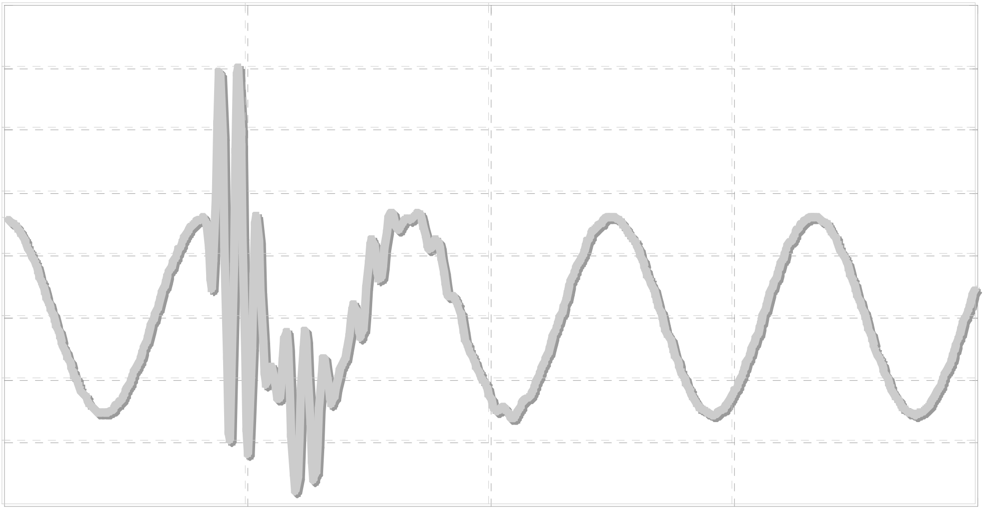
Utility Capacitor Applications and Concerns



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Electrotek Concepts, Inc.

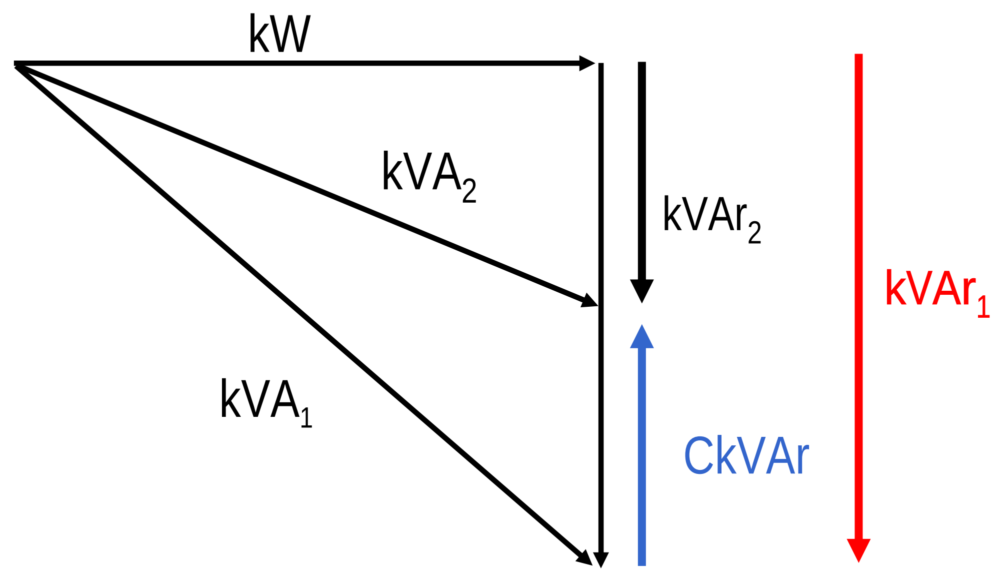
Introduction

- **Introduction to the Utility Capacitor Applications and Concerns Presentation:**
  - **Purpose and Benefits of Applying Power System Capacitors**
  - **Capacitor Bank Design**
  - **Capacitor Bank Protection**
  - **Harmonic Resonance and Distortion**
  - **Transient Disturbances**
  - **Impact of Capacitors on Power Quality**

Based on seminar: http://www.electrotek.com/seminars/capswitc.htm

Purpose of Shunt Capacitor Banks

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



Summary of Benefits

- **VAr support and voltage control are the primary benefits for transmission systems, distribution system 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

ref: IEEE Std. 1036

Capacitor Related Standards

- **ANSI/IEEE Std. 18**
  Shunt Power Capacitors
- **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. 519**
  Recommended Practice for Harmonic Control

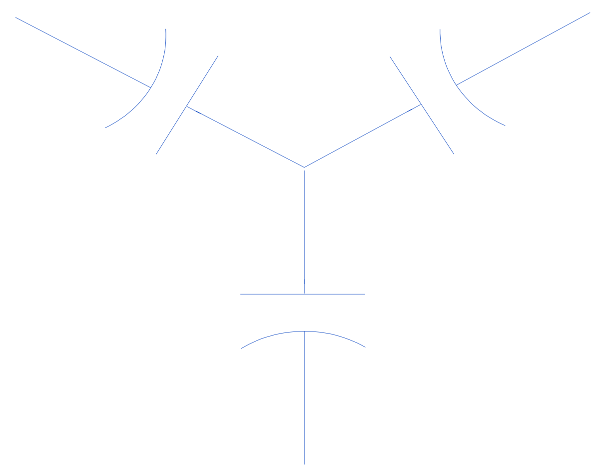
IEEE Capacitor Subcommittee

- **IEEE T&D Committee, 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:**
  - Shunt Capacitor Standard Working Group
  - Series Capacitor Standard Working Group
  - Shunt Capacitor Application Guide Working Group
  - Harmonic Filter Working Group
  - Capacitor Technical Paper Working Group
  - Capacitor Bibliography Working Group

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

Capacitor Bank Design

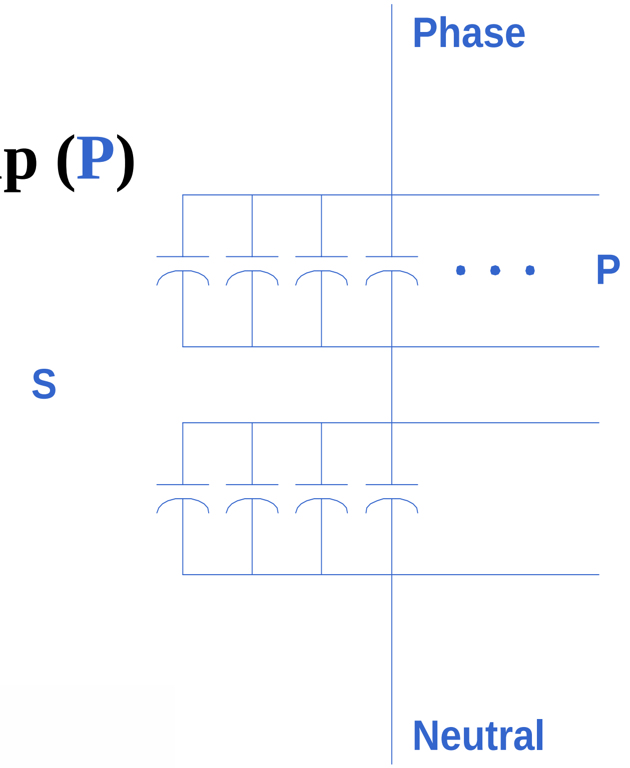
- **Capacitor Bank Connections:**
  - **Delta**
    - » **generally distribution, industrial - single series group**
  - **Grounded Wye**
    - » **low impedance path for lightning current (also triplen harmonics)**
  - **Grounded Double-Wye**
  - **Ungrounded Wye**
  - **Ungrounded Double-Wye**



Capacitor Bank Configuration

- **Number of phases**
- **Number of series groups (S)**
- **Number of parallel units in group (P)**
- **Unit rating ($kVAr_{unit}$ & kV_{unit})**
- **Neutral connection**
- **Three-Phase Bank Rating:**

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



Capacitor Bank Sizing

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

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

(typical range 2%-3%)

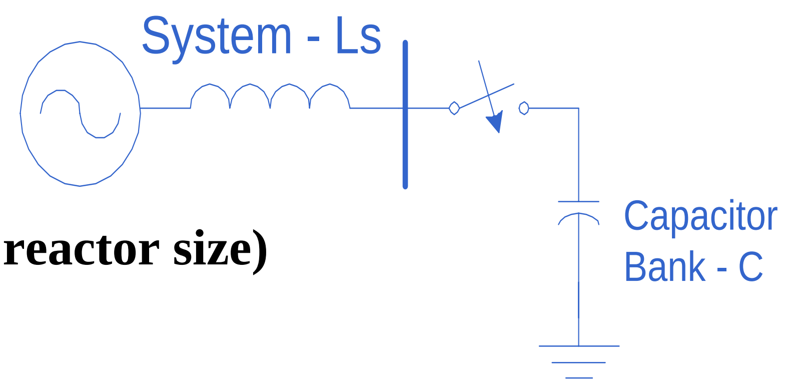
- **Minimum bank size influenced by:**
  - **type of capacitor bank used (e.g., externally fused, fuseless, etc.)**
  - **capacitor bank unbalance considerations**
  - **fuse performance and coordination**
  - **cost of required switchgear and protection**

Capacitor Bank Switching Devices

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

Inrush Current Control

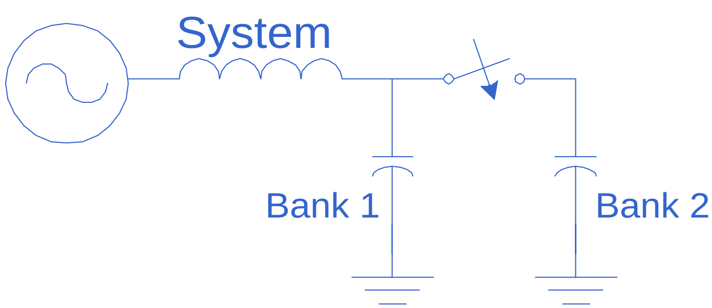
- **Energizing a shunt capacitor bank results in a transient inrush current.**
- **Magnitude and frequency of inrush current is a function of:**
  - **Applied voltage**
  - **Source inductance (L_s)**
  - **Bank capacitance (C)**
  - **Inrush reactor (or preinsertion reactor size)**



