Medium Voltage Transient Problems

Thomas Grebe
Senior Consultant
Electrotek Concepts, Inc.
tgrebe@electrotek.com
www.electrotek.com

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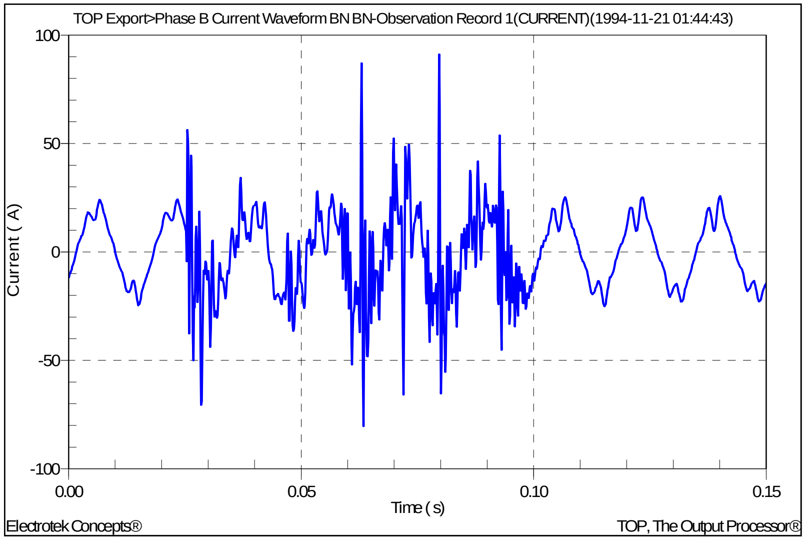


- Introduction and Definitions
- Load Switching
- Lightning
- Transformer Energizing
- Ferroresonance
- Utility Capacitor Energizing
  - Voltage Magnification
  - Nuisance Tripping of Adjustable-Speed Drives
- Voltage Notching

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.

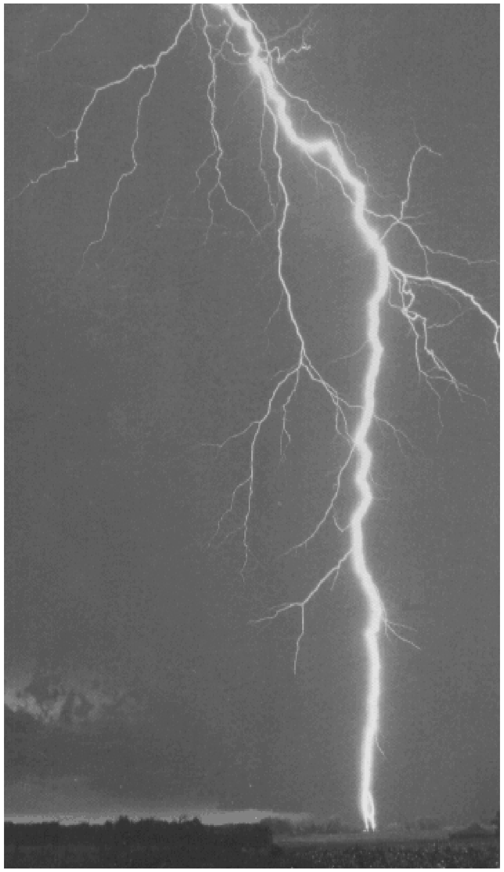
Transient overvoltages and overcurrents are classified by peak magnitude, frequency, and duration.

Characterizing Transient Disturbances

- Transient Oscillations:
  - Oscillatory
    - Low Frequency - less than 300 Hertz
    - Medium Frequency - 300 Hz - 2 kHz
    - High Frequency - 2 kHz - 5 kHz
  - Characterized by waveform data points
- Transient Impulses:
  - Unidirectional
  - Less than 200μsec in duration
  - Frequency components greater than 5 kHz
  - Characterized by magnitude and duration

Sources of Transient Disturbances

- Power Quality-Related Sources of Transient Voltages and Currents:
  - Lightning
  - Load Switching
  - Transformer Switching
  - Ferroresonance
  - Capacitor Switching
  - Voltage Notching (rectifier switching)
  - ASD Motor Transients (inverter switching)
  - And many others…



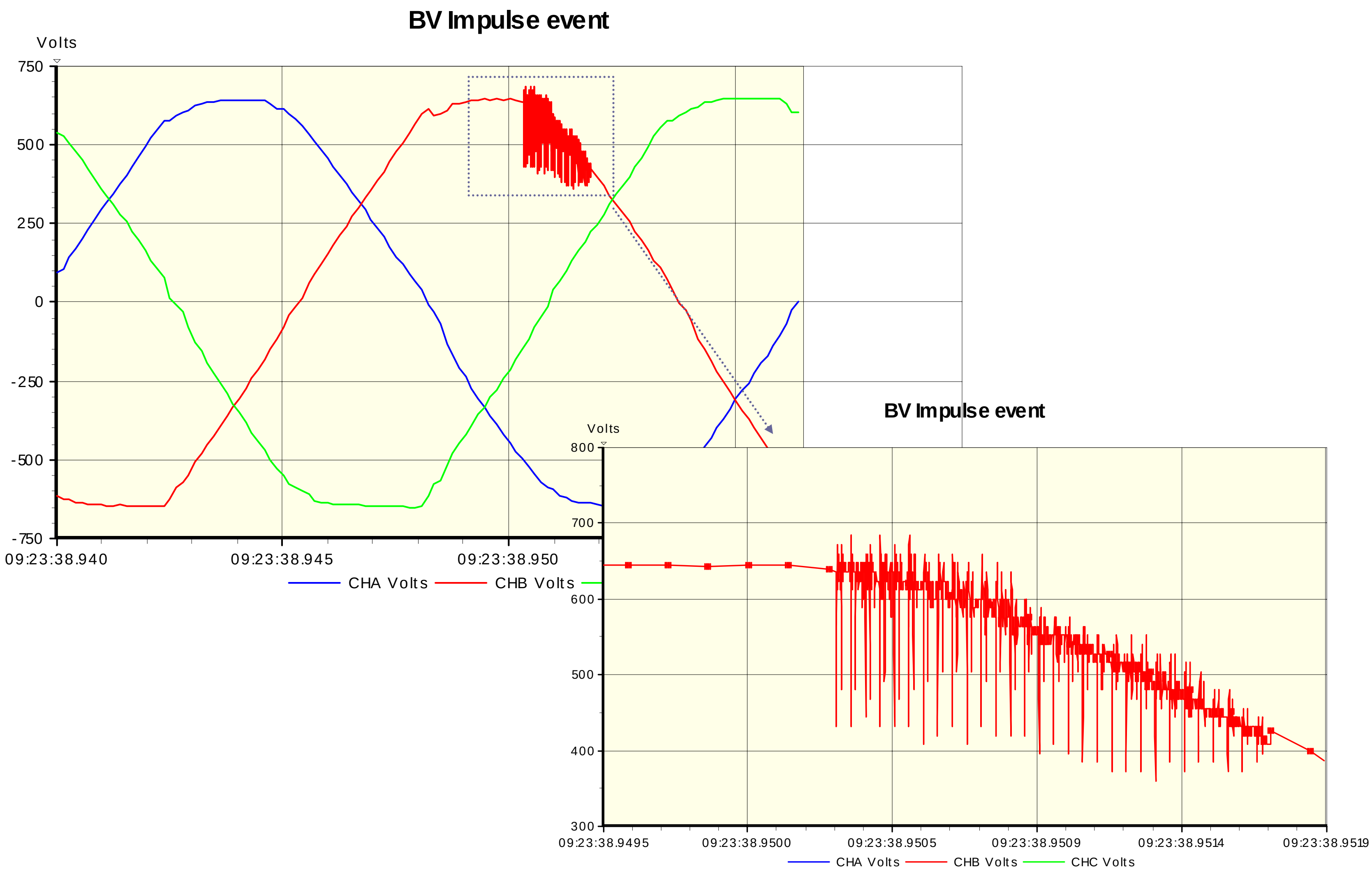
How do Transients Propagate?

- 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

High Frequency Load Switching Transients

- High-frequency transients are often initiated by some type of switching event.
- Circuit switching (de-energizing) and inductive loads cycling on-and-off (contactors) can produce a burst of high frequency impulses.
- Most high frequency transients occurring within customer facilities do not have significant energy associated with them (e.g., less than 1 Joule). This means that equipment can often be protected with simple surge protection devices.

Measured Load Switching Waveform

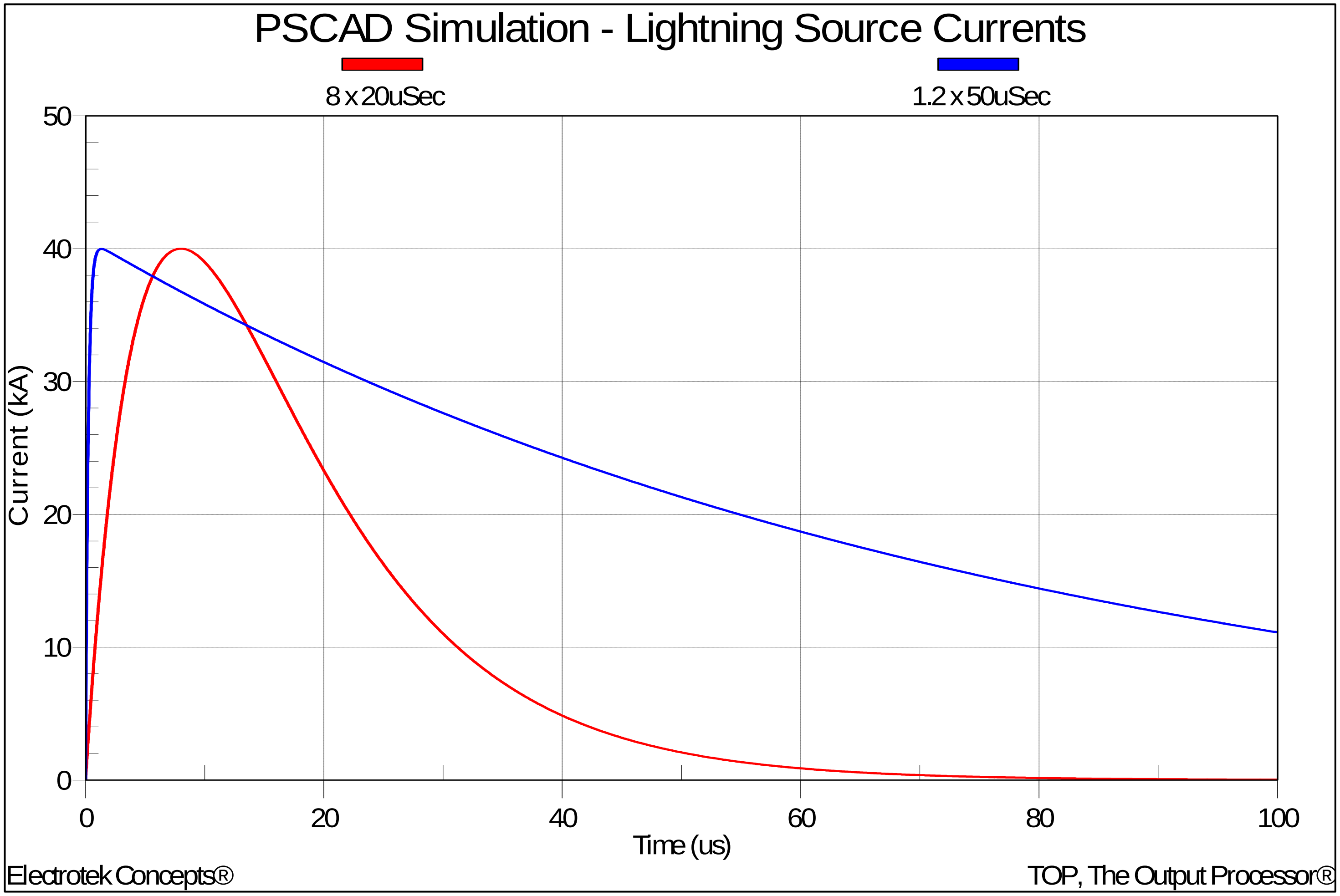


Source: Dranetz-BMI 658

Lightning Transients

- Lightning transients are caused by the injection of current impulses into the system.
- High frequency, high magnitude transients can propagate on the system and into customer facilities.
- A direct stroke to a distribution line will cause the voltage to rise rapidly, resulting in an arrester operation or line flashover.
- Fast wavefronts can couple through transformers by capacitance ratio, rather than turns ratio
  - High rate-of-rise can cause failures in power electronic equipment (e.g., SCRs, etc.)

