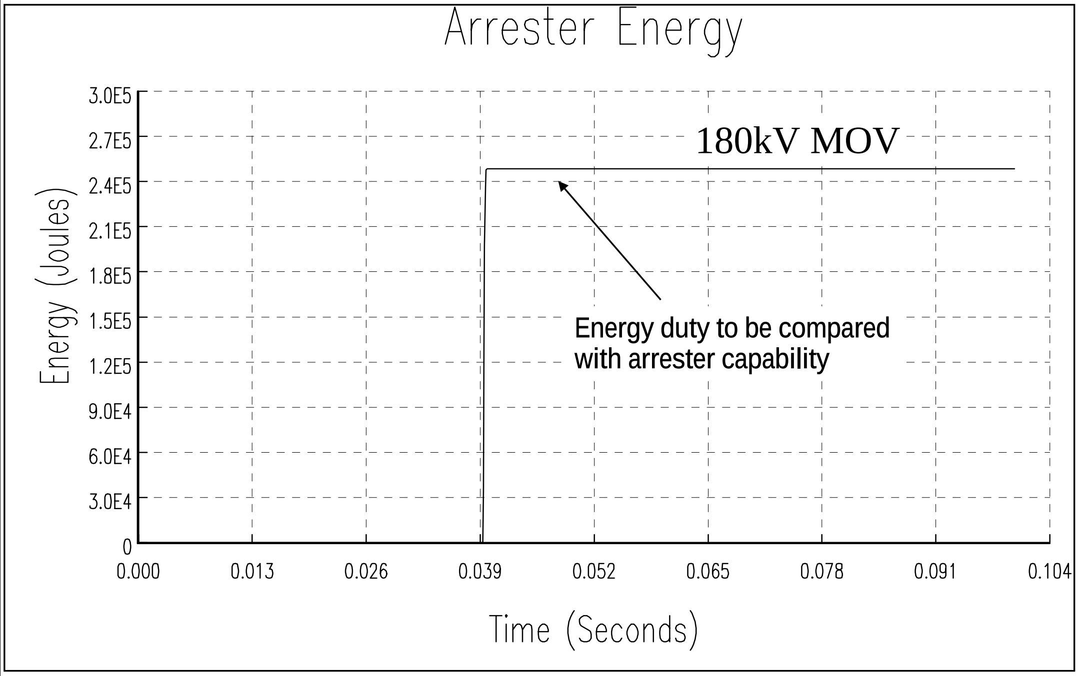


The arrester energy during a restrike depends on the following parameters:

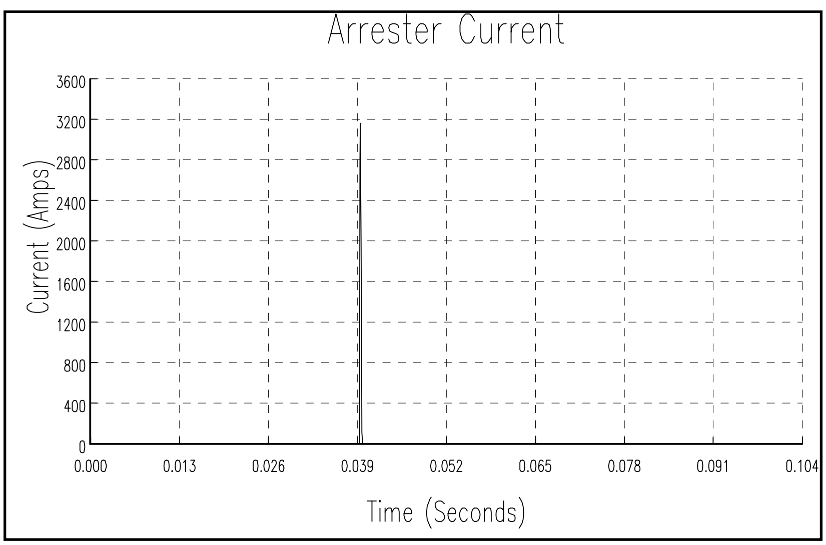
- Capacitor configuration
- Capacitor rating
- Existence of other parallel capacitors
- Source strength
- Number of lines leaving substation
- Nearby capacitor banks
- Arrester protective level

Arrester applications at large shunt capacitor banks need to be evaluated carefully due to the high energy duties that can occur in the event of a restrike in the capacitor switch. The energy levels will depend on whether the capacitor bank is grounded or ungrounded.

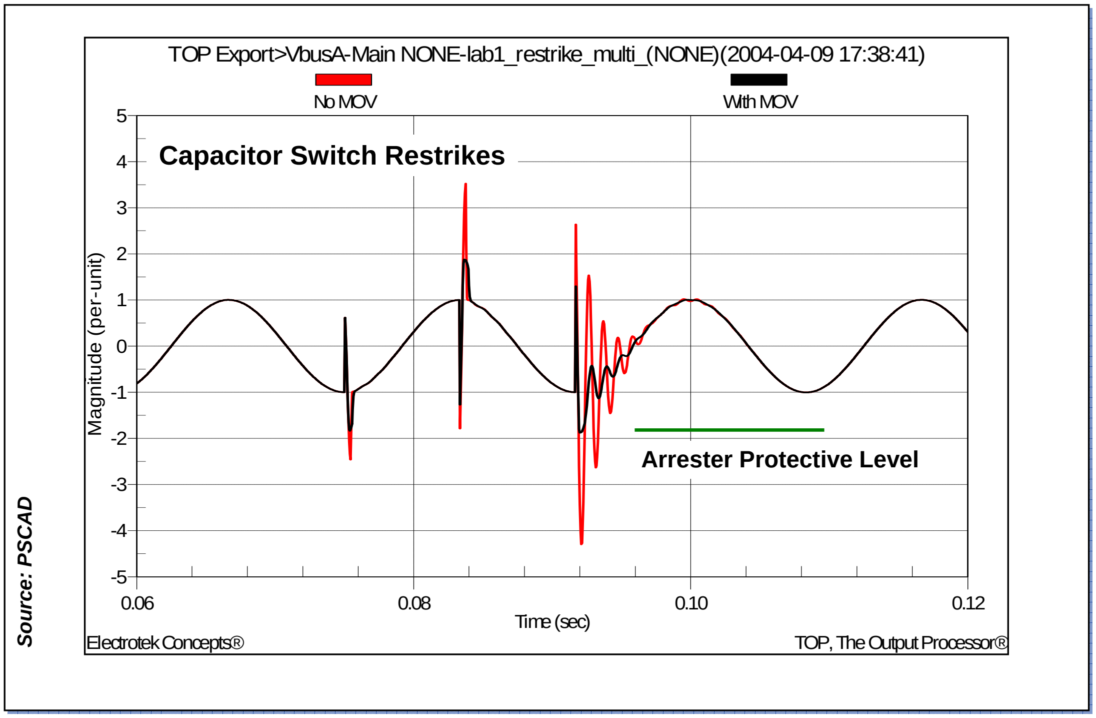
Example Restrike Waveforms – continued

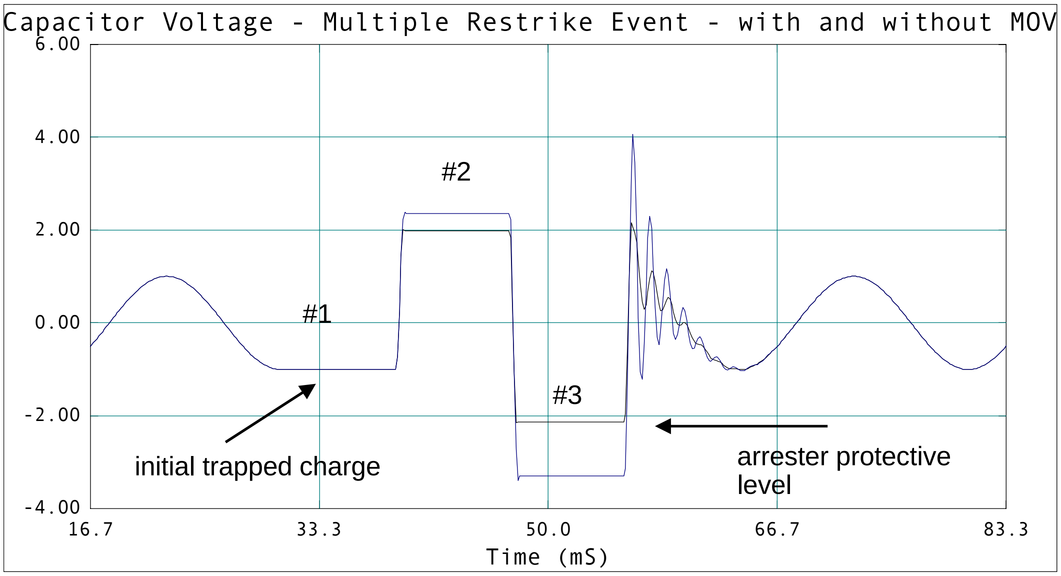


Arrester Current:

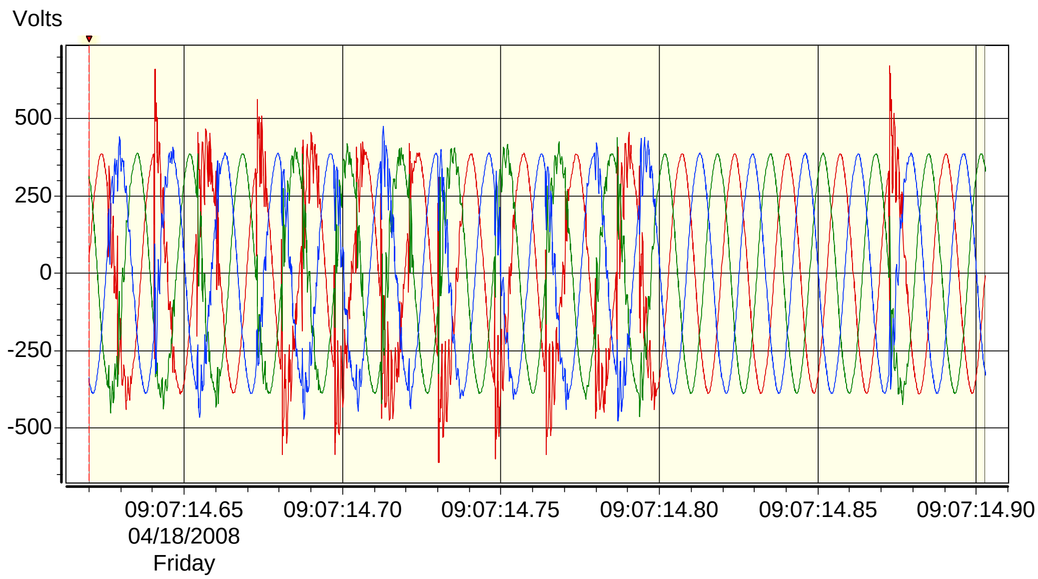


Simulated Multiple Restrike Event



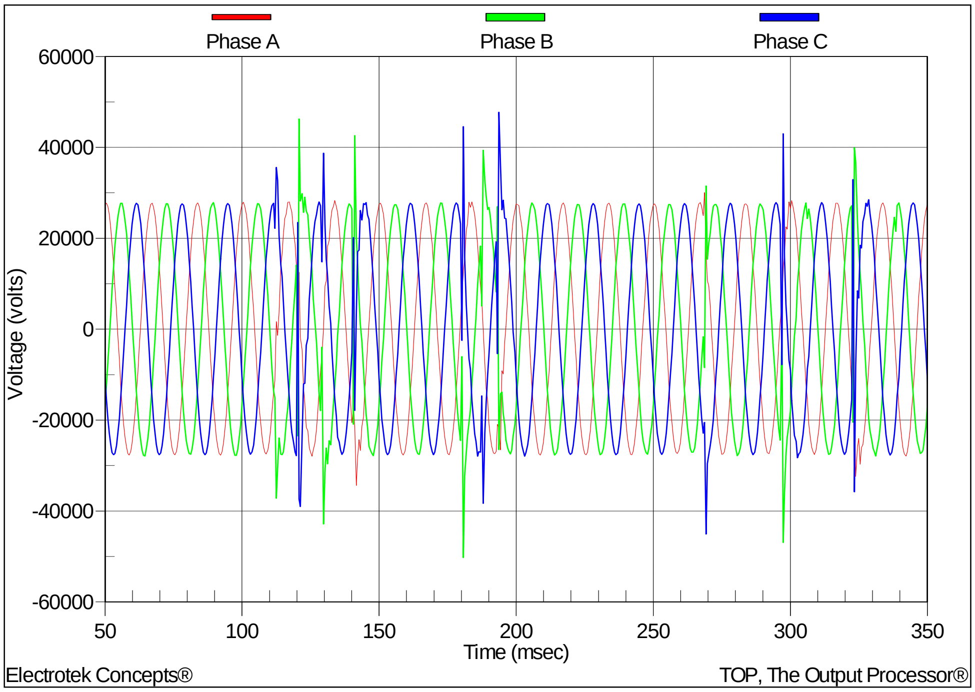


Measured Multiple Restrike Voltage



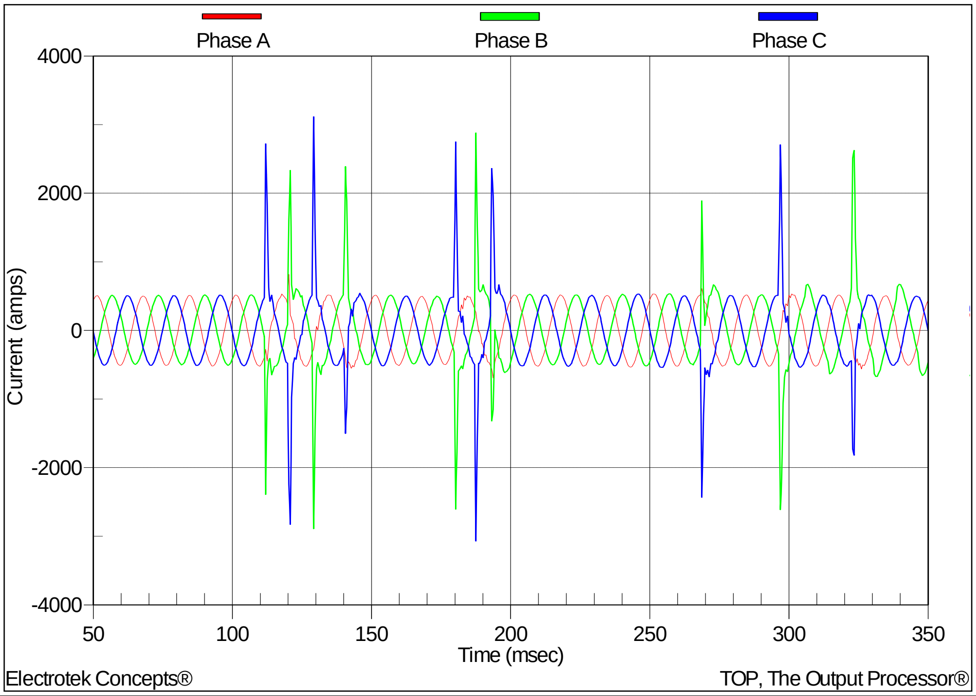
Customer secondary voltage during multiple restrike of a 14.4 MVAr, 34.5kV substation capacitor bank switch.

Measured Multiple Restrike Voltage



Bus voltage for measurement of a multiple restrike on an ungrounded 7,800 kVAr, 34.5kV capacitor bank that was protected with a 27kV MOV arrester.

Measured Multiple Restrike Current



Transformer secondary current for measurement of a multiple restrike on an ungrounded 7,800 kVAr, 34.5kV capacitor bank that was protected with a 27kV MOV arrester.

Arrester Options

- MOV/SiC coordination is often difficult to achieve. If coordination is not possible, there are three options for arrester protection at the substation involved:
    - Replace all of the gapped type arresters in the substation with MOV arresters. The arresters will share the energy duty in the event of a restrike and there should be minimal danger of arrester failure.
    - Add one set of MOV arresters. This will greatly decrease the probability that a conventional arrester will fail during a capacitor restrike event because the MOV arrester will reduce the chance of a conventional arrester sparkover. The minimum rated MOV should be used for best coordination with existing arresters.
    - Use only conventional gapped type arresters at the substation. This option relies on the integrity of the capacitor switch to prevent a restrike event. If a restrike would occur, it is unlikely the conventional arresters would be able to withstand the associated energy duty.

The energy duty requirements for arresters at capacitor bank locations depends on the rating of the capacitor and on existing arresters located at the substation. In general, the most severe duty for an arrester near a capacitor bank occurs during a switch restrike. This is due to the trapped charge on the capacitor at the instant the restrike occurs, and results in a greater magnitude of the voltage oscillation.

The arrester energy during a restrike depends on the following parameters:

Capacitor configuration (grounded vs. ungrounded)

Capacitor rating

Existence of other parallel capacitors

Source strength

Number of lines/feeders leaving the substation

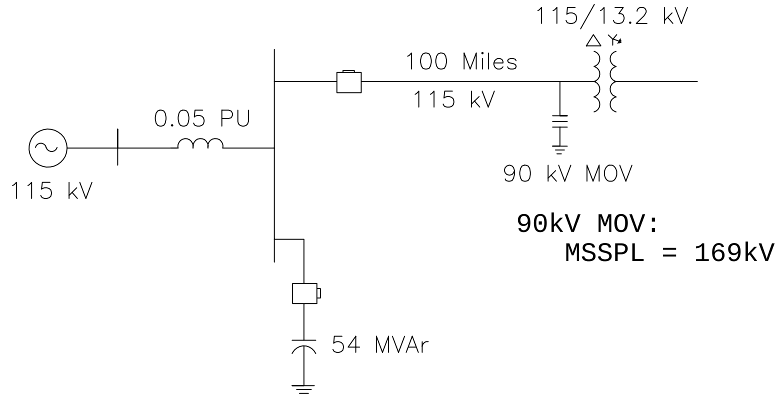
Nearby capacitor banks

Arrester protective level(s)

Transients at Transformer Terminations

- Energizing a shunt capacitor bank can subject remote system equipment, especially three-phase transformers at line terminations, to excessive phase-to-phase transients.