- **Breaker (switch) inrush capability I_{pk} and f should be evaluated.**

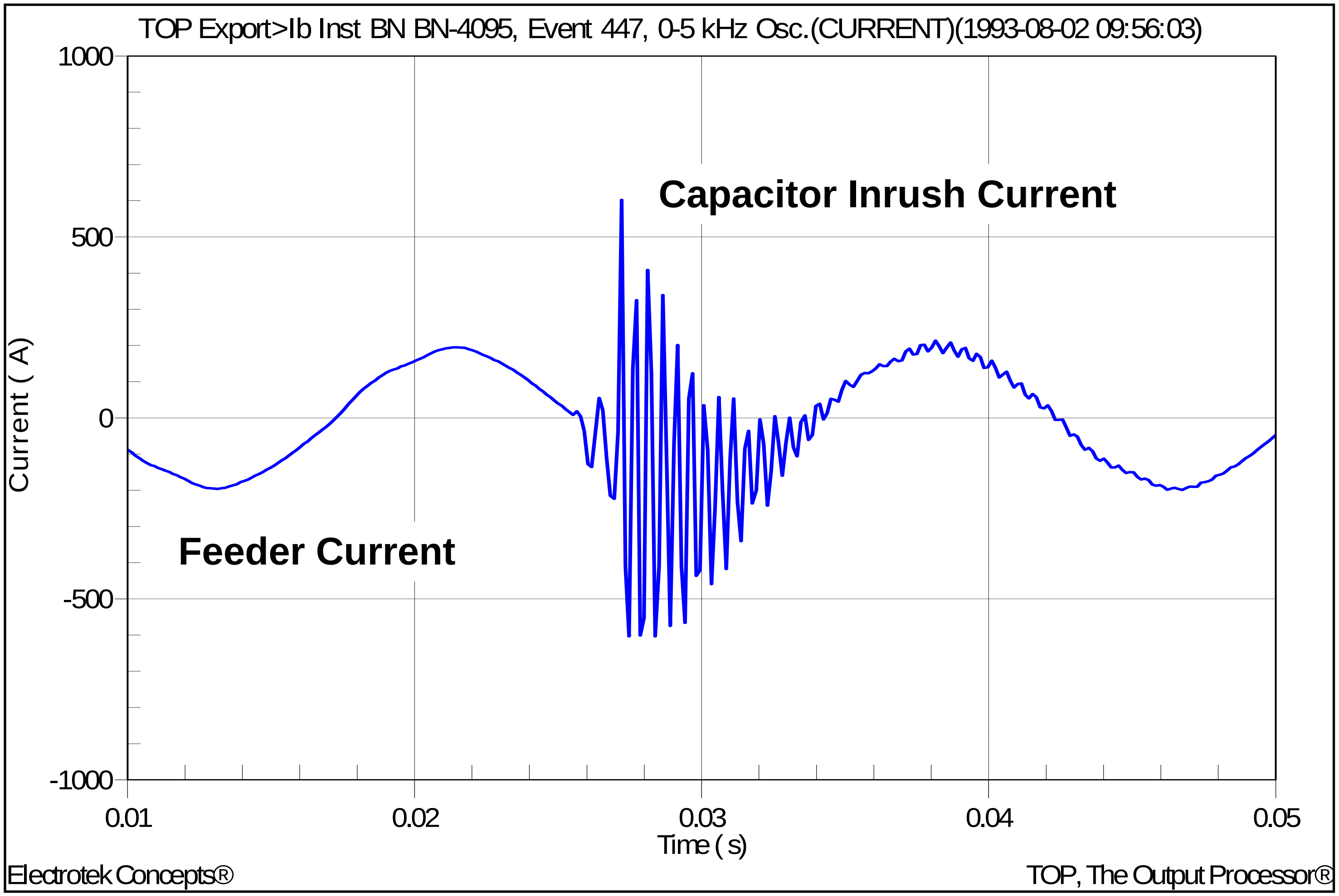
Back-to-Back Capacitor Bank Switching

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



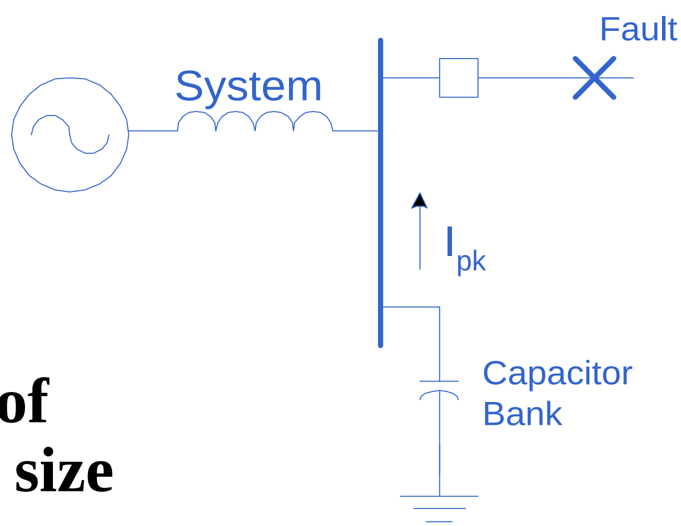
Back-to-Back Switching Snapshot #1

Source: D-BMI 8010 PQNode

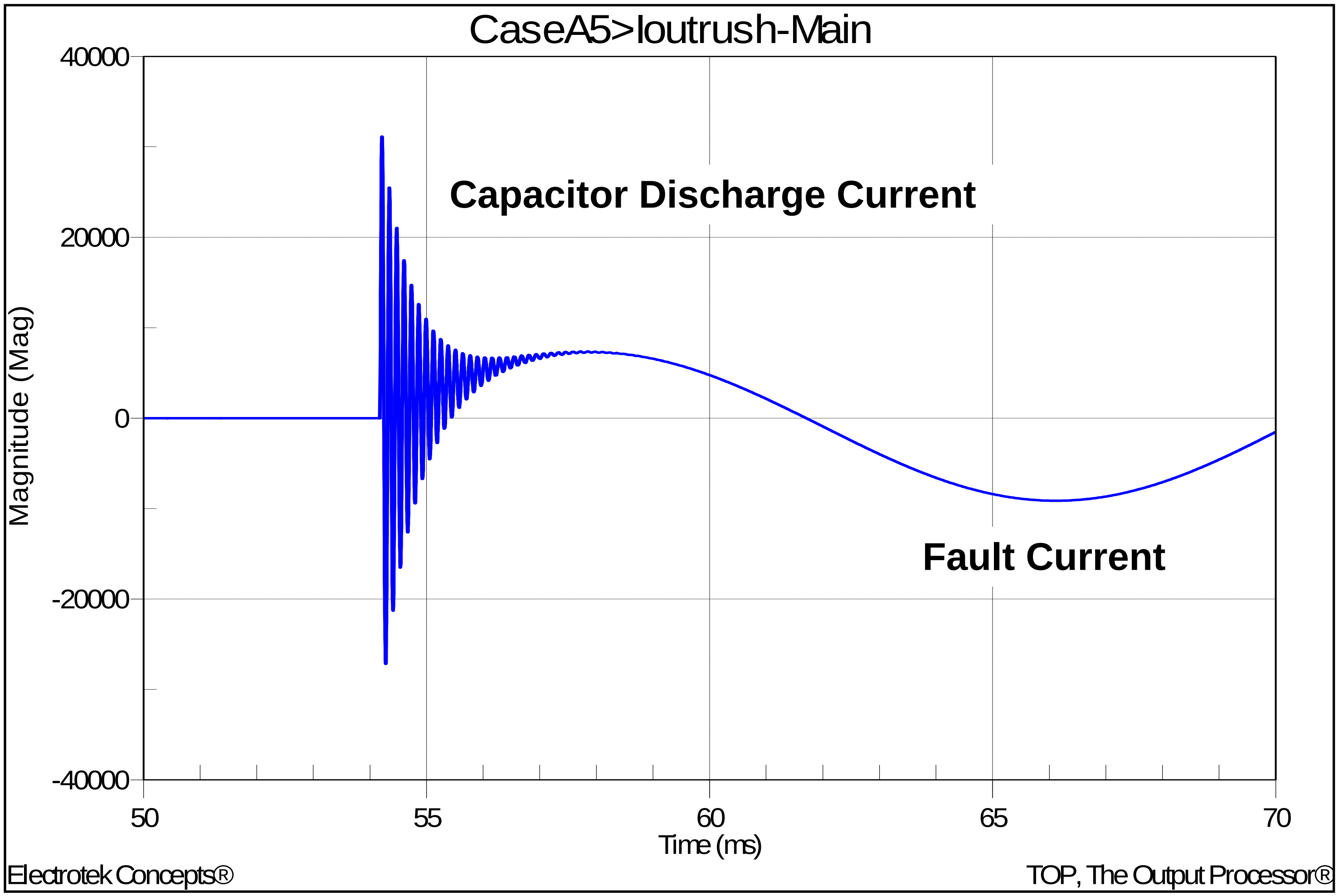


Outrush Current Control

- Outrush current from a shunt capacitor bank into a nearby fault can be a concern.
- The close and latch rating of the circuit breaker is the important factor.
- General purpose breakers:
  - $I_{pk} < 50kA$
  - $I_{pk} * f < 2x10^7$
- Ipk * f product is independent of capacitor size (can be standard size for each voltage level).



Outrush Current Snapshot #1



Source: PSCAD

Bank Overvoltages - Surge Arresters

- **Lightning and capacitor bank switching transients can cause significant overvoltages.**
- **Restrikes of the capacitor bank switch may cause the highest overvoltages (and most severe arrester duties).**
- **Voltage magnification can cause severe duties for arresters at lower voltage locations.**
- **MOV arresters are generally better (higher energy duty for same rating vs. SiC).**
- **Arrester coordination/location should be evaluated (e.g., degraded protective levels).**

Harmonic Resonance and Distortion

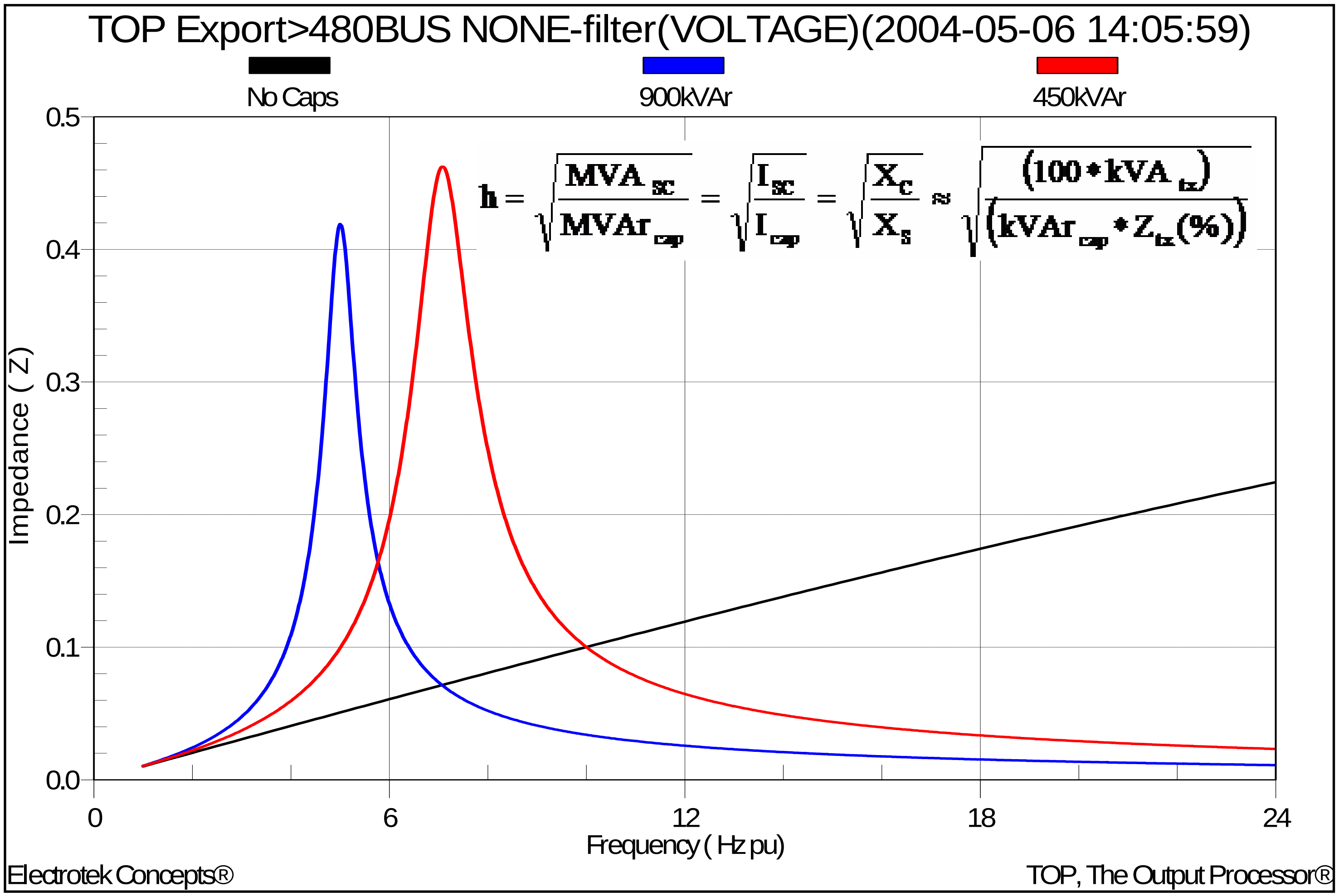
- **Fundamental objective of electric utility operations is to supply each electric customer with a fairly constant sinusoidal voltage.**
- **Present trends in the electric power industry have placed an increased emphasis on the impact of nonlinear equipment. These include:**
  - **The increasing size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

