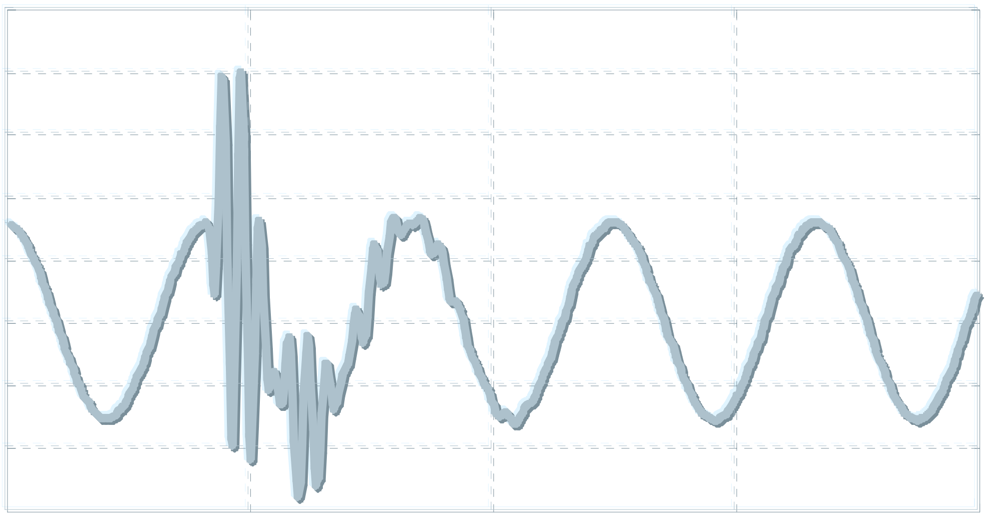
Characteristics of Power System Transients



November 30, 2004

Thomas Grebe
Electrotek Concepts, Inc.

Introduction

- Characterizing Transient Disturbances
- Sources of Power Quality-Related Transient Disturbances
  - Example Waveforms
- Several Transient Problems and Solutions
- Using Measurements to Characterize Transients
- Using Simulations to Predict Transients
- Additional Information

Power System Transients

- Sudden changes in the electric power system are called transients. All transients are caused by one of two actions:

  1. Connection or disconnection of elements within the electric circuit.
  2. 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

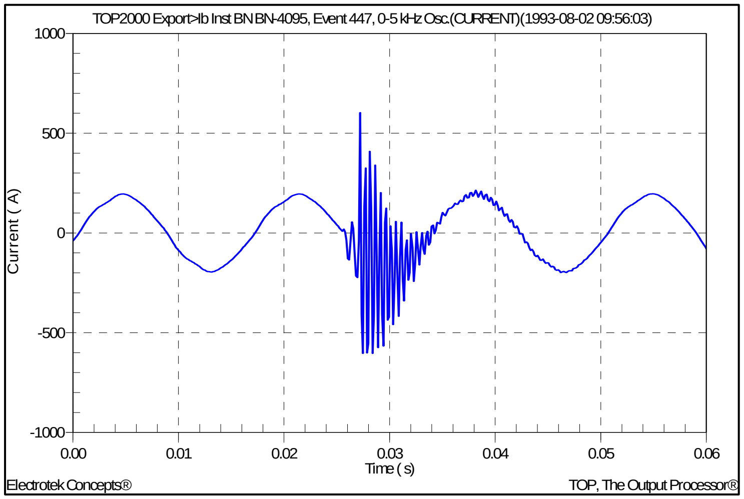
How do Transients Propagate?

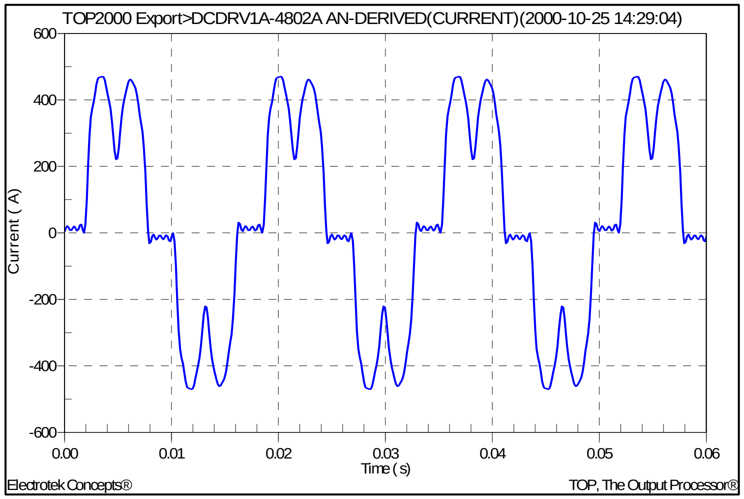
- High frequency transients do not propagate over long distances:
  - this is a good reason for separating sensitive loads and disturbing loads
- Local resonances can cause oscillations remote from the transient source:
  - can be particularly important for transients caused by utility capacitor switching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

Transients vs. Harmonics

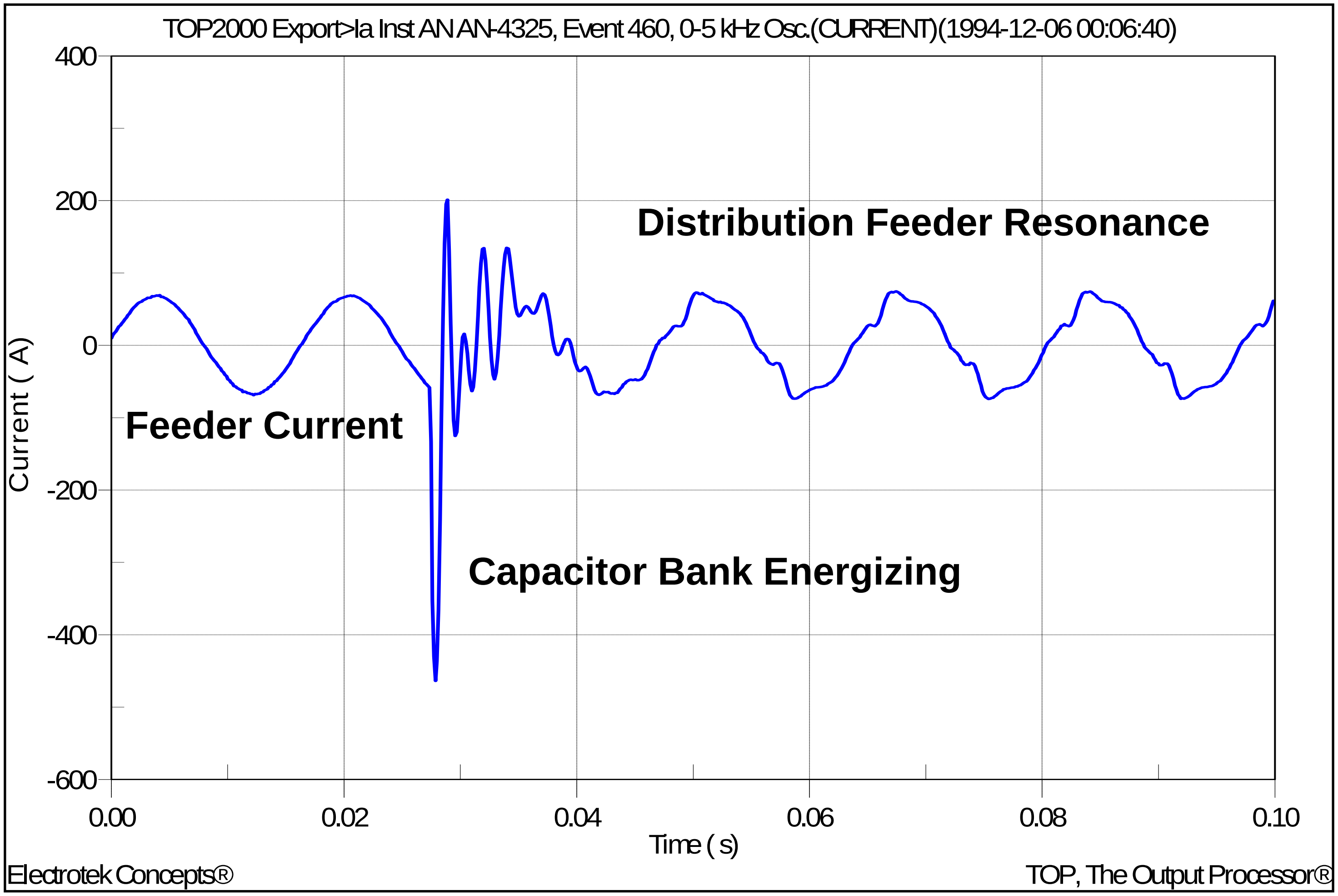
- Sudden changes in the power system.
- Classified by peak magnitude, frequency, and duration.