Simplified Oneline Diagram:



Surges generated by the energization of the capacitor bank would travel down the line towards the transformer and double at that point. It would be possible to get a +2.0 per-unit surge on one phase and a -2.0 per-unit on another. This would result in 4.0 per unit phase-to-phase. (Voltages are given in per unit of the rated peak line-to-ground voltage.) This could be a potential problem for transformers that are applied in this configuration.

The actual severity of the transient is a function of the system configuration and can be significantly higher than the 4.0 per-unit value mentioned above. In general, this transient can be reduced by any of a number of methods including closing resistors, controlled closing, staggered closing, capacitor bank reactors, and surge arresters.

Important System Parameters

- Source characteristic:
  - Transient magnitudes are generally reduced by stronger sources and/or more lines at the substation.
- Switched capacitor bank rating:
  - Varying the switched capacitor bank rating changes the energizing frequency and therefore the phase-to-phase transients.
- Surge arresters:
  - Arresters located at the transformer location can help reduce the phase-to-phase transients. Usually these arresters are connected phase-to-ground and therefore limit the phase-to-phase voltage to twice the arrester protective level.
- Radial line length:
  - Line length is important because it determines the travel time of the traveling wave and therefore has a significant impact on the magnitude of the phase-to-phase transient.

The trial-use IEEE standard for transformers (262b-1977) specifies a phase-to-phase switching surge insulation level of 1050kV (3.73pu) for 345kV transformers with BIL of 950kV, 1050kV, or 1300kV. This limit can be used as a guideline when evaluating phase-to-phase overvoltages.

System Voltage kV	Ph-Ph Switching Impulse Level (kV Crest)
345	1050
500	1550
765	2300

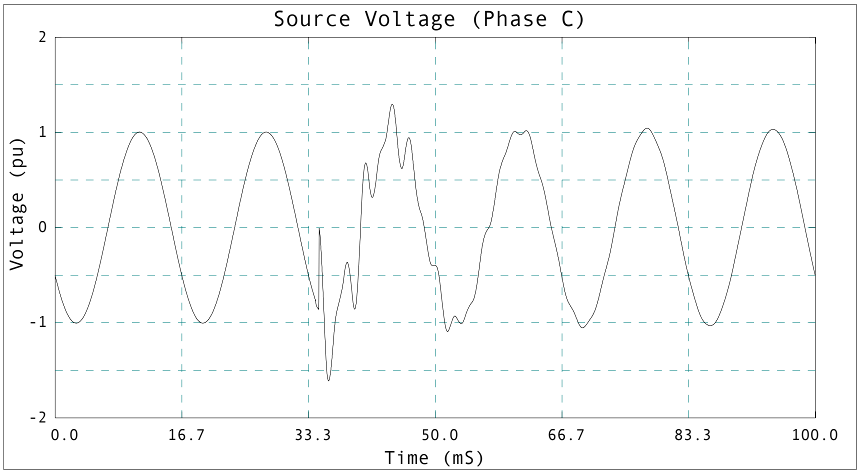
Transformer:

BIL	BSL
350	280
450	375
550	460

Simulated Waveforms – Source

- 115kV bus (phase-to-ground) voltage, during energization of the 54MVAr capacitor bank:

Note: $1pu = 115kV * \frac{\sqrt{2}}{\sqrt{3}}$



...Bayless, et. al (IEEE 86 SM 419-6):

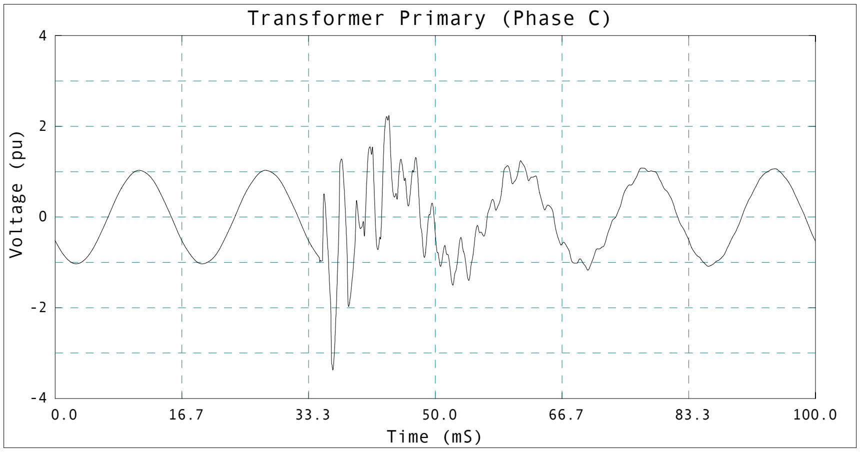
"In normal insulation coordination, at least a 15% margin is applied between the arrester protective level and the equipment basic switching impulse level (BSL)." Applying this 15% to standard insulation levels yields:

System Voltage kV	Calculated Ph-Ph BSL(kV Crest)
115	450
138	550
161	650
230	900
345	1300
500	1925
765	2925

Simulated Waveforms – Line End

- Transformer primary (phase-to-ground) voltage, during energization of the 54MVAr capacitor bank:

Note: $1\text{pu} = 115\text{kV} * \frac{\sqrt{2}}{\sqrt{3}}$



It can be seem in the figure above that the transient at the transformer termination is made up of steep fronted waves occurring at a high frequency. These are exactly the kind of transient. voltage that can excite internal resonances within the transformer. This phenomena should be studied with detailed representations of the internal winding capacitances and mutual inductances of the transformer being evaluated.

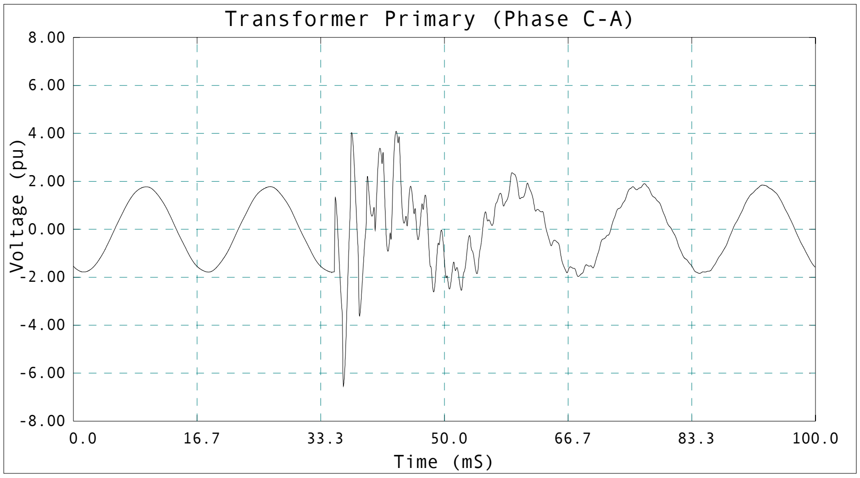
...Bayless, et. al (IEEE 86 SM 419-6):

“A Working Group on Resonant Overvoltages with the IEEE Transformer Committee worked on this topic from early 1970s to the mid 1980s. This group studied the phenomena extensively and attempted to define a dielectric test which would identify potential problems with resonant overvoltages. Although much was leaned, no such test was defined. The basic problem is that every transformer has internal natural frequencies, and these may be excited of the corresponding transient is applied at its terminal.“

Simulated Waveforms – Line End

- Transformer primary (phase-to-phase) voltage, during energization of the 54MVAr capacitor bank:

Note: $1\text{pu} = 115\text{kV} * \frac{\sqrt{2}}{\sqrt{3}}$



Reducing these voltage and their effects:

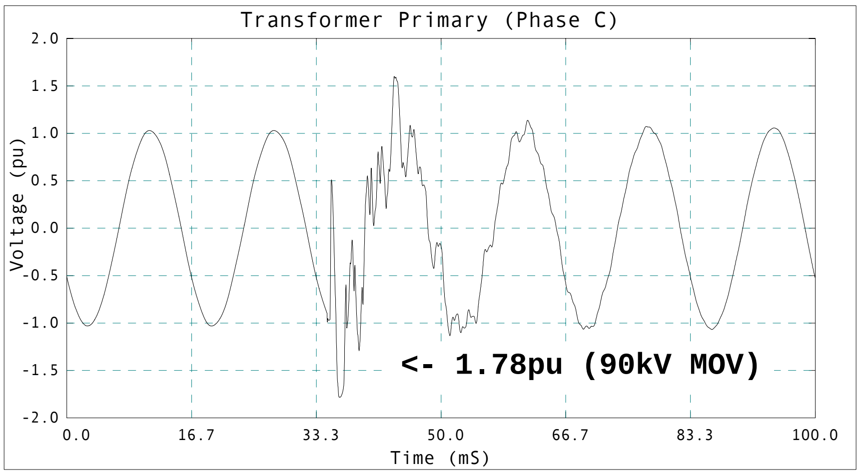
- closing resistors / inductors
- controlled closing (synchronous closing control)
- staggered closing
- capacitor bank reactors
- surge arresters

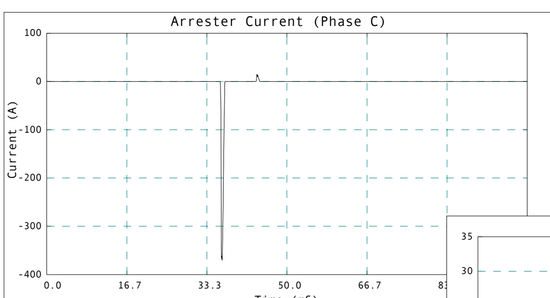
The probability of obtaining high phase-to-phase surges is greater for an ungrounded capacitor bank than for a grounded bank. However, the peak magnitude of the maximum surge is approximately the same for both cases.

Simulated Waveforms – Effect of Arrester

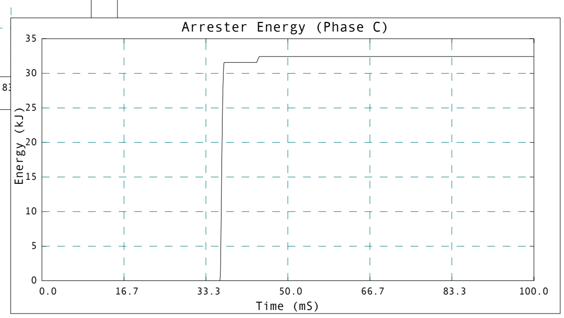
- Transformer primary (phase-to-phase) voltage, during energization of the 54MVAr capacitor bank:

Note: $1\text{pu} = 115\text{kV} * \frac{\sqrt{2}}{\sqrt{3}}$





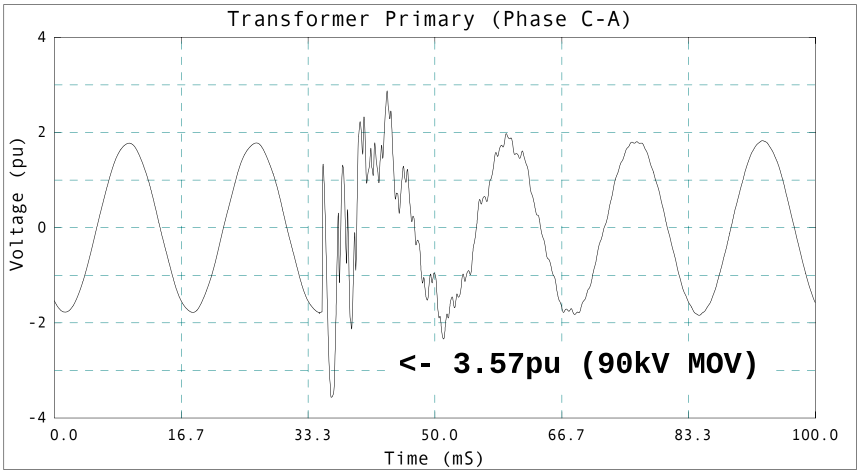
7.2kJ/kV (648kJ) ->



Simulated Waveforms – Effect of Arrester

- Transformer primary (phase-to-phase) voltage, during energization of the 54MVAr capacitor bank:

Note: $1\text{pu} = 115\text{kV} * \frac{\sqrt{2}}{\sqrt{3}}$



$$3.57\text{pu} * 115\text{kV} * \left(\sqrt{2} \middle/ \sqrt{3} \right) = 335\text{kV} * 1.15 = 385\text{kV}$$

115kV Transformer:

BIL	BSL	
350	280	[low BIL transformer]
450	**375**	
550	460	

Ferroresonance

- Ferroresonance is a term generally applied to a wide variety of interactions between capacitors and iron-core inductors that results in unusual voltage and/or currents.
- Several of the more common causes include:
  - single-phase cutouts / single-phase reclosers
  - fuse blowing or opening (transformer or line fuse)
    (or a lineman pulls an elbow connector)
  - manual cable switching to reconfigure a cable circuit during an emergency condition
  - three-phase switch with large pole closing span

Ferroresonance is a term generally applied to a wide variety of interactions between capacitors and iron-core inductors that results in unusual voltage and/or currents. In linear circuits, resonance occurs when the capacitive reactance equals the inductive reactance at the frequency at which the circuit is excited. Iron-core inductors have a nonlinear characteristic and therefore a range of inductance values. This relationship may lead to a number of operating conditions where the inductive reactance does not equal the capacitive reactance, but yet very high and damaging overvoltages occur.

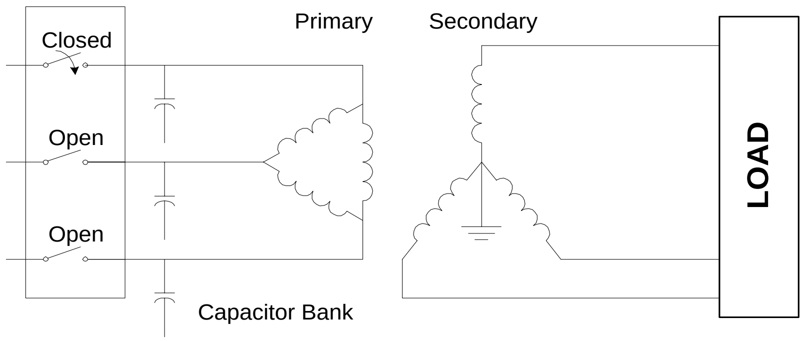
Two additional conditions must be satisfied for ferroresonance to occur:

The length of cable between the transformer and open conductor location must have sufficient capacitance to produce excessive ferroresonant voltages

The losses in the circuit and the resistive load on the transformer must be low.

Ferroresonance – continued

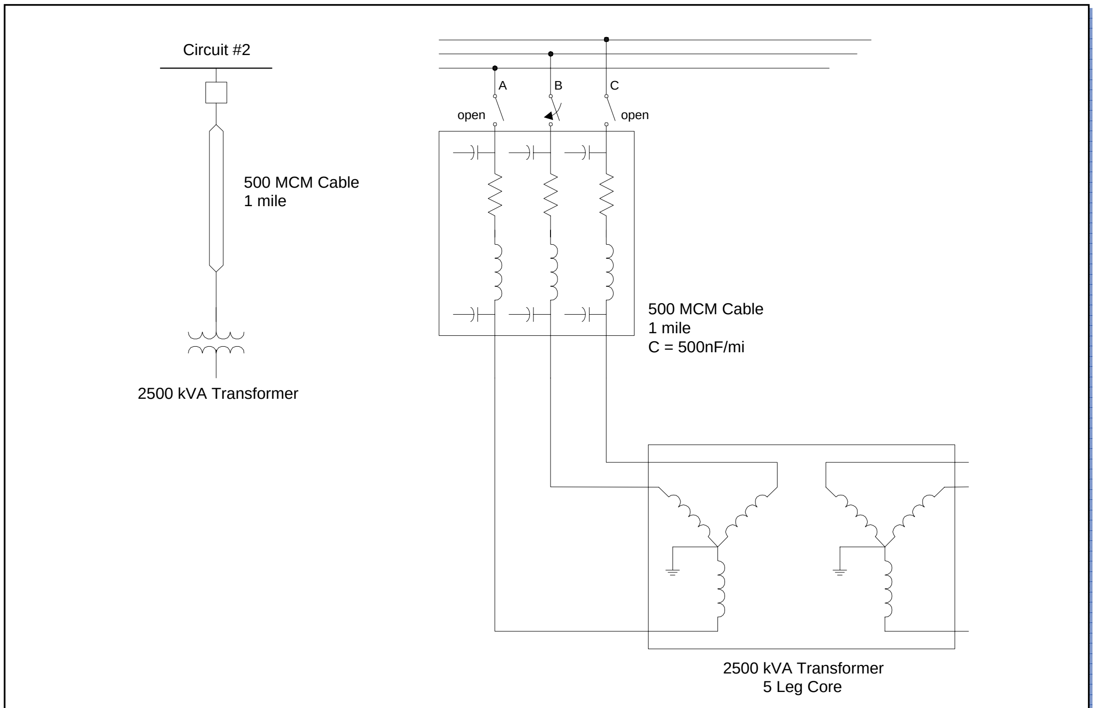
- For resonant circuit, capacitive reactance must be equal to transformer magnetizing reactance:
  - Overvoltages produce core saturation causing the magnetizing reactance to vary.