Effect of Shunt Capacitors

- **Capacitors alter the frequency response by creating parallel resonances that can magnify harmonic currents and cause increased voltage distortion levels.**
- **At the frequency where the capacitive reactance (X_C) and the inductive reactance (X_L) are equal, the resulting impedance becomes very large.**
- **This is known as the parallel resonant frequency and can be estimated from:**

$$f_r = \frac{1}{2 \cdot \pi \cdot \sqrt{L \cdot C}} = \sqrt{\frac{MVA_{SC}}{MVAr_C}} \cdot 60$$

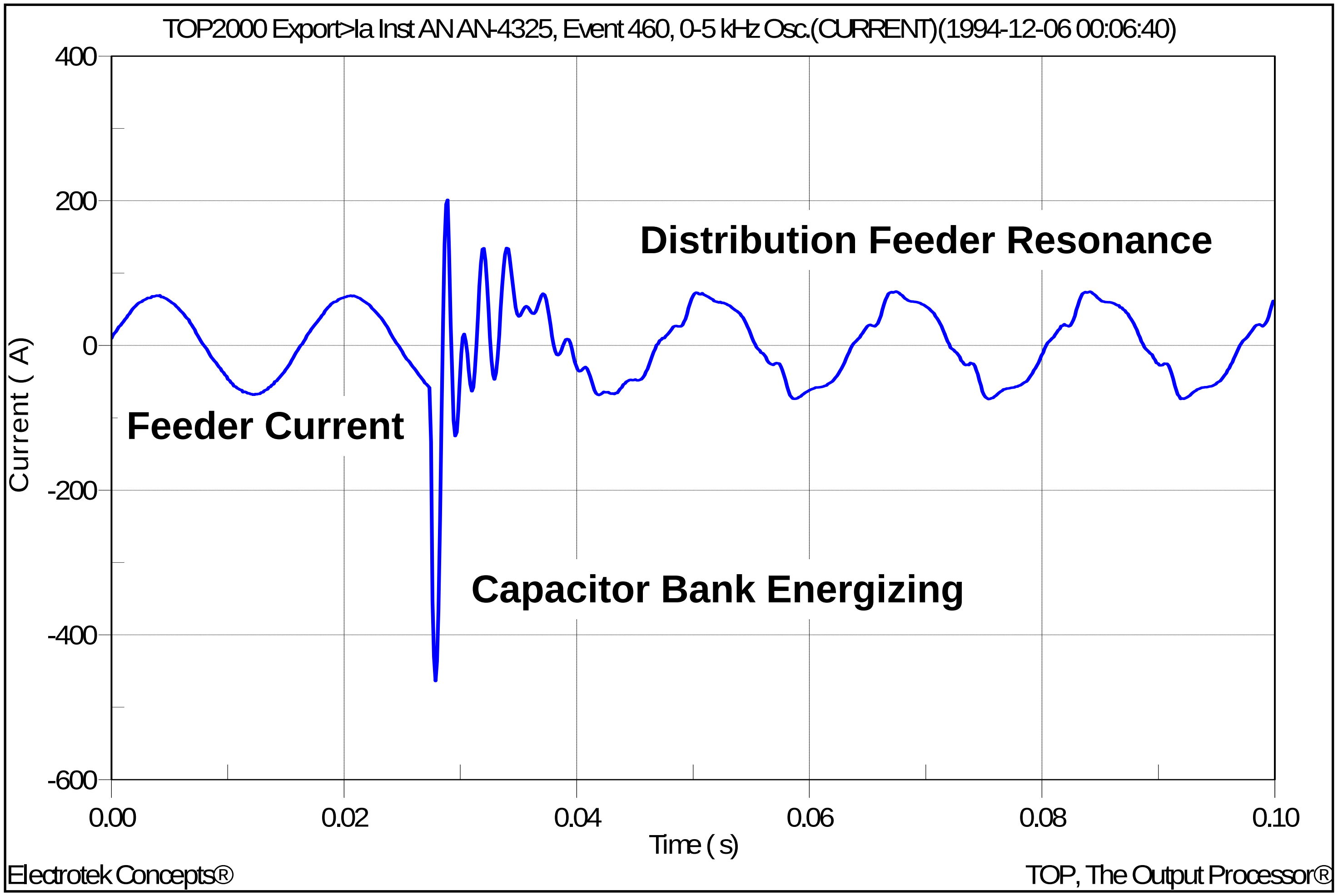
Effect of Shunt Capacitors - continued



$$h = \sqrt{\frac{MVA_{sc}}{MVAr_{cap}}} = \sqrt{\frac{I_{sc}}{I_{cap}}} = \sqrt{\frac{X_c}{X_s}} \approx \sqrt{\frac{(100 * kVA_{tx})}{(kVAr_{cap} * Z_{tx}(\%))}}$$