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





Transients vs. Harmonics - continued



Source: D-BMI 8010 PQNode

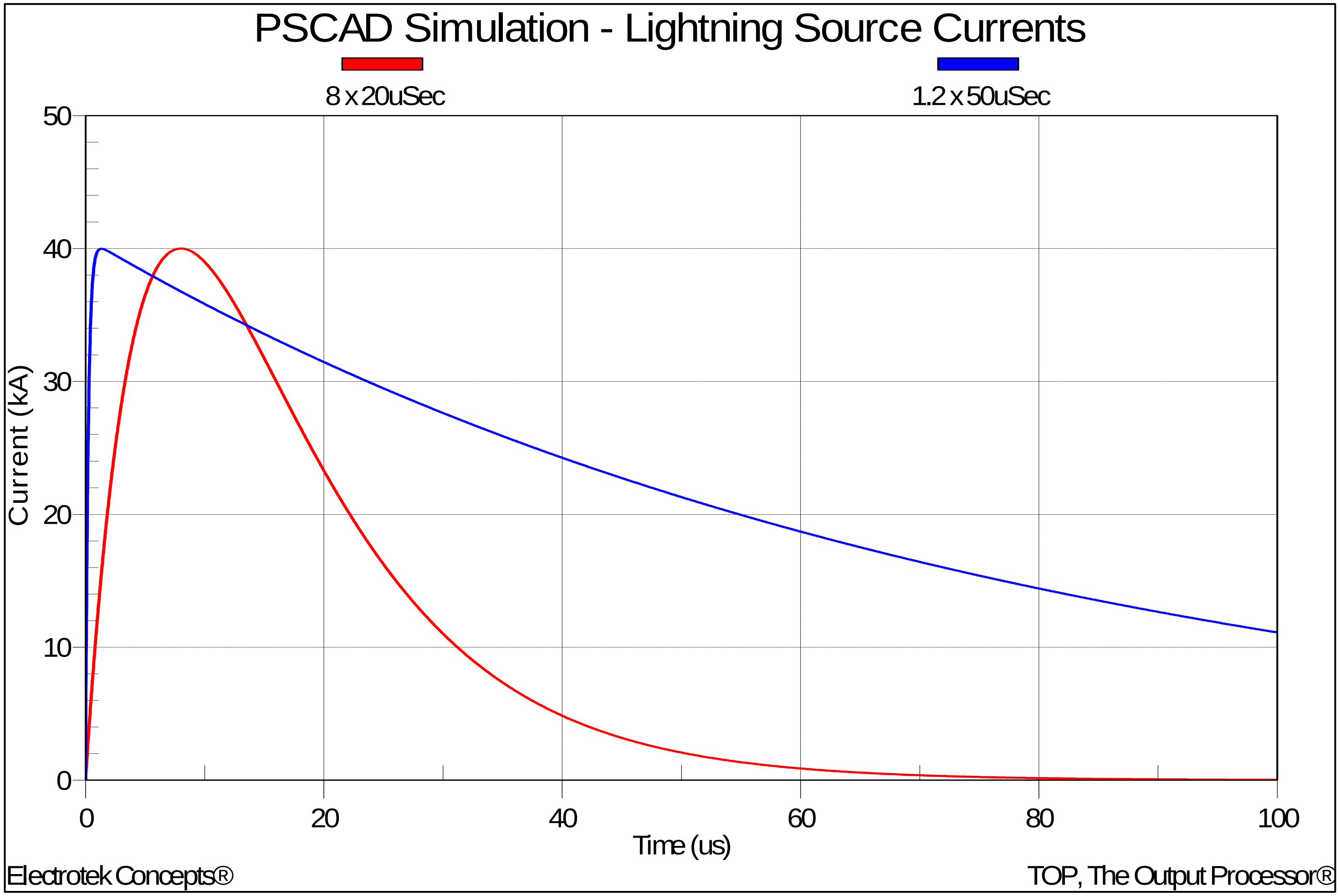
Sources of Transient Disturbances

- 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…

Lightning

- 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

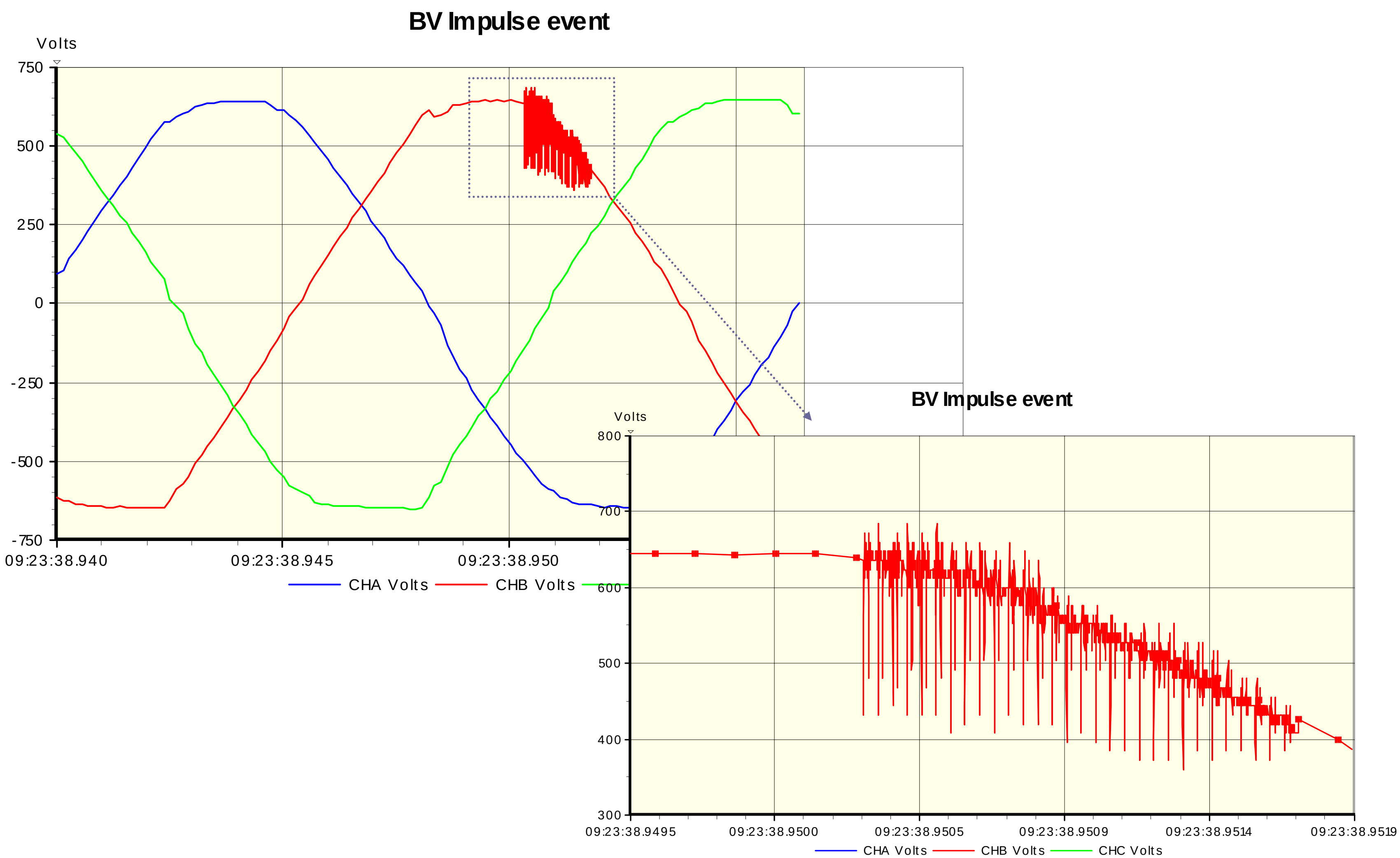


Source: PSCAD

Load Switching

- 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 Waveforms

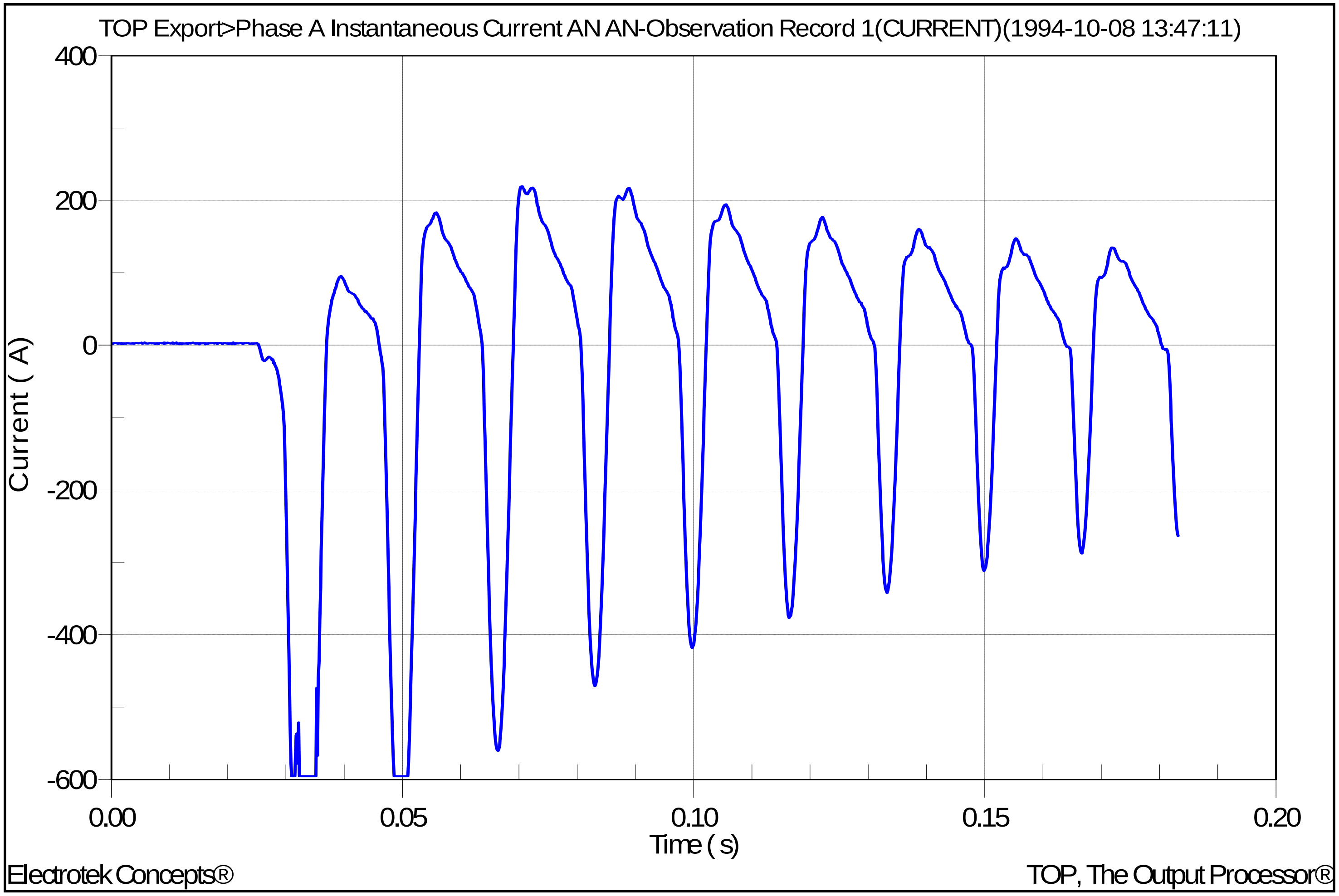


Source: Dranetz-BMI 658

Transformer Switching

- 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

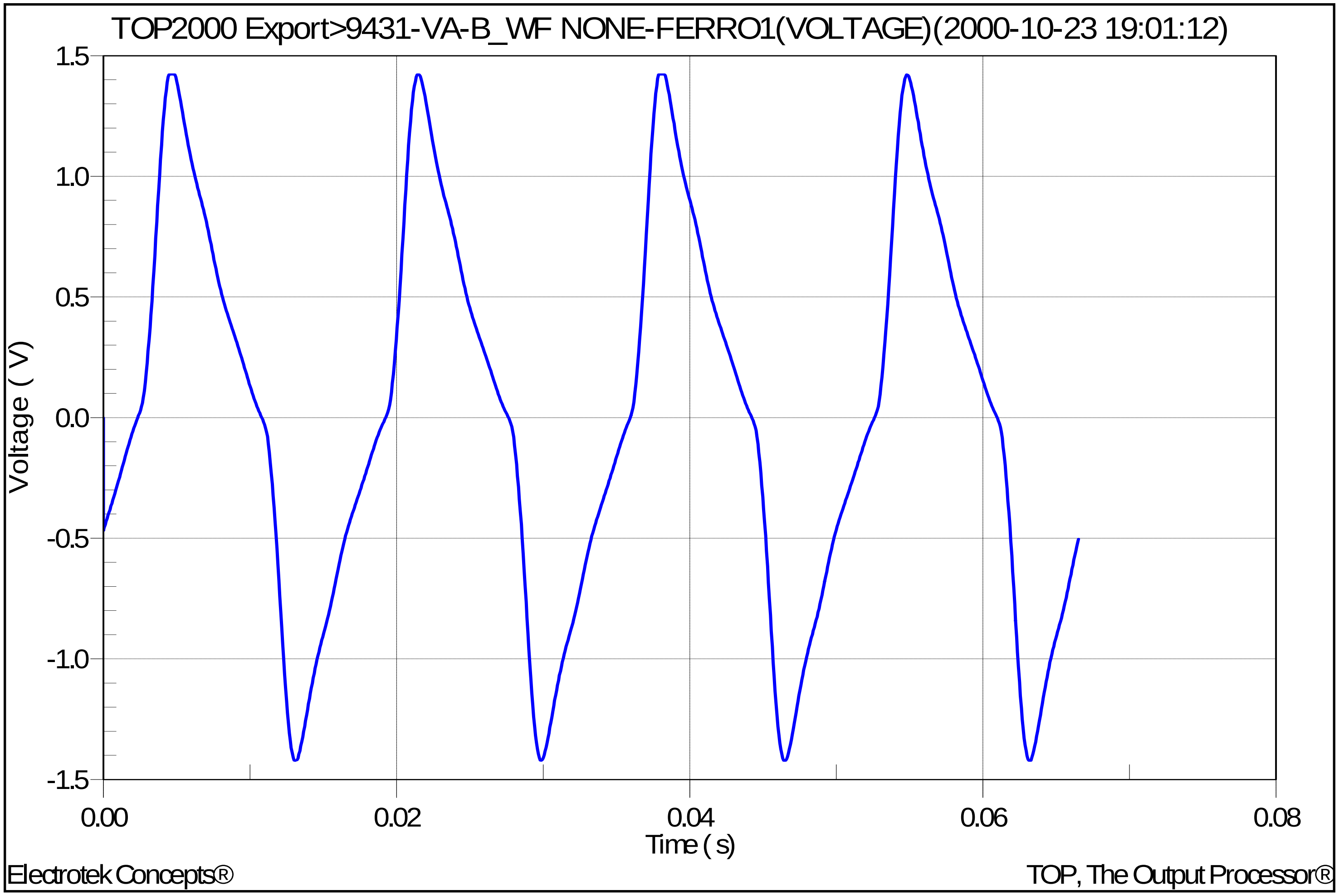


Source: Dranetz-BMI 5530 DataNode

Ferroresonance

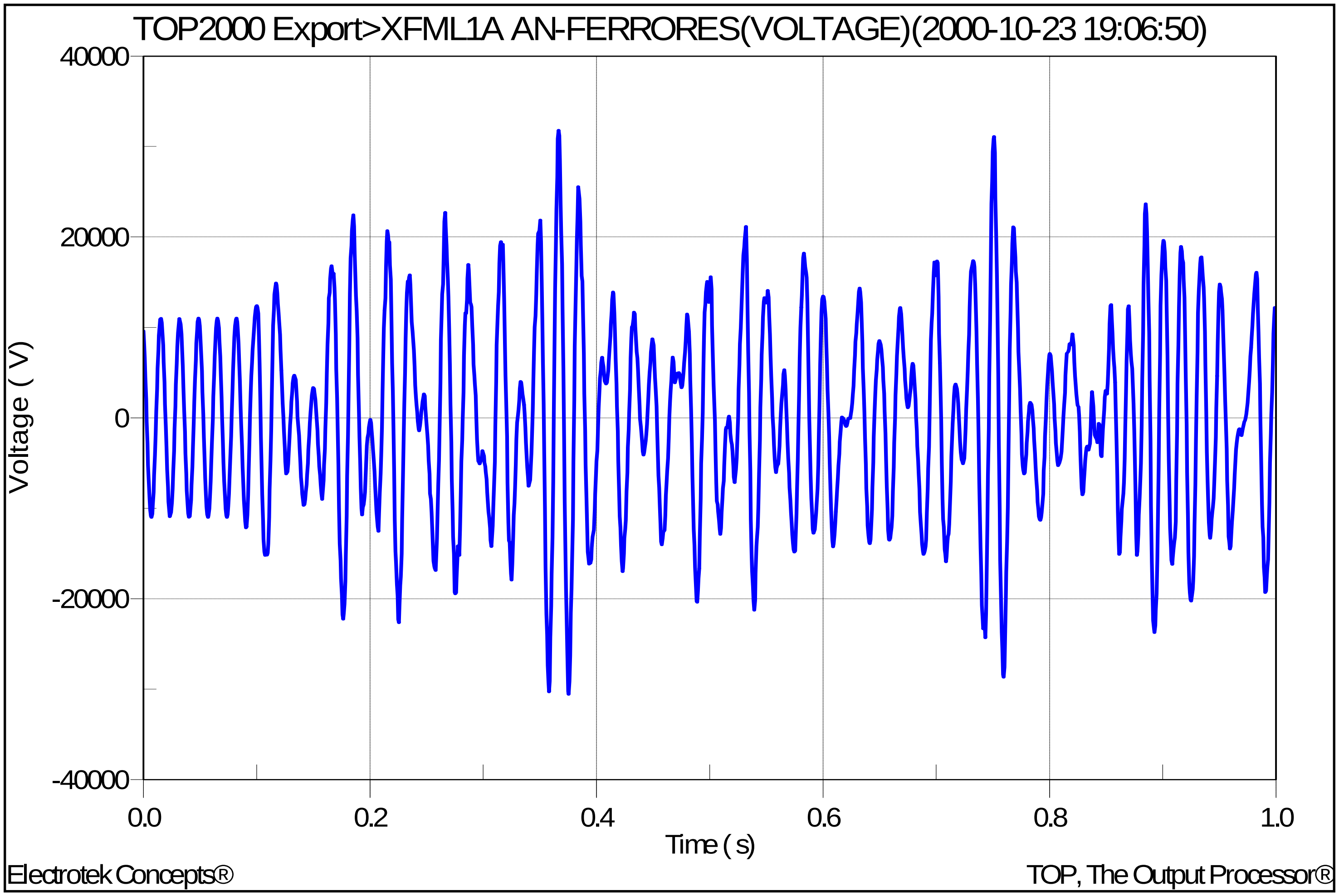
- Ferroresonance is a term generally applied to a wide variety of interactions between capacitors and iron-core inductors that results in unusual voltage and/or currents.
- Several of the more common causes include:
  - single-phase cutouts / single-phase reclosers
  - fuse blowing or opening (transformer 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