Simulated Lightning Current Waveforms

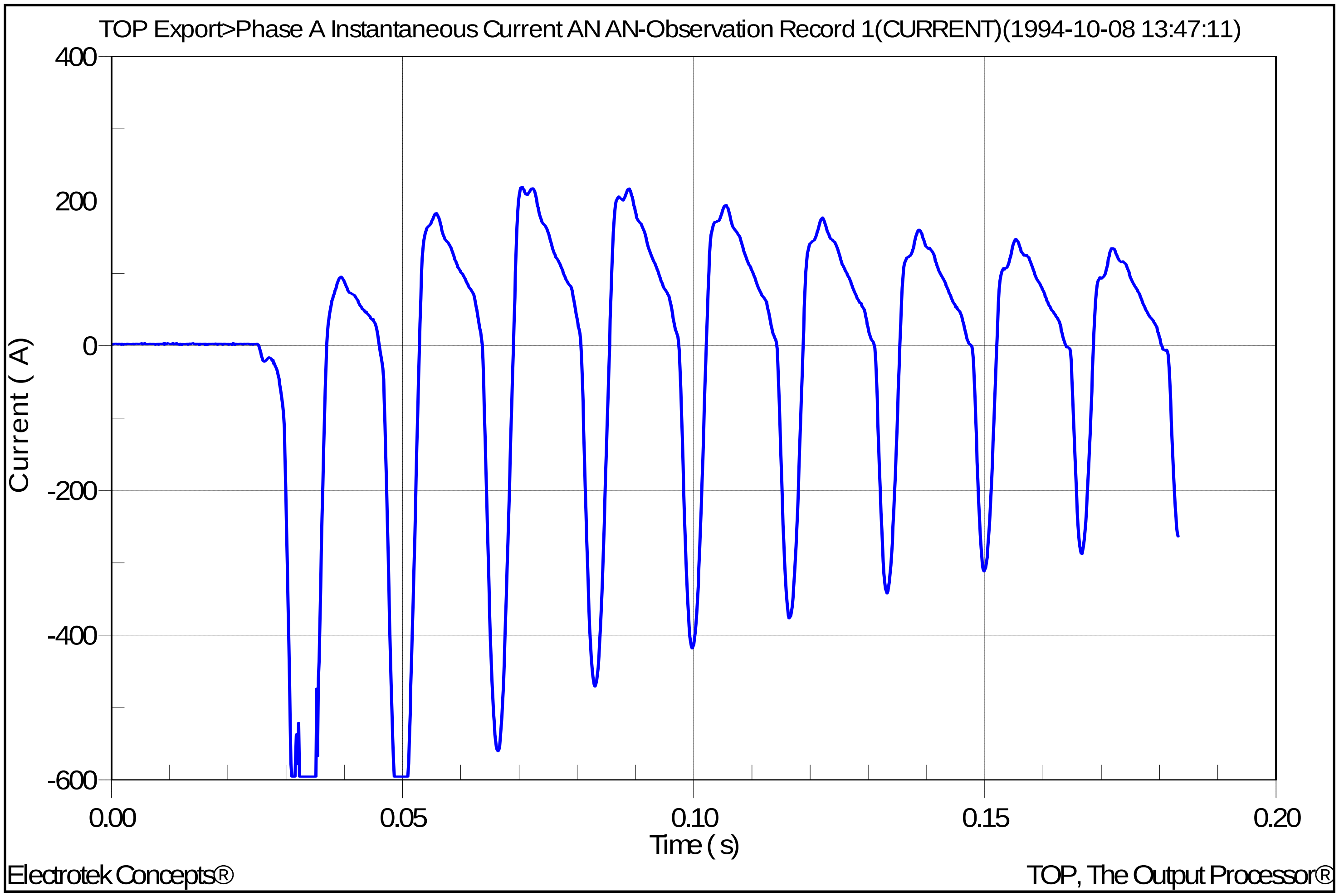


Source: PSCAD

Transformer Energizing

- When a transformer (device with magnetic core) is energized, a transient inrush current flows:
  - current interacts with the system impedance to create a voltage waveform that can have significant harmonic components (> full-load current by a factor of 8-10)
  - may excite local resonances (cables, capacitors), causing dynamic overvoltages
  - current typically decays in several seconds
  - characteristic of the current is determined by:
    - magnitude of input voltage at the instant of energization
    - residual flux in the core
    - impedance of the supply circuit

Measured Transformer Energizing



Source: Dranetz-BMI 5530 DataNode

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:

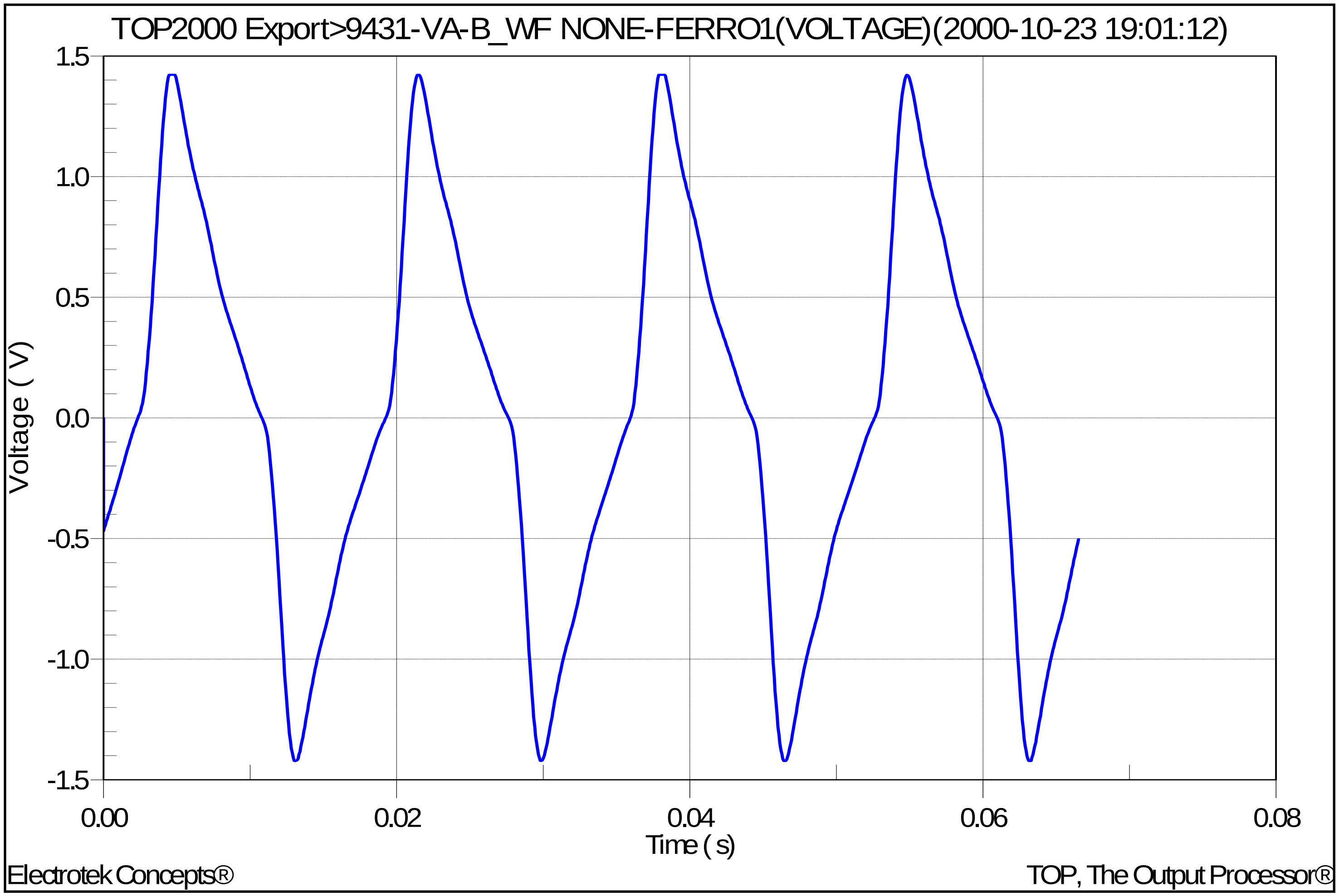
  - single-phase cutouts / single-phase reclosers

  - 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

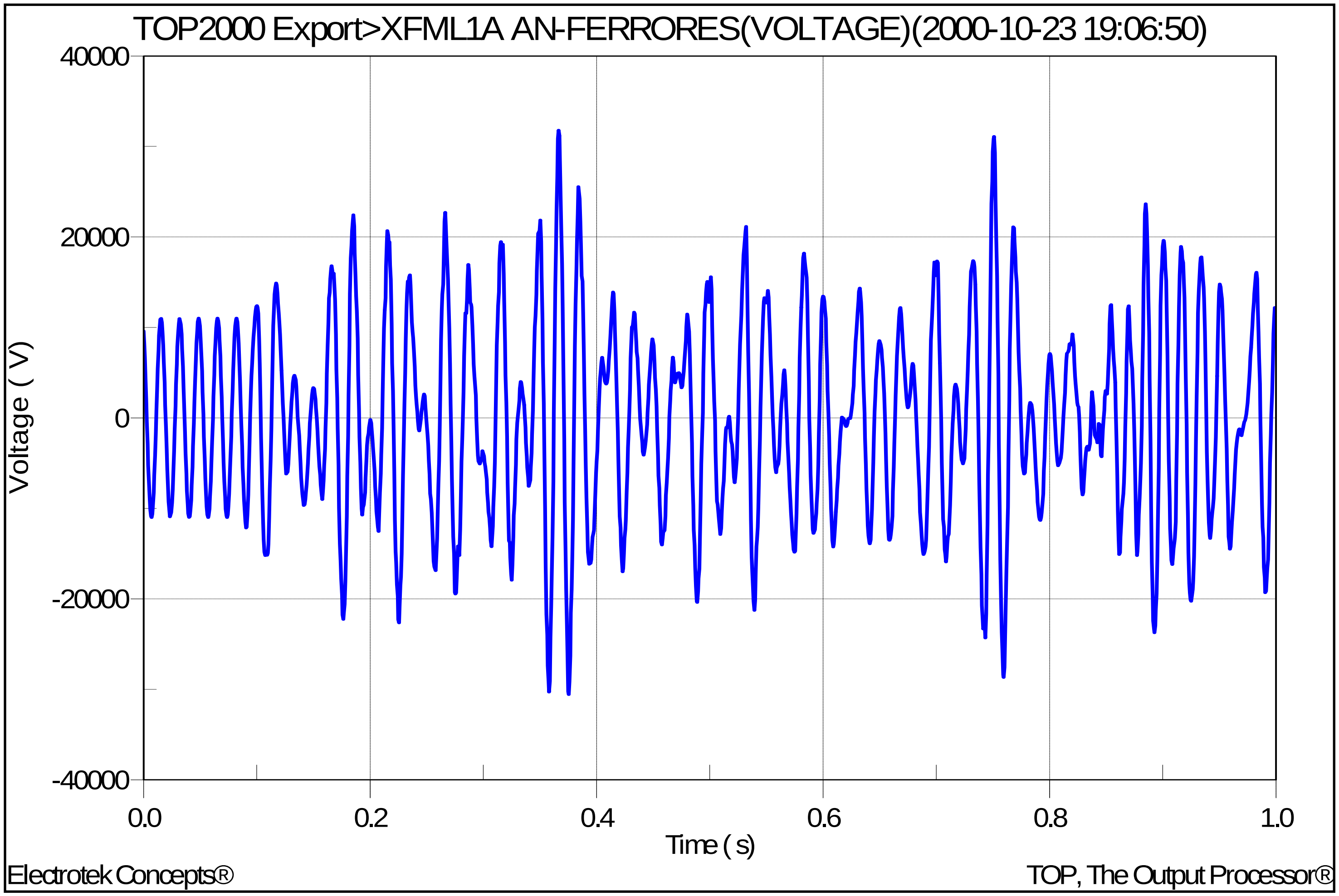
  - three-phase switch with large pole closing span

