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IEEE Fort Worth PES Chapter

Presentation on:

Potential Concerns and Mitigation for Shunt Capacitor and Reactor Switching

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Prepared by:

Mitsubishi Electric Power Products, Inc. (MEPPI)
Power System Engineering Services Department
Warrendale, Pennsylvania

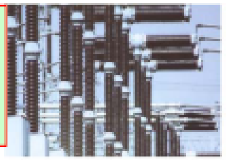
Overview of Topics in Presentation

- Shunt Capacitor Bank Switching
  - Applicable Standards and Criteria
  - Overview of Shunt Capacitor Bank Potential Concerns
  - Example Simulation Waveforms
  - Mitigation Solutions

- Shunt Reactor Bank Switching
  - Applicable Standards and Criteria
  - Overview of Shunt Reactor Bank Potential Concerns
  - Example Simulation Waveforms
  - Mitigation Solutions