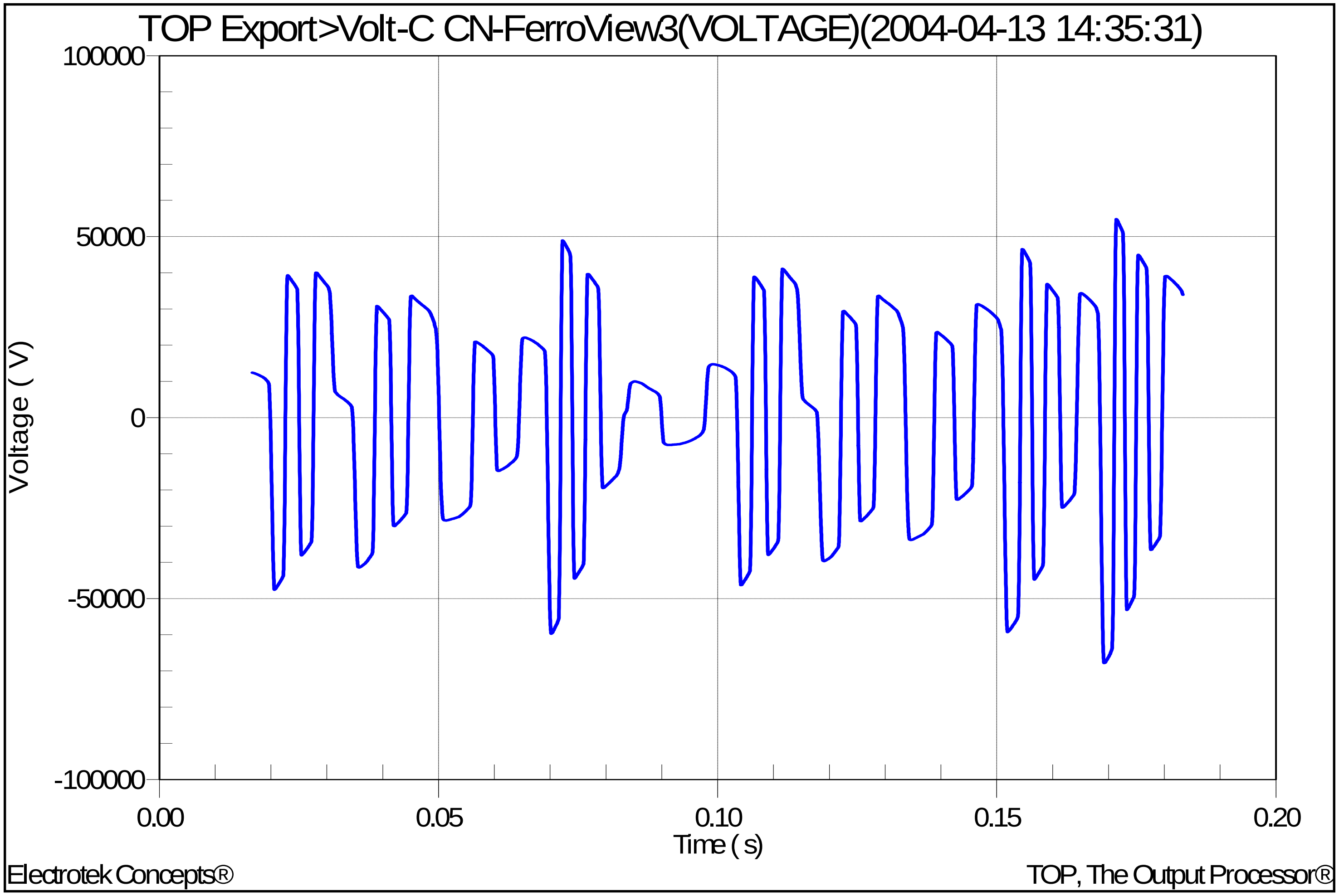
Source: D-BMI 8010 PQNode

Simulated Ferroresonance Waveform



Source: EMTP

Simulated Ferroresonance Waveform



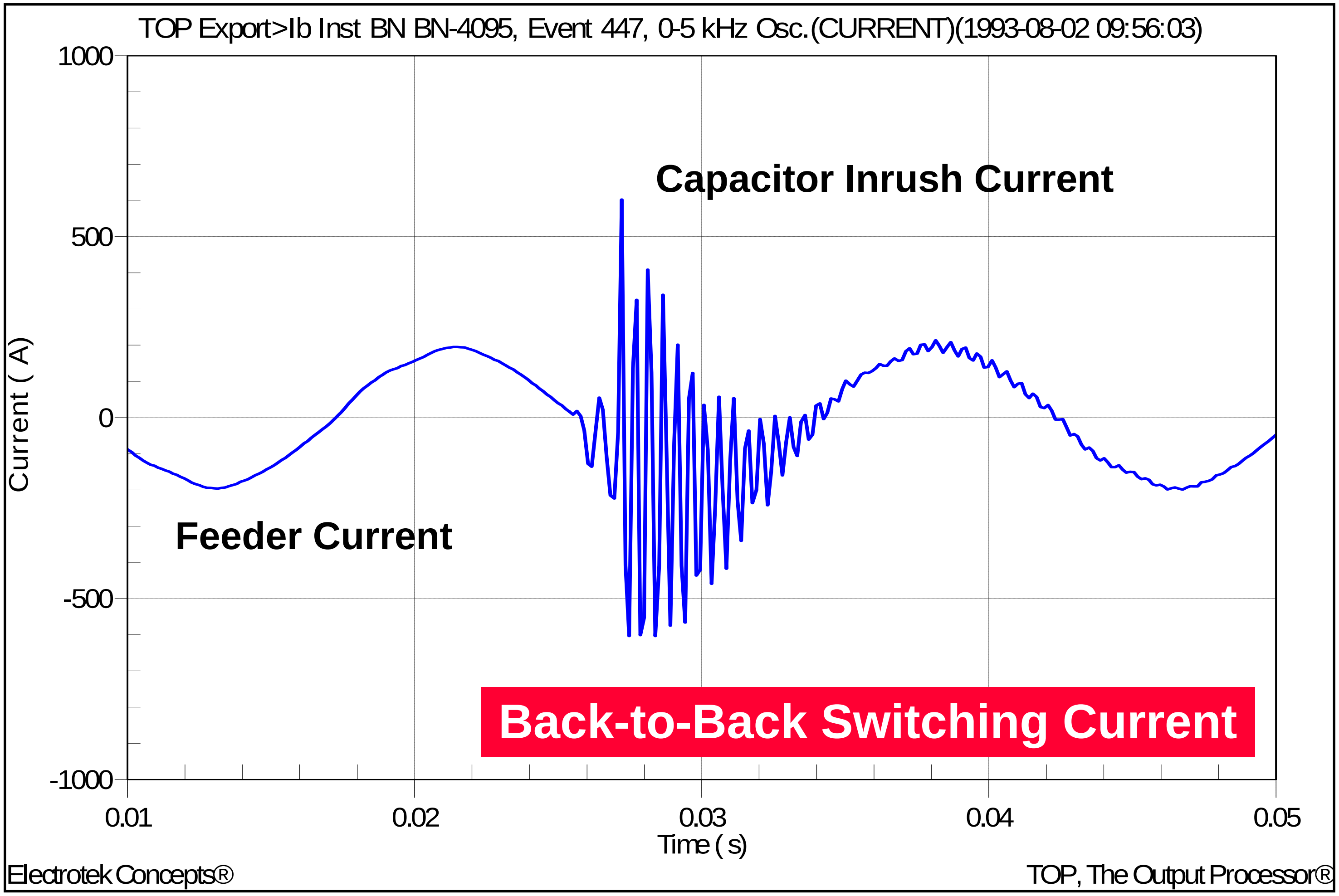
Source: FerroView

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

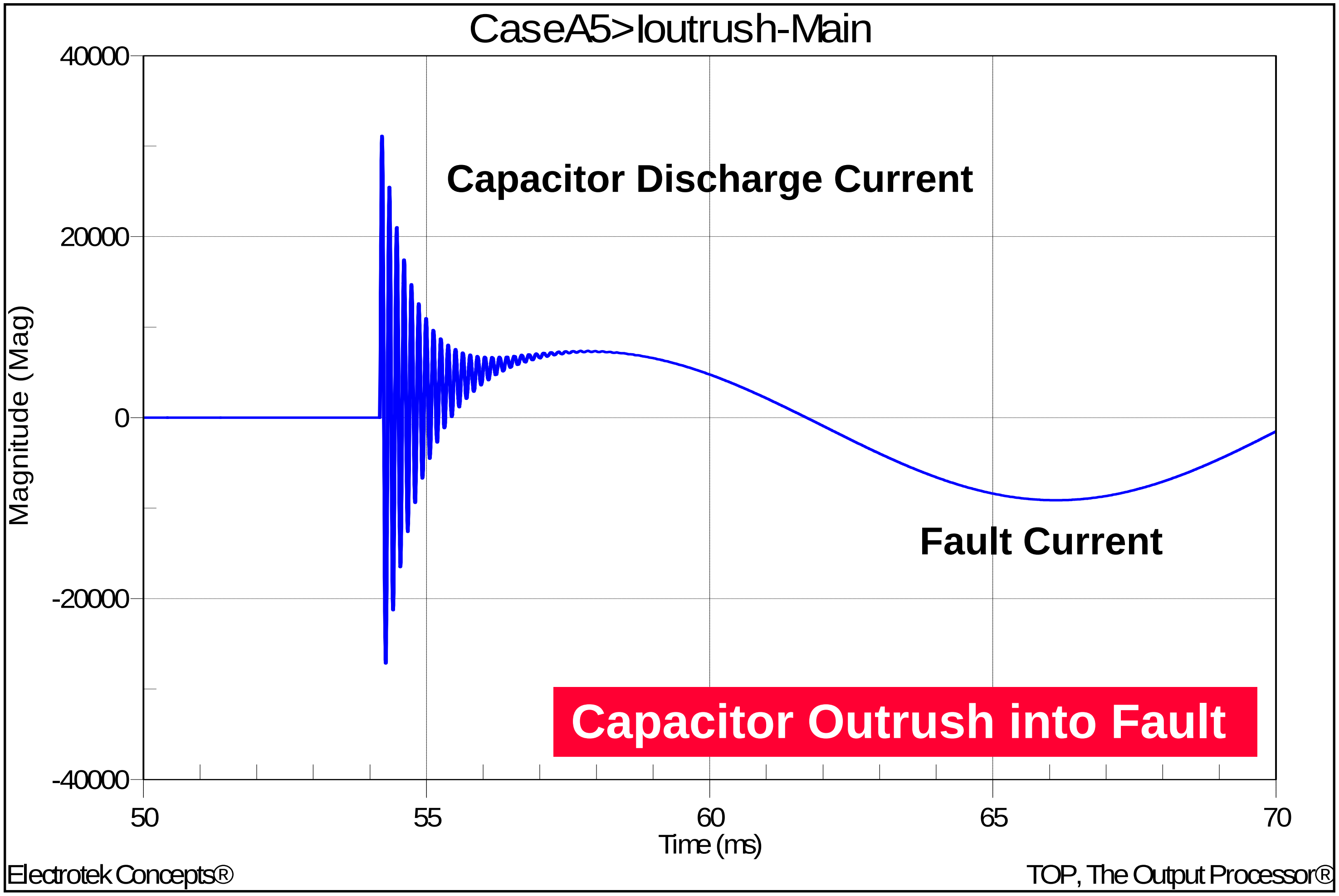
$$f_s = \frac{1}{2\pi\sqrt{L_s C}} \approx f_{system} * \sqrt{\left(\frac{X_c}{X_s}\right)} \approx f_{system} * \sqrt{\left(\frac{MVA_{sc}}{MVA_r}\right)} \approx f_{system} * \sqrt{\left(\frac{1}{\Delta V}\right)}$$