Measured Ferroresonance Waveform



Source: D-BMI 8010 PQNode

Simulated Ferroresonance Waveform



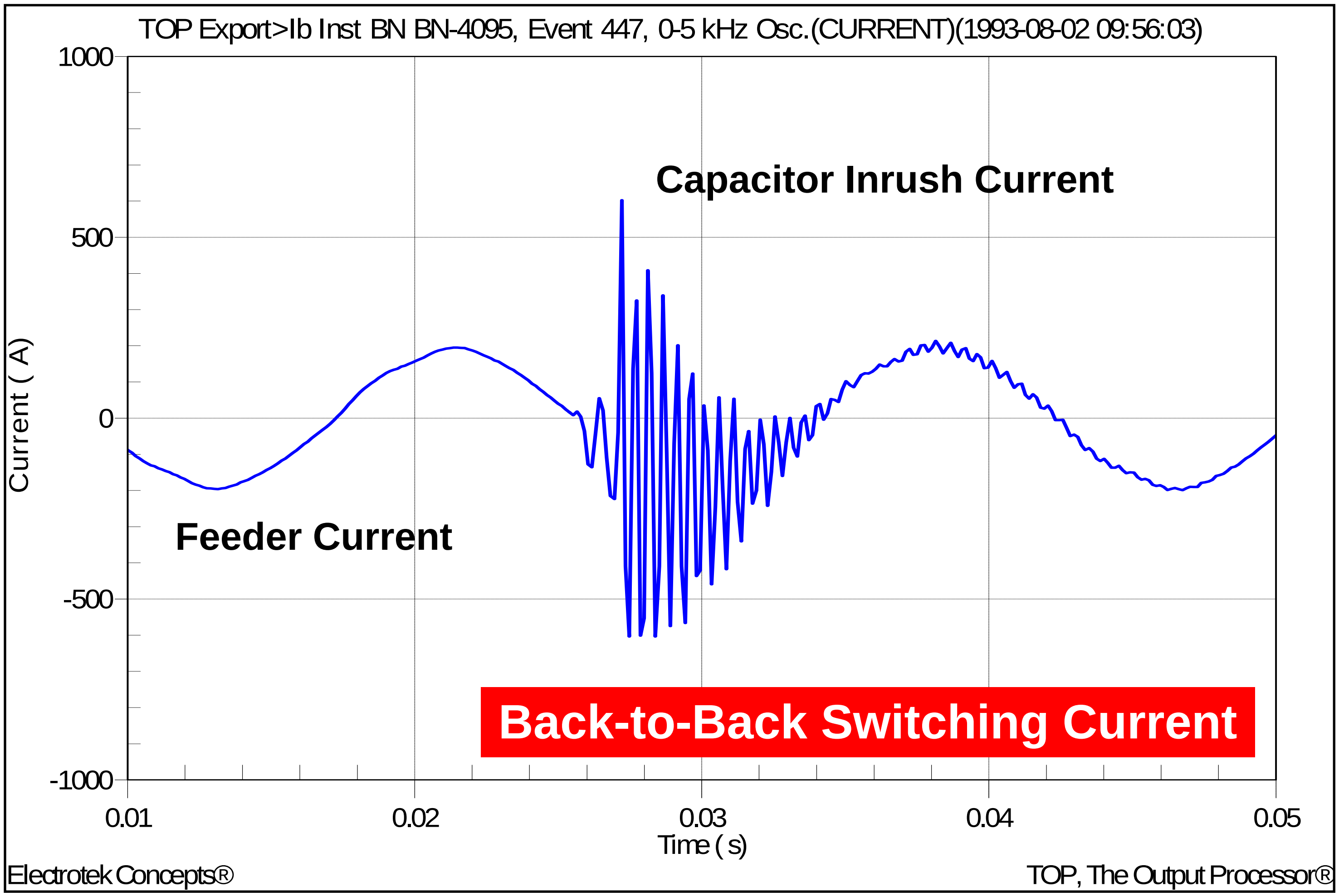
Source: EMTP

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

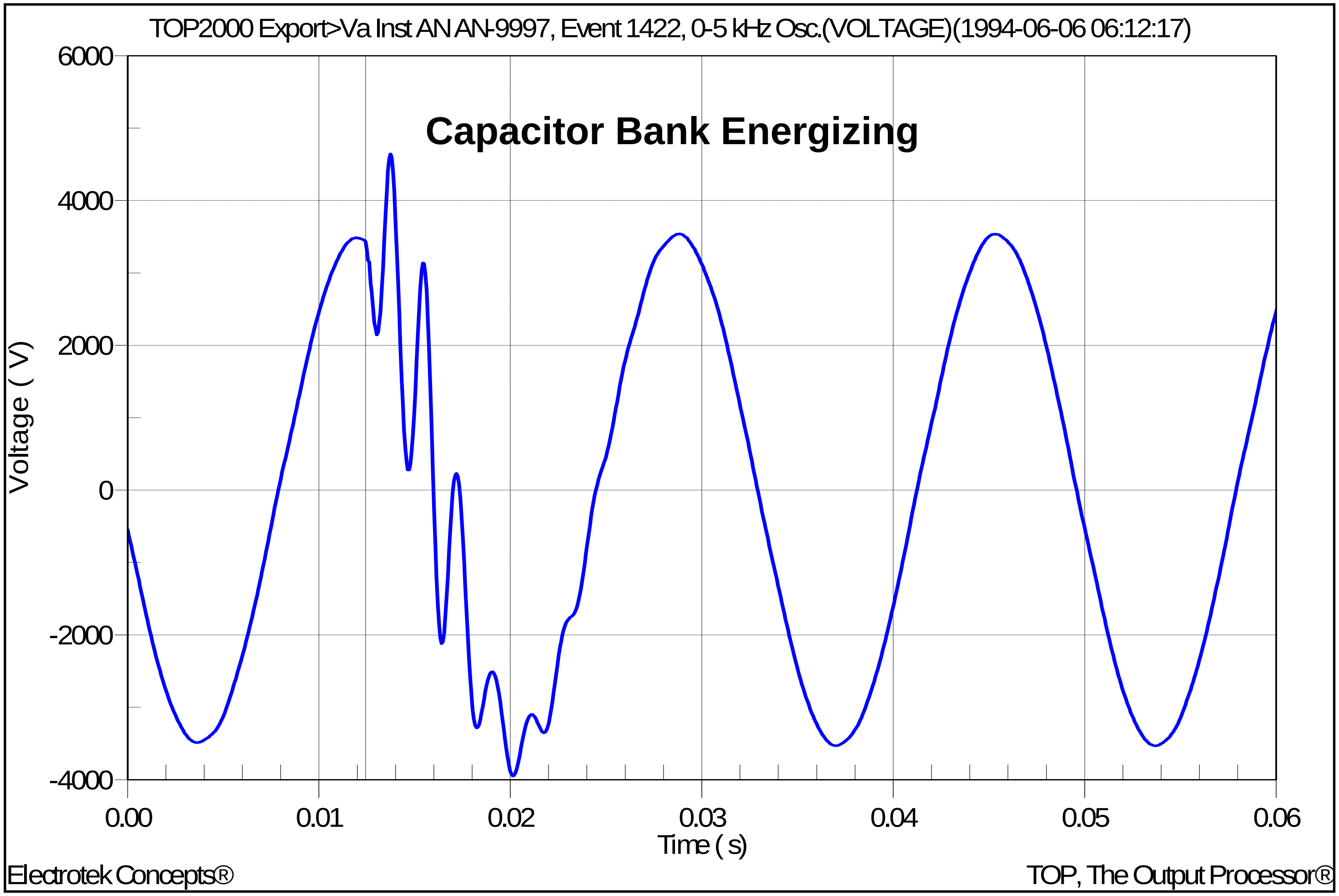
$$f_s = \frac{1}{2\pi\sqrt{L_s C}} \approx f_{system} * \sqrt{\left(\frac{X_c}{X_s}\right)} \approx f_{system} * \sqrt{\left(\frac{MVA_{sc}}{MVA_r}\right)} \approx f_{system} * \sqrt{\left(\frac{1}{\Delta V}\right)}$$