In a typical power system, ferroresonance occurs when a transformer becomes isolated on a cable section in such a manner that the cable capacitance appears to be in series with the magnetizing characteristic of the transformer. An unbalanced switching operation is required to initiate the condition. Several of the more common causes include:

- single-phase cutouts
- fuse blowing or opening (transformer or line fuse)(or a lineman pulls an elbow connector)
- single-phase reclosers
- cable connector of splice opening
- manual cable switching to reconfigure a cable circuit during an emergency condition
- open conductor fault in overhead line feeding cable
- three-phase switch with large pole closing span

Example Circuit Configuration

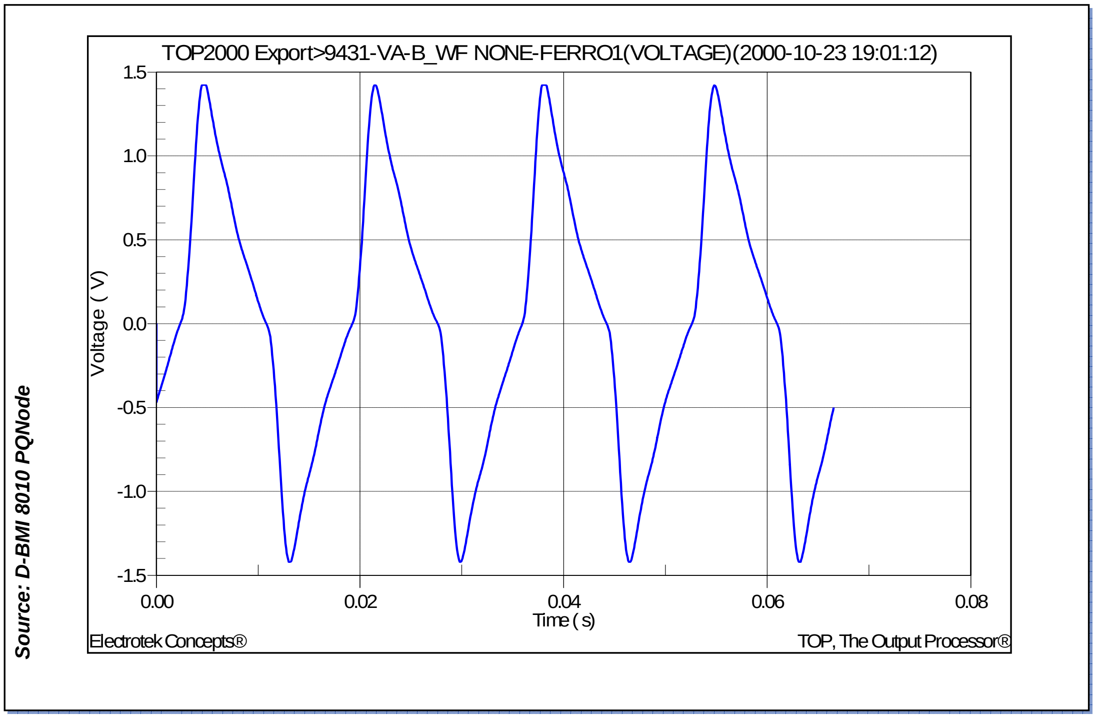


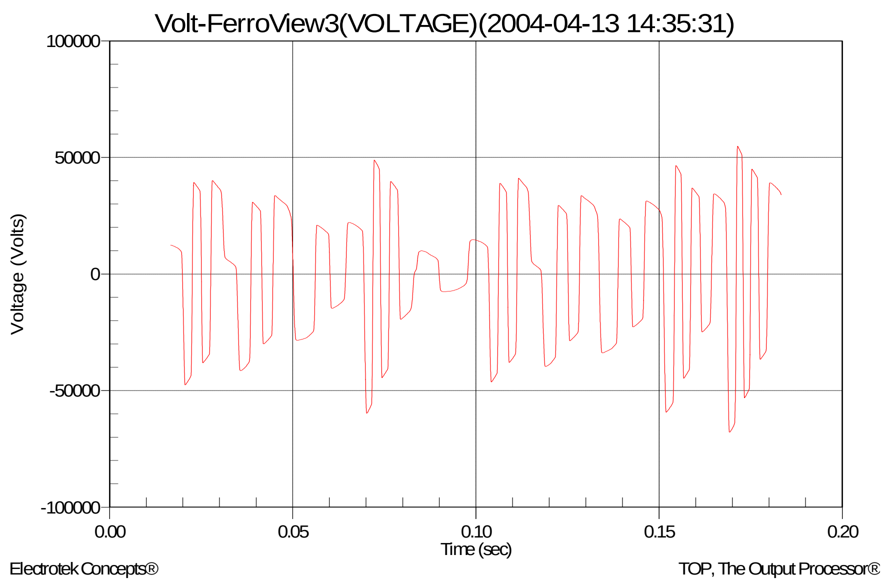
One thing common to all types of ferroresonance is that the steel core is driven into saturation, often deeply and randomly (otherwise, it is conventional resonance). As the core goes into a high flux density, it will make an audible noise due to the magnetostriction of the steel and movement of the core laminations. The sound produced is distinctly different and louder than the normal hum of a transformer.

Another reported symptom of the high magnetic field is charring or bubbling of the paint on the top of the transformer tank. This is due to stray flux heating in parts of the transformer where magnetic flux is not expected. Since the core is saturated repeatedly, the magnetic flux will find its way into the tank wall and other metallic parts.

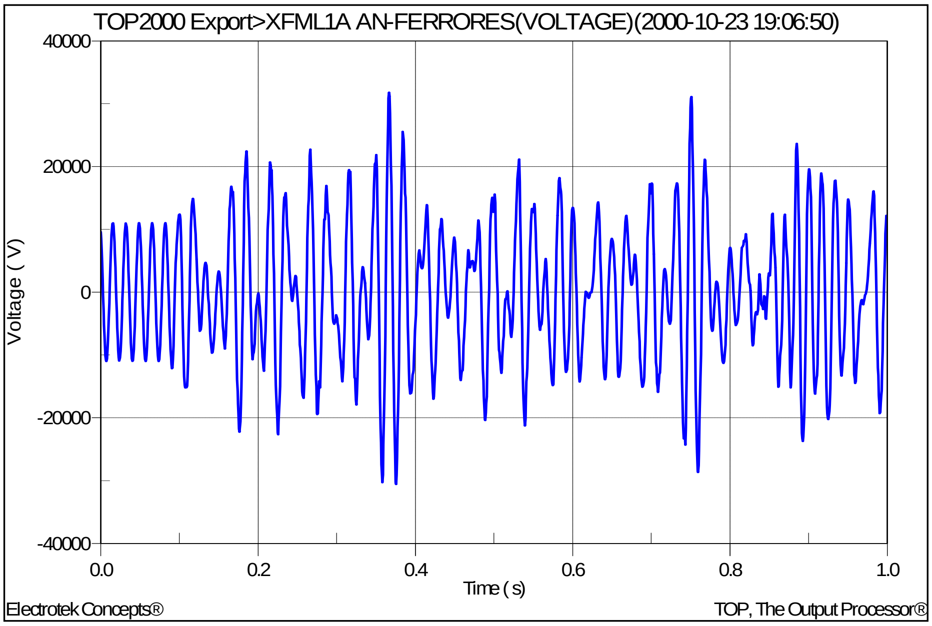
Ferroresonance cannot always be entirely avoided, however, steps can be taken to reduce the probability of occurrence. These include locating fuses or disconnects near the transformer (to minimize capacitance), and using three-phase switches. However, neither of these remedies will provide protection for the broken conductor case.

Measured Ferroresonance Waveform

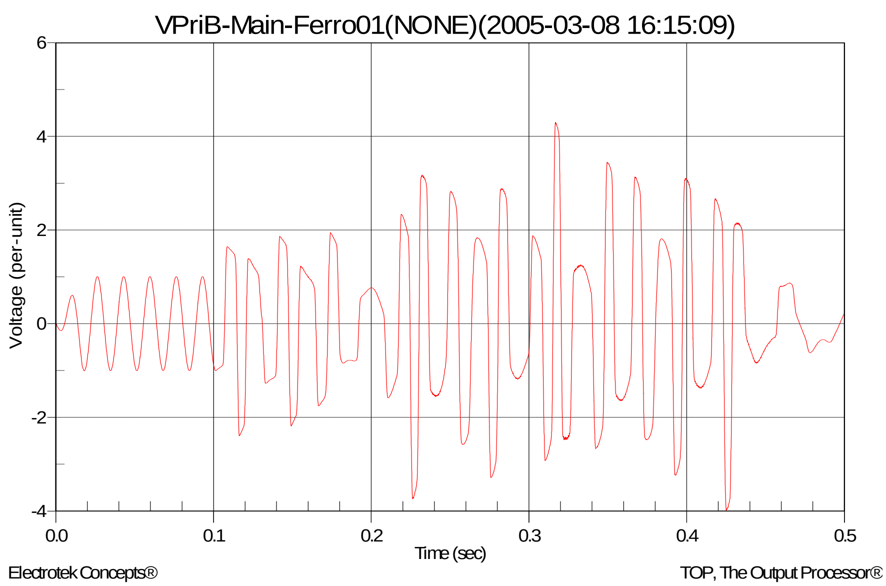




Simulated Ferroresonance Waveform



Source: EMTP



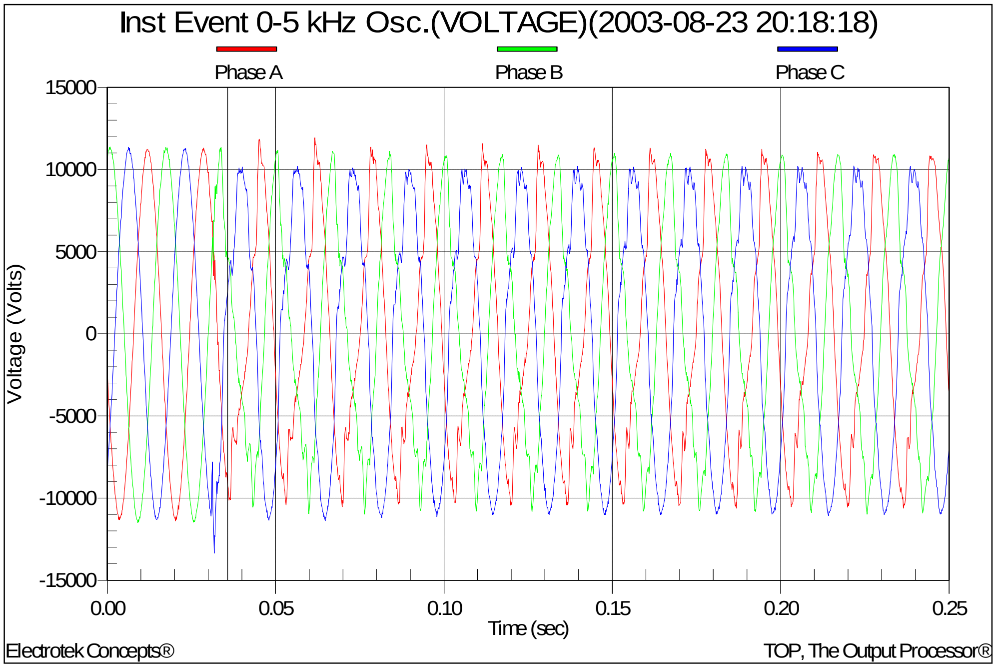
Dynamic Overvoltages

- Energizing a transformer and a capacitor bank together can cause excessive dynamic overvoltages that affect the transformer, the capacitors, the fuses, and the arresters. These overvoltages may be evidenced by capacitor failures and/or spurious fuse operations.

- The nature of the problem involves generation of high voltages due to the transformer inrush currents that are rich in harmonics by a system whose natural frequency is near one of these harmonics.

Transformer inrush current includes significant magnitudes of harmonics of the fundamental frequency, i.e., second, third, fourth, fifth, etc. The highest magnitudes tend to occur for the lowest order harmonics. If the system equivalent impedance at one or more of those frequencies is high, then the voltage at the point will also be high (V = IZ). This tends to happen when a shunt power capacitor bank is applied, causing a parallel resonance with the system. The problem exhibits itself in the form of a long-term overvoltage, which has a high harmonic content, lasting for many cycles-even seconds.

Dynamic Overvoltages – Waveform



The waveform above shows the three-phase voltage during a 13.2kV distribution system transformer energizing event. The inrush current interacts with the impedance to create a voltage that has significant harmonic components.

Because arresters cannot effectively protect against steady-state or dynamic overvoltages, switching transformers and capacitor banks together is not recommended unless detailed studies show that the resulting overvoltages will not be excessive. This type of switching is commonly done on distribution circuits where the resistive component of the load usually effectively dampens this type of transient.

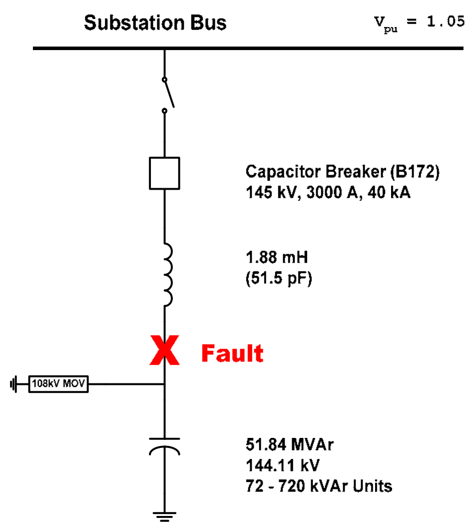
Outrush Reactor Faults – Excessive TRV

- Current limiting outrush reactors are sometimes installed with utility transmission capacitor banks. These reactors limit the high-magnitude, high-frequency currents that flow when the capacitor bank discharges into a nearby fault.
- While an outrush reactor reduces the magnitude and frequency of the current during close-in faults, it may cause excessive transient recovery voltages (TRVs) for the capacitor bank circuit breaker due to the very high frequency component of the recovery voltage associated with the reactor.
- Excessive TRVs may cause the capacitor bank circuit breaker to fail to clear during certain fault conditions.
- Possible solutions include adding capacitance to reduce the rate-of-rise of the recovery voltage.

The analysis of high-frequency transient recovery voltages frequently requires the use of sophisticated digital simulation programs. Simulations provide a convenient means to characterize transient events, determine resulting problems, and evaluate possible mitigation alternatives. Occasionally, they are performed in conjunction with system monitoring for verification of models and identification of important power system problems. The complexity of the models required for the simulations generally depends on the system characteristics and the transient phenomena under investigation.

Outrush Reactor Modeling

- An outrush reactor may be installed with a capacitor bank to provide substation circuit breaker protection in the event of reclosing into a close-in fault. The reactor rating may have been based on the older general purpose circuit breaker limitation in IEEE Std. C37.06 (Ipk*f < $2x10^7$).



$$f = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(1.88mH * 51.5\rho F)}} = 511.491kHz$$

The transient recovery voltage is the voltage across the terminals of a pole of circuit breaker following current zero when interrupting faults. Transient recovery voltage waveshapes can be oscillatory, exponential, cosine-exponential or combinations of these forms. Transient recovery voltages due to short-line faults (SLFs) are characterized by triangular-shaped waveshapes and a very steep initial rate-of-rise. The triangular shape of the recovery voltage arises from positive and negative reflections of the traveling waves that oscillate between the open circuit breaker and the fault. Due to the short distance involved, the initial rate-of-rise of the recovery voltage (RRRV) can be very steep.

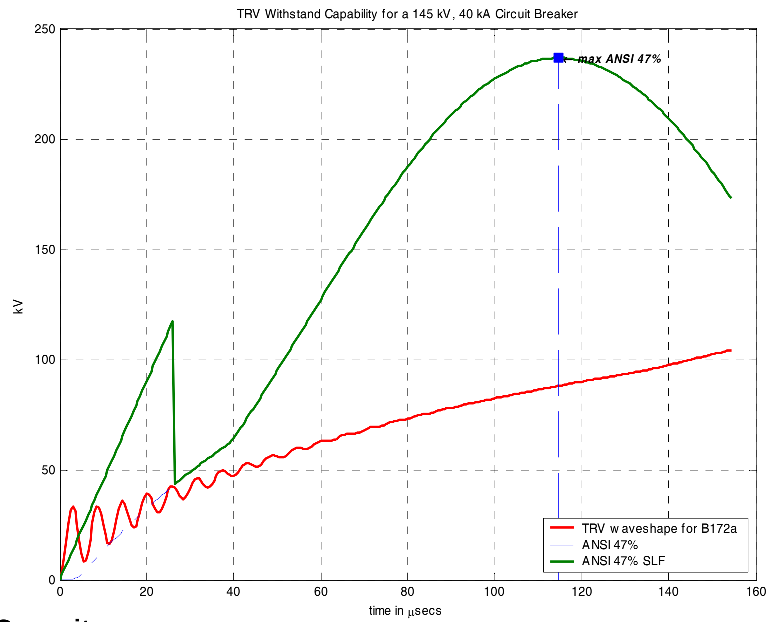
TRV Evaluation Criteria

- Criteria for a TRV evaluation can be based on IEEE Std. C37.011, which states that evaluations should be conducted for three-phase ungrounded faults at the circuit breaker terminals when the system voltage is at maximum. The maximum voltage is 1.05 per-unit of the nominal voltage.

- The TRV evaluation for a capacitor bank circuit breaker considers the following conditions:
  - during the clearing of a three-phase ungrounded symmetrical fault at the circuit breaker terminal when the system voltage is at the maximum (1.05 per-unit).
  - during the clearing of a single-line-to-ground fault at the circuit breaker terminal when the system voltage is at the maximum (1.05 per-unit).
  - during the clearing of a three-phase-ungrounded fault at the outrush reactor terminal.
  - during the clearing of a three-phase-to-ground fault at the outrush reactor terminal.
  - during the clearing of a single-line-to-ground fault at the outrush reactor terminal.

For conditions where the simulated transient recovery voltage exceeds the circuit breaker’s withstand capability, the mitigation option of added capacitance is evaluated.

Simulation Results – Reactor Faults

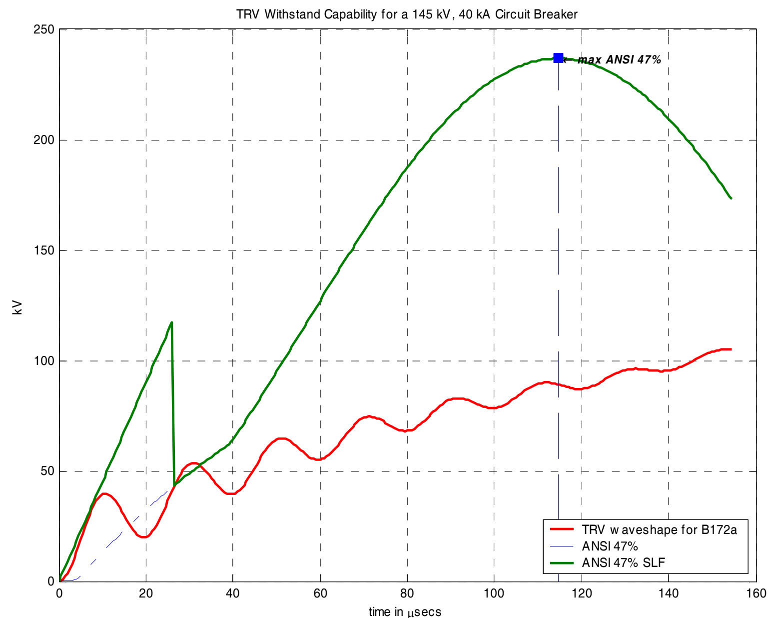


No Added Capacitance

The simulated transient recovery voltages exceeded the short-line fault capability limits when clearing three-phase ungrounded, three-phase grounded, and single-line-to-ground faults at the reactor terminals.