Measured Capacitor Bank Switching



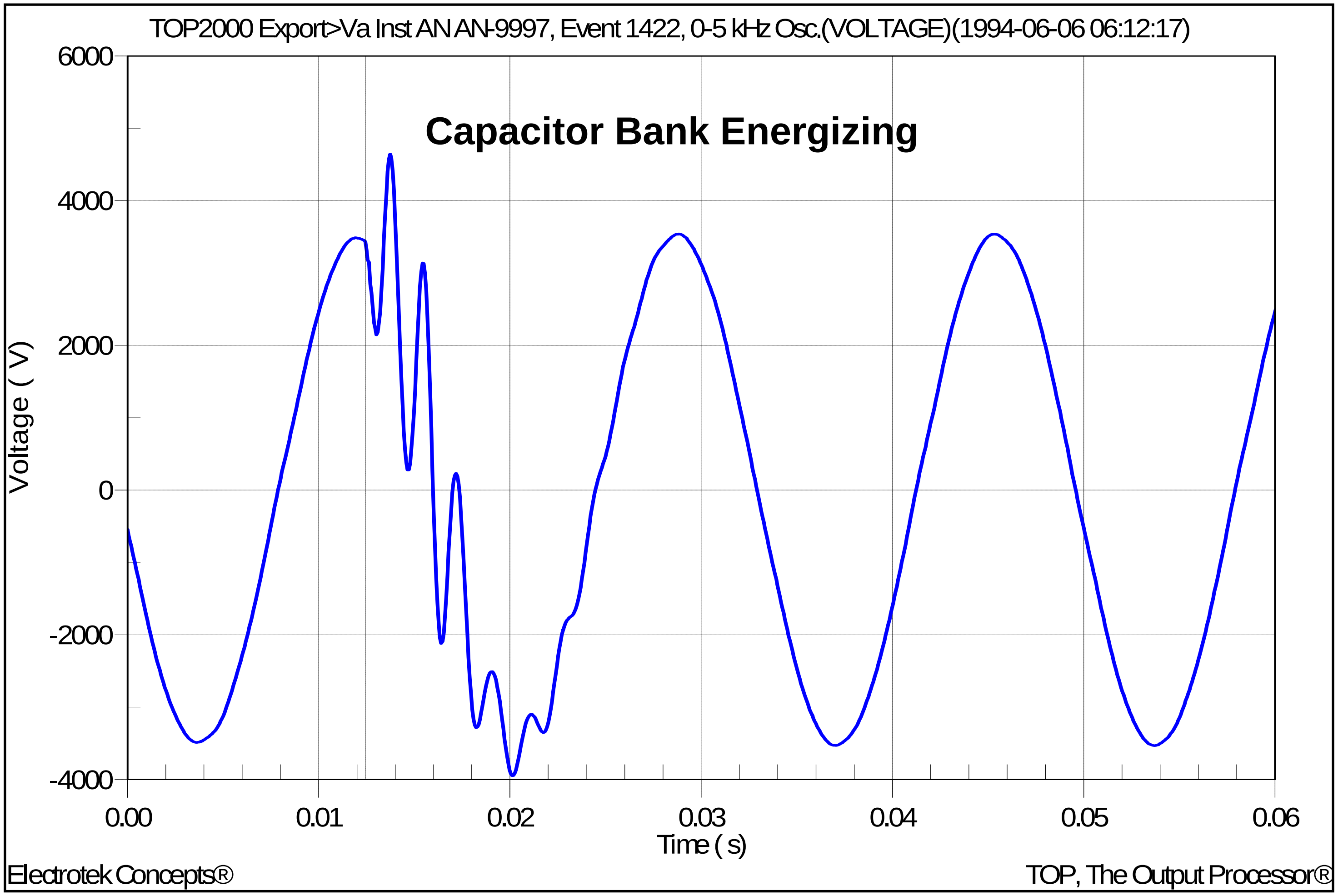
Source: D-BMI 8010 PQNode

Simulated Capacitor Outrush Current



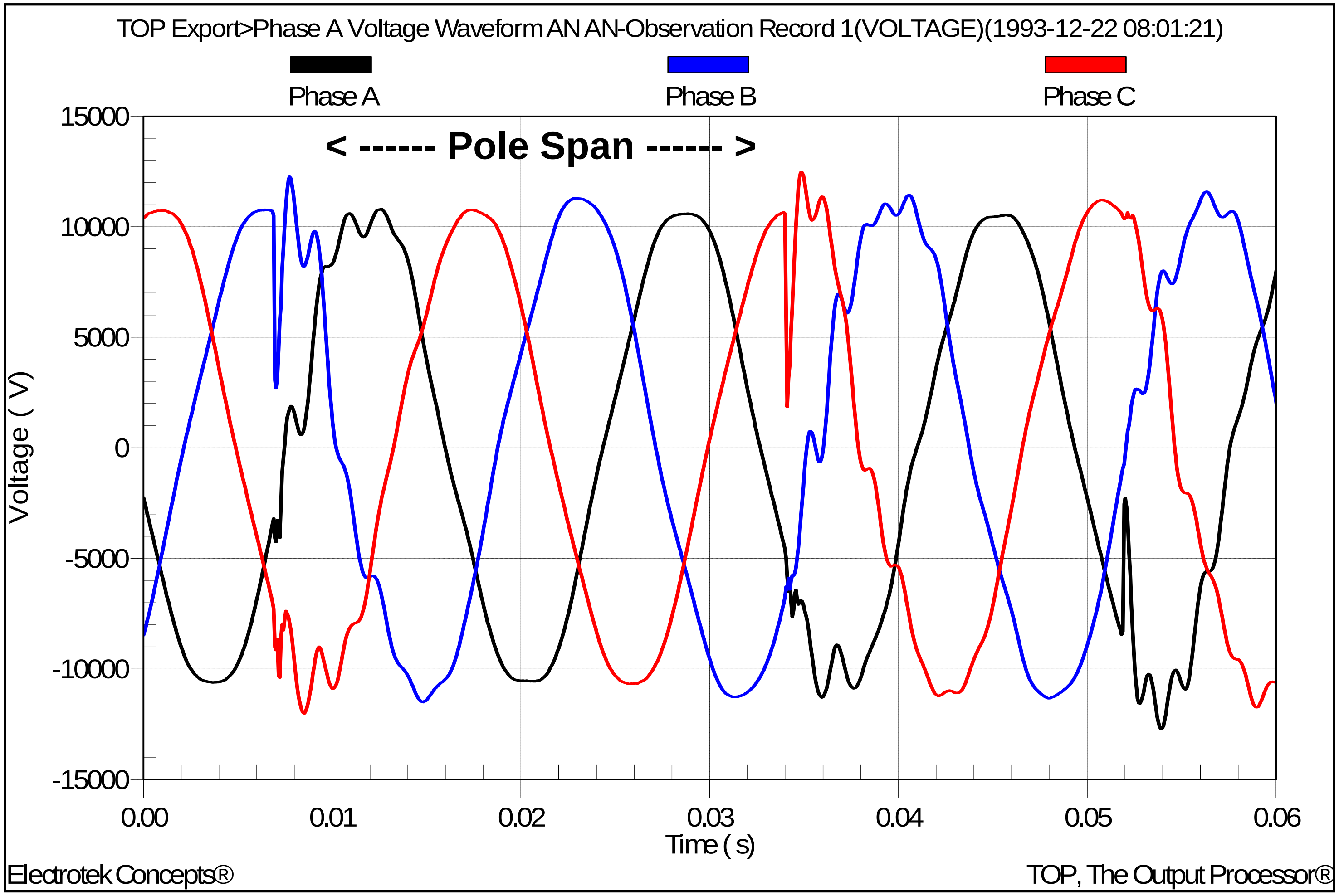
Source: PSCAD

Measured Capacitor Energizing Voltage



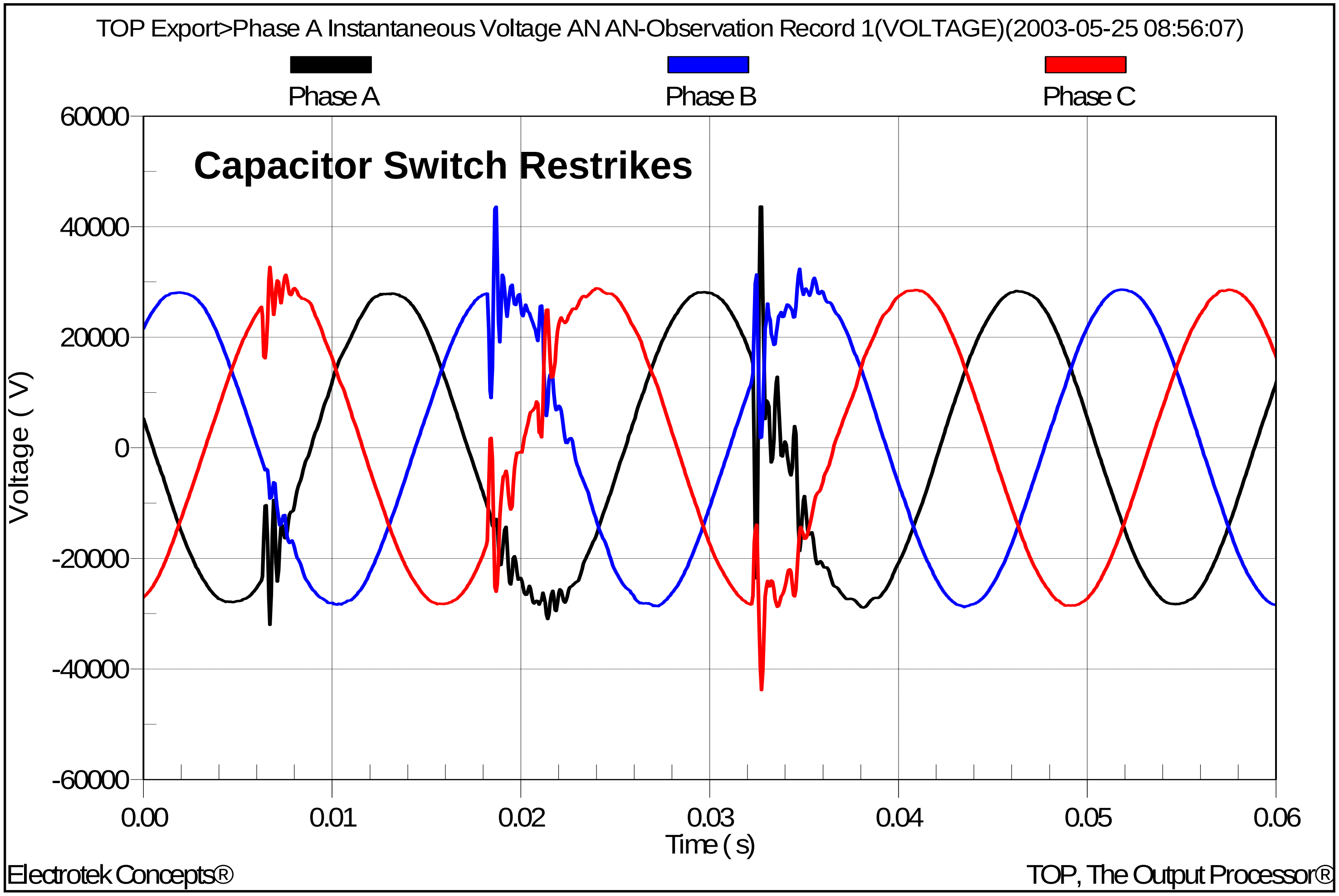
Source: D-BMI 8010 PQNode

Measured Capacitor Energizing



Source: D-BMI 8010 PQNode

Measured Capacitor Switch Restrikes

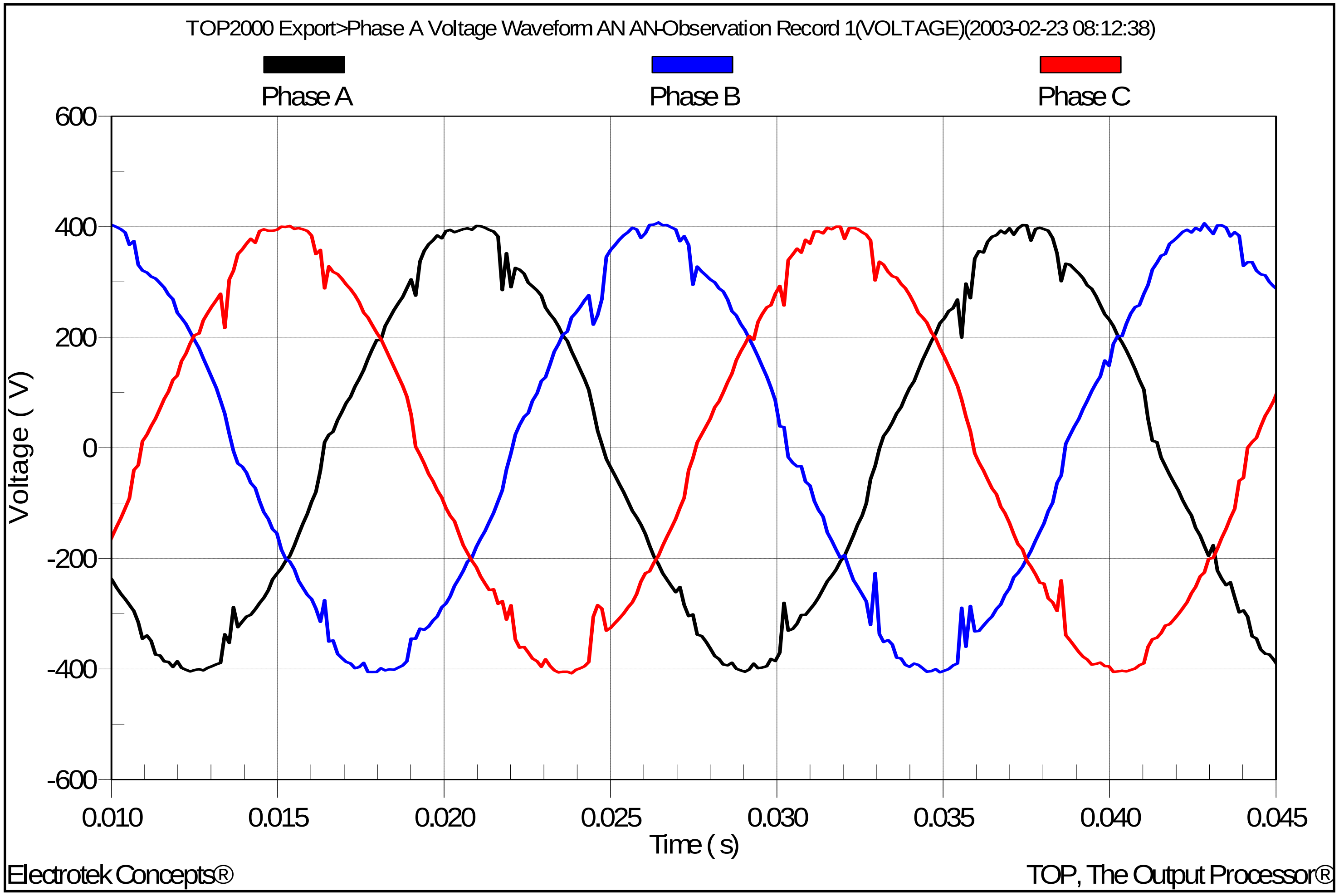


Source: D-BMI 8010 PQNode