Measured Capacitor Bank Energizing Current



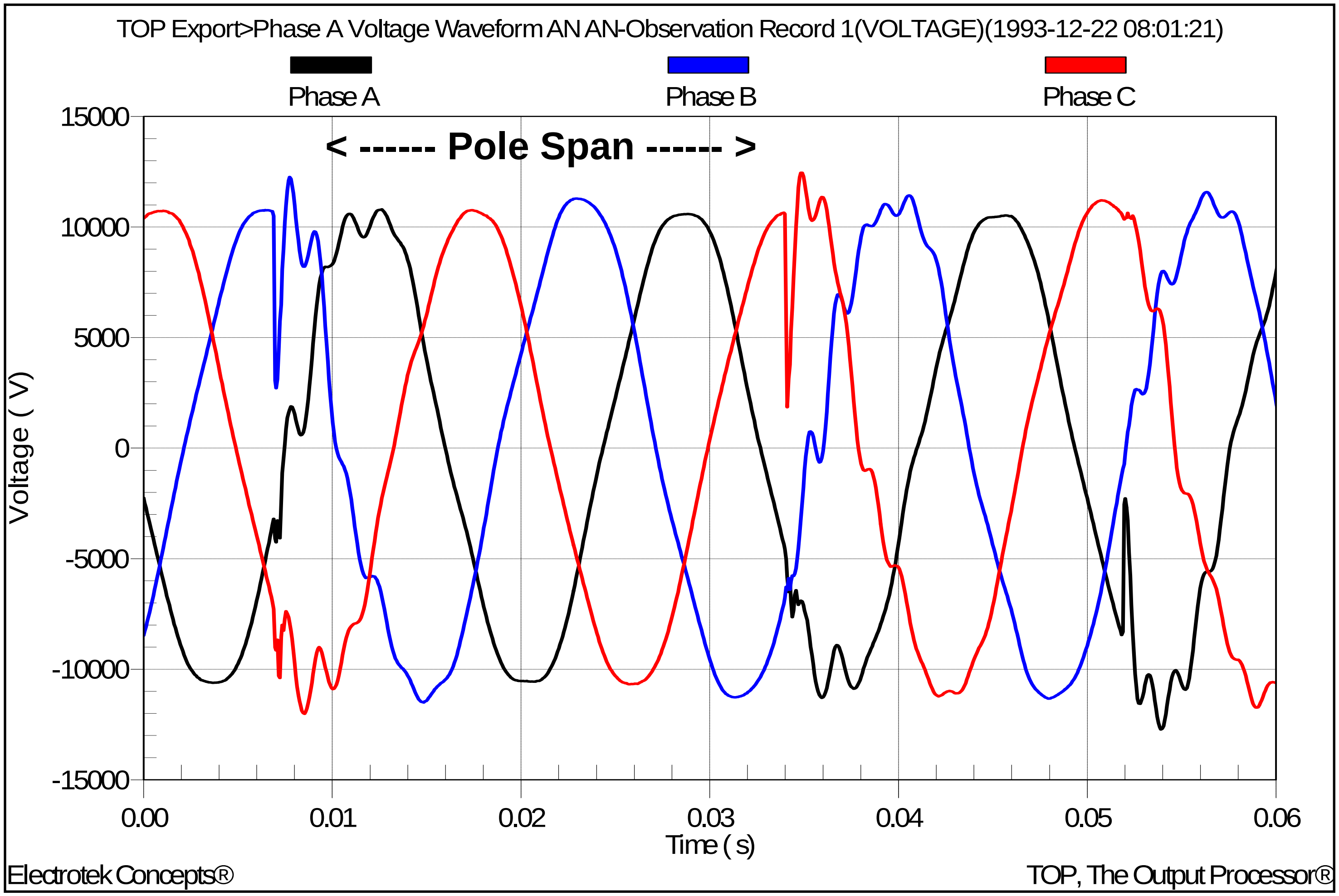
Source: D-BMI 8010 PQNode

Measured Capacitor Energizing Voltage



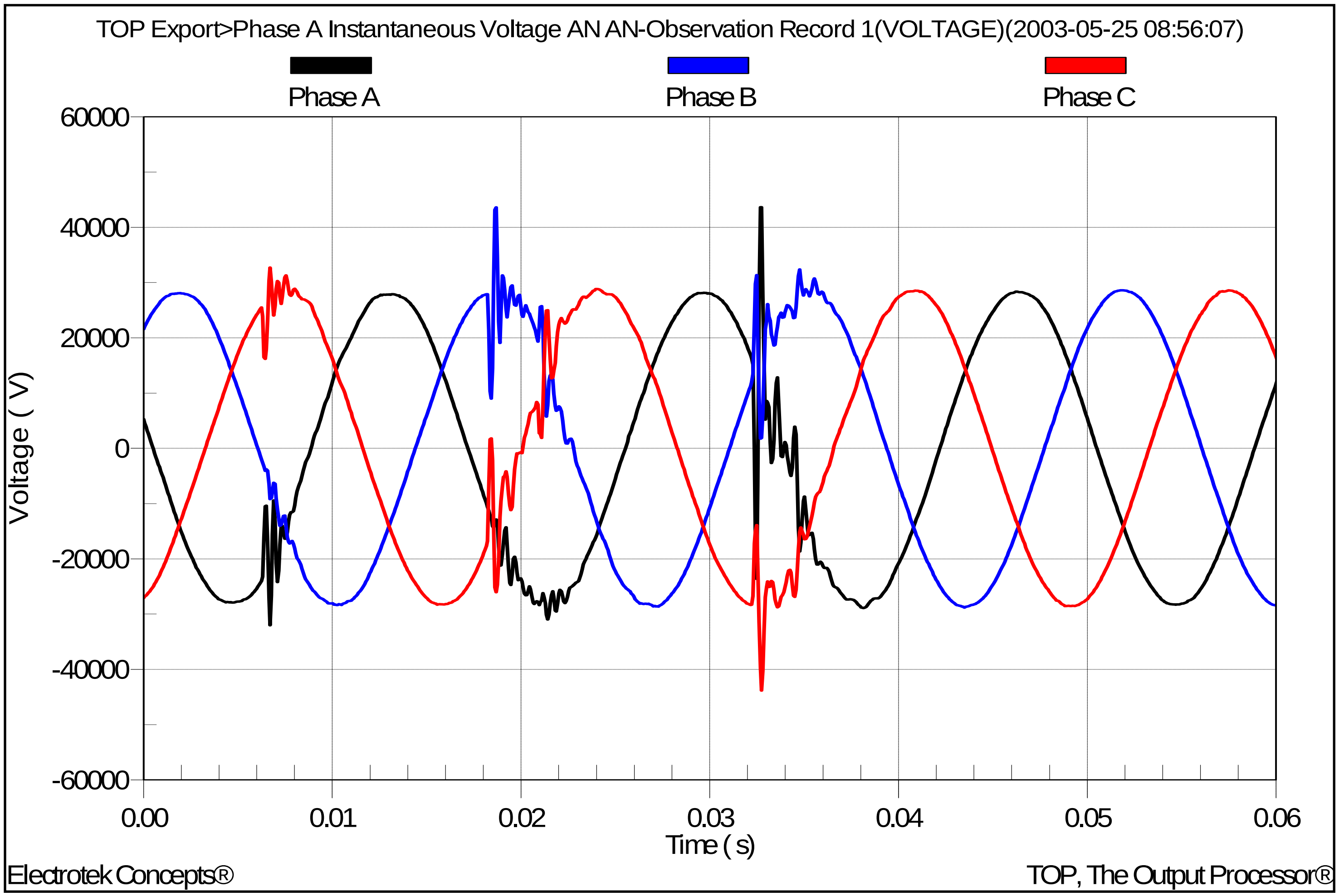
Source: D-BMI 8010 PQNode

Measured Capacitor Energizing Voltage



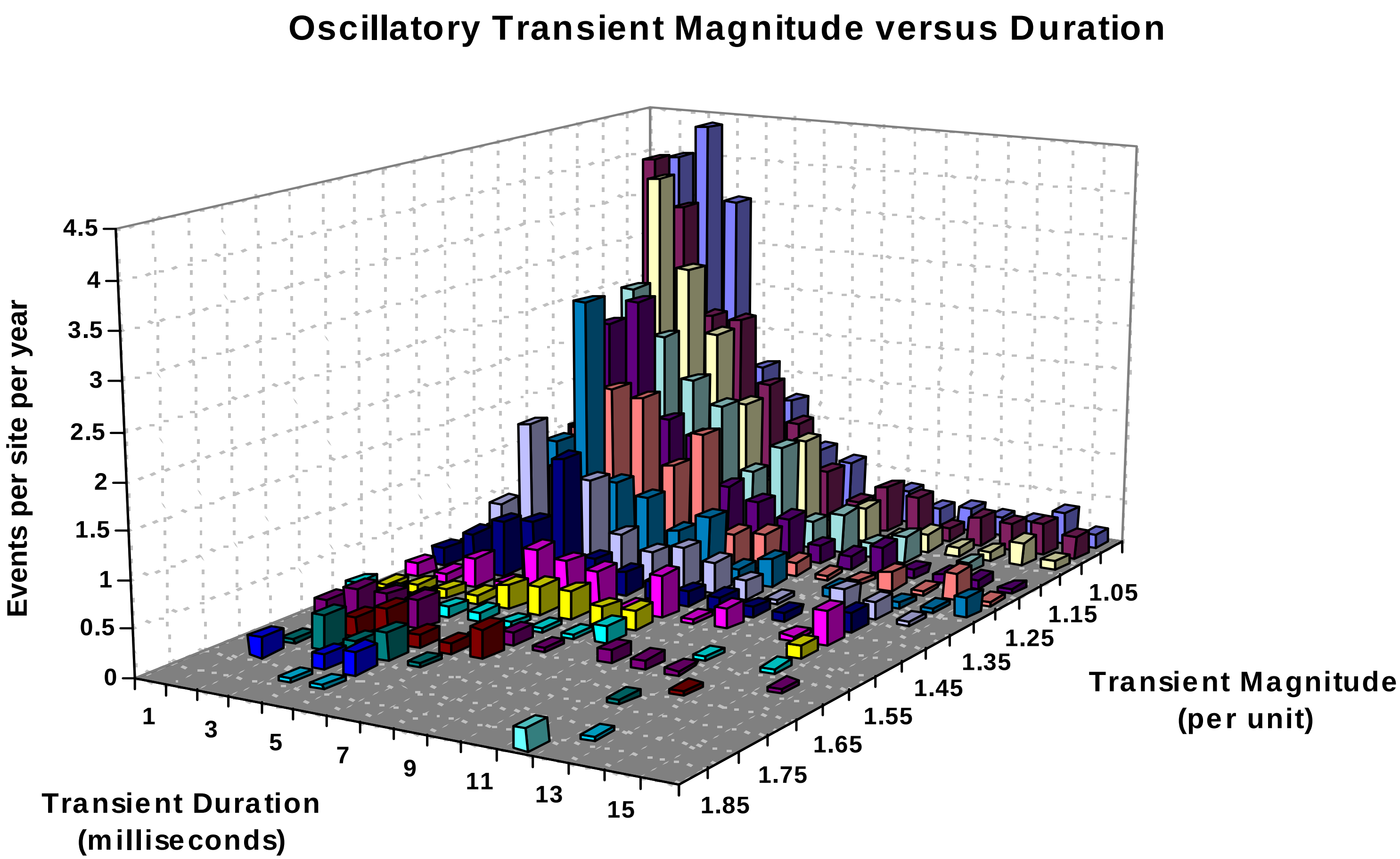
Source: D-BMI 8010 PQNode

Measured Capacitor Switch Restrikes



Source: D-BMI 8010 PQNode

Capacitor Energizing - Characteristics



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

Solutions to Capacitor Switching Transients

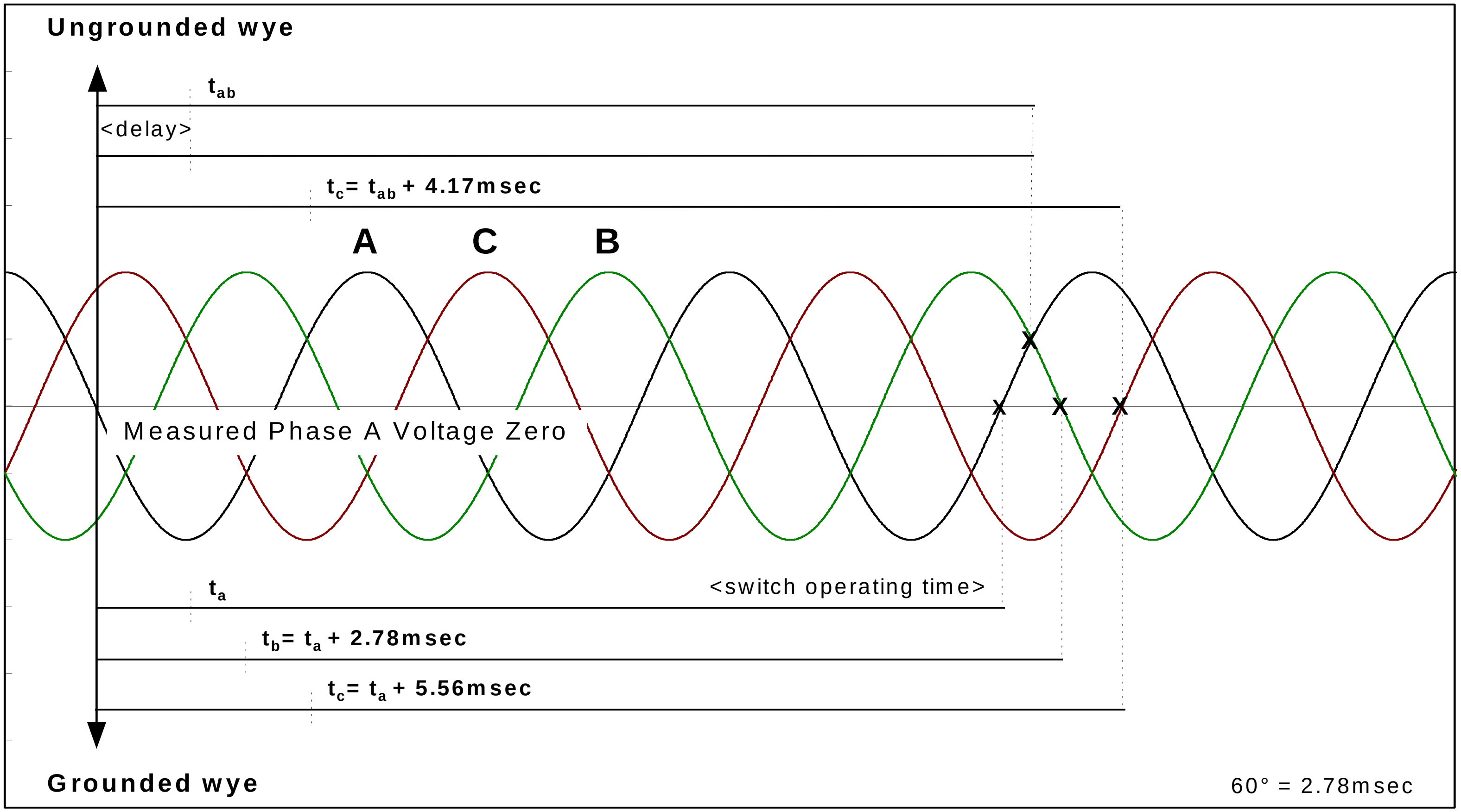
- Uncontrolled
  - No preventative means applied (always simulation basecase for comparison of effectiveness of other methods).
- Synchronous closing control
  - Method for controlling overvoltage by switching when the voltage across the switch at the closing instant is equal to zero (zero voltage on 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.

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 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.

Illustration of Controlled Switch Closing

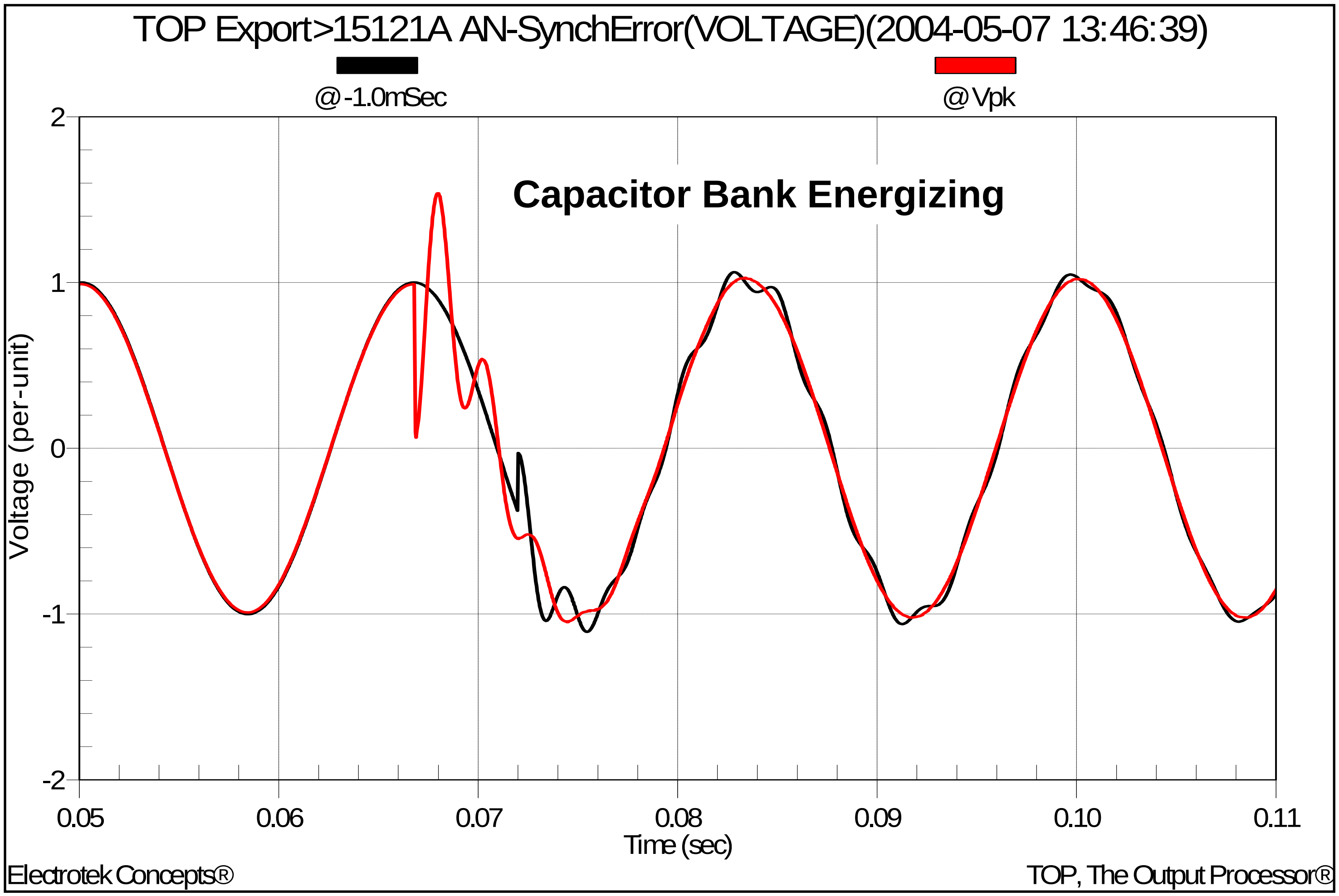
- Timing control for grounded and ungrounded banks:



Pre-insertion Devices

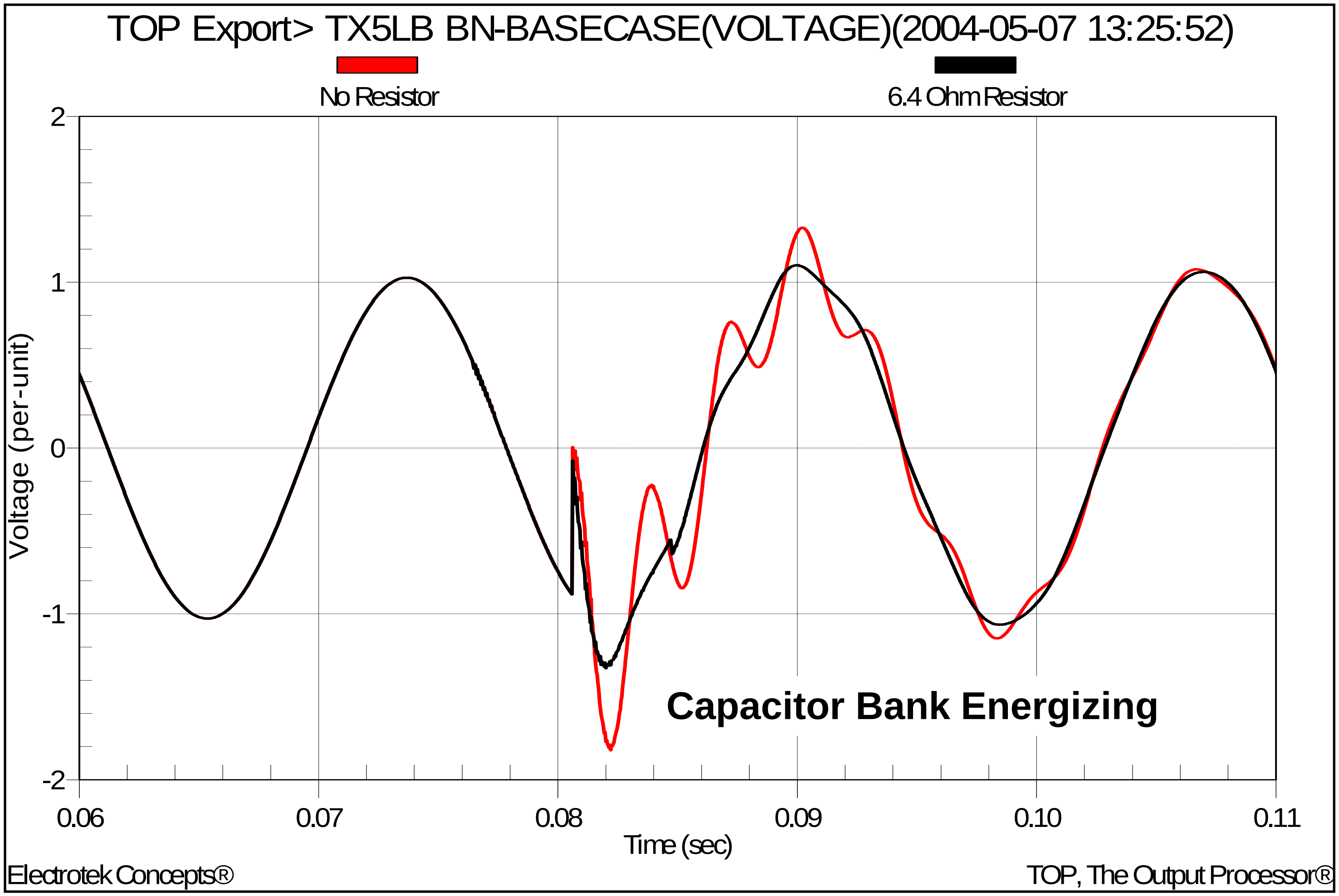
- Many options available available at T&D voltage levels.
- Devices typically include resistors and/or inductors.
- In general, resistors provide better overvoltage control and inductors provide better overcurrent control.
- Can be used in combination with synchronous closing control for added protection.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

Effectiveness of Closing Control



Source: EMTP

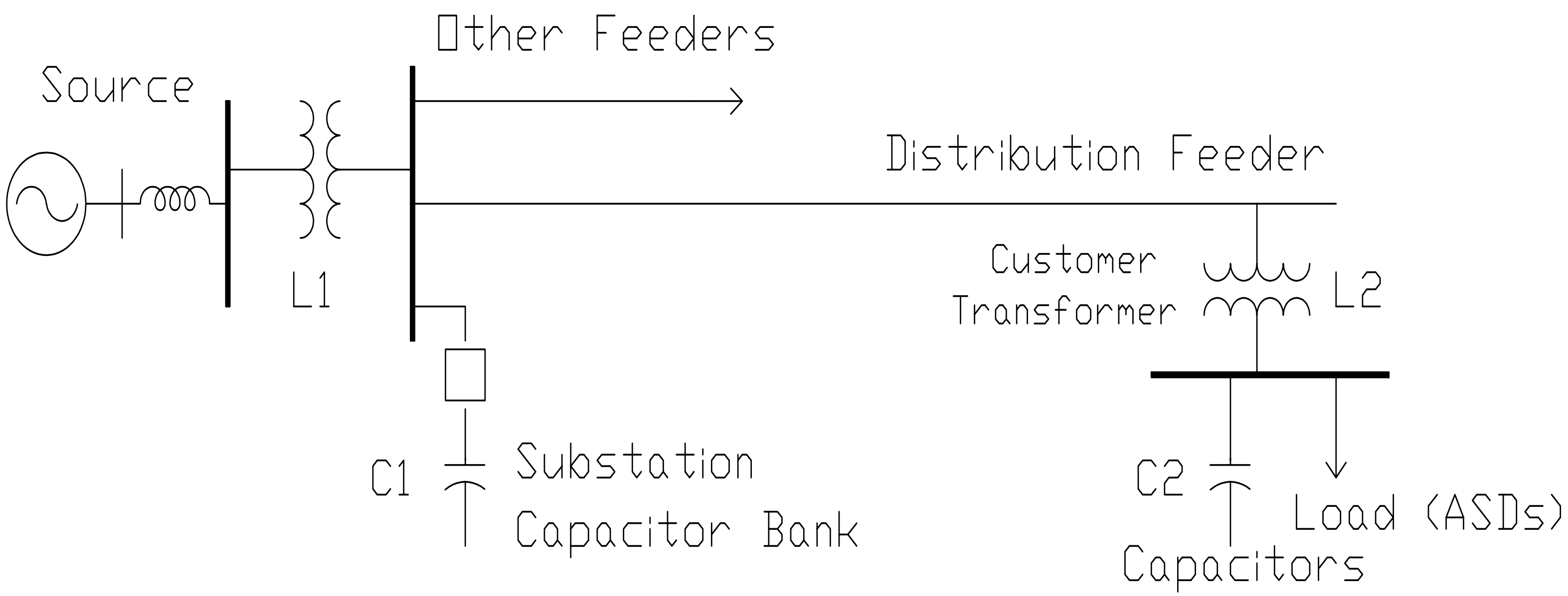
Effectiveness of Preinsertion Resistor



Source: EMTP

Case Study - Voltage Magnification

- 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:

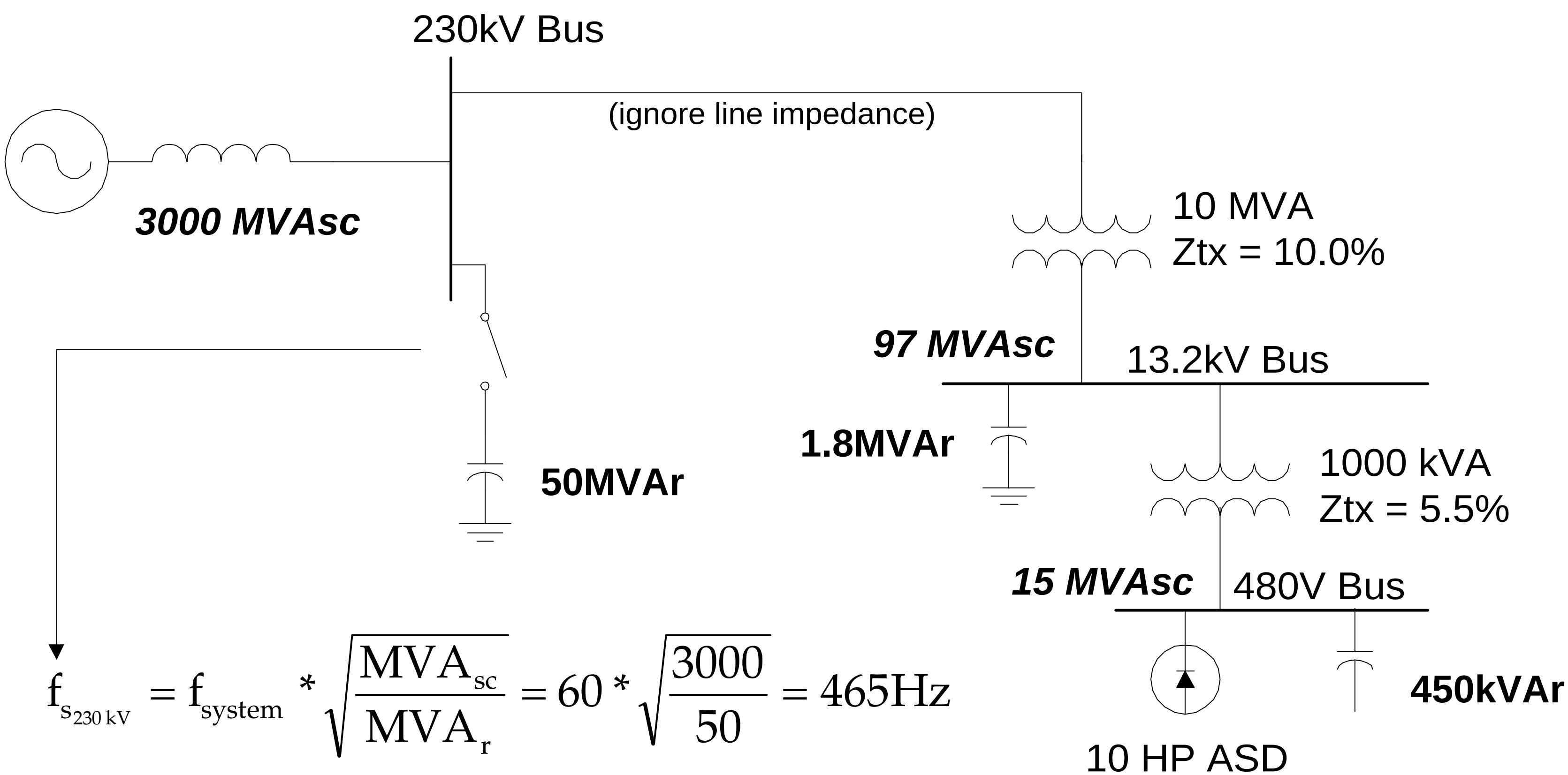
  [1] The natural frequencies f_1 and f_2 are nearly equal.

  [2] The capacitive rating (MVAr) of the switched capacitor bank is significantly greater (>10) than the lower voltage capacitor rating (kVAr).

  [3] There is little damping on the low voltage system (mostly motor load).