This is because the recovery voltage severity is worsened by the very high frequency component of the transient voltage on the reactor side of the circuit breaker.

Simulation Results – Added Capacitance

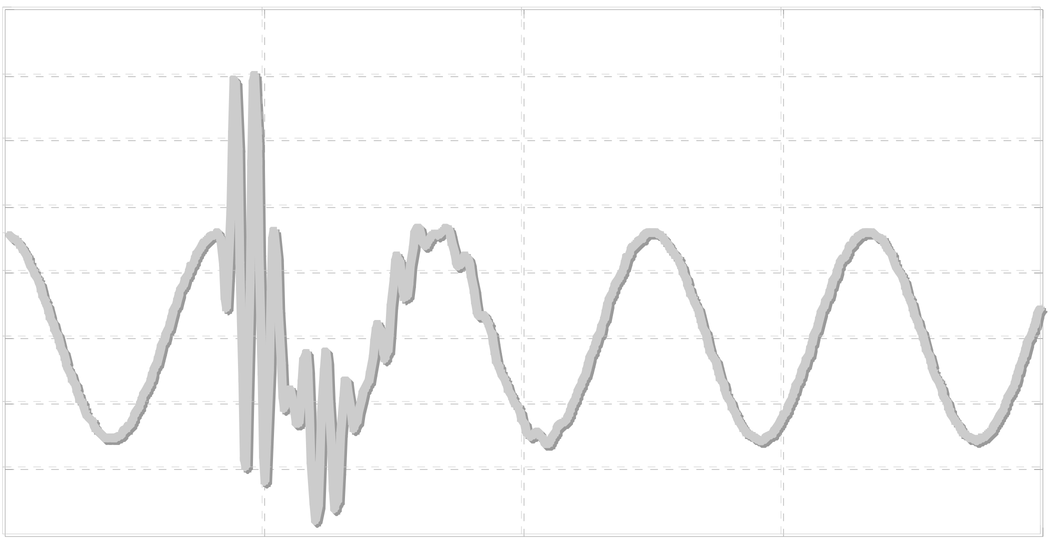


5000pF Added Capacitance

One method for improving this condition is with the application of an additional capacitance to ground between the circuit breaker and the outrush reactor. This capacitance reduces the severity of the transient recovery voltage.

Supplemental simulation cases can be completed to evaluate important contingency operating conditions. The severity of the transient recovery voltages may not be changed significantly because the characteristic is dominated by the very high frequency component of the transient voltage on the reactor side of the circuit breaker.

IMPACT OF CAPACITORS ON POWER QUALITY



Impact of Capacitors on Power Quality

- Power quality is one of the most important concerns facing electric utilities today. The increasing dependence on sophisticated electronic controls and manufacturing within customer facilities is resulting in a requirement for higher levels of reliability.
- The emphasis on overall power system efficiency is causing a growth in the application of shunt capacitor banks for power factor and voltage correction.
  - This is occurring within customer facilities, as well as on the utility power system.
  - Capacitor banks change the system frequency response characteristics, resulting in resonances that can magnify transient disturbances and harmonic distortion levels.

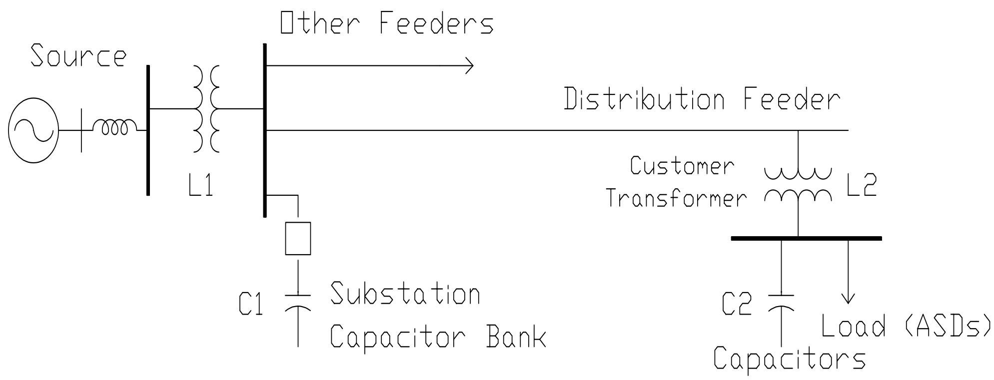
The devices and equipment being applied on the power system are more sensitive to power quality variations than equipment applied in the past. New equipment includes microprocessor-based controls and power electronics devices that are sensitive to many types of disturbances. Controls can be affected, resulting in nuisance tripping or misoperation as part of an important process, or actual device failures can occur.

An increasing awareness of power quality issues by the end-users. Utility customers are becoming better informed about such issues as interruptions, voltage sags, and switching transients. As a result, they often challenge their utility to improve the quality of the power delivered.

The recent proliferation of sensitive, electronic-based end-use equipment has caused many utilities to reevaluate their capacitor application criteria. Low voltage problems include voltage magnification and nuisance tripping of power electronic-based equipment (i.e. ASDs & UPSs).

Magnification of Capacitor Switching

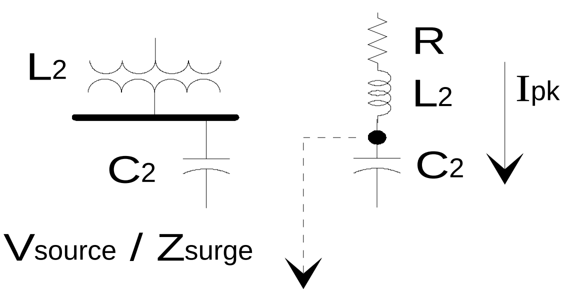
- Phenomena occurs when a large capacitor is energized at a higher voltage, resulting in magnification of the transient at a lower voltage capacitor bank.



$$f_1 = \frac{1}{2 \cdot \pi \cdot \sqrt{L_1 \cdot C_1}} \qquad f_2 = \frac{1}{2 \cdot \pi \cdot \sqrt{L_2 \cdot C_2}}$$

If F_1 is approximately equal to the series resonant frequency (F_2) of the transformer - capacitor combination, the potential exists for a high current (I_{pk}), resulting in a large bus overvoltage (V_{bus})

60 Hz + Transient Voltage



$$X_c = \frac{1}{\omega C}$$

$I_{pk} = V_{source} / Z_{surge}$

$V_{bus} = I_{pk} * X_c$

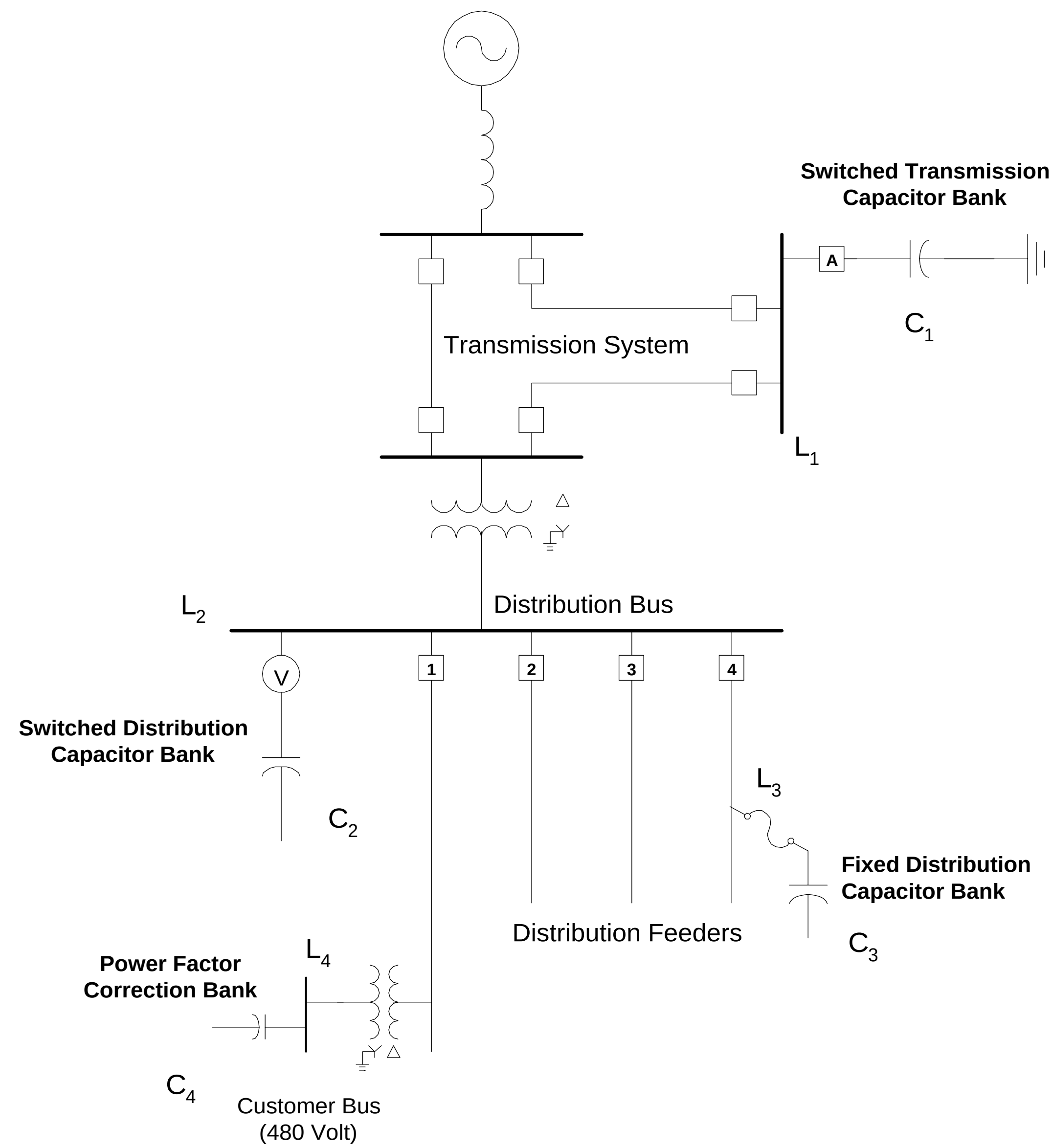
Conditions for Voltage Magnification

- The highest transient voltages occur at the lower voltage capacitors (e.g., 480 volt bus) when the following conditions are met:
  - The natural frequencies f_1 and f_2 are nearly equal.
  - The capacitive rating (MVAr) of the switched capacitor bank is significantly greater (>10) than the lower voltage capacitor rating (kVAr).
  - There is little damping on the low voltage system (mostly motor load – common configuration for many industrial faculties).

The magnified transient at the low voltage bus can reach 4 per-unit.

Important variables to consider:

- Switched capacitor bank rating
- Lower voltage capacitor rating
- System loading (motor vs resistive)
- Transformer characteristics
- Circuit breaker characteristics (closing resistors, timing control)
- Arrester ratings and locations

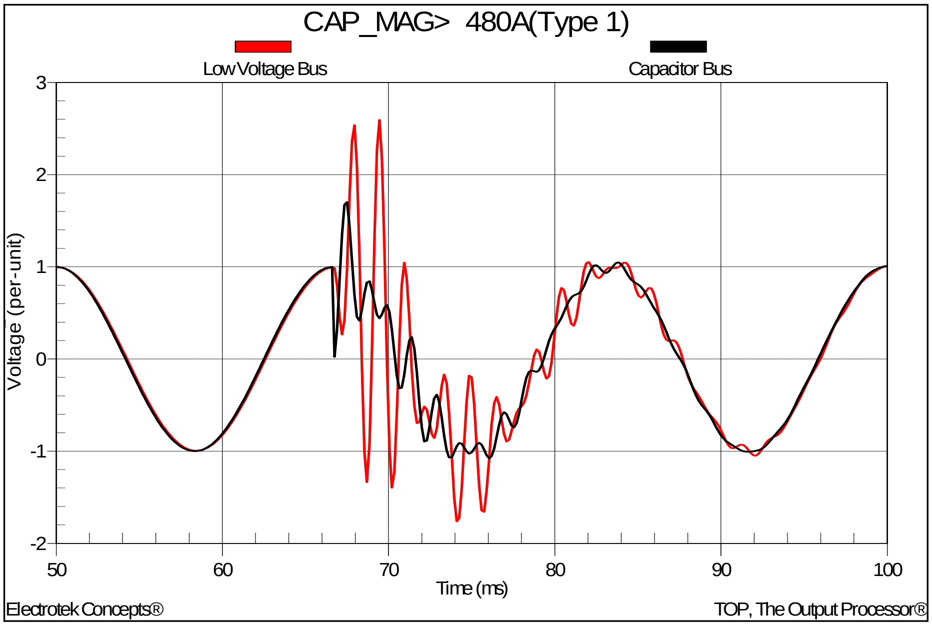


$$C_n = \frac{MVAr_n}{\omega \cdot kV_n^{\ 2}} \qquad L_n = \frac{kV_n^{\ 2}}{\omega \cdot MVA_{sc_n}}$$

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

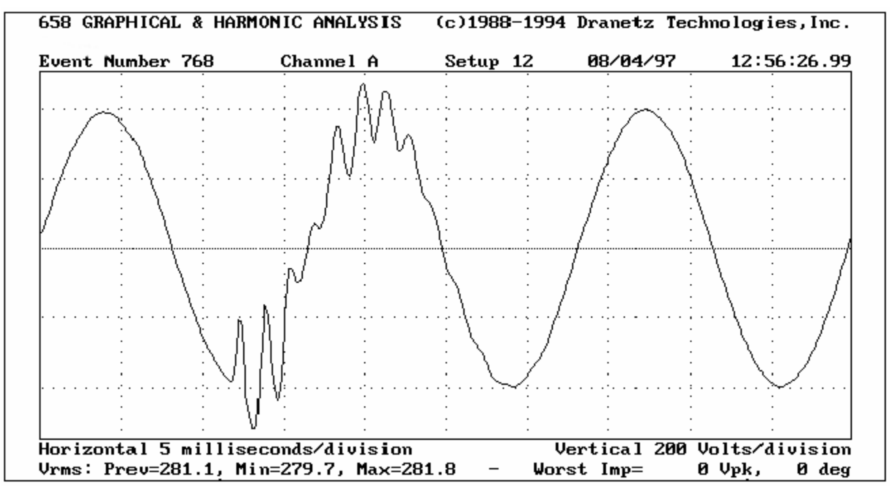
where: f_n = characteristic frequency (f_1 & f_2)
$\omega = 2*\pi*f_{sys}$
$MVAr_n$ = three-phase rating of the capacitor bank
$MVAsc_n$ = three-phase short circuit capacity (kAscn in amps)
kV_n = system voltage (line-to-line)

Magnified Transient at Low Voltage Bus

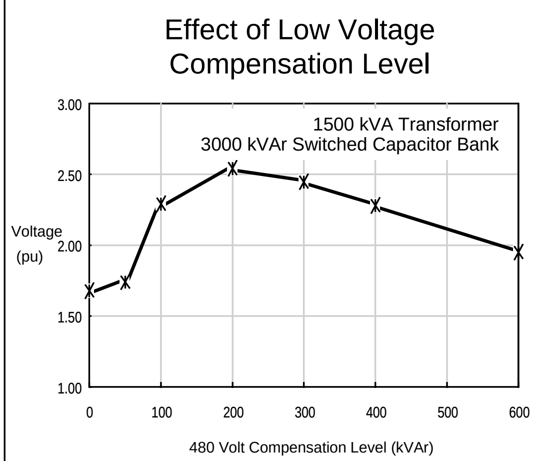


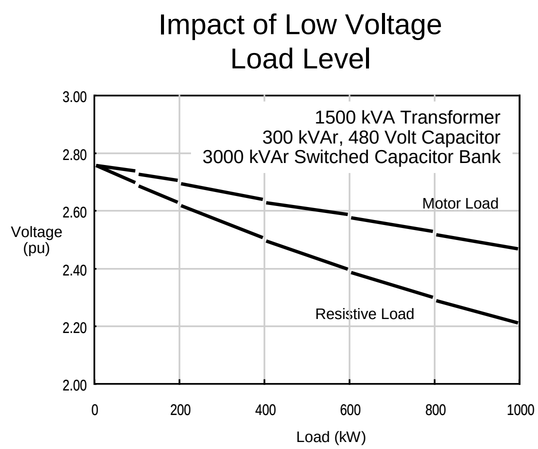
Source: EMTP

Example low voltage bus during utility capacitor switching:



Effect of Compensation and Load Level

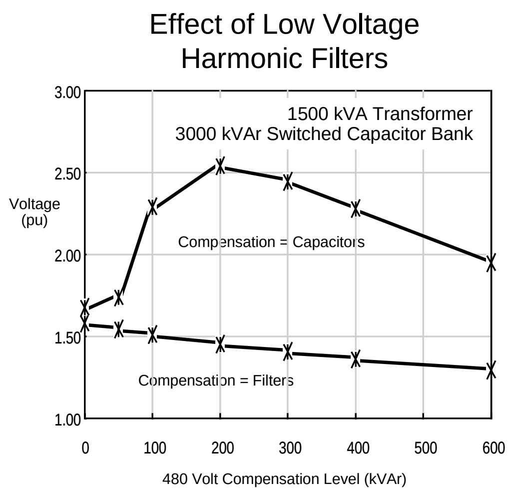


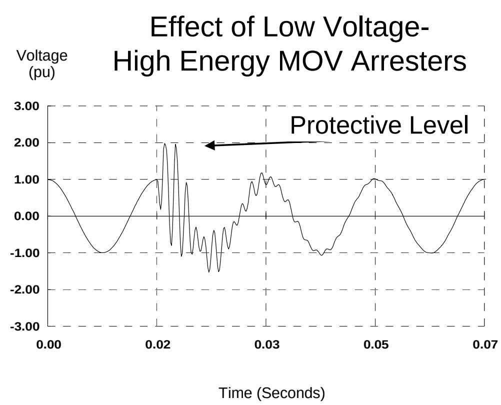


The impact of load on electromagnetic transients is often ignored or significantly underrepresented during system studies. However, previous field tests and on-going power quality monitoring indicate that loads can have an important impact on these phenomena, particularly in reducing peak values and increasing the level of damping. In addition, the EMTP does not contain any "built-in" load model, therefore complicating this issue by requiring the user to develop a representative model using standard components. Unfortunately, this process is often quite difficult due to the fact that presently very little is known about how to properly model loads at high frequencies. Simple load models used for load flow and stability studies will generally yield incorrect results.