Voltage Notching (Rectifier Switching)

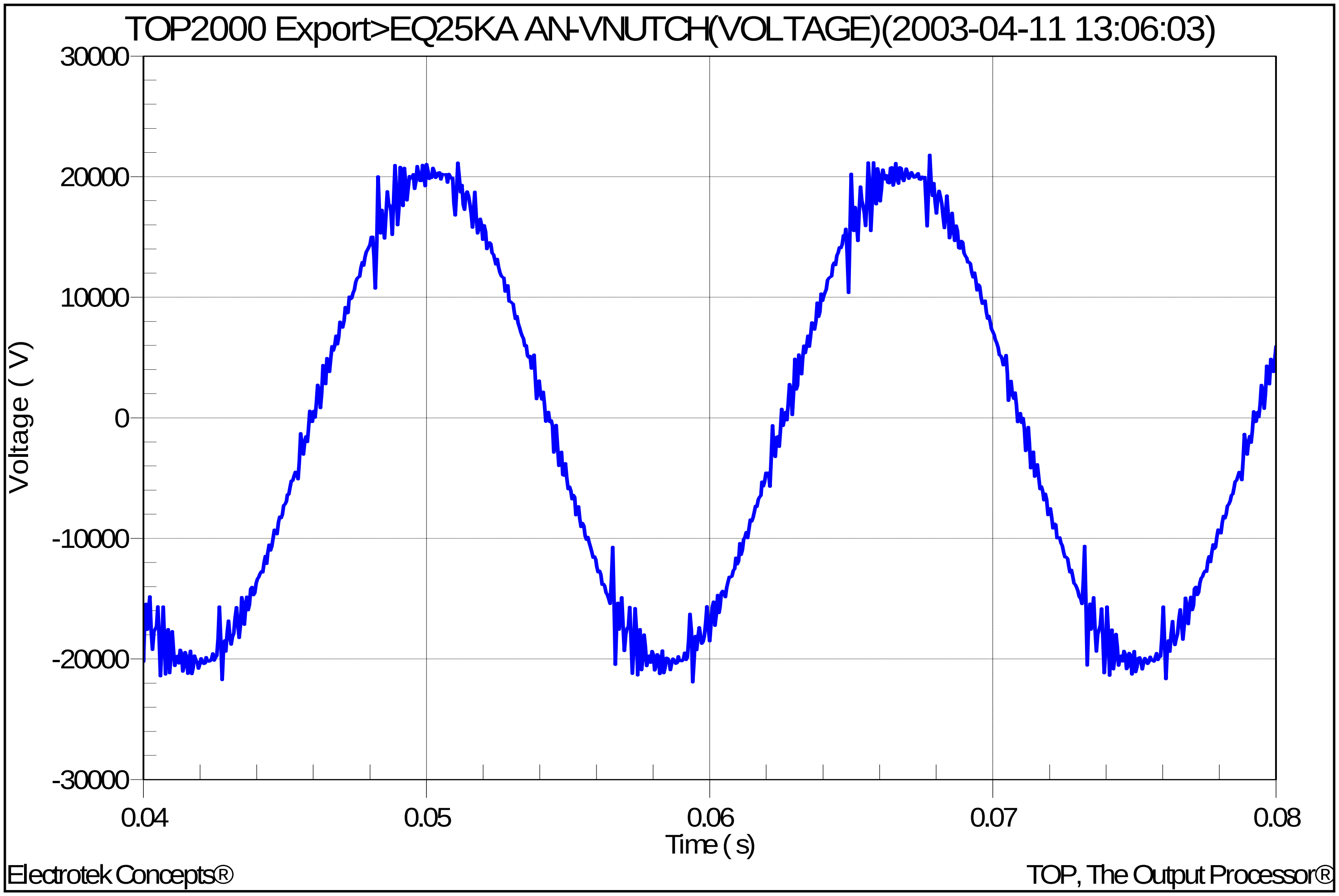
- Voltage notches are a special case that falls in between transients and harmonic distortion.
- Natural result of commutation in power electronic devices:
  - Notching of the input voltage waveform is a normal characteristic of the switching that occurs in the power electronics of a rectifier during continuous current operation.
- High frequency components.
- Additional zero crossings cause timing problems.