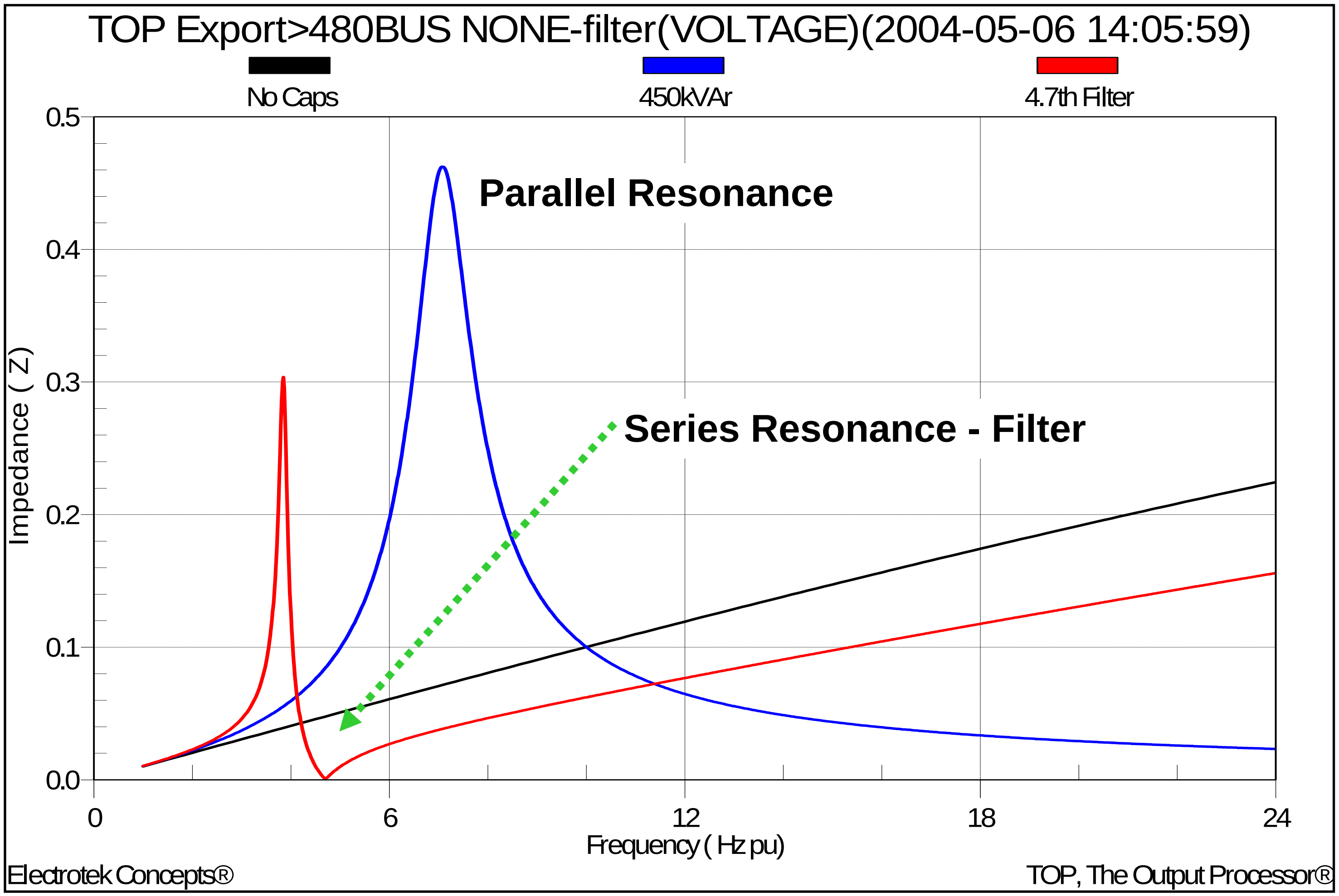
Source: SuperHarm

Effect of Shunt Capacitors - continued



Source: D-BMI 8010 PQNode

Effect of Filters on Frequency Response



Source: SuperHarm

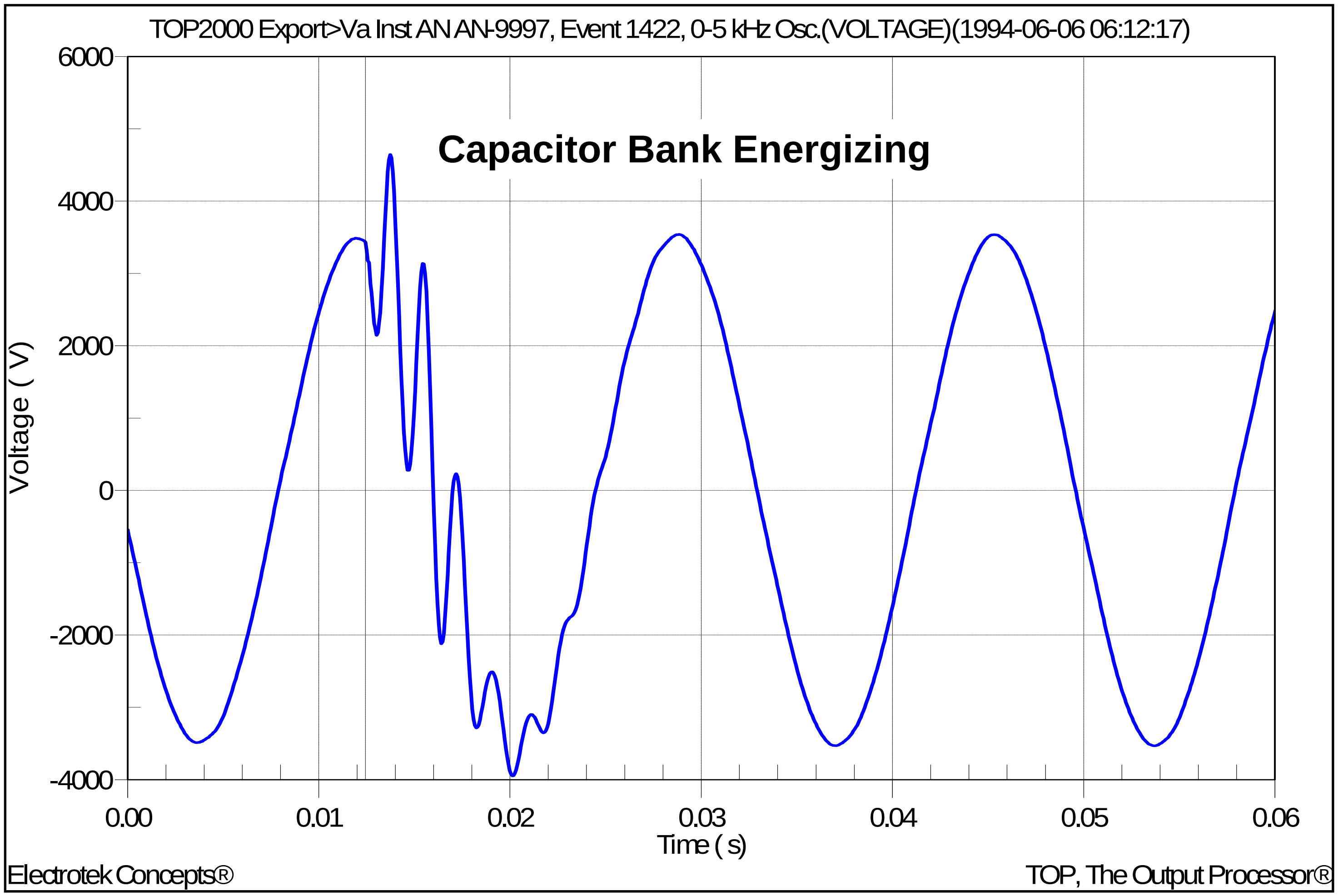
Transient Disturbances

- **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**

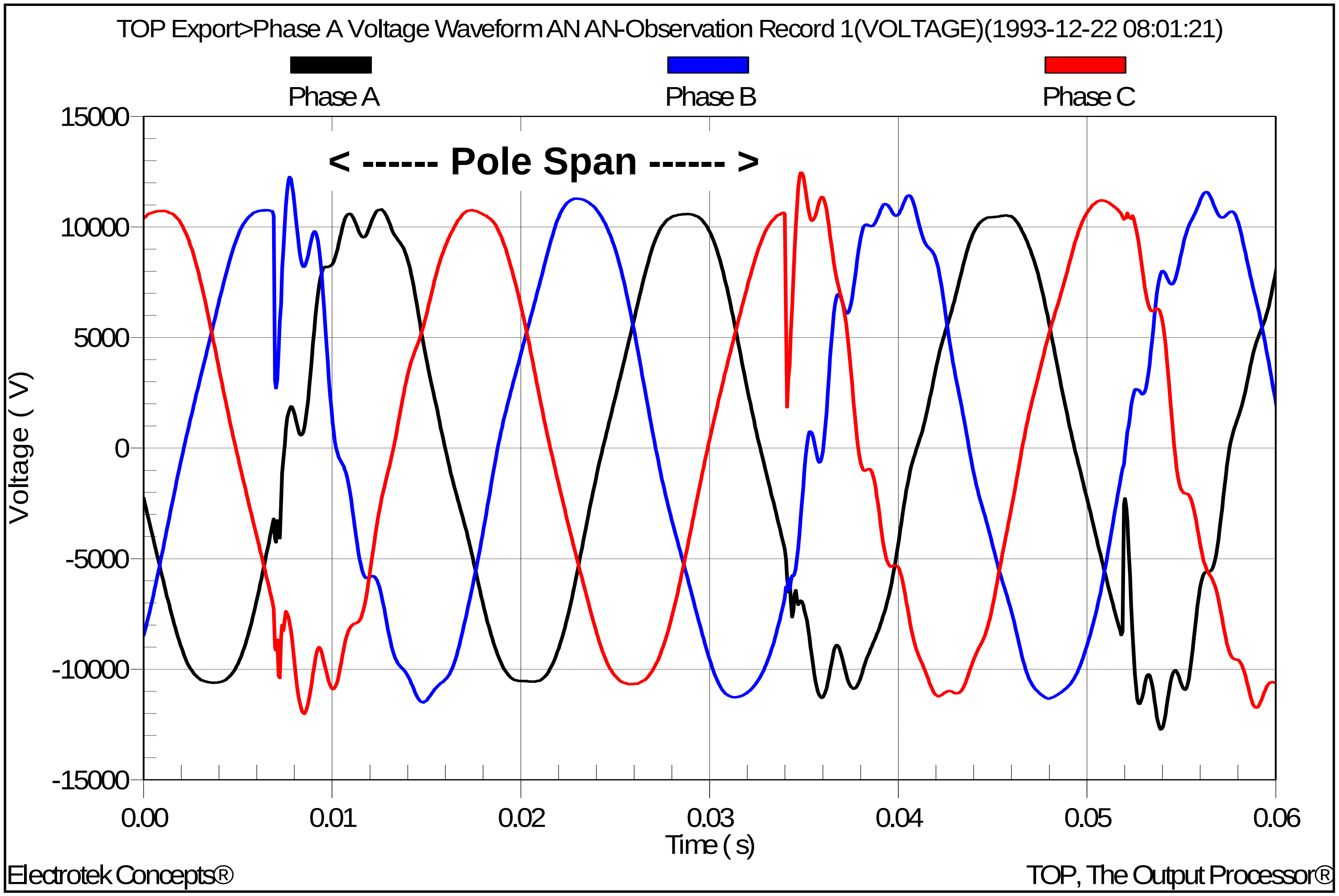
$$f_s = \frac{1}{2\pi\sqrt{L_s C}} \approx f_{system} * \sqrt{\left(\frac{X_c}{X_s}\right)} \approx f_{system} * \sqrt{\left(\frac{MVA_{sc}}{MVA_r}\right)} \approx f_{system} * \sqrt{\left(\frac{1}{\Delta V}\right)}$$

Capacitor Energizing - Snapshot #1



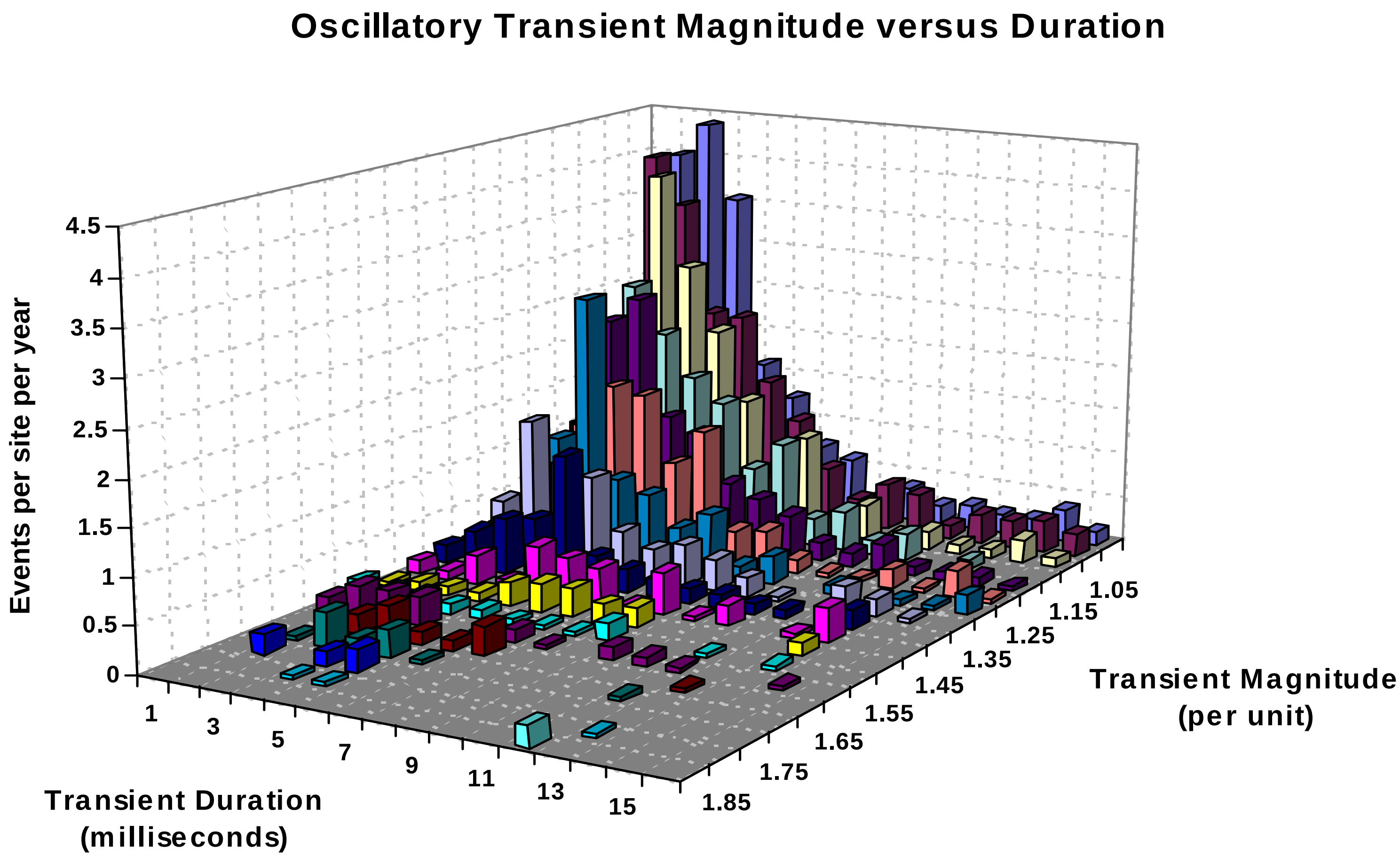
Source: D-BMI 8010 PQNode

Capacitor Energizing - Snapshot #2



Source: D-BMI 8010 PQNode

Capacitor Energizing - Characteristics



Only one transient per 5 minute period counted - measurement and phase with largest absolute magnitude used