The load model should satisfy two requirements. First, the fundamental frequency solution, namely the watt and var flow must be accurate in order to properly determine initial conditions. Second, the high frequency characteristic should also match the actual physical load so the correct level of damping is achieved.

Low Voltage Filters and Arresters





Harmonic filters are often applied to reduce harmonic voltage distortion levels. Since power factor correction capacitors are the key element in the voltage magnification case, it is important to evaluate the impact of the filter inductor on the transient voltage. In most cases, converting a power factor correction bank into a harmonic filter will reduce the transient overvoltages.

Low voltage (480 volt) arresters may be used to limit overvoltages to acceptable levels. MOV arresters have two important ratings. The first is maximum continuous operating voltage (MCOV), which must be higher than the line voltage and is often at least 125 percent of the system nominal voltage. The second rating is the energy dissipation rating (in joules). MOVs are available in a wide range of energy ratings.

Solutions to Magnification Phenomena

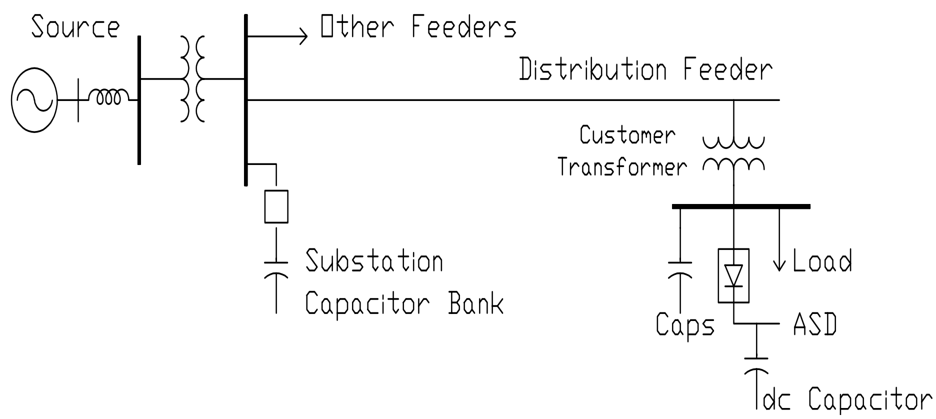
- Controlling the transient overvoltage at the source, on the utility system is sometimes possible.
  - Synchronous closing control
  - Closing capacitor bank through a resistor/inductor first
- Surge arresters at the customer location can be used.
- Conversion of capacitor banks to harmonic filters is effective for control of the magnification problem.

Solutions to the voltage magnification usually involve:

1. Detuning the circuit by changing capacitor bank ratings, moving banks, and/or removing banks from service.
2. Switching large banks in more than one section.
3. Using an overvoltage control methods (e.g., pre-insertion resistor/inductor or synchronous closing control).
4. Applying surge arresters (MOVs) at the remote location.
5. Converting low voltage power factor correction banks into harmonic filters.

Nuisance Tripping of ASDs

- System oneline diagram:



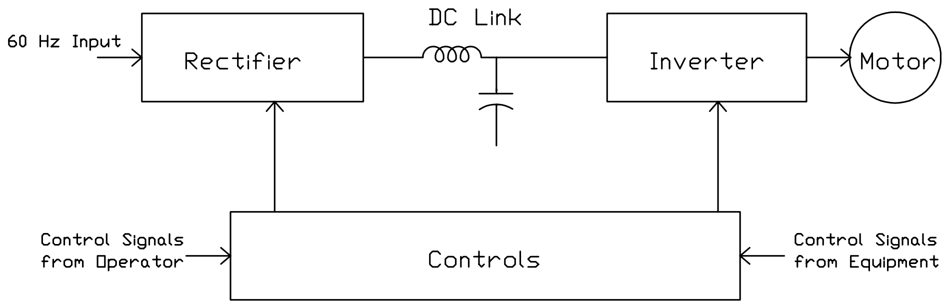
ref: IEEE Paper 91 WM 086-9 PWRD

"Nuisance tripping" refers to the undesired shutdown of an adjustable-speed drive (or other power electronic process device) due to the transient overvoltage on the device's dc bus (or ac control signal voltage). Very often, this overvoltage is caused by utility capacitor bank energization. The nuisance tripping event consists of an overvoltage trip due to a dc bus overvoltage on voltage-source inverter drives (pulse-width modulated — PWM). Typically, for the protection of the dc capacitor and inverter components, the dc bus voltage is monitored and the drive tripped when it exceeds a preset level. This level is typically around 780 volts (for 480 volt applications), which is only 120% of the nominal dc voltage.

The potential for nuisance tripping is primarily dependent on the switched capacitor bank rating, overvoltage controls for the switched bank, the dc bus capacitor rating, and the inductance between the two capacitors. It is important to note that nuisance tripping can occur even if the customer does not have power factor correction capacitors.

ASD Components

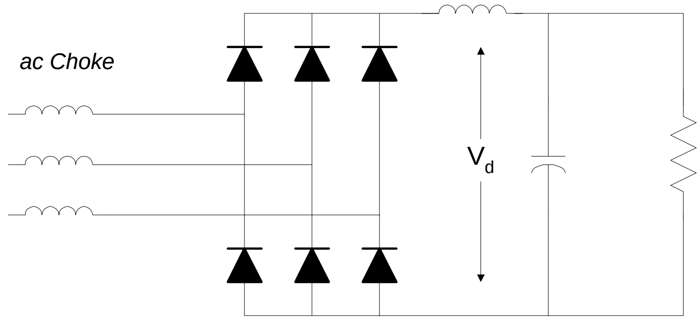
- Small ASDs typically have a voltage source inverter (VSI) type of design and use pulse width modulation (PWM) inverters to supply the motor.



The dc link capacitor is very sensitive to transient voltages on the ac power side. It is not uncommon for the dc overvoltage control to cause tripping of the drive whenever the dc voltage exceeds 1.2 pu (typical value).

Because the dc capacitors are connected to the ac system through the rectifier bridge, only one half cycle of the transient current can make it through to the capacitor. The current cannot flow in the reverse direction because of the diodes or SCRs in the rectifier bridge. Therefore, the capacitor switching transient causes an impulse of current that "charges up" the dc circuit. The dc circuit must then discharge through the load before normal operation can resume.

ASD Representation



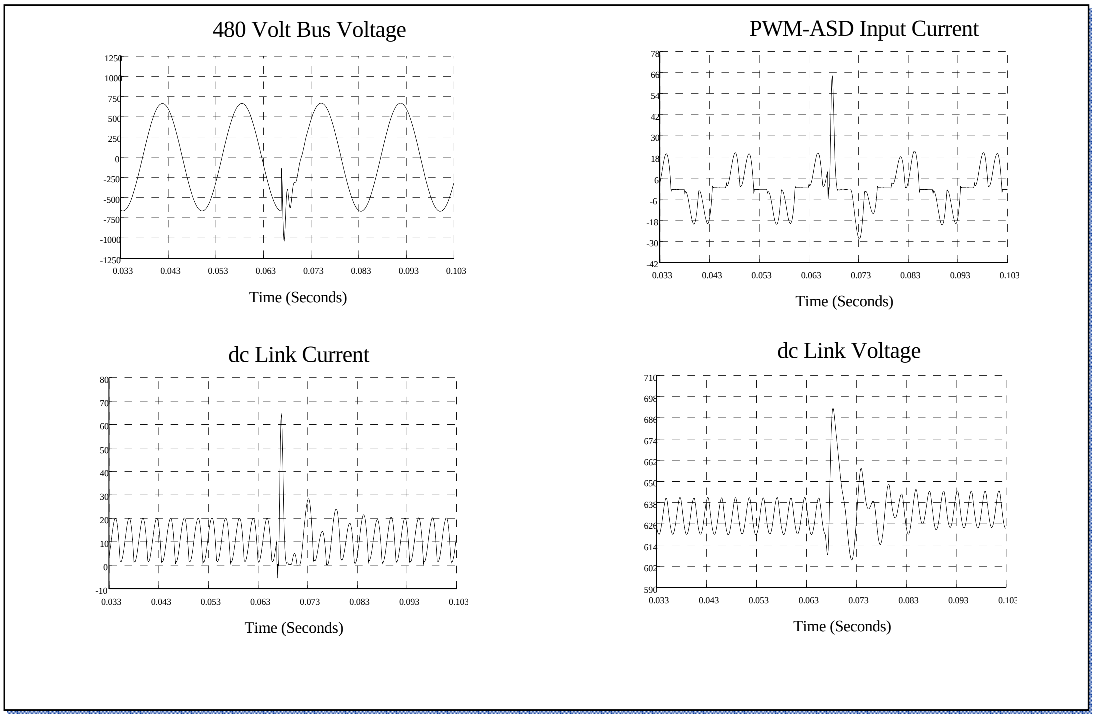
$$R_d = \frac{V_d^{\,2}}{P_{motor}}$$

Nominal bus voltage: 480 Volts
Nominal dc bus voltage: 650 Volts

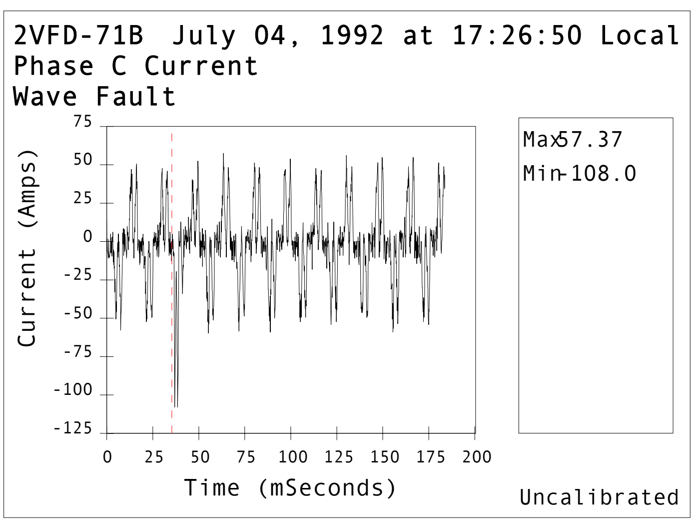
$$V_d = \frac{3\sqrt{2}}{\pi} V_{LL} \approx 1.35 * 480 \approx 650\text{V}$$

Because the dc capacitors are connected to the ac system through the rectifier bridge, only one half cycle of the transient current can pass through to the capacitor. The current cannot flow in the reverse direction because of the diodes or SCRs in the rectifier bridge. Therefore, the capacitor switching transient produces an impulse of current that "charges up" the dc circuit. The dc circuit must then discharge through the load before normal operation can resume. The dc bus voltage is the quantity of concern when evaluating overvoltage tripping due to capacitor switching. An inrush current (300-1000 Hz) charges the dc capacitor and causes the drive to shutdown, if the overvoltage trip level is exceeded (a minimum trip level of 120% of the nominal dc voltage ¾ or approximately 780 volts ¾ is considered typical). Although this simplified model does not include the inverter or motor, previous measurements and simulations have proven that this modeling assumption is valid for the nuisance tripping evaluation. It is important to note that this is the minimum model that will allow evaluation of the capacitor switching transient / drive interaction. The possibility of drive tripping cannot be determined simply by monitoring (or simulating) the 480 volt bus voltage (line-to-line or line-to-ground).

dc Bus Voltage and Current Surge

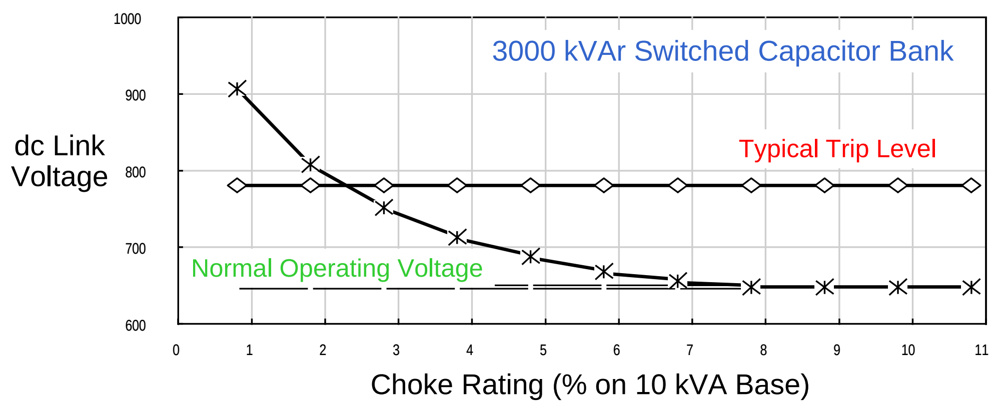


Measured drive current during utility capacitor switching:

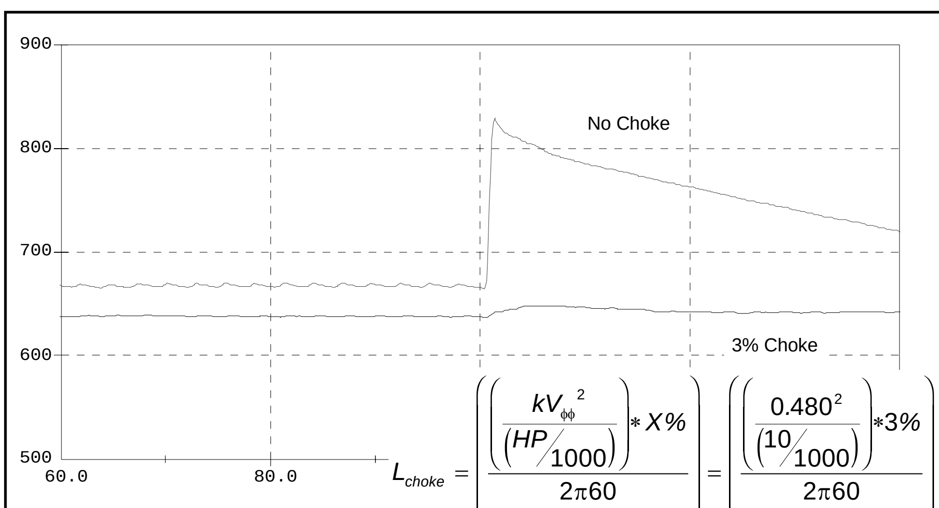


Solution to Nuisance Tripping – Chokes

- Inductance on the ac side, in the form of an isolation transformer or simple inductive choke, has the most dramatic effect on the current surge because it introduces a large impedance into the circuit where the current flows.