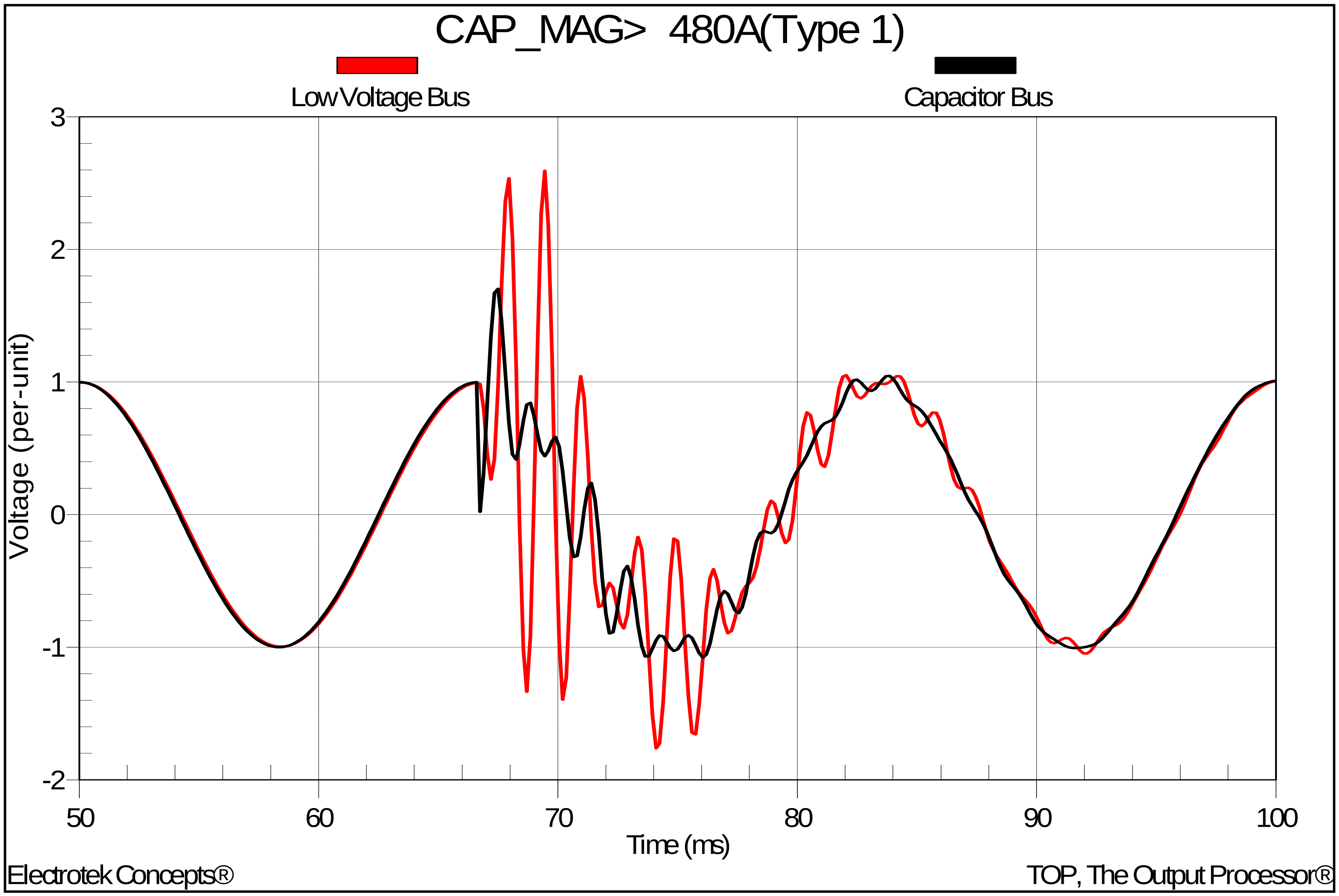
Conditions for Voltage Magnification

a quick check...



$$f_{s_{230\,kV}} = f_{system} * \sqrt{\frac{MVA_{sc}}{MVA_{r}}} = 60 * \sqrt{\frac{3000}{50}} = 465\,Hz$$

Magnified Transient at Low Voltage Bus



Source: EMTP

Solutions to Magnification Phenomena

- Controlling the transient overvoltage at the source, on the utility system is sometimes possible.

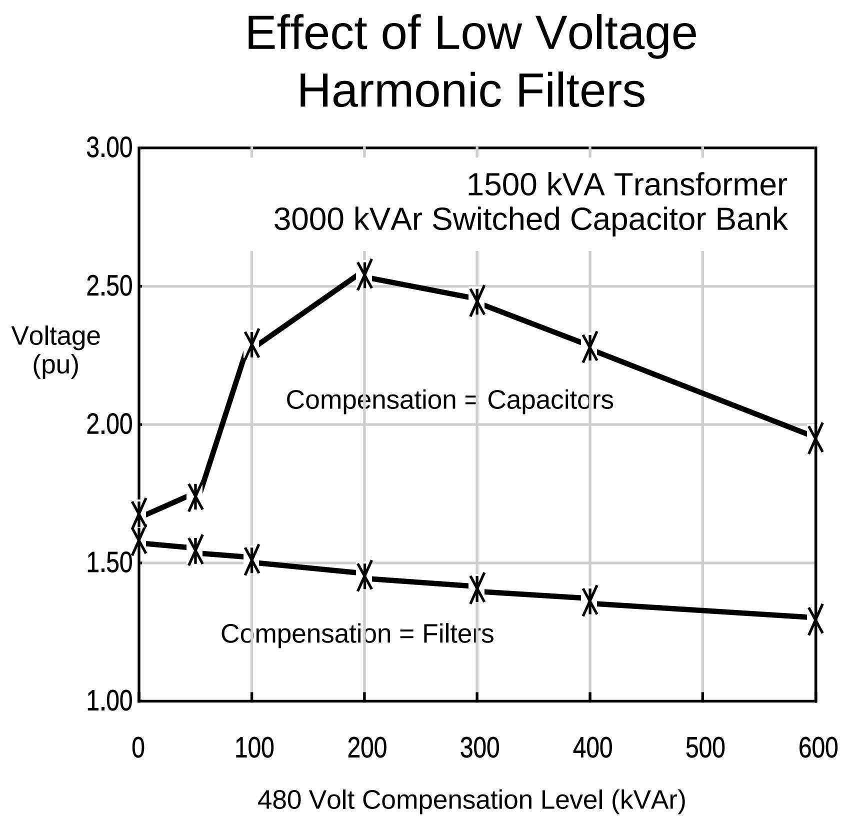
    a) Synchronous closing control

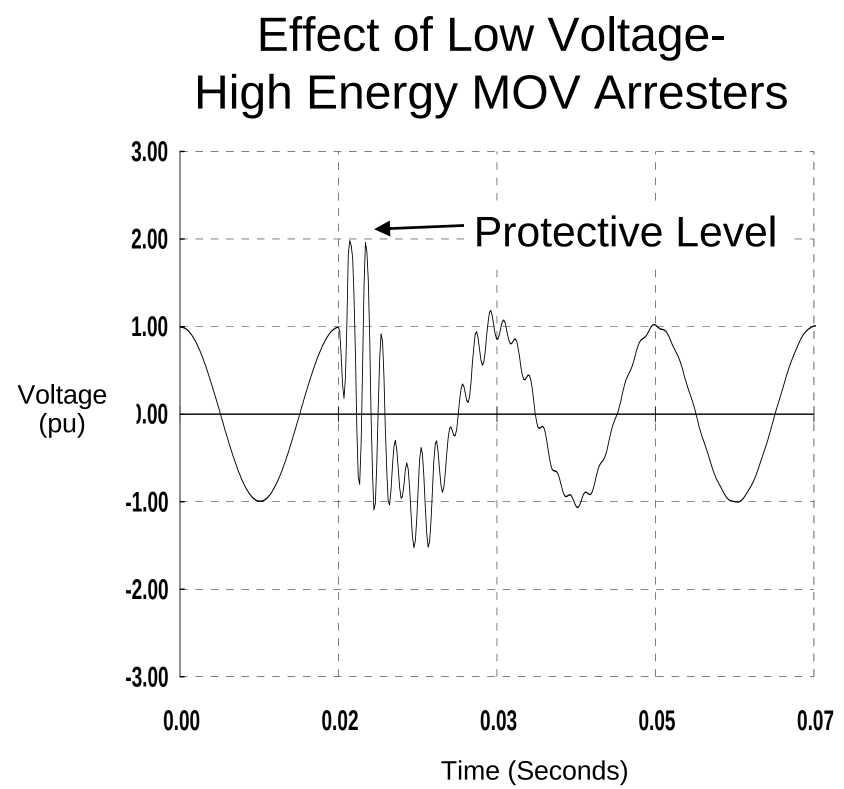
    b) Closing capacitor bank through a resistor/inductor first

- Surge arresters at the customer location can be used.

- Conversion of capacitor banks to harmonic filters is effective for control of the magnification problem.

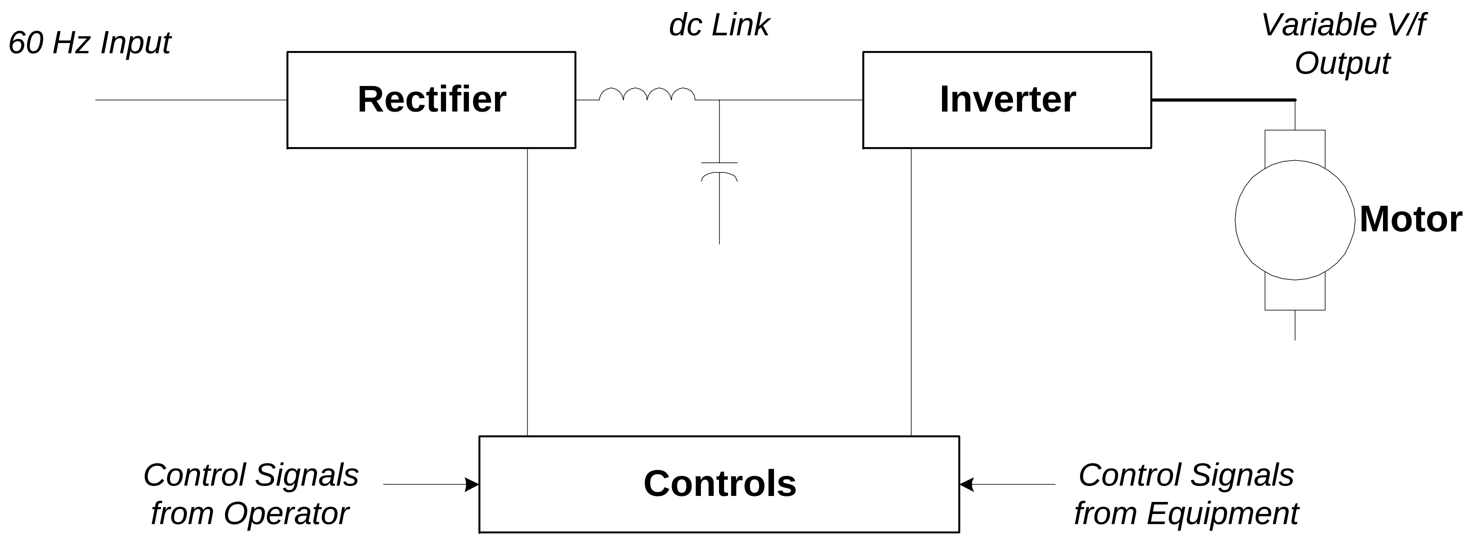
Effect of Low Voltage Filters and Arresters