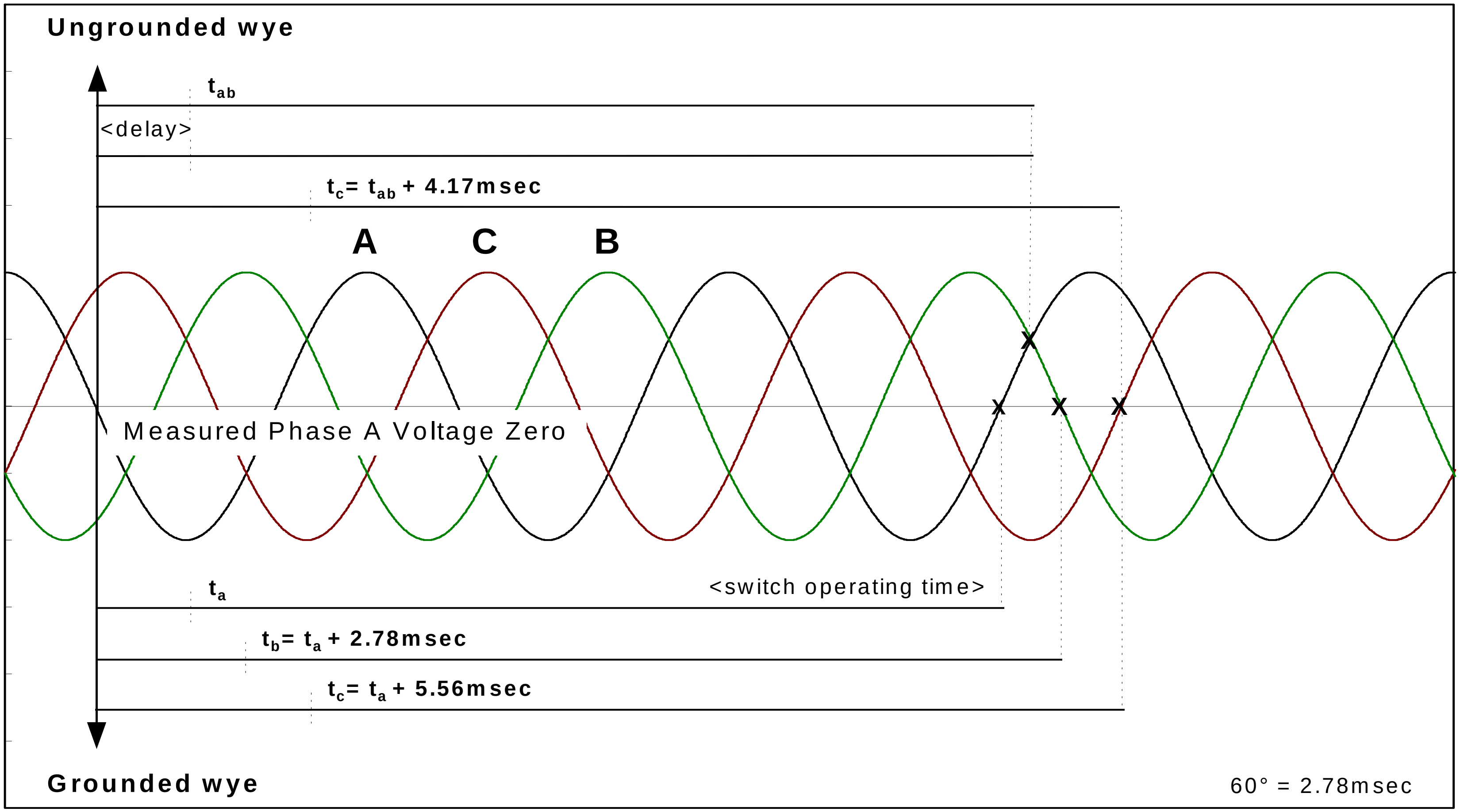
Overvoltage Control Methods

- **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 (e.g., zero voltage on capacitor - zero voltage on bus).**
- **Preinsertion device**
  - **Method for controlling overvoltage by inserting an impedance (usually inductance or resistance) in series with the component to be energized.**
- **Arresters**
  - **Method for controlling overvoltage by "clipping" at a specified protective level.**

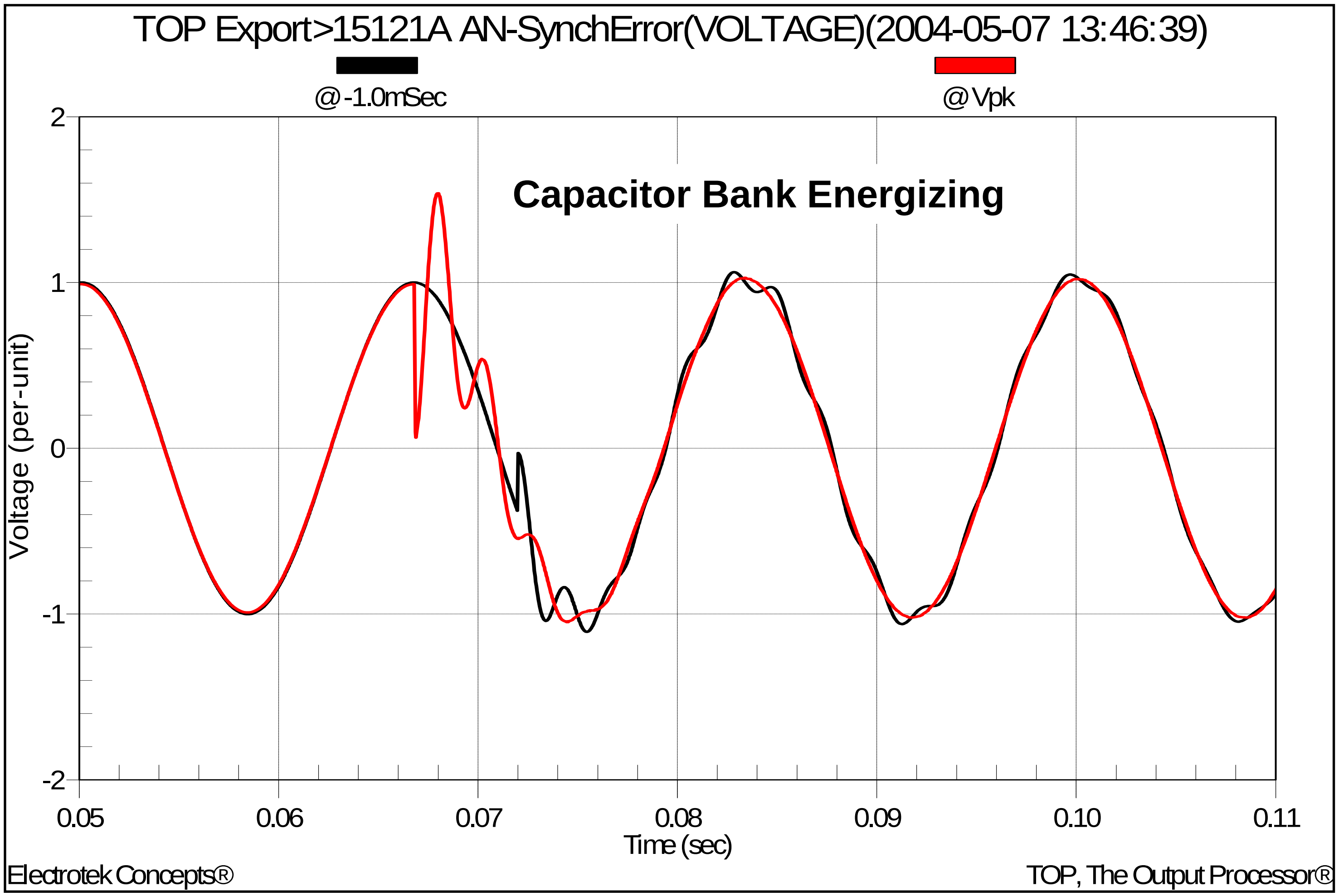
Synchronous Closing Control

- **A number of manufacturers now have synchronous closing available at T&D voltage levels.**
- **Methods include analog and microprocessor controls.**
- **Can be used in combination with preinsertion 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 - Timing



Effectiveness of Closing Control

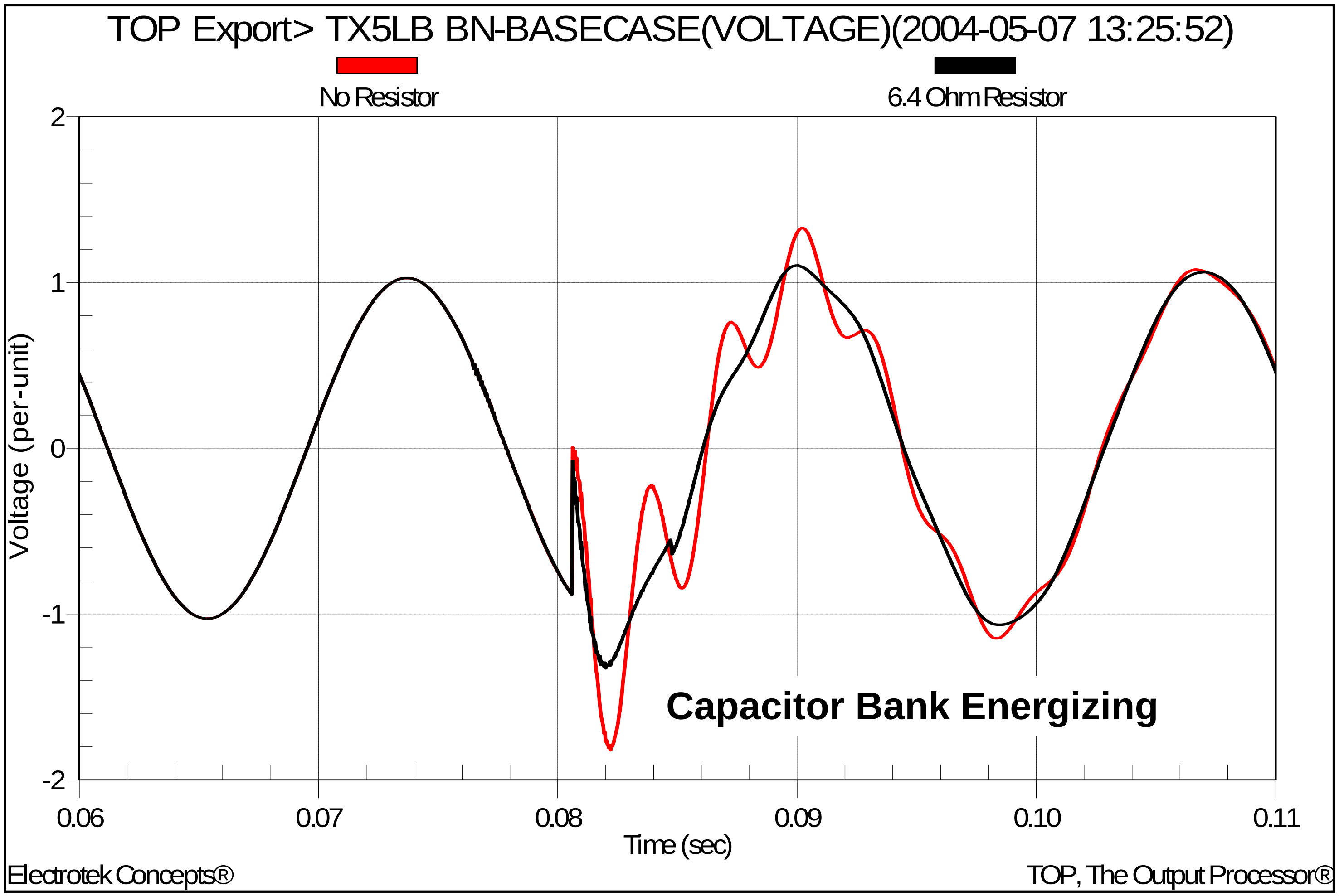


Source: EMTP

Preinsertion Devices

- Many options 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).