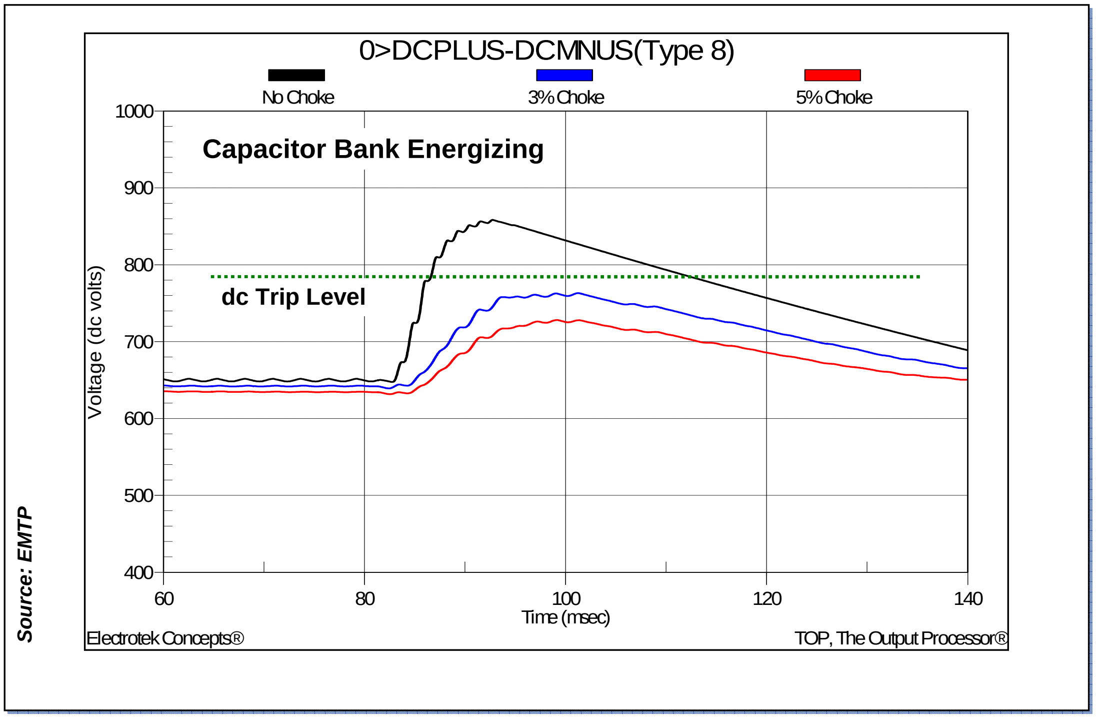


dc Link Voltage



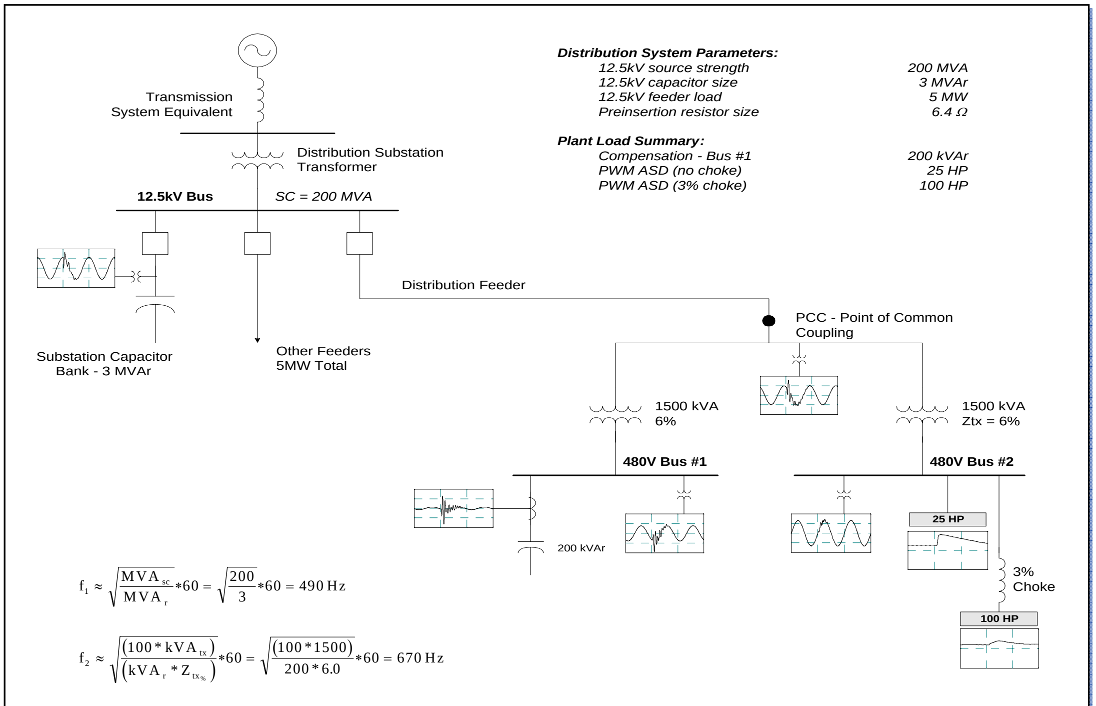
$$L_{choke} = \left(\frac{\left(\frac{kV_{\phi\phi}^{2}}{\left(HP/1000 \right)} \right) * X\%}{2\pi 60} \right) = \left(\frac{\left(\frac{0.480^{2}}{\left(10/1000 \right)} \right) * 3\%}{2\pi 60} \right) = 183mH$$

Effect of Choke on dc Link Overvoltage



The likelihood of nuisance tripping of adjustable-speed drives, due to utility capacitor switching, can be greatly reduced through the application of an input choke. Typically, a value of 3% is sufficient. This is a very economical solution on the customer side and it provides the additional benefit of reduced harmonic components in the drive input current.

Magnification and Nuisance Tripping



Power quality symptoms related to distribution capacitor switching include: customer equipment damage or failure (due to excessive overvoltage), adjustable-speed drive or other process equipment shutdown (due to dc bus overvoltage), TVSS failure, and computer network problems. Two specific concerns include:

1. Magnification of capacitor switching transients.
2. Nuisance tripping of end-use equipment (adjustable-speed drives).

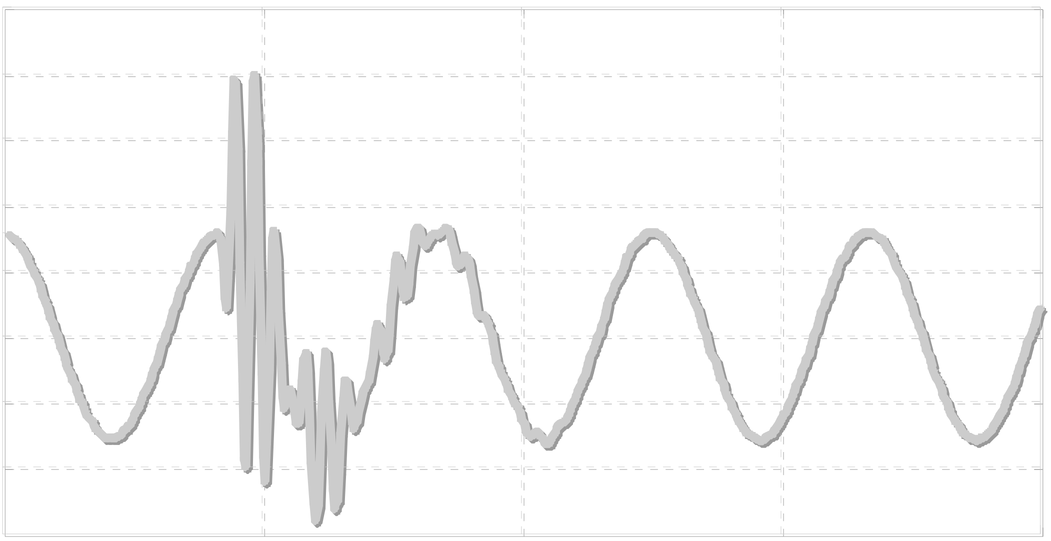
These concerns have become particularly important as utilities institute higher power factor penalties, thereby encouraging customers to install power factor correction capacitors. In addition, nontraditional customer loads, such as adjustable-speed drives, are being applied in increasing numbers due to the improved efficiencies and flexibility that can be achieved. This type of load can be very sensitive to the transient voltages produced during capacitor switching.

Economic Aspects of Mitigation

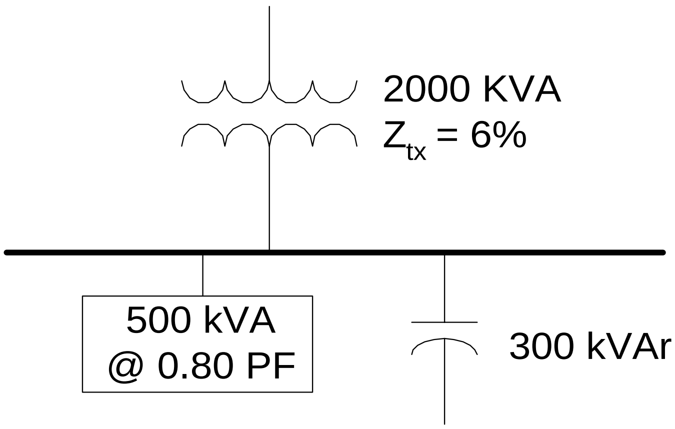
- Economic aspects of customer production:
  - **Lost Production -** factory costs associated with the production process being disrupted. These costs represent the factory value of the shortfall in product shipped due to the power quality event.
  - **Scrap -** costs associated with product that must be scrapped and cannot be recovered by recycling the raw materials.
  - **Restart -** costs associated with restarting the production process.
  - **Labor -** extra labor costs associated with restarting the product line, reloading machines, cleaning up scrap, etc.
  - **Repair -** costs for repair of machines and equipment damaged during the transient event.
  - **Replacement -** costs for the replacement of machinery damaged during the transient event.
  - **Process Inefficiency -** costs due to the process not begin able to run to its optimal efficiency due to the event.
  - **Demand Charges -** increased utility charges because the customer is unable to operate equipment such as capacitors and adjustable-speed drives that might reduce demand charges.

The widespread application of (capacitor energizing) overvoltage mitigation equipment has not occurred for a number of reasons. In general, the additional expenditure must be weighed against the possible negative impacts of uncontrolled energizing. The primary factor in this evaluation would seem to be the effect on customer systems. As with many power quality problems, an economic evaluation may be difficult to complete, since it is often very difficult to determine the cost of a particular event for an individual customer. In addition, these costs may vary drastically from customer to customer.

CAPACITOR APPLICATIONS EXAMPLE PROBLEMS



Example Problem #1



Determine:

- Voltage rise on 480 volt bus when 300 kVAr power factor capacitor bank is switched on:

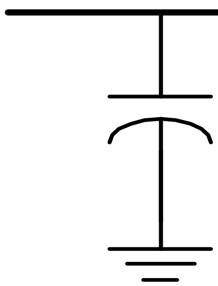
- New power factor:

- %Loss reduction:

- Released capacity:

Example Problem #2

230kV Bus
Three-Phase Short Circuit = 3000 MVA



Capacitor Units:	300kVAr
Voltage Rating:	14.4kV
Number of Series Groups:	10
Number of Units/Group:	13

Determine:

- Capacitor bank ratings: ________ kV, _______MVAr

- Adjusted bank rating when applied at 230kV:

- Capacitor unit current:

- Rated and operating capacitor bank full load currents:

Example Problem #2 - continued

Determine:

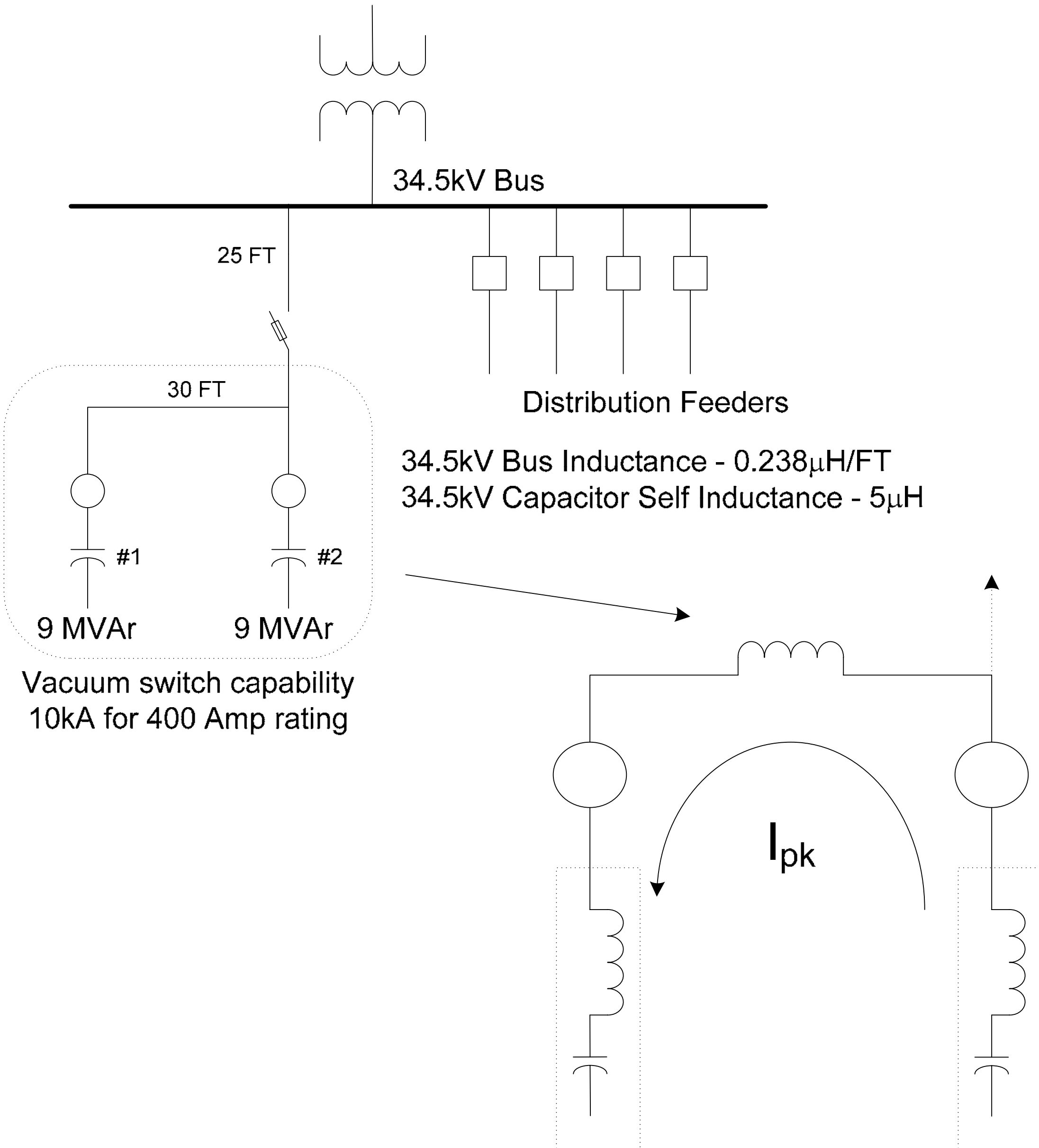
- Neutral current for two units out:

- Voltage (in percent) on remaining units with three units out:

- Capacitance of bank and inductance of system:

- Inrush current magnitude and frequency:

Example Problem #3



Example Problem #3 - continued

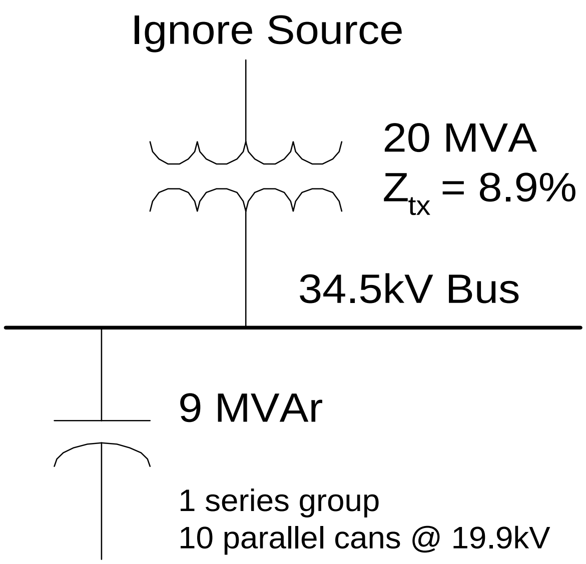
Determine:

- Back-to-back switching current magnitude and frequency:

- Select the optimum inrush reactor (to meet the 8kA spec) from the following list:

  20μH   40μH   100μH   200μH

Example Problem #4



Determine:

- Capacitor bank full load current:

- Capacitor bank & source reactances:

- Harmonic resonance:

Example Problem #4 - continued

Determine:

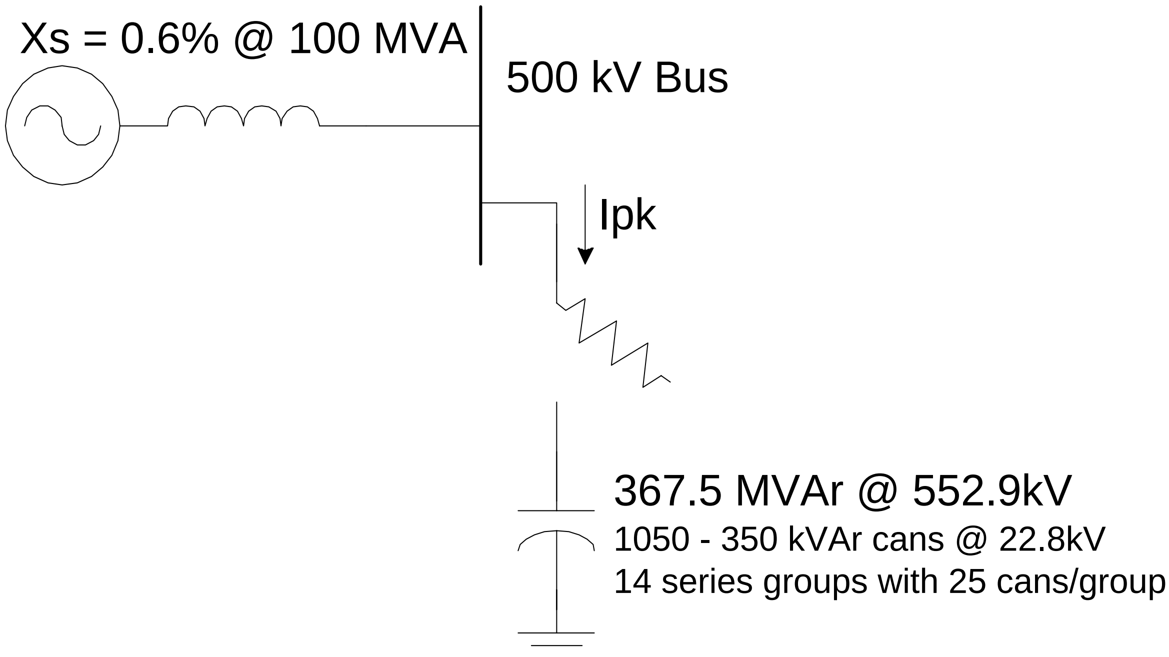
- Size reactor to convert bank into 5th harmonic filter:

- 60 Hz voltage rise on the capacitor bank:

- Voltage rating of capacitor units:
  (Question - When configuring a bank as a filter is it acceptable to use units rated at system voltage?)