Measured Customer Voltage Notching



Source: Dranetz-BMI 5530 DataNode

Simulated Feeder Voltage Notching

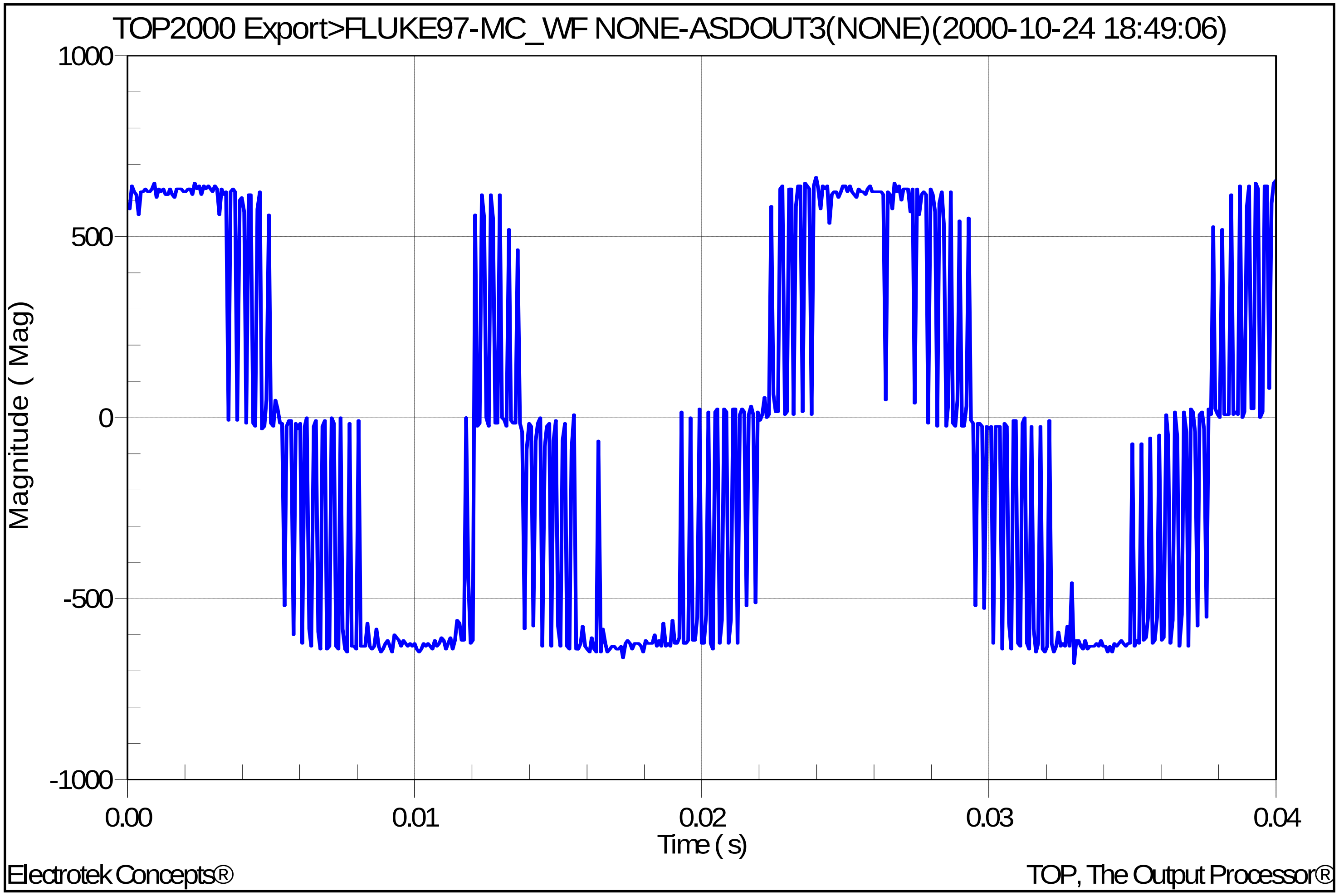


Source: EMTP

Motor Transients (Inverter Switching)

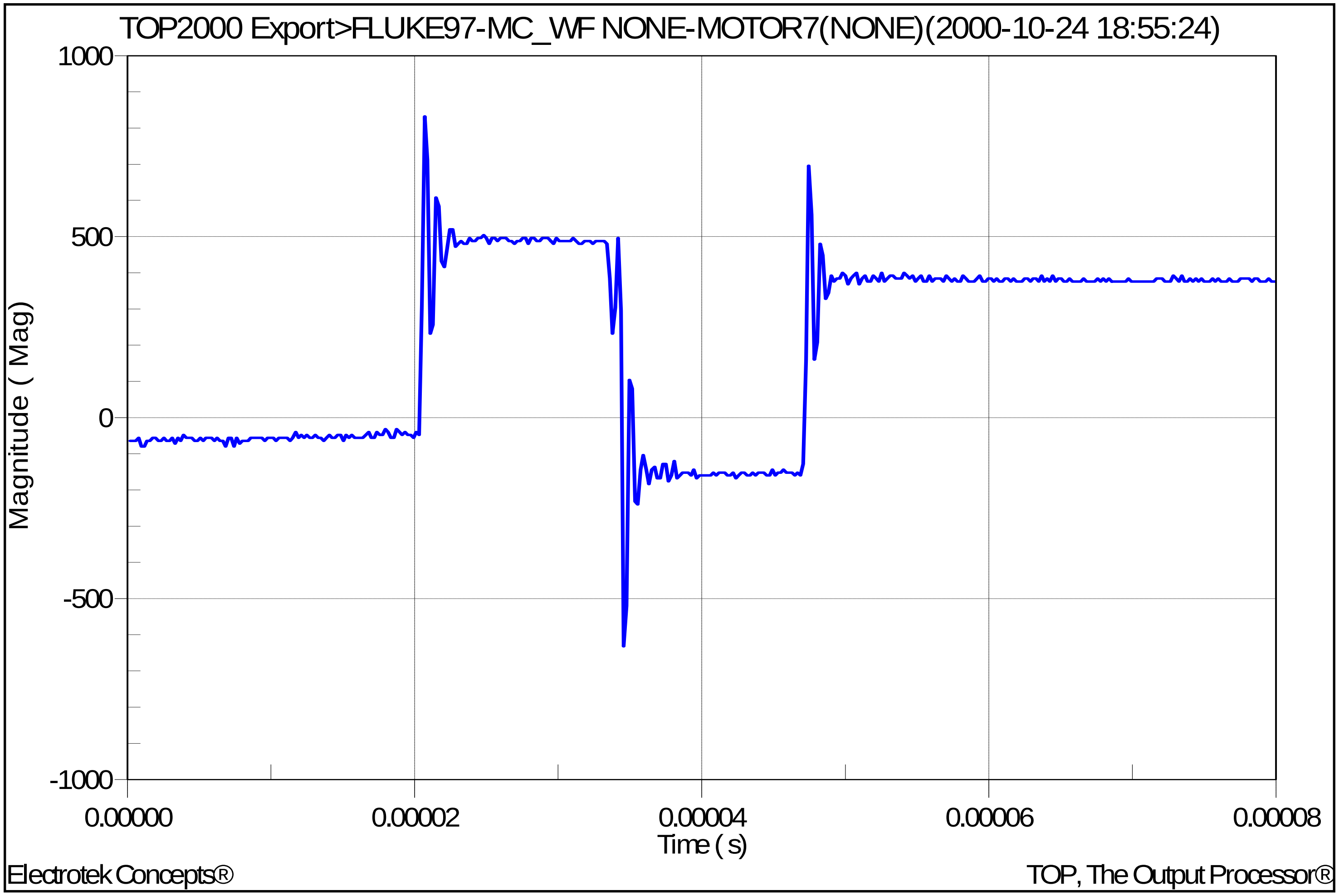
- Voltage reflections (up to 2 per-unit) at the motor terminals can cause insulation failure. Quantities that impact the voltage include:
  - PWM switching frequency
  - cable length
  - damping
- Possible solutions to ASD motor transients:
  - Change cable length (not practical, and may not eliminate transient)
  - Change PWM frequency (not practical, and may not eliminate transient)
  - Surge capacitors across motor terminals
  - Line reactors ("chokes") at the drive terminal (sizing may be a problem)