Effectiveness of Preinsertion Resistor

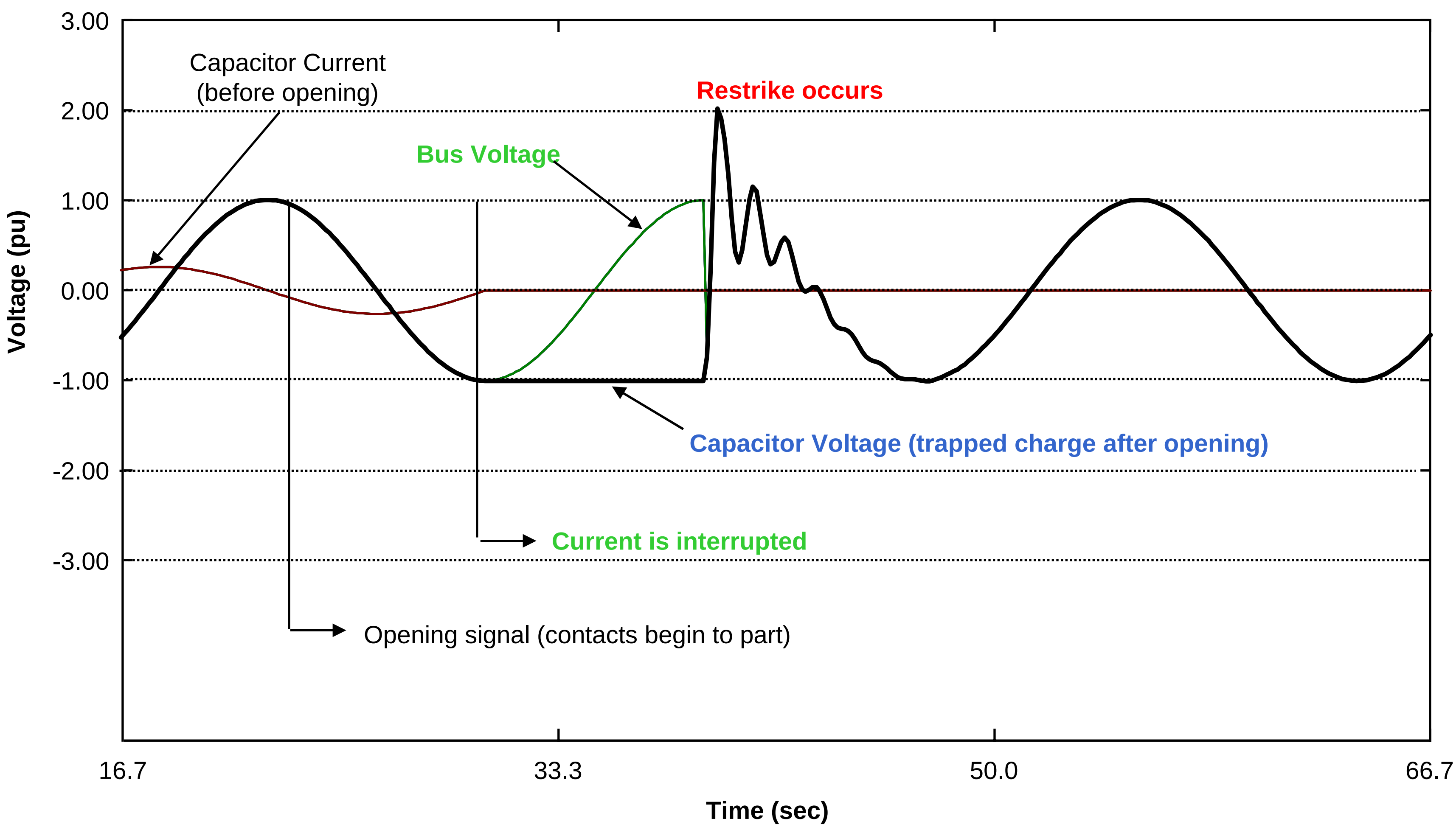


Source: EMTP

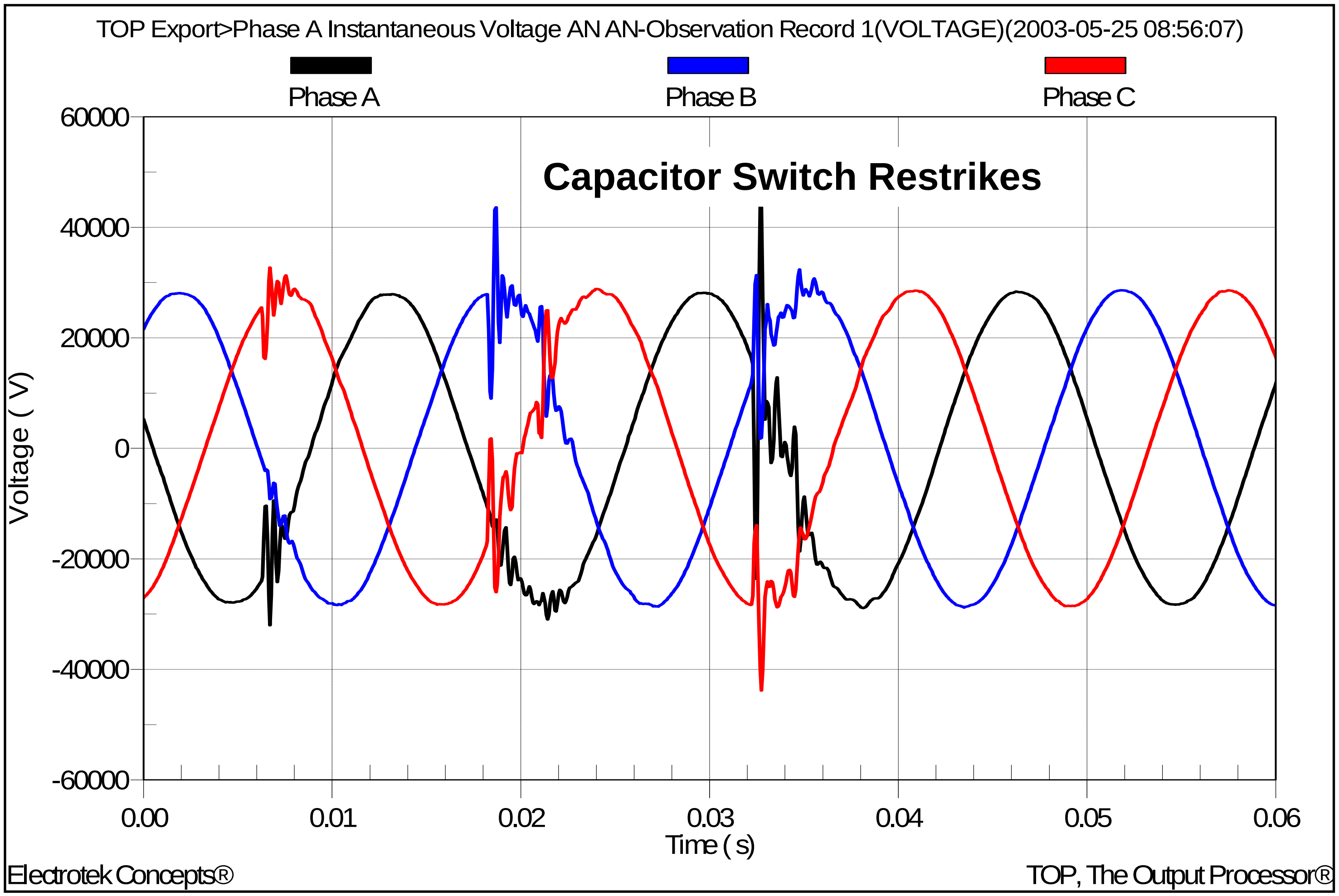
Restrike Transients

- Restrikes can occur during capacitor switch opening:
  - High frequency inrush currents (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.

The Capacitor Switch Restrike Event

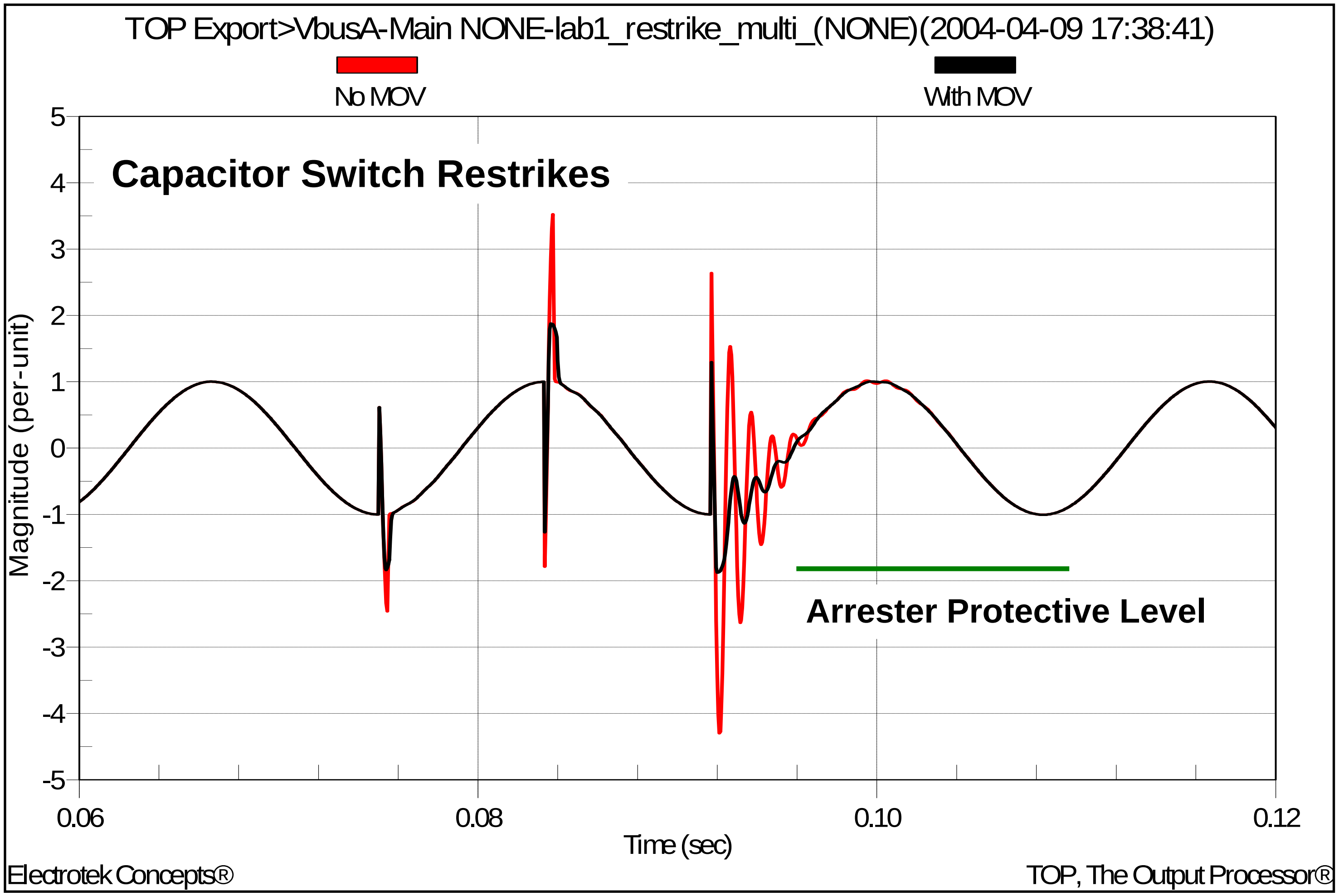


Capacitor Switch Restrike Snapshot #1



Source: D-BMI 8010 PQNode

Simulation of a Multiple Restrike Event



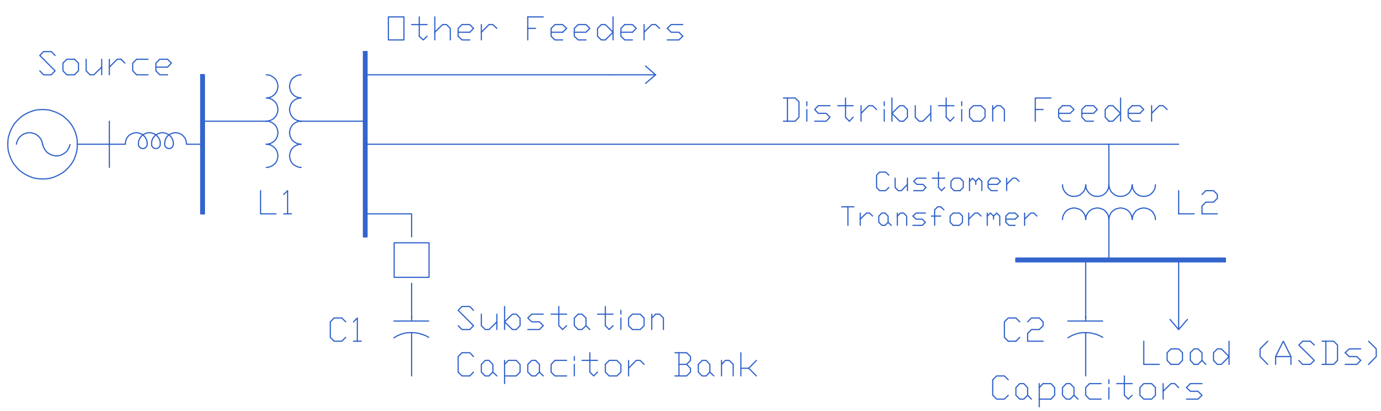
Source: PSCAD

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 capacitors for power factor and voltage correction.
  - This is occurring within customer facilities, as well as on the utility power system.
  - Capacitors change the system frequency response characteristics, resulting in resonances that can magnify transient disturbances and harmonic distortion levels.