  19.2kV   or   21.6kV

Example Problem #5



Determine:

- Capacitor bank full load current:

- Capacitor bank & source reactances:

- Optimum pre-insertion resistor rating:

Example Problem #5 - continued

Determine:

- Arrester energy duty for a single restrike:

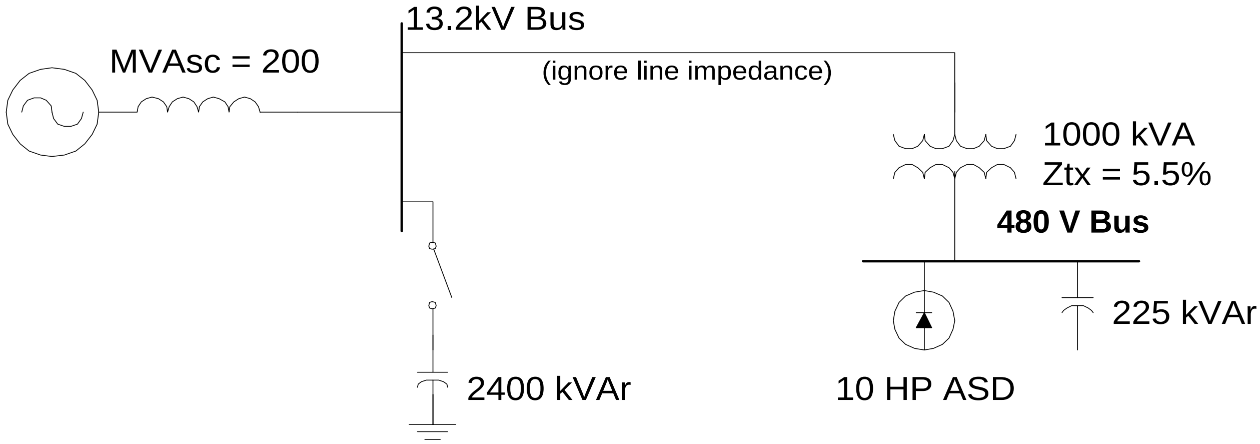
    Arrester data:

    396kV MOV

    MSSPL = 779kV @ 3000 A

    Capability = 13.1kJ/kV

Example Problem #6



Determine:

- Energizing frequency f_1:

- Step-down transformer / low voltage capacitor series resonant frequency f_2 :

- Inductance of a 3% choke added to the 10 HP drive:

Related Reading

[1] "Power Quality Considerations for ASD Applications", EPRI CU.3036, 1991.

[2] "Impact of Power Factor Correction on the Operation of Adjustable-Speed Motor Drives", presented at the PCIM/Power Quality ’90 Conference.

[3] "Why Power Factor Correction Capacitors May Upset Adjustable-Speed Drives", published in the May/June 1991 issue of Power Quality Magazine.

[4] “Surge Protection of High Voltage Shunt Capacitor Banks on AC Power Systems”, Report by Working Group 3.14.17., SPD Committee 91 WM 004-2 PWRD.

[5] IEEE Standard 519-1992, "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems".

[6] "Magnification of Switching Surge”, A,J, Shultz, et. al., Paper 58-1178, AIEE.

[7] "Overvoltage Protection of Shunt Capacitor Banks Using MOV Arresters”, M.F. McGranaghan, et. al., 84 WM 032-9

[8] "Why Switched Capacitors Drive Customers Crazy", Electrical World Magazine, July, 1991

[9] "Impact of Utility Switched Capacitors on Customer Systems - Magnification at Low Voltage Capacitors", presented at 1991 IEEE T&D Show.

[10] "Impact of Utility Switched Capacitors on Customer Systems - Part II - Adjustable Speed Drive Concerns", 91 WM 086-9 PWRD.

[11] “Consideration of Phase-to-Phase Surges in the Application of Capacitor Banks”, R. A. Jones, et. al., IEEE Trans. Pwr. Del., Vol. PWRD-1, No. 3, July 1986.

[12] “Evaluation of Switching Concerns Associated with 345kV Shunt Capacitor Applications”, S.S. Mikhail, M.F. McGranaghan, IEEE Trans. Pwr. Sys. Vol. PWRD-1, No. 2, April 1986.

[13] “Synchronous Closing Control for Shunt Capacitors”, R.W. Alexander, IEEE 85 WM 221-7.

[14] “Application of a Superconducting Magnetic Energy Storage Device to Improve Facility Power Quality”, presented at PQA92, Atlanta.

[15] “Analysis of Harmonic and Transient Concerns for PWM ASDs using the Electromagnetic Transients Program”, presented at ICHIPS, 1992

[16] "Innovations for Protection and Control of High Voltage Capacitor Banks on the Virginia Power System", J.F. Peggs, et. al., 1994 IEEE T&D Conference, April 10, 1994, Chicago, IL.

[17] "Overvoltage Protection of Shunt Capacitor Banks Using MOV Arresters", M.F. McGranaghan, et. al, IEEE Transactions, Vol. PAS-103, No. 8, August 1994.

Glossary

Active Filter. Any of a number of sophisticated power electronic devices for eliminating harmonic distortion.

CBEMA Curve. A set of curves representing the withstand capabilities of computers in terms of the magnitude and duration of the voltage disturbance. Developed by the Computer Business Equipment Manufacturers Association (CBEMA), it has become a de facto standard for measuring the performance of all types of equipment and power systems, and is commonly referred to by this name.

Common Mode Voltage. The noise voltage that appears equally from current-carrying conductor to ground.

Coupling. Circuit element or elements, or network, that may be considered common to the input mesh and the output mesh and through which energy may be transferred from one to another.

Crest Factor. A value reported by many power quality monitoring instruments representing the ratio of the crest value of the measured waveform to the rms of the fundamental. For example, the crest factor of a sinusoidal wave is 1.414.

Critical Load. Devices and equipment whose failure to operate satisfactorily jeopardizes the health or safety of personnel, and/or results in loss of function, financial loss, or damage to property deemed critical by the user.

Current Distortion. Distortion in the ac line current. See Distortion.

Differential Mode Voltage. The voltage between any two of a specified set of active conductors.

Dip. See Sag.

Distortion. Any deviation from the normal sine wave for an ac quantity.

Dropout. A loss of equipment operation (discrete data signals) due to noise, sag, or interruption.

Dropout Voltage. The voltage at which a device will release to its de-energized position (for this document, the voltage at which a device fails to operate).

Glossary

Electromagnetic Compatibility. The ability of a device, equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment.

Equipment Grounding Conductor. The conductor used to connect the non-current carrying parts of conduits, raceways, and equipment enclosures to the grounded conductor (neutral) and the grounding electrode at the service equipment (main panel) or secondary of a separately derived system (e.g., isolation transformer). See NFPA 70-1990, Section 100.

Failure Mode. The effect by which failure is observed.

Fast Tripping. Refers to the common utility protective relaying practice in which the circuit breaker or line recloser operates faster than a fuse can blow. Also called fuse saving. Effective for clearing transient faults without a sustained interruption, but is somewhat controversial because industrial loads are subjected to a momentary or temporary interruption.

Fault. Generally refers to a short circuit on the power system.

Flicker. Impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time.

Frequency Deviation. An increase or decrease in the power frequency. The duration of a frequency deviation can be from several cycles to several hours.

Frequency Response. In power quality usage, generally refers to the variation of impedance of the system, or a metering transducer, as a function of frequency.

Fundamental (Component). The component of order 1 (50 to 60 Hz) of the Fourier series of a periodic quantity.

Ground. A conducting connection, whether intentional or accidental, by which an electric circuit or equipment is connected to the earth, or to some conducting body of relatively large extent that serves in place of the earth. Note: It is used for establishing and maintaining the potential of the earth (or of the conducting body) or approximately that potential, on conductors connected to it, and for conducting ground currents to and from earth (or the conducting body).

Glossary

Ground Electrode. A conductor or group of conductors in intimate contact with the earth for the purpose of providing a connection with the ground.

Ground Grid. A system of interconnected bare conductors arranged in a pattern over a specified area and on or buried below the surface of the earth. The primary purpose of the ground grid is to provide safety for workmen by limiting potential differences within its perimeter to safe levels in case of high currents which could flow if the circuit being worked became energized for any reason or if an adjacent energized circuit faulted. Metallic surface mats and gratings are sometimes utilized for the same purpose . This is not necessarily the same as a Signal Reference Grid.

Ground Loop. A potentially detrimental loop formed when two or more points in an electrical system that are nominally at ground potential are connected by a conducting path such that either or both points are not at the same ground potential.

Ground Window. The area, through which, all grounding conductors, including metallic raceways enter a specific area. It is often used in communications systems through which the building grounding system is connected to an area that would otherwise have no grounding connection.

Harmonic (component). A component of order greater than one of the Fourier series of a periodic quantity.

Harmonic Distortion. Periodic distortion of the sine wave. See Distortion and Total Harmonic Distortion (THD).

Harmonic Filter. On power systems, a device for filtering one or more harmonics from the power system. Most are passive combinations of inductance, capacitance, and resistance. Newer technologies include active filters that can also address reactive power needs.

Harmonic Number. The integral number given by the ratio of the frequency of a harmonic to the fundamental frequency.

Harmonic Resonance. A condition in which the power system is resonating near one of the major harmonics being produced by nonlinear elements in the system, thus exacerbating the harmonic distortion.

Glossary

Impulse. A pulse that, for a given application, approximates a unit pulse or a Dirac function. When used in relation to the monitoring of power quality, it is preferred to use the term impulsive transient in place of impulse.

Instantaneous. When used to quantify the duration of a short duration variation as a modifier, refers to a time range from one-half cycle to 30 cycles of the power frequency.

Instantaneous Reclosing. A term commonly applied to reclosing of a utility breaker as quickly as possible after interrupting fault current. Typical times are 18-30 cycles.

Interruption, Momentary (electric power systems). An interruption of duration limited to the period required to restore service by automatic or supervisory-controlled switching operations or by manual switching at locations where an operator is immediately available. Note: Such switching operations must be completed in a specified time not to exceed 5 minutes.

Interruption, Momentary (power quality monitoring). A type of short duration variation. The complete loss of voltage (<0.1 pu) on one or more phase conductors for a time period between 30 cycles and 3 seconds.

Interruption, Temporary. A type of short duration variation. The complete loss of voltage (<0.1 pu) on one or more phase conductors for a time period between 3 seconds and 1 minute.

Interruption, Sustained (electric power systems). Any interruption not classified as a momentary interruption.

Interruption, Sustained (power quality). A type of long duration variation. The complete loss of voltage (<0.1 pu) on one of more phase conductors for a time greater than 1 minute.

Isolated Ground. An insulated equipment grounding conductor run in the same conduit or raceway as the supply conductors. This conductor is insulated from the metallic raceway and all ground points throughout its length. It originates at an isolated ground-type receptacle or equipment input terminal block and terminates at the point where neutral and ground are bonded at the power source. See NFPA 70-1990, Section 250-74, Exception #4 and Section 250-75, Exception.

Glossary

Linear Load. An electrical load device which, in steady state operation, presents an essentially constant load impedance to the power source throughout the cycle of applied voltage.

Long Duration Variation. A variation of the rms value of the voltage from nominal voltage for a time greater than one minute. Usually further described using a modifier indicating the magnitude of a voltage variation (e.g., Undervoltage, Overvoltage, or Voltage Interruption).

Momentary. When used to quantify the duration of a short duration variation as a modifier, refers to a time range at the power frequency from 30 cycles to 3 seconds.

Noise. Unwanted electrical signals which produce undesirable effects in the circuits of the control systems in which they occur. (For this document, "control systems" is intended to include sensitive electronic equipment in total or in part.)

Nonlinear Load. Electrical load which draws current discontinuously or whose impedance varies throughout the cycle of the input ac voltage waveform.

Normal Mode Voltage. A voltage that appears between or among active circuit conductors.

Notch. A switching (or other) disturbance of the normal power voltage waveform, lasting less than a half-cycle; which is initially of opposite polarity than the waveform, and is thus subtracted from the normal waveform in terms of the peak value of the disturbance voltage. This includes complete loss of voltage for up to a half cycle.

Oscillatory Transient. A sudden, non-power frequency change in the steady state condition of voltage or current that includes both positive or negative polarity value.

Overvoltage. When used to describe a specific type of long duration variation, refers to a voltage having a value of at least 10% above the nominal voltage for a period of time greater than 1 minute.

Glossary

Passive Filter. A combination of inductors, capacitors, and resistors designed to eliminate one or more harmonics. The most common variety is simply an inductor in series with a shunt capacitor, which short-circuits the major distorting harmonic component from the system.

Power Factor, Displacement. The power factor of the fundamental frequency components of the voltage and current wave forms.

Power Factor (True). The ratio of active power (watts) to apparent power (voltamperes).

Reclosing. The common utility practice on overhead lines of closing the breaker within a short time after clearing a fault taking advantage of the fact that most faults are transient, or temporary.

Safety Ground. See: Equipment Grounding Conductor.

Sag. A decrease to between 0.1 and 0.9 pu in rms voltage or current at the power frequency for durations of 0.5 cycles to one minute.

Shield. As normally applied to instrumentation cables, refers to a conductive sheath (usually metallic) applied, over the insulation of a conductor or conductors, for the purpose of providing means to reduce coupling between the conductors so shielded and other conductors which may be susceptible to, or which may be generating unwanted electrostatic or electromagnetic fields (noise).

Short Duration Variation. A variation of the rms value of the voltage from nominal voltage for a time greater than one-half cycle of the power frequency but less than or equal to one minute. Usually further described using a modifier indicating the magnitude of a voltage variation (e.g. Sag, Swell, or Interruption) and possibly a modifier indicating the duration of the variation (e.g., Instantaneous, Momentary or Temporary).

Swell. A temporary increase in the rms value of the voltage of more than 10% the nominal voltage, at the power frequency, for durations from 0.5 cycle to one minute.

Total Demand Distortion (TDD). The ratio of the root-mean- square of the harmonic current to the root-mean-square value of the rated or maximum demand fundamental current, expressed as a percent.

Glossary

Total Harmonic Distortion (THD). The ratio of the root-mean- square of the harmonic content to the root-mean-square value of the fundamental quantity, expressed as a percent of the fundamental.

Transient. Pertaining to or designating a phenomenon or a quantity which varies between two consecutive steady states during a time interval that is short compared to the time scale of interest. A transient can be a unidirectional impulse of either polarity or a damped oscillatory wave with the first peak occurring in either polarity.

Triplen Harmonics. A term frequently used to refer to the odd multiples of the third harmonic, which deserve special attention because of their natural tendency to be zero sequence.

Undervoltage. When used to describe a specific type of long duration variation, refers to a measured voltage having a value at least 10% below the nominal voltage for a period of time greater than one minute.

Voltage Fluctuation. A series of voltage changes or a cyclical variation of the voltage envelope.

Voltage Imbalance (Unbalance). A condition in which the three phase voltages differ in amplitude or are displaced from their normal 120 degree phase relationship or both. Frequently expressed as the ratio of the negative sequence or zero sequence voltage to the positive sequence voltage, in percent.

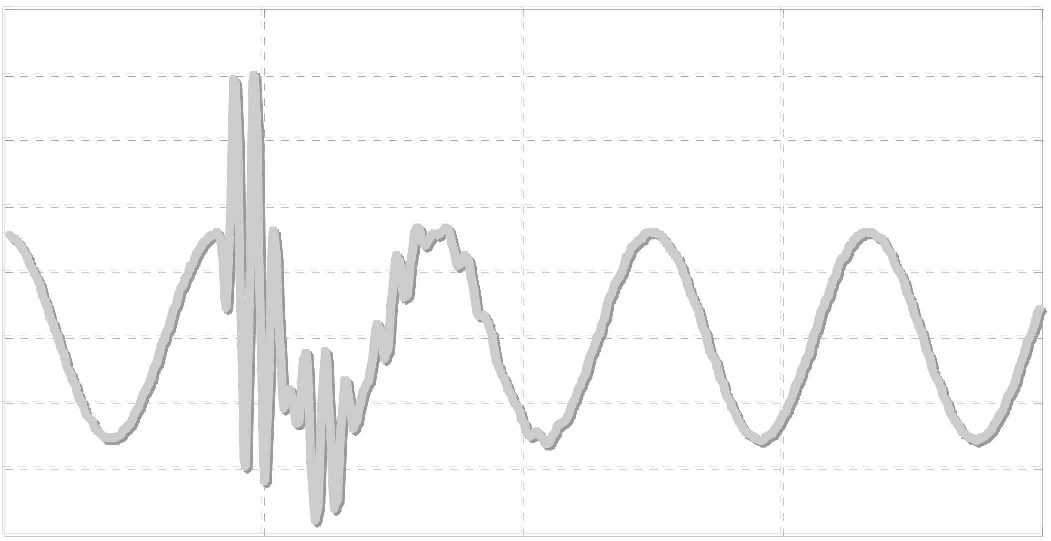
Voltage Interruption. Disappearance of the supply voltage on one or more phases. Usually qualified by an additional term indicating the duration of the interruption (e.g., Momentary, Temporary, or Sustained.)

Voltage Regulation. The degree of control or stability of the rms voltage at the load. Often specified in relation to other parameters, such as input-voltage changes, load changes, or temperature changes.

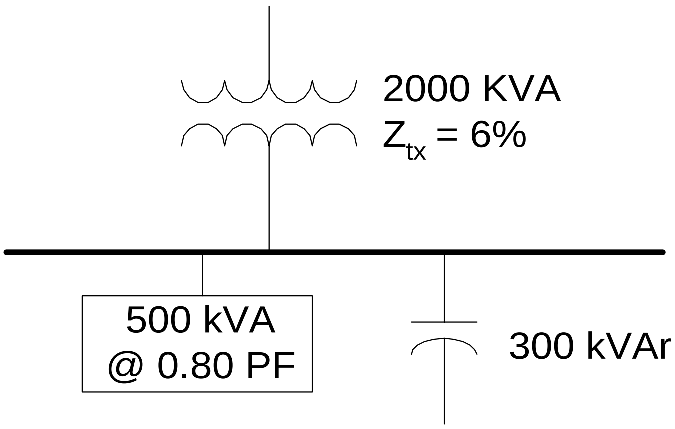
Voltage Magnification. The magnification of capacitor switching oscillatory transient voltage on the primary side by capacitors on the secondary side of a transformer.

Waveform Distortion. A steady state deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation.