Measured PWM ASD Output Voltage



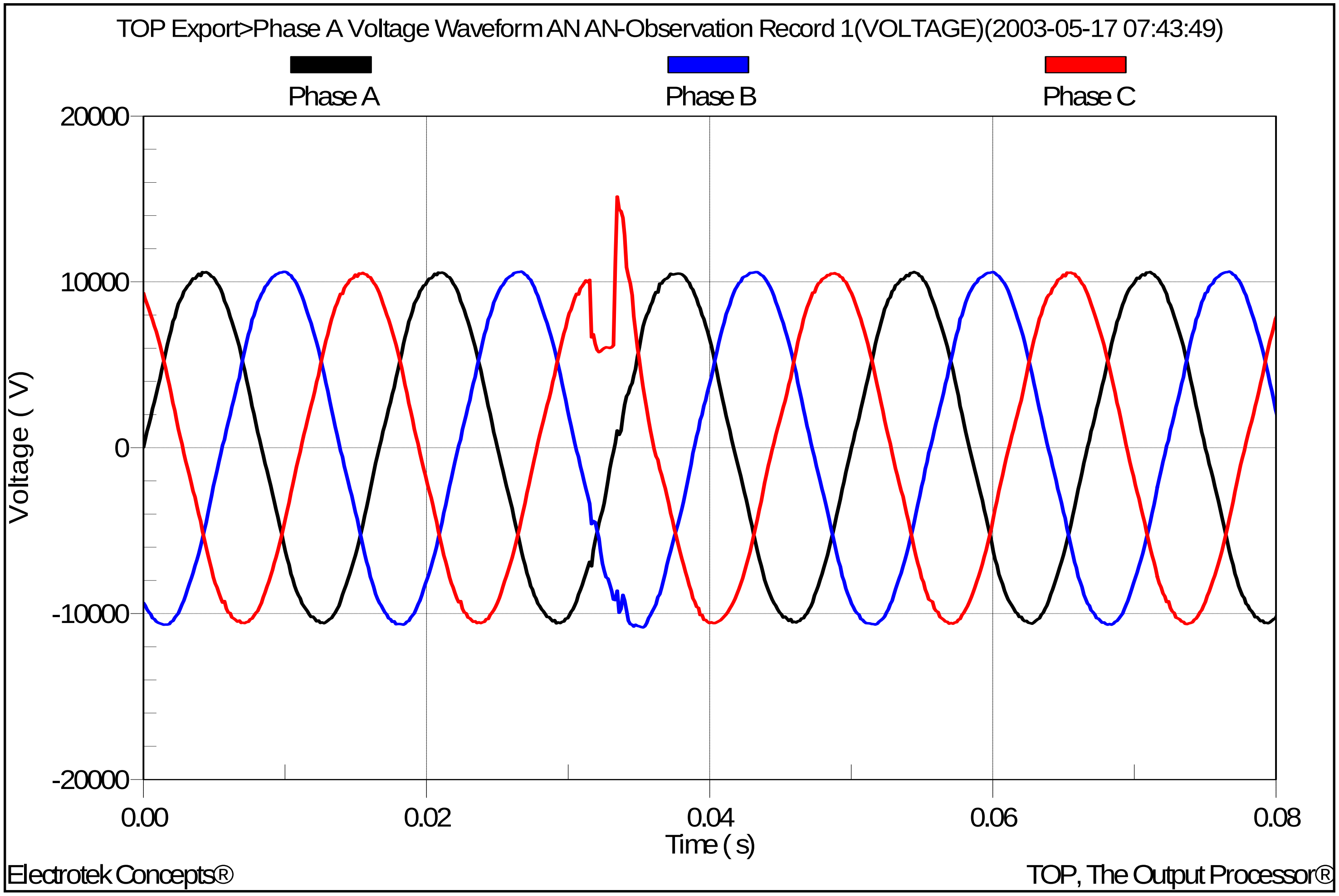
Source: Fluke 97

Measured Motor Terminal Voltage



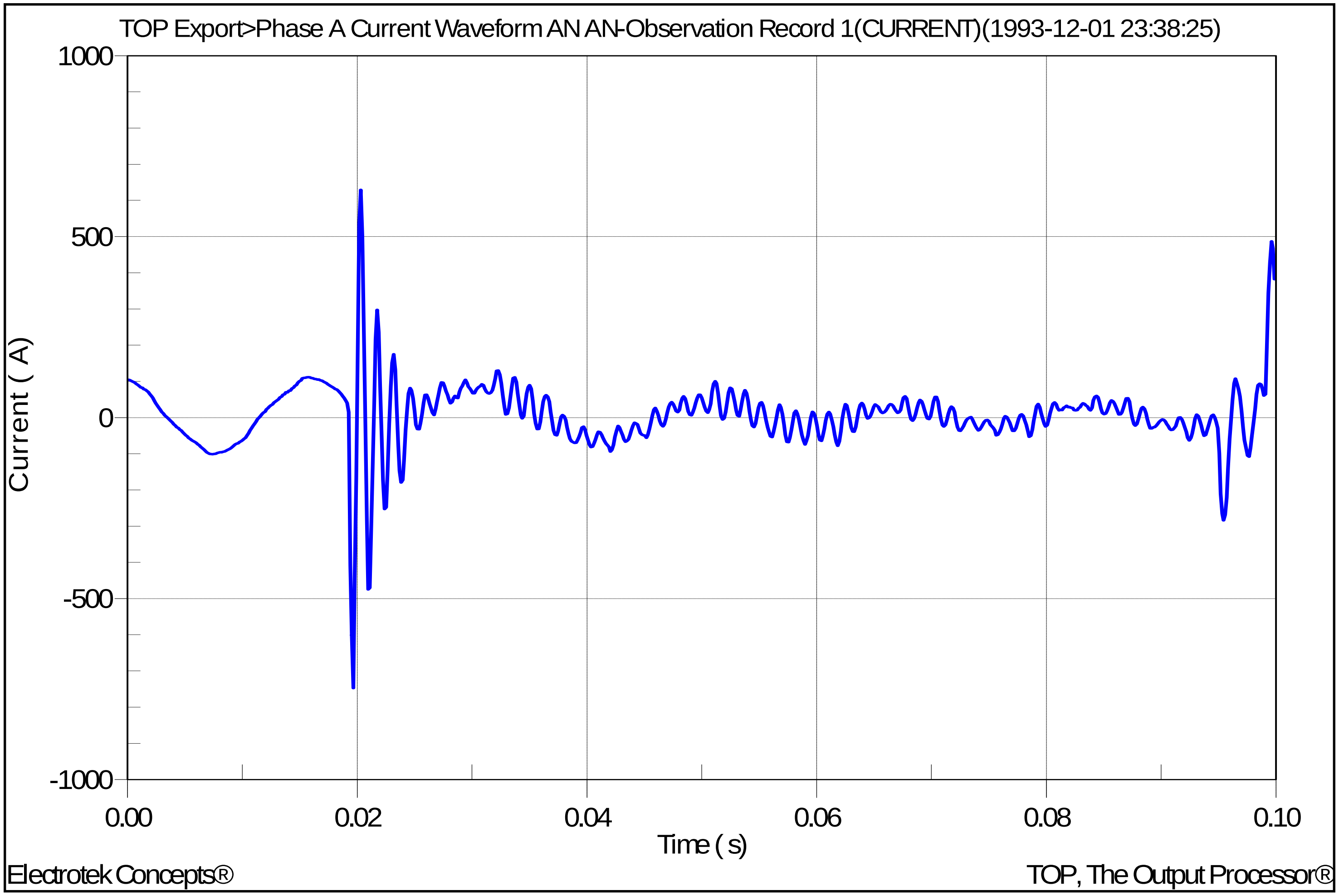
Source: Fluke 97

Other Transients: CLF Operation



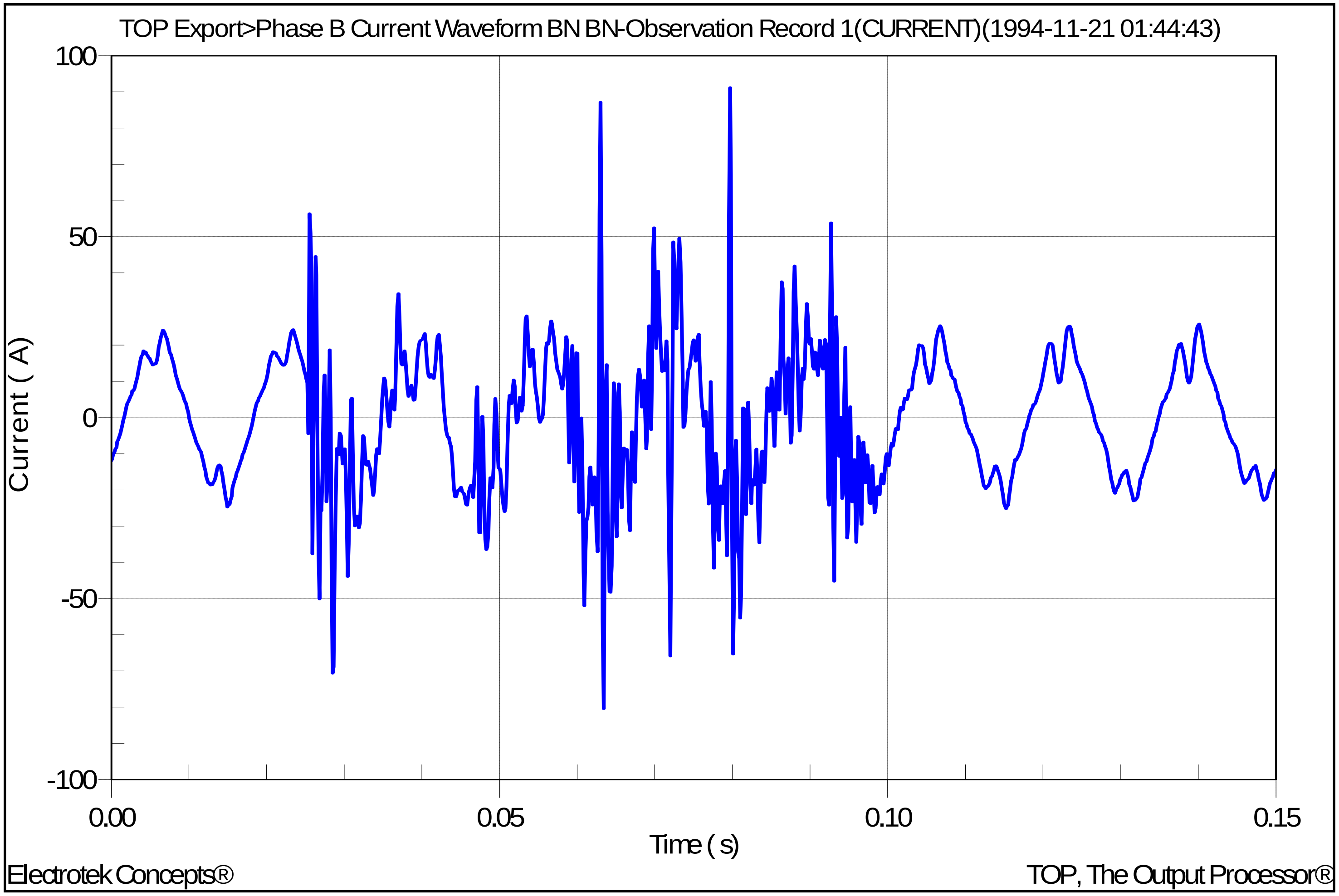
Source: Dranetz-BMI 5530 DataNode

Other Transients: Arcing Fault Current



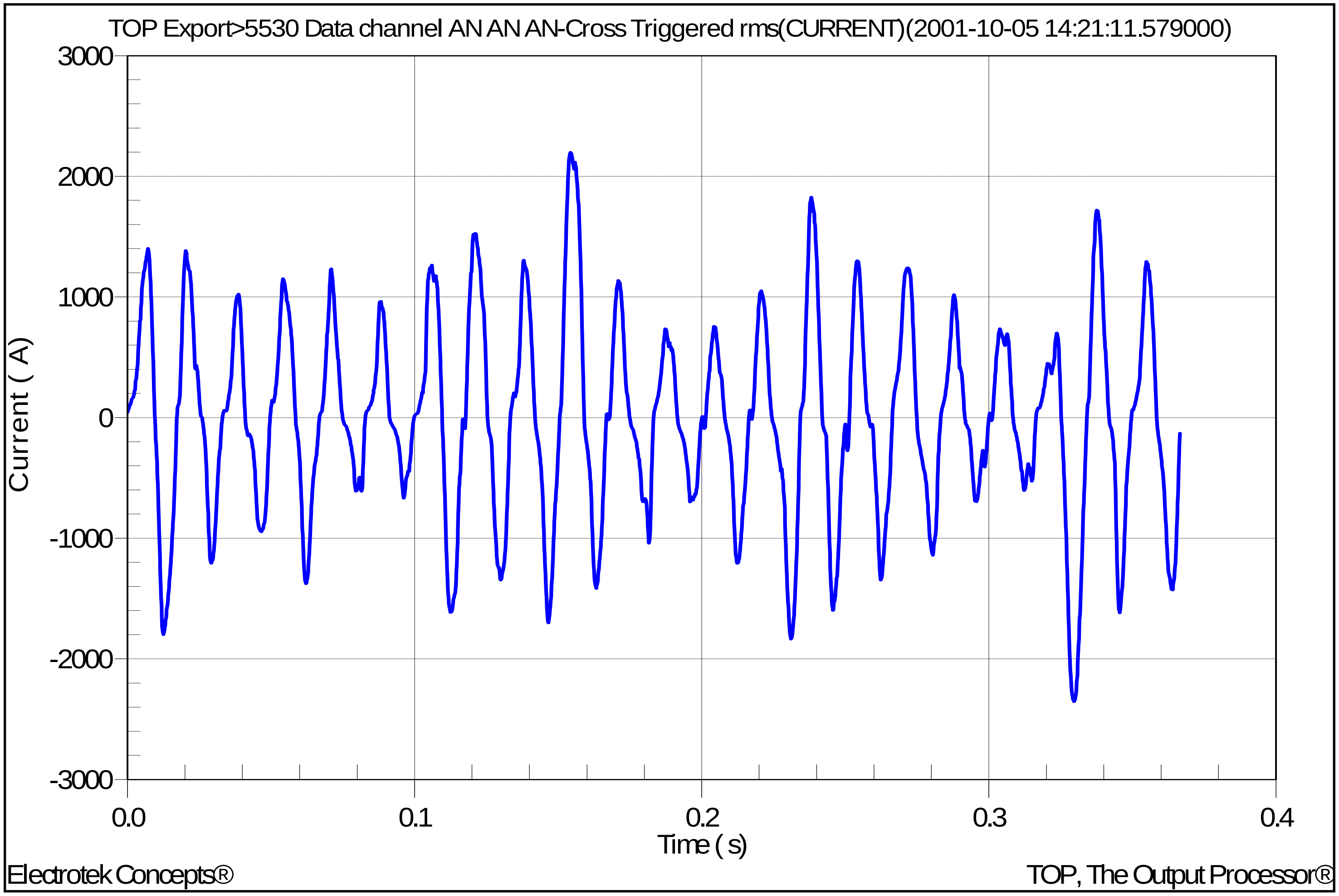
Source: D-BMI 8010 PQNode

Other Transients: Arcing Fault Current



Source: D-BMI 8010 PQNode

Other Transients: Arc Furnace Current

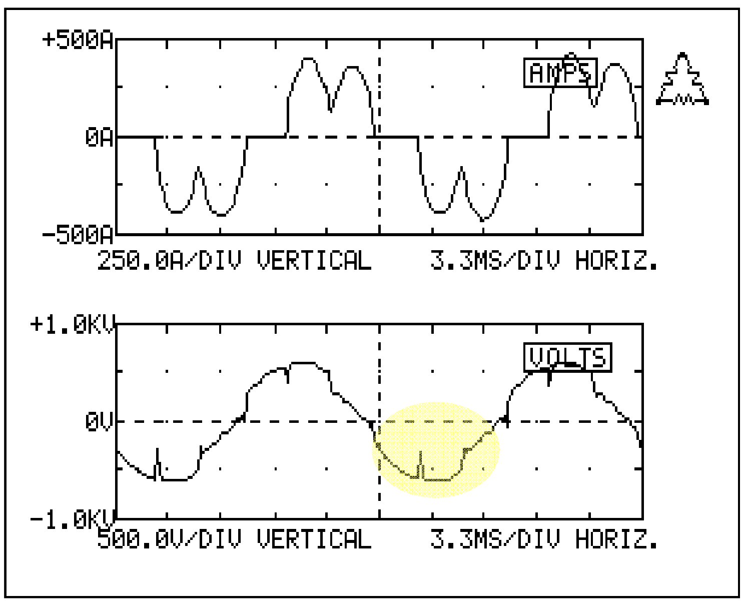


Source: Dranetz-BMI 5530 DataNode

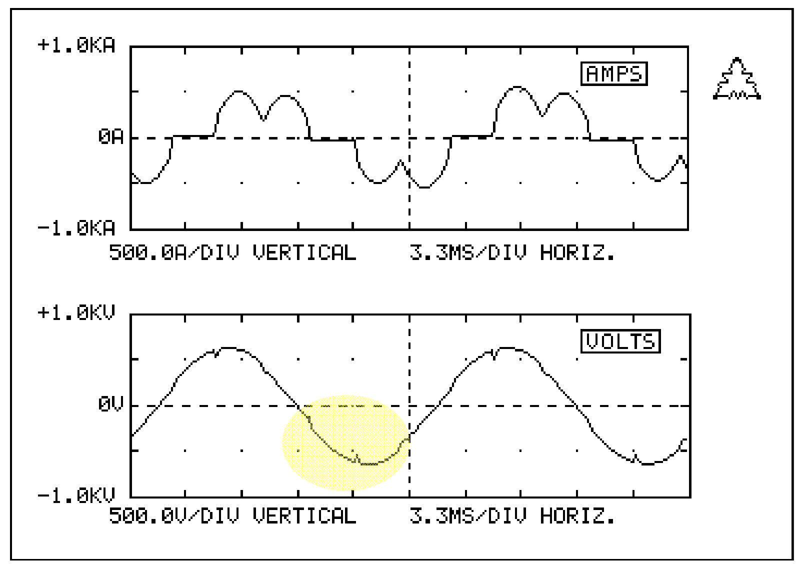
Transient Problem/Solution #1

- Adjustable-Speed Drive - Voltage Notching:
  - 400 HP dc Drive Current and Voltage Waveforms