Magnification of Capacitor Switching

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



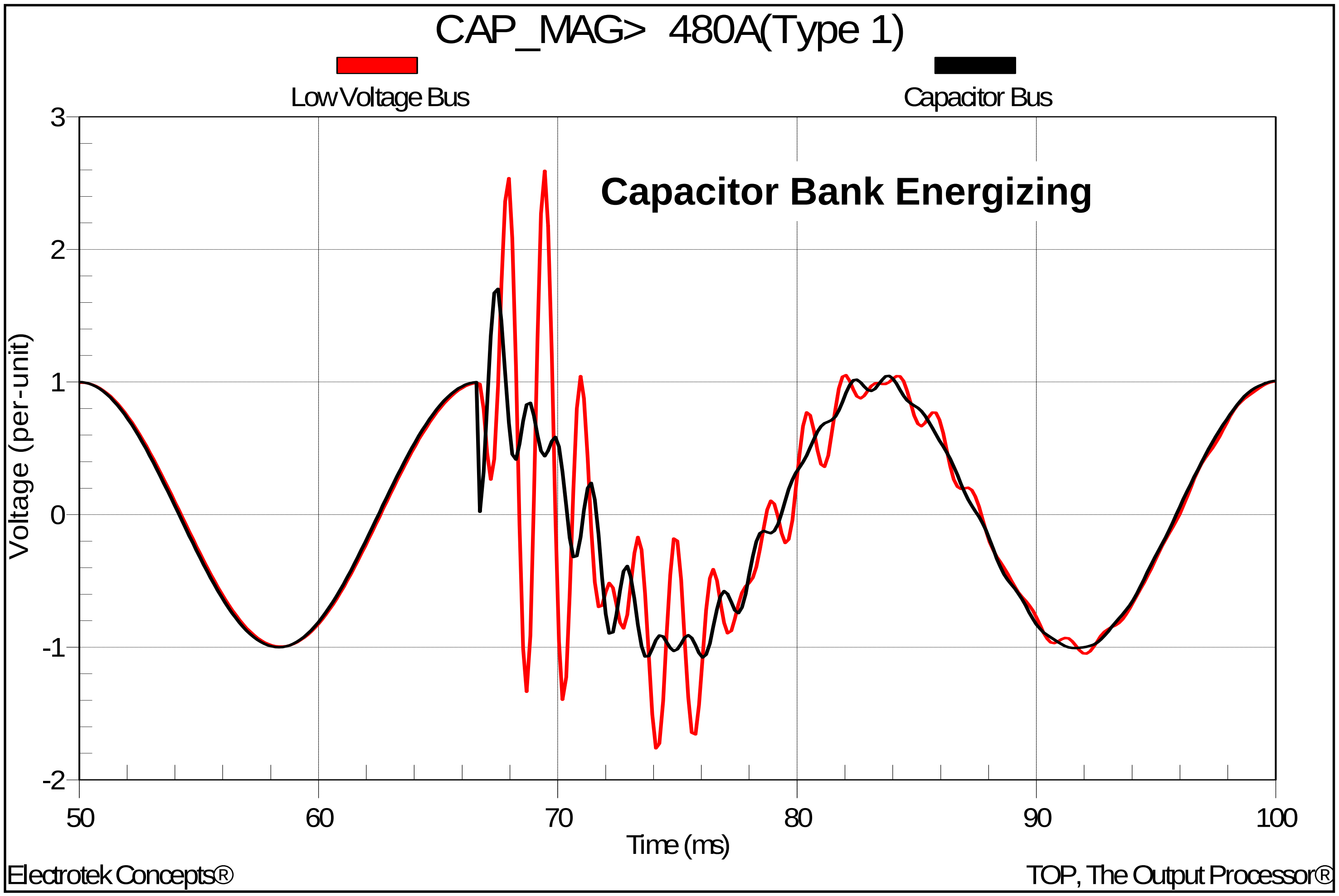
$$f_1 = \frac{1}{2 \cdot \pi \cdot \sqrt{L_1 \cdot C_1}} \qquad f_2 = \frac{1}{2 \cdot \pi \cdot \sqrt{L_2 \cdot C_2}}$$

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 MVAr of the switched capacitor bank is significantly greater (>10) than the lower voltage capacitor.**
  - **There is little damping on the low voltage system (mostly motor load).**

The magnified transient at the low voltage bus can reach <u>4</u> per-unit.

Magnified Transient at Low Voltage Bus



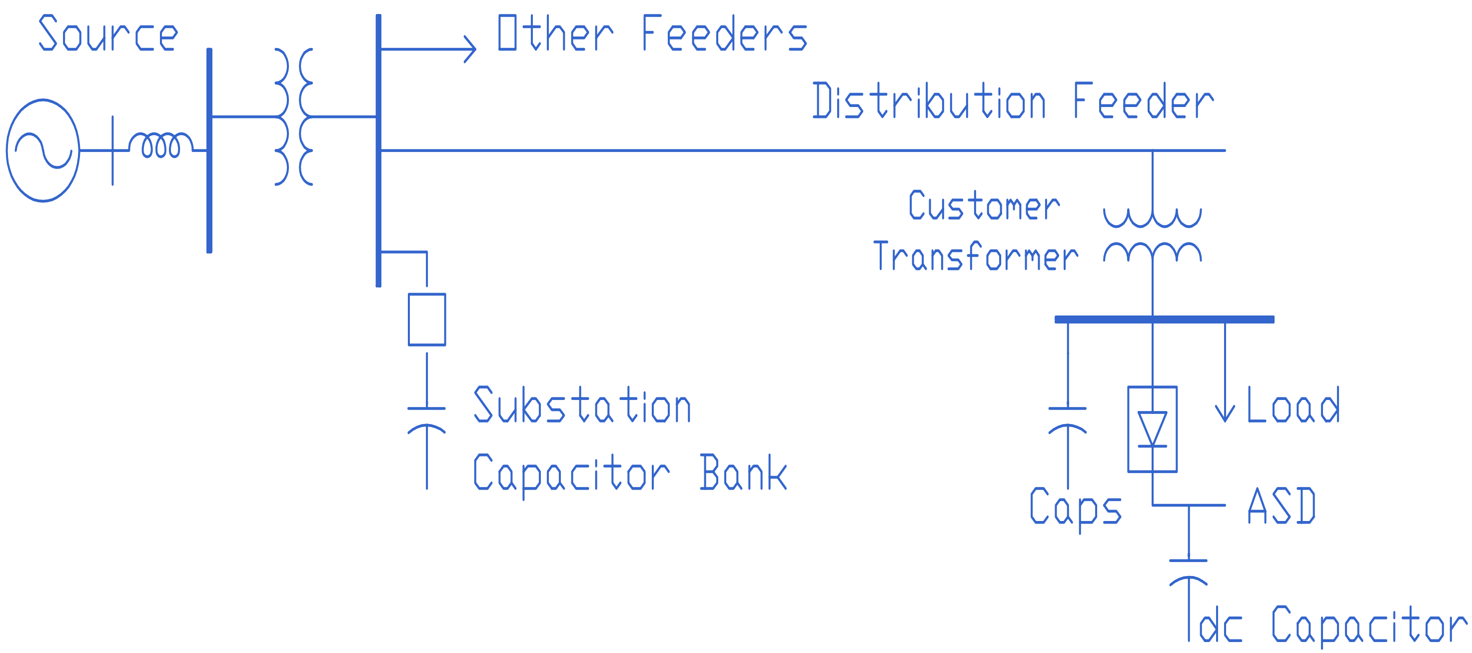
Source: EMTP

Solutions to Magnification Phenomena

- **Controlling the transient overvoltages at the source (the utility system) is sometimes possible:**
  - **Synchronous closing control**
  - **Closing through a resistor/inductor first**
- **Surge arresters at the customer location can be used (limit voltages to protective levels, concern for duty).**
- **Conversion of capacitor banks to harmonic filters is effective for control of the magnification problem (transient voltage dropped across filter inductor).**