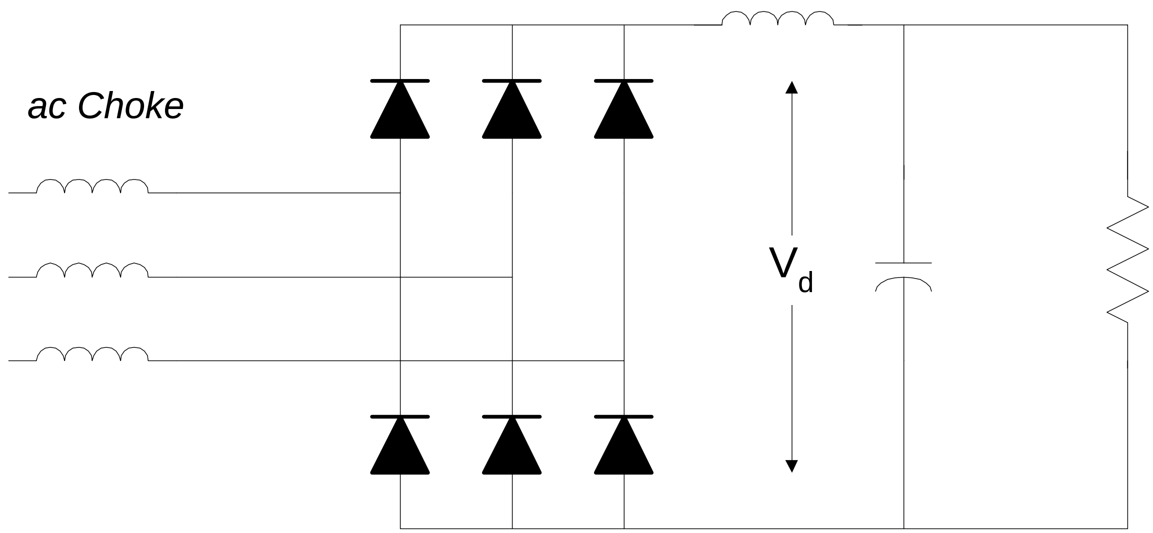
Case Study - Nuisance Tripping of ASDs

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



ref: IEEE Paper 91 WM 086-9 PWRD

ASD Representation



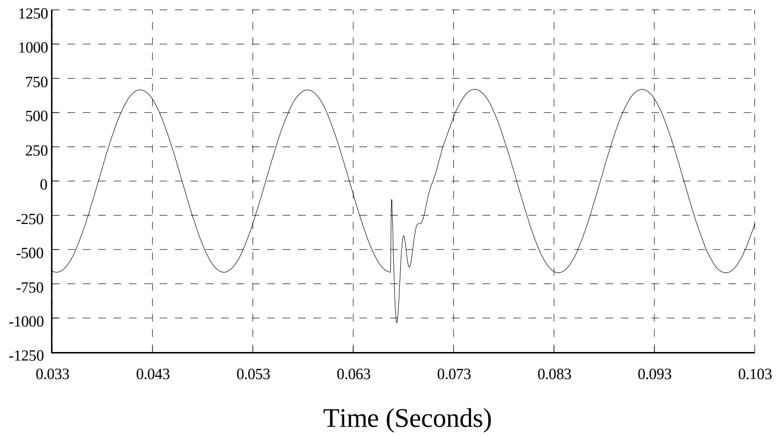
$$R_d = \frac{V_d^{\,2}}{P_{motor}}$$

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

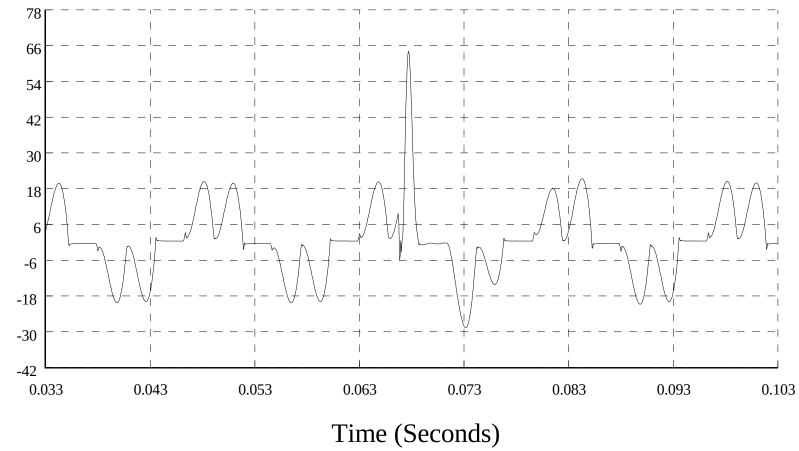
$$V_d = \frac{3\sqrt{2}}{\pi} V_{LL} \approx 1.35 * 480 \approx 650V$$

dc Bus Voltage and Current Surge

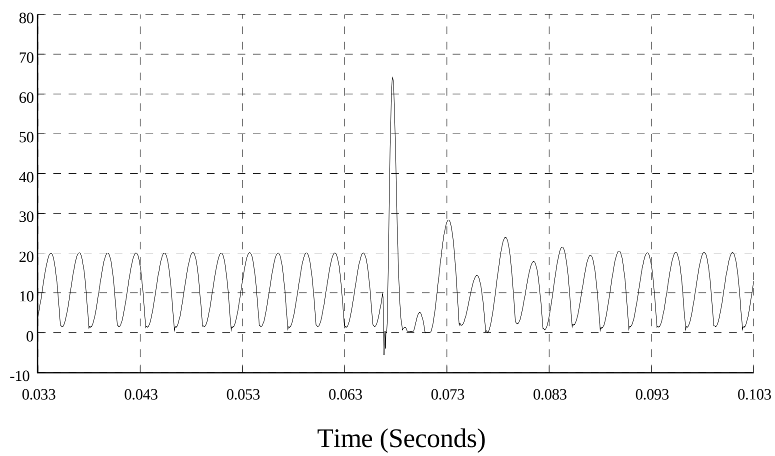
480 Volt Bus Voltage



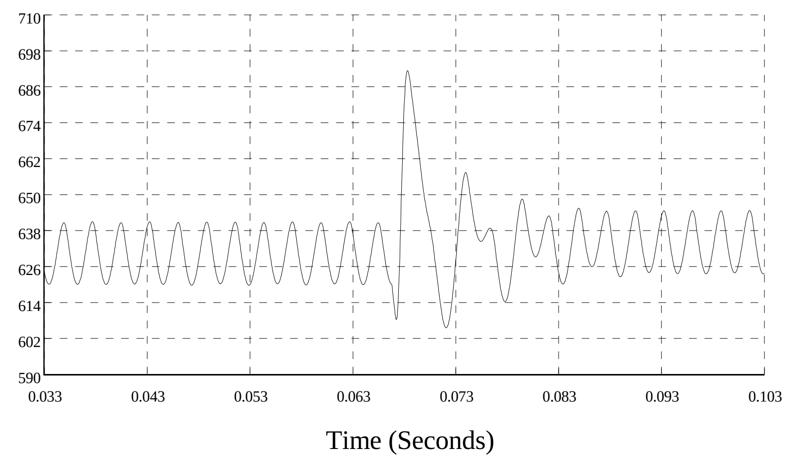
PWM-ASD Input Current



dc Link Current

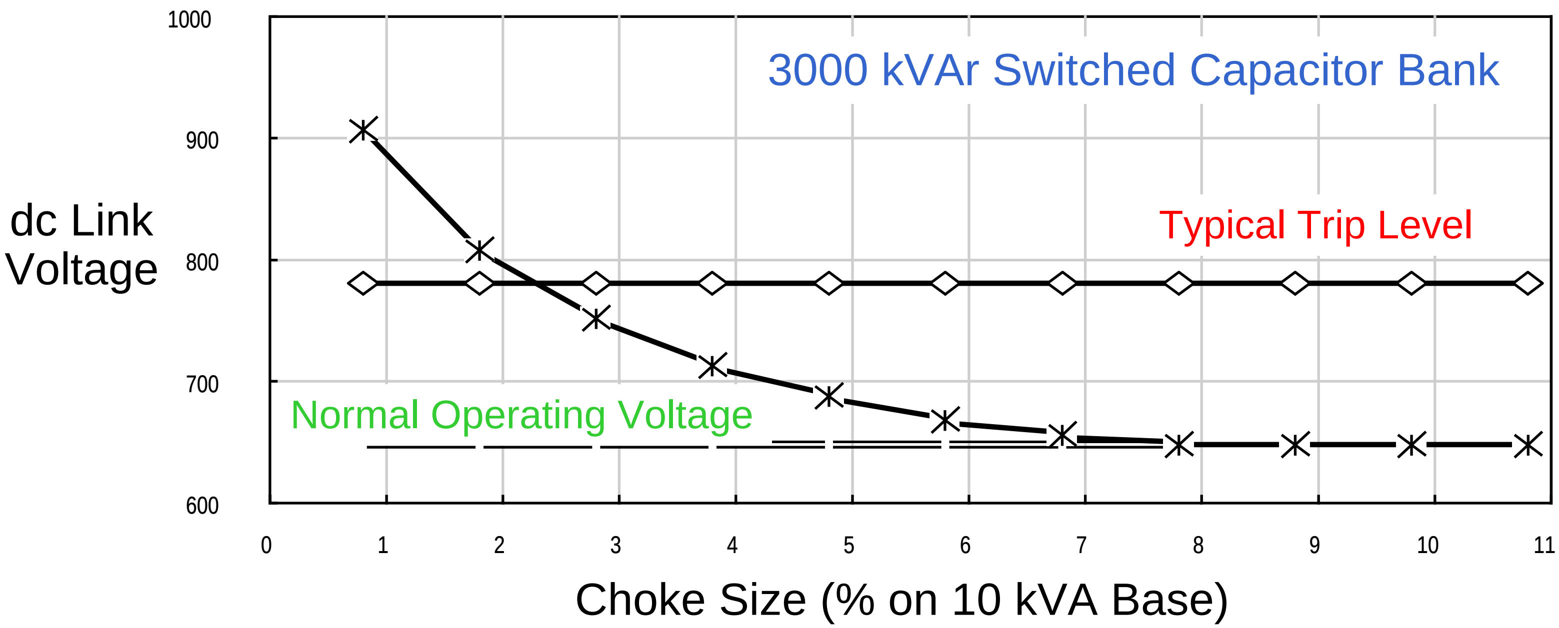


dc Link Voltage

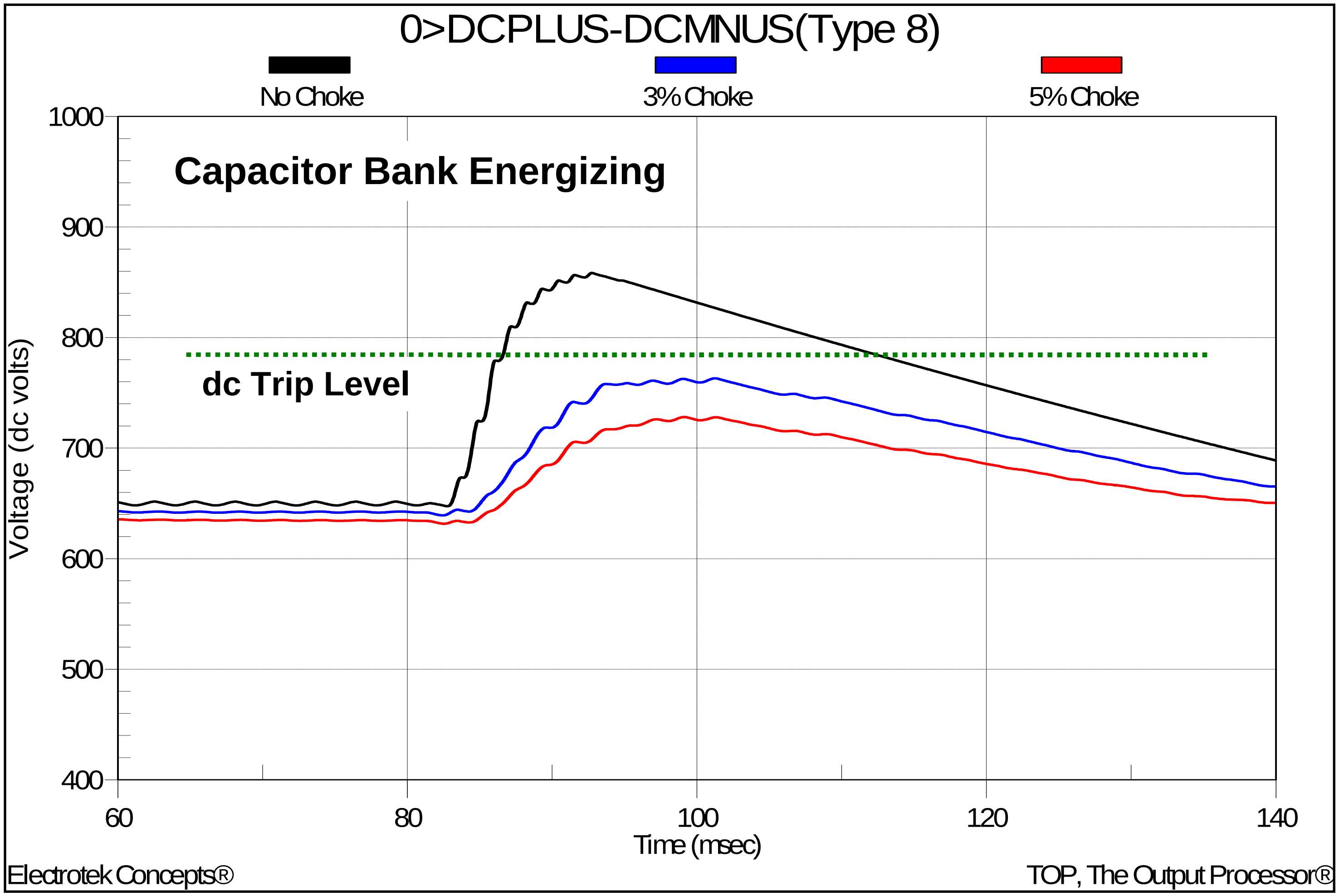


Solution to Nuisance Tripping - Chokes

- 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.