CAPACITOR APPLICATIONS SOLUTIONS TO EXAMPLE PROBLEMS



Example Problem #1



Determine:

- Voltage rise on 480 volt bus when 300 kVAr power factor capacitor bank is switched on:

$$\%\Delta V = \frac{kVAr * Z_{tx\%}}{kVA_{tx}} = \frac{300 * 6}{2000} = 0.9\%$$

- New power factor:

$$500kVA@0.80PF = (400kW - j300kVAr) + 300kVAr = 400kW$$

power factor = unity

- %Loss reduction:

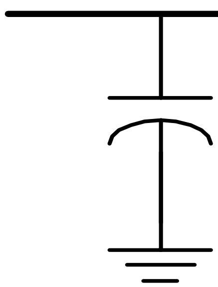
$$\%Loss\,Reduction = 100\left[1 - \left(\frac{PF_{old}}{PF_{new}}\right)^2\right] = 100\left[1 - \left(\frac{0.8}{1.0}\right)^2\right] = 36\%$$

- Released capacity:

500kVA - 400kVA = 100kVA

Example Problem #2

230kV Bus
Three-Phase Short Circuit = 3000 MVA



Capacitor Units:	300kVAr
Voltage Rating:	14.4kV
Number of Series Groups:	10
Number of Units/Group:	13

Determine:

- Capacitor bank ratings: ________ kV, _______MVAr

$$14.4\mathrm{kV} * 10 * \sqrt{3} = 249.4\mathrm{kV} \qquad 3 * 10 * 13 * 300\mathrm{kVAr} = 117\mathrm{MVAr}$$

- Adjusted bank rating when applied at 230kV:

$$\mathrm{MVAr}_{actual} = \mathrm{MVAr}_{rated} * \frac{\mathrm{kV}^2{}_{operating}}{\left(\sqrt{3} * \mathrm{S} * \mathrm{kV}_{can_{rated}}\right)^2} = 117 * \frac{230^2}{\left(\sqrt{3} * 10 * 14.4\right)^2} = 99.49\mathrm{MVA}$$

- Capacitor unit current:

$$\mathrm{I}_{can} = \frac{300\mathrm{kVAr}}{14.4\mathrm{kV}} = 20.8\mathrm{A}$$

- Rated and operating capacitor bank full load currents:

$$\mathrm{I}_{bank_{rated}} = \frac{117\mathrm{MVAr}}{\sqrt{3} * 249\mathrm{kV}} = 271.3\mathrm{A} \qquad \mathrm{I}_{bank_{actual}} = \frac{99.49\mathrm{MVAr}}{\sqrt{3} * 230\mathrm{kV}} = 249.7\mathrm{A}$$

Example Problem #2 - continued

Determine:

- Neutral current for two units out:

$$\%I_n = \left[\frac{100F}{S(P-F)+F}\right] = \left[\frac{100*2}{10(13-2)+2}\right] = 1.78\% * 249.7A = 4.46A$$

- Voltage (in percent) on remaining units with three units out:

$$\%V = \left[\frac{100PS}{S(P-F)+F}\right] * \left[\frac{V_{terminal}}{S*V_{can}}\right] = \left[\frac{100*13*10}{10(13-2)+2}\right] * \left[\frac{132.79}{10*14.4}\right] = 107.0\%$$

- Capacitance of bank and inductance of system:

$$X_C = \frac{kV^2}{MVAr} = \frac{249.7^2}{117} = 532.91\Omega$$

$$C = \frac{1}{\omega X_C} = \frac{1}{2*\pi*60*532.91\Omega} = 4.978\mu F$$

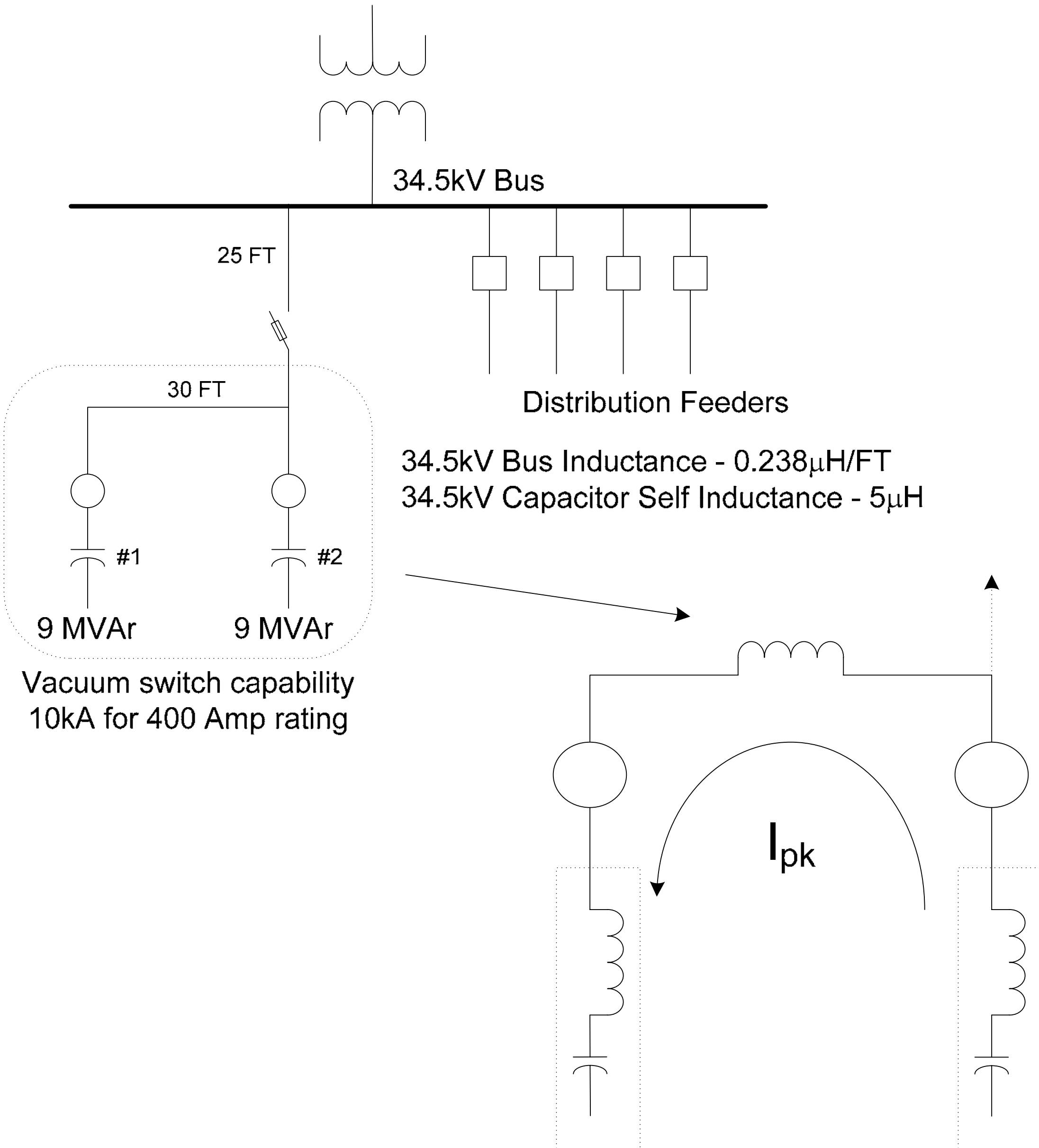
$$L_s = \frac{\left(\frac{kV^2}{MVA_{sc}}\right)}{\omega} = \frac{\left(\frac{230^2}{3000}\right)}{2*\pi*60} = 46.77mH$$

- Inrush current magnitude and frequency:

$$I_{pk} = \frac{V_{pk}}{\sqrt{\left(L_s/C\right)}} = \frac{230kV*\left(\sqrt{2}/\sqrt{3}\right)}{\sqrt{\left(46.77mH/4.978\mu F\right)}} 1937.4A$$

$$f = \frac{1}{2\pi\sqrt{L_s*C}} = \frac{1}{2\pi\sqrt{46.77mH*4.978\mu F}} = 329.8Hz$$

Example Problem #3



$$L_{total} = (80ft * 0.24\mu H / ft) + (2 * 5\mu H) = 29.2\mu H$$

$$C_{bank} = \frac{MVAr}{\omega * kV^2} = \frac{4.5}{\omega * 34.5^2} = 10.02\mu F \qquad C_{total} = \frac{C_{bank}}{2} = 5.01\mu F$$

Example Problem #3 - continued

Determine:

- Back-to-back switching current magnitude and frequency:

$$I_{pk} = \frac{V_{pk}}{\sqrt{\left(L_{total}/C_{total}\right)}} = \frac{34.5kV * \left(\sqrt{2}/\sqrt{3}\right)}{\sqrt{\left(29.20\mu H/5.01\mu F\right)}} = 11.7kA$$

$$f = \frac{1}{2\pi\sqrt{\left(L_{total} * C_{total}\right)}} = \frac{1}{2\pi\sqrt{\left(29.20\mu H * 5.01\mu F\right)}} = 13.2kHz$$

- Select the optimum inrush reactor (to meet the 8kA spec) from the following list:

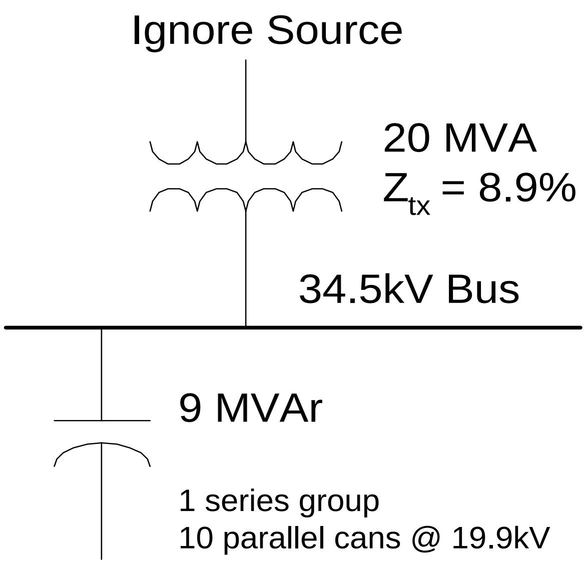
20μH 40μH 100μH 200μH

solving for L...

$$L = \left(\frac{V_{pk}}{I_{pk}}\right)^2 * C_{total} = \left(\frac{34.5kV * \left(\sqrt{2}/\sqrt{3}\right)}{8000}\right)^2 * 5.01\mu F = 62.11\mu F$$

62.1μH-29.2μH=32.9μH (select 40μH)

Example Problem #4



Determine:

- Capacitor bank full load current:

$$I = \frac{9.0\text{MVAr}}{\sqrt{3} * 34.5\text{kV}} = 150.6\text{A}$$

- Capacitor bank & source reactances:

$$X_c = \frac{\text{kV}^2}{\text{MVAr}} = \frac{34.5^2}{9} = 132.25\Omega$$

$$X_s = \frac{\text{kV}^2}{\text{MVA}_{tx}} * Z_{tx} = \frac{34.5^2}{20} * 0.089 = 5.29\Omega$$

- Harmonic resonance:

$$h = \sqrt{\frac{X_c}{X_s}} = \sqrt{\frac{132.25}{5.29}} = 5 \quad (300\text{Hz})$$

Example Problem #4 - continued

Determine:

- Size reactor to convert bank into 5th harmonic filter:

$$h_f = \sqrt{\frac{X_c}{X_f}} \qquad X_f = \frac{X_c}{{h_f}^2} = \frac{132.25}{5^2} = 5.29\Omega = 14.03\text{mH}$$

- 60 Hz voltage rise on the capacitor bank:

$$V_c = \sqrt{3} * \left(\frac{\left(34.5\text{kV} \big/ \sqrt{3} \right)}{\left| 5.29 - 132.25 \right|} \right) * 132.25\Omega = 35937.5\text{V}$$

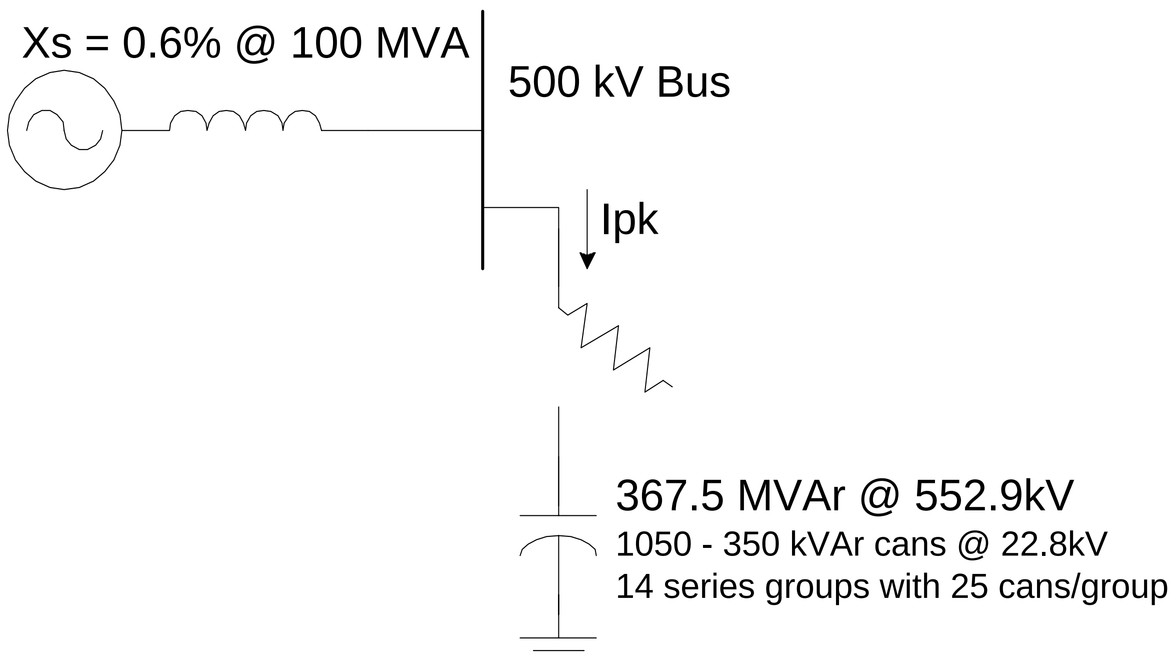
- Voltage rating of capacitor units:
  (Question - When configuring a bank as a filter is it acceptable to use units rated at system voltage?)

19.2kV or 21.6kV

$$\frac{35937.5\text{V}}{\sqrt{3}} = 20.7\text{kV}$$

choose 21.6kV

Example Problem #5



Determine:

- Capacitor bank full load current:

$$I = \frac{367.5\text{MVAr}}{\sqrt{3} * 552.9\text{kV}} = 381.7\text{A}$$

- Capacitor bank & source reactances:

$$X_c = \frac{\text{kV}^2}{\text{MVAr}} = \frac{552.9^2}{367.5} = 831.8\Omega \quad X_s = \frac{\text{kV}^2}{\text{MVA}_{tx}} * Z_{src} = \frac{500^2}{100} * 0.006 = 15.0\Omega$$

- Optimum pre-insertion resistor rating:

$$R = \sqrt{\frac{L}{C}} = \sqrt{\frac{39.8\text{mH}}{3.19\mu\text{F}}} = 112\Omega$$

Example Problem #5 - continued

Determine:

- Arrester energy duty for a single restrike:

Arrester data:

396kV MOV

MSSPL = 779kV @ 3000 A

Capability = 13.1kJ/kV

Vs = 408248.3V Vc= - 408248.3V Vp=779000V

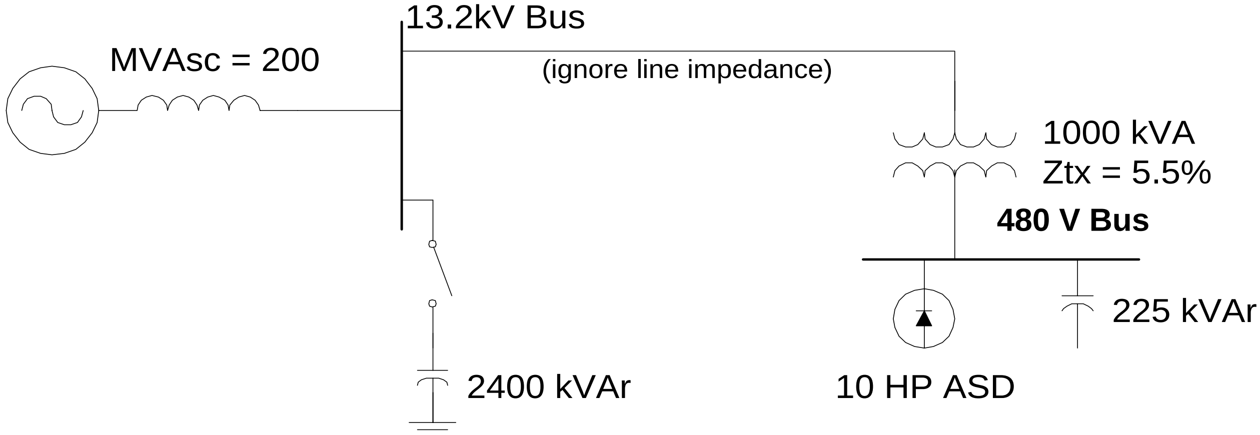
$$I_m = \frac{\sqrt{\left((V_s - V_c)^2 - (V_p - V_s)^2\right)}}{\sqrt{\frac{L_s}{C}}} = 6503.6A$$

$$t = \frac{L_s * I_m}{V_p - V_s} = 0.6982\,\mathrm{m\,sec}$$

$$\text{Energy} = \frac{1}{2} I_m * t * V_p = 1768.5\text{kJ}$$

Capability = 13.1kJ/kV * 396kV = 5187.6kJ

Example Problem #6



Determine:

- Energizing frequency f_1:

$$f_1 = \sqrt{\frac{MVA_{sc}}{MVAr}} = \sqrt{\frac{200}{2.4}} = 9.13 * 60 = 547.8\text{Hz}$$

- Step-down transformer / low voltage capacitor series resonant frequency f_2 :

$$f_{480} \approx \sqrt{\frac{(100 * kVA_{tx})}{(kVAr * Z_{tx_{\%}})}} = \sqrt{\frac{(100 * 1000)}{(225 * 5.5)}} = 8.99 * 60 = 539.4\text{Hz}$$

- Inductance of a 3% choke added to the 10 HP drive:

$$L_{choke} = \frac{\left(\frac{0.480^2}{\left(10/1000\right)}\right) * 0.03}{\omega} = 1.83\text{mH}$$