Nuisance Tripping of ASDs

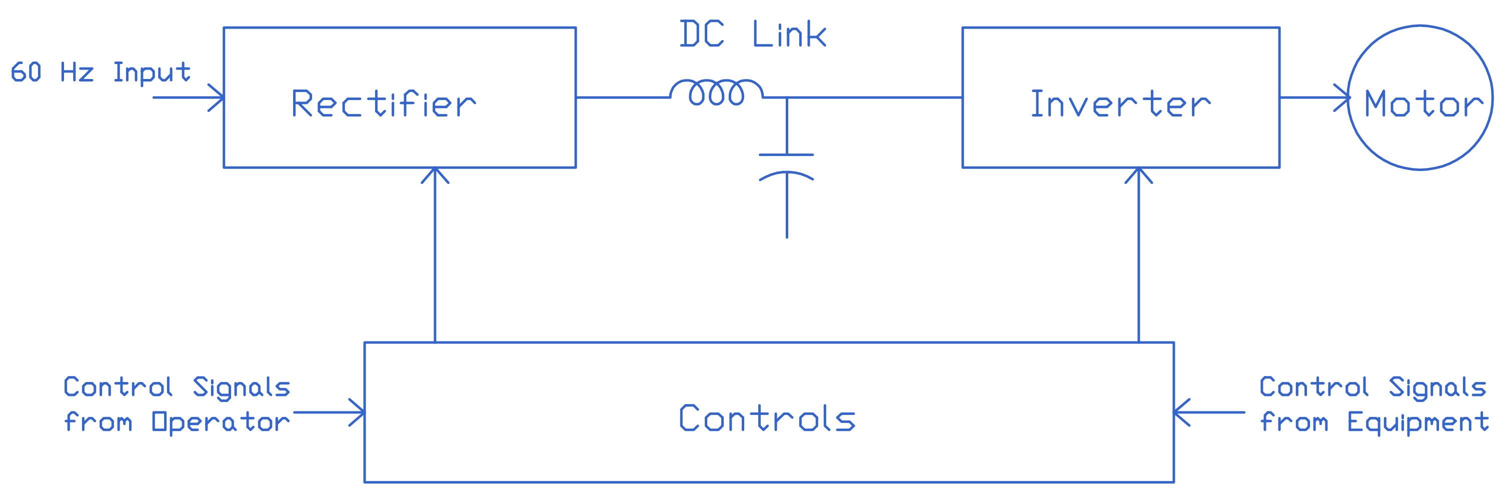
- **System oneline diagram:**



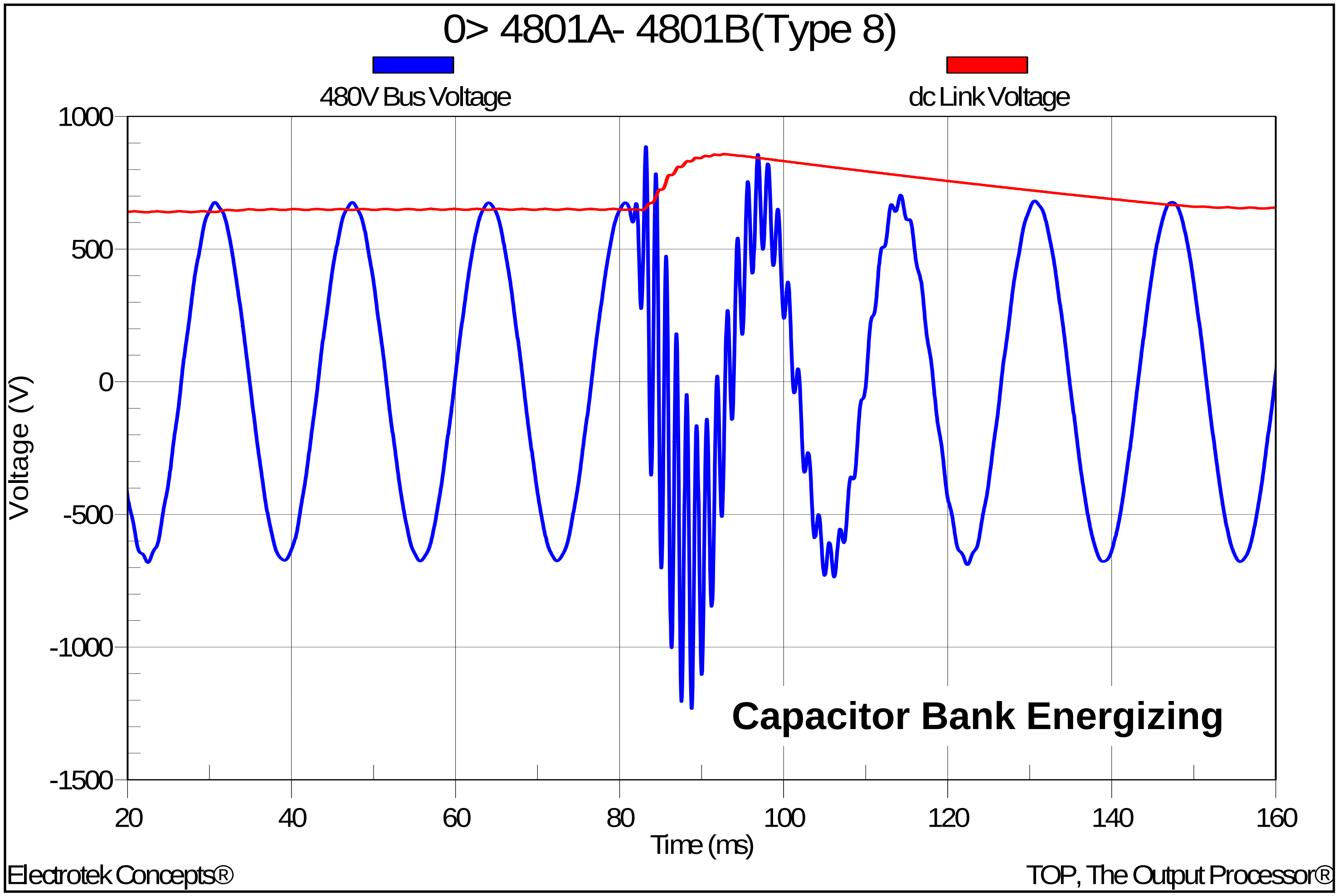
ref: IEEE Paper 91 WM 086-9 PWRD

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.**



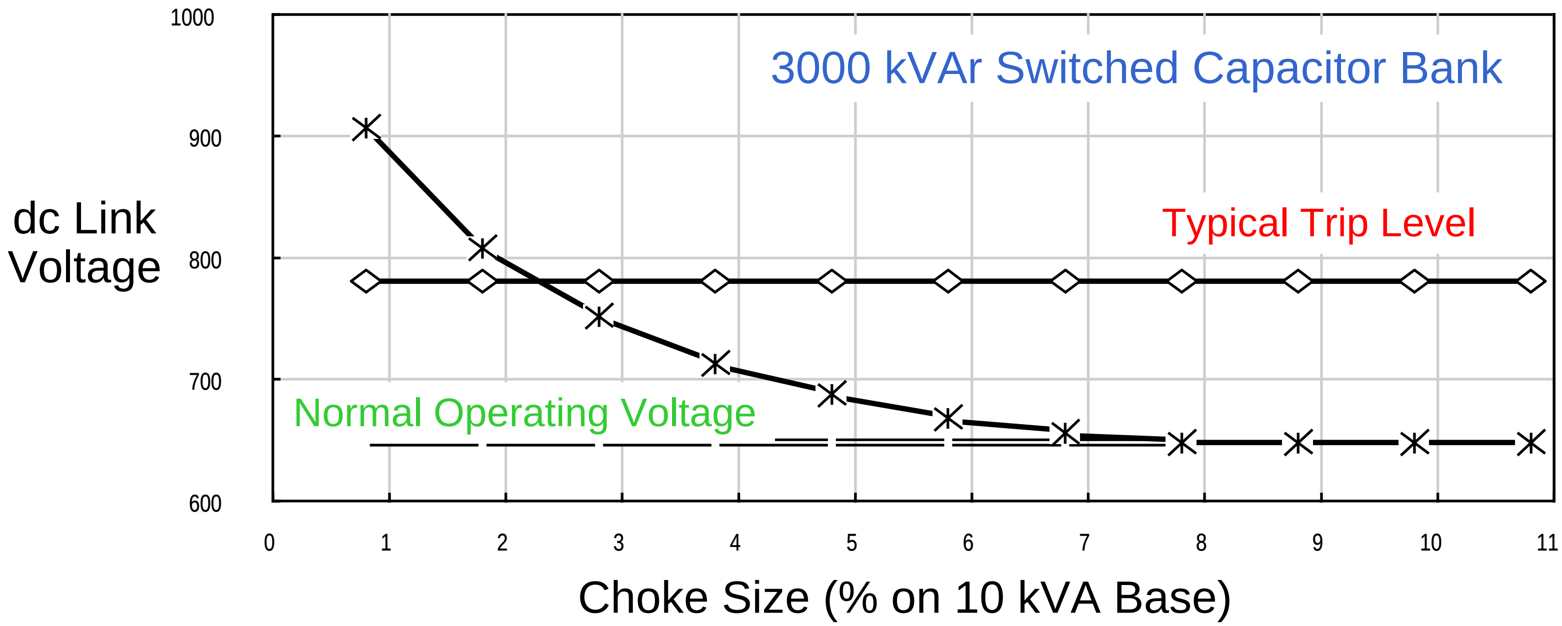
dc Link Voltage during Switching



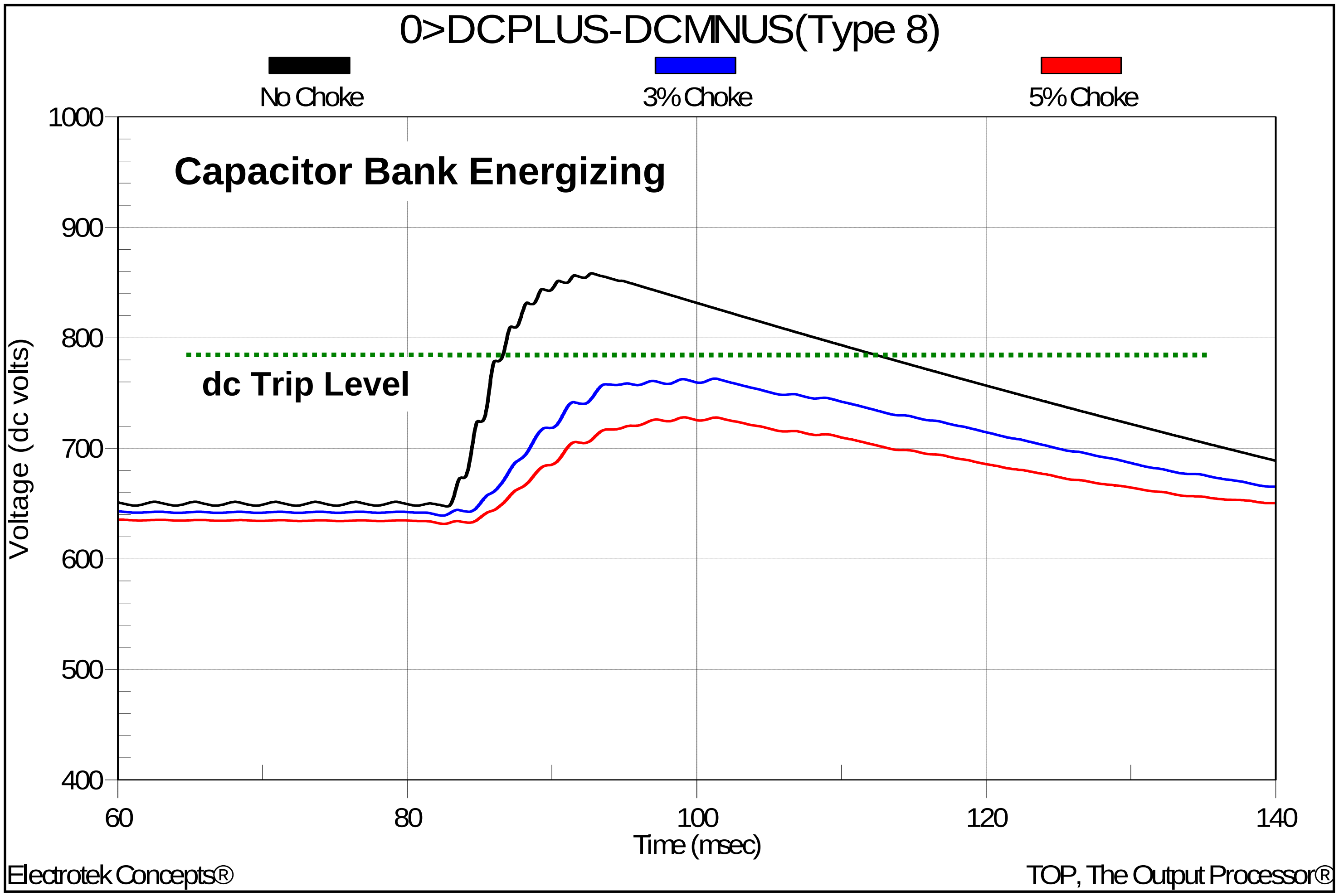
Source: EMTP

Solution to Nuisance Tripping - Chokes

- **Inductance on the ac side (e.g., isolation transformer or choke) has the most dramatic effect on the switching surge because it introduces a large impedance into the circuit where the current flows.**



Effect of Choke on dc Link Voltage



Source: EMTP

Additional Information

- **Electrotek provides consulting services related to capacitor applications including transient and harmonic studies using tools such as PSCAD, EMTP, and SuperHarm.**
- **Additional Information:**

Electrotek (studies and capacitor application seminar):
http://www.electrotek.com/

PQSoft (simulation and analysis tools and support):
http://www.pqsoft.com/

Monitoring instruments for capturing capacitor switching transients:
http://www.dranetz-bmi.com/

Questions?
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