Effect of Choke on dc Link Voltage

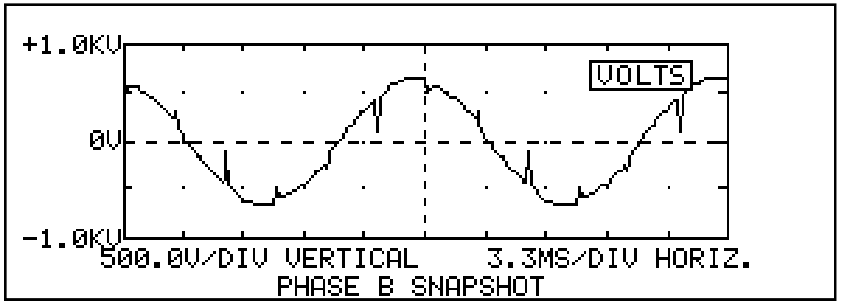


Source: EMTP

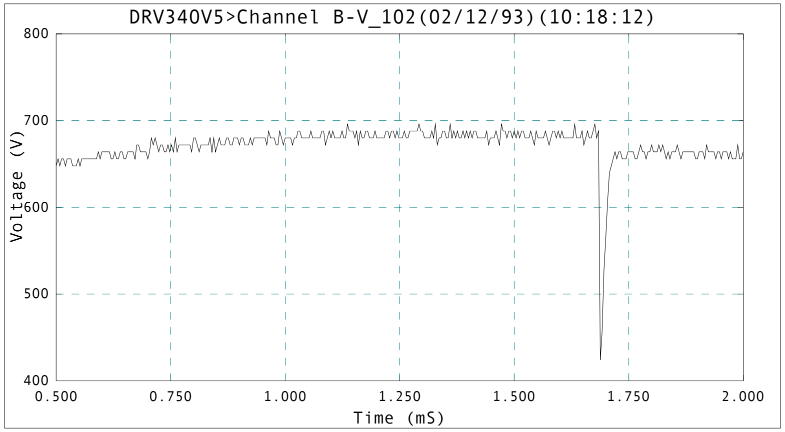
Case Study - Voltage Notching

- Notching of the input voltage waveform is a normal characteristic of the switching that occurs in the power electronics of a rectifier during continuous current operation.

Voltage Notching Snapshot



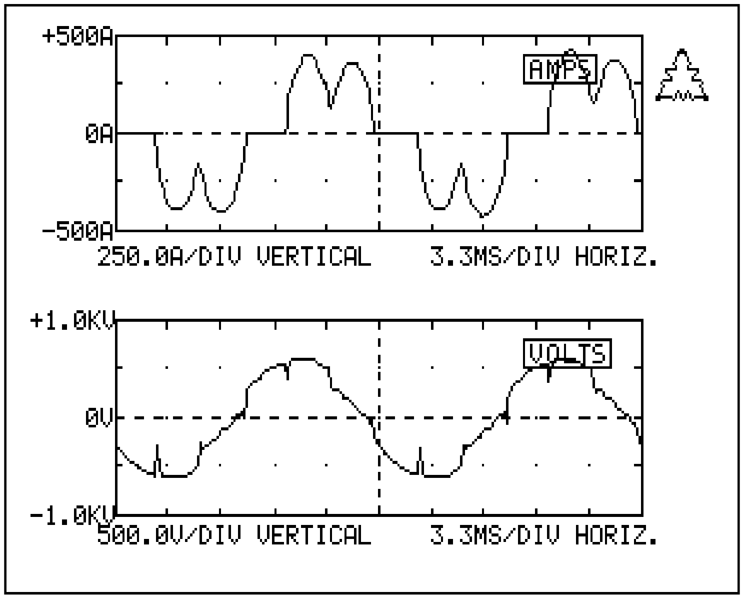
Expanded Waveform



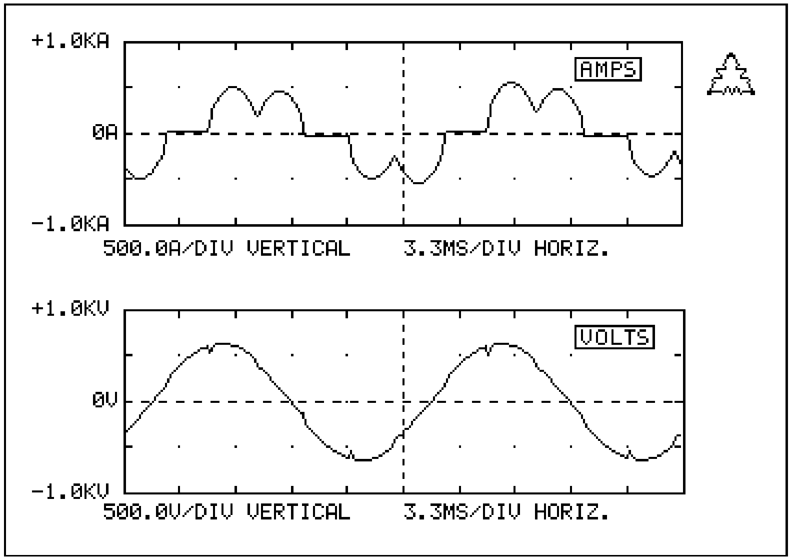
Voltage Notching – Impact of Reactor

400 HP dc Drive Input (ac) Current and Voltage Waveforms:

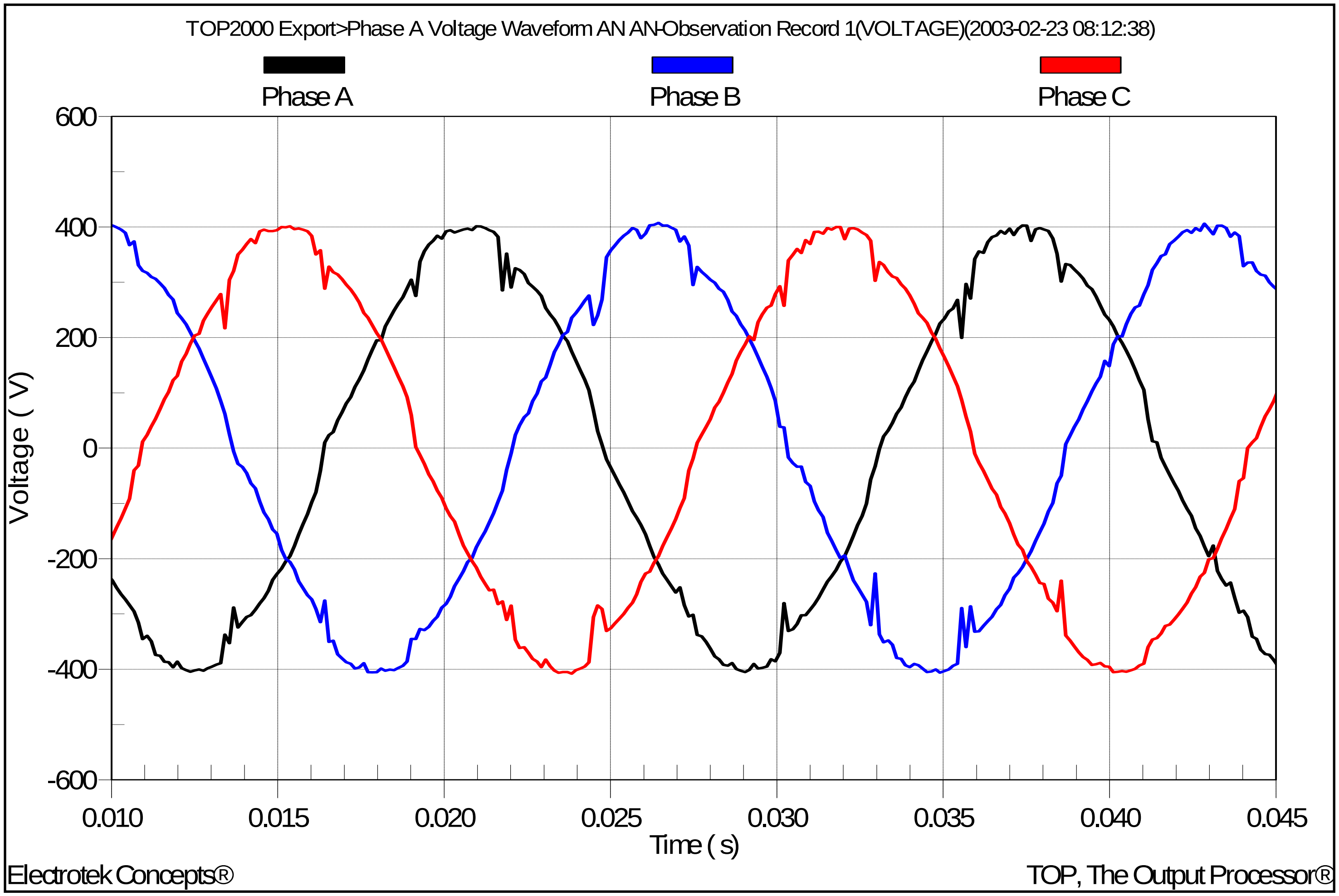
Drive Side of Input Reactor



Bus Side of Input Reactor

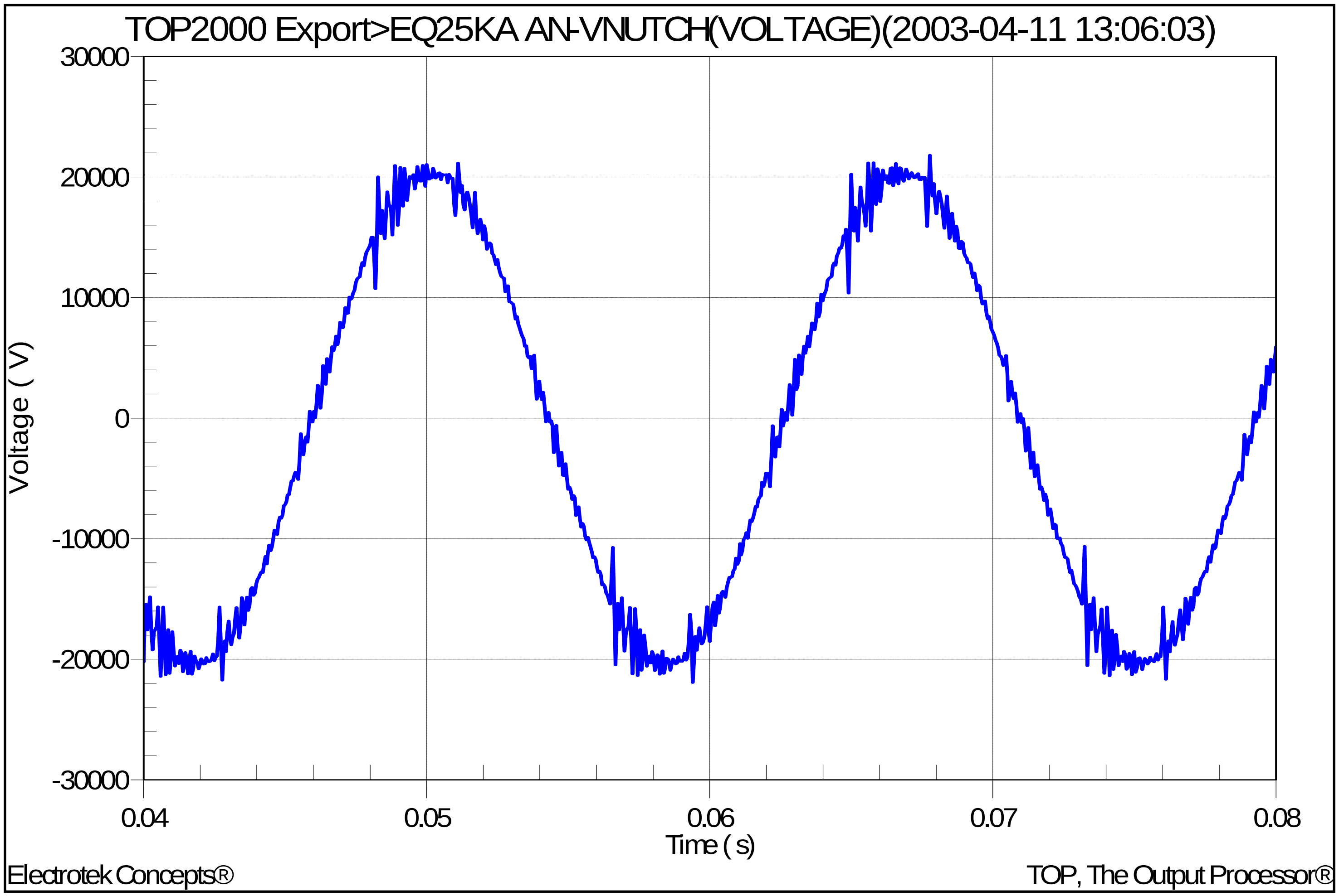


Measured Customer Voltage Notching



Source: Dranetz-BMI 5530 DataNode

Simulated Feeder Voltage Notching



Source: EMTP