Drive Side of Input Reactor

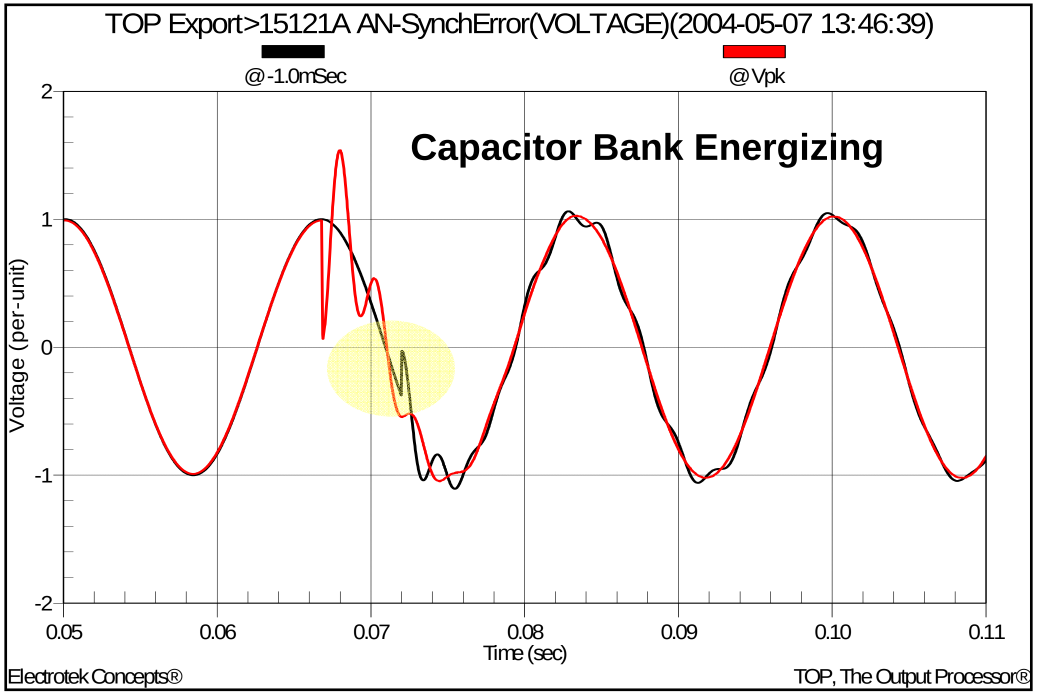


Bus Side of Input Reactor



Transient Problem/Solution #2

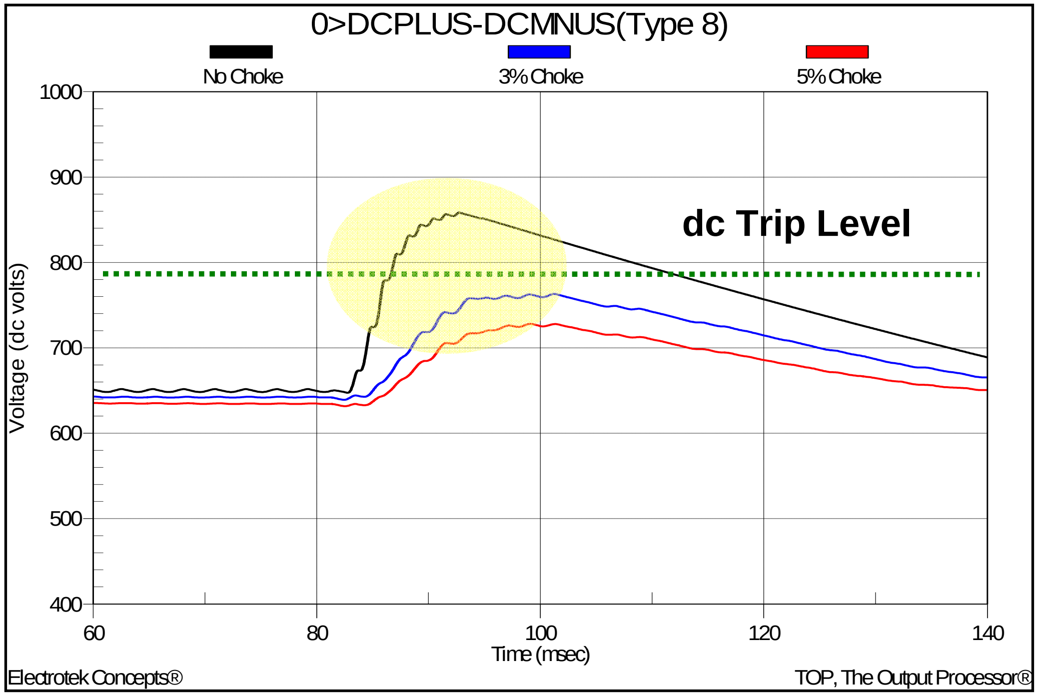
- Capacitor Switching – Transient Voltage:
  - Control transient by switching when the voltage is approximately zero (synchronous closing control).



Source: EMTP

Transient Problem/Solution #3

- Capacitor Switching – dc Bus Overvoltage:
  - Control transient by adding inductance (choke) on the ac side of the adjustable-speed drive.

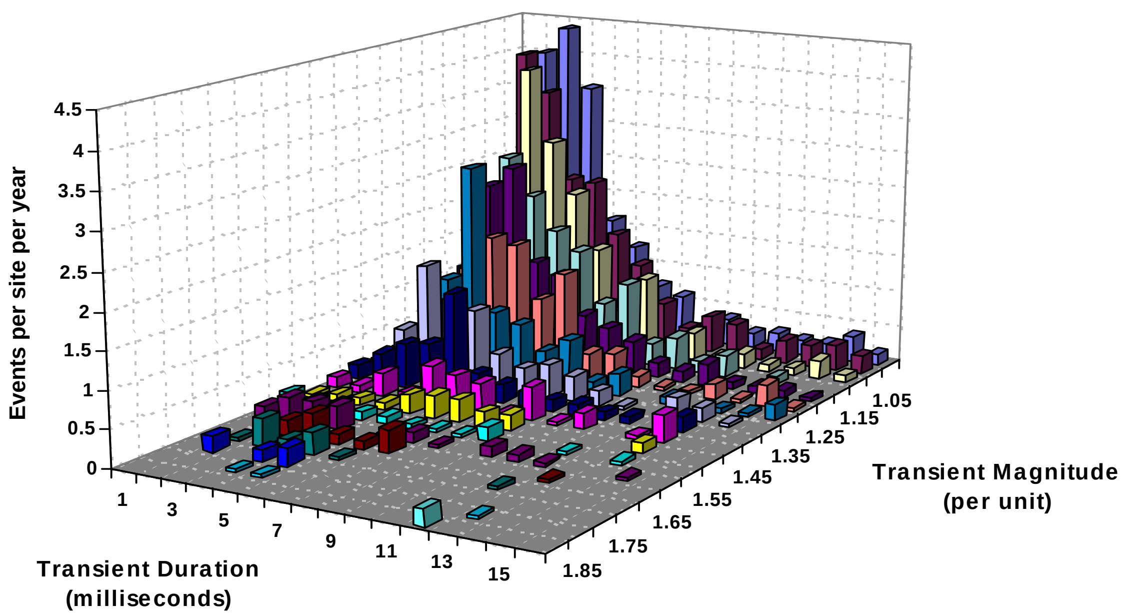


Source: EMTP

Measurements to Characterize Transients

- Using tools (e.g., PQView) to characterize transient voltages and currents.

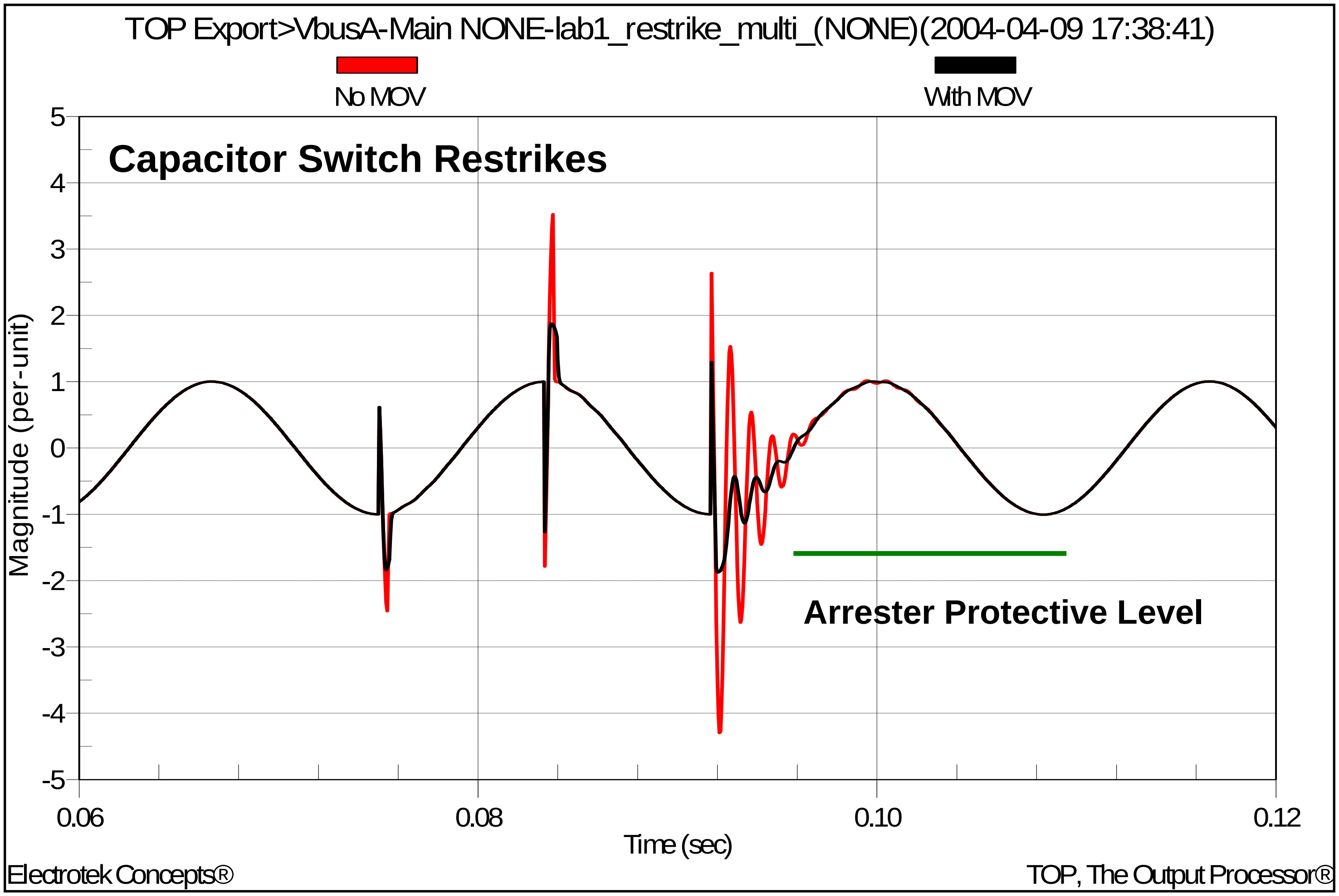
Oscillatory Transient Magnitude versus Duration



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

More Information: *www.pqview.com*

Simulations to Predict Transients



Source: PSCAD

Additional Information

- Electrotek provides consulting services related to transient and harmonic studies using tools such as PSCAD, EMTP, and SuperHarm.
- Additional Information:
  - Electrotek (studies, training, and seminars): http://www.electrotek.com/
  - PQSoft (simulation and analysis tools and support): http://www.pqsoft.com/
  - Monitoring service: http://www.powermonitoring.com/
  - Monitoring instruments for capturing transients: http://www.dranetz-bmi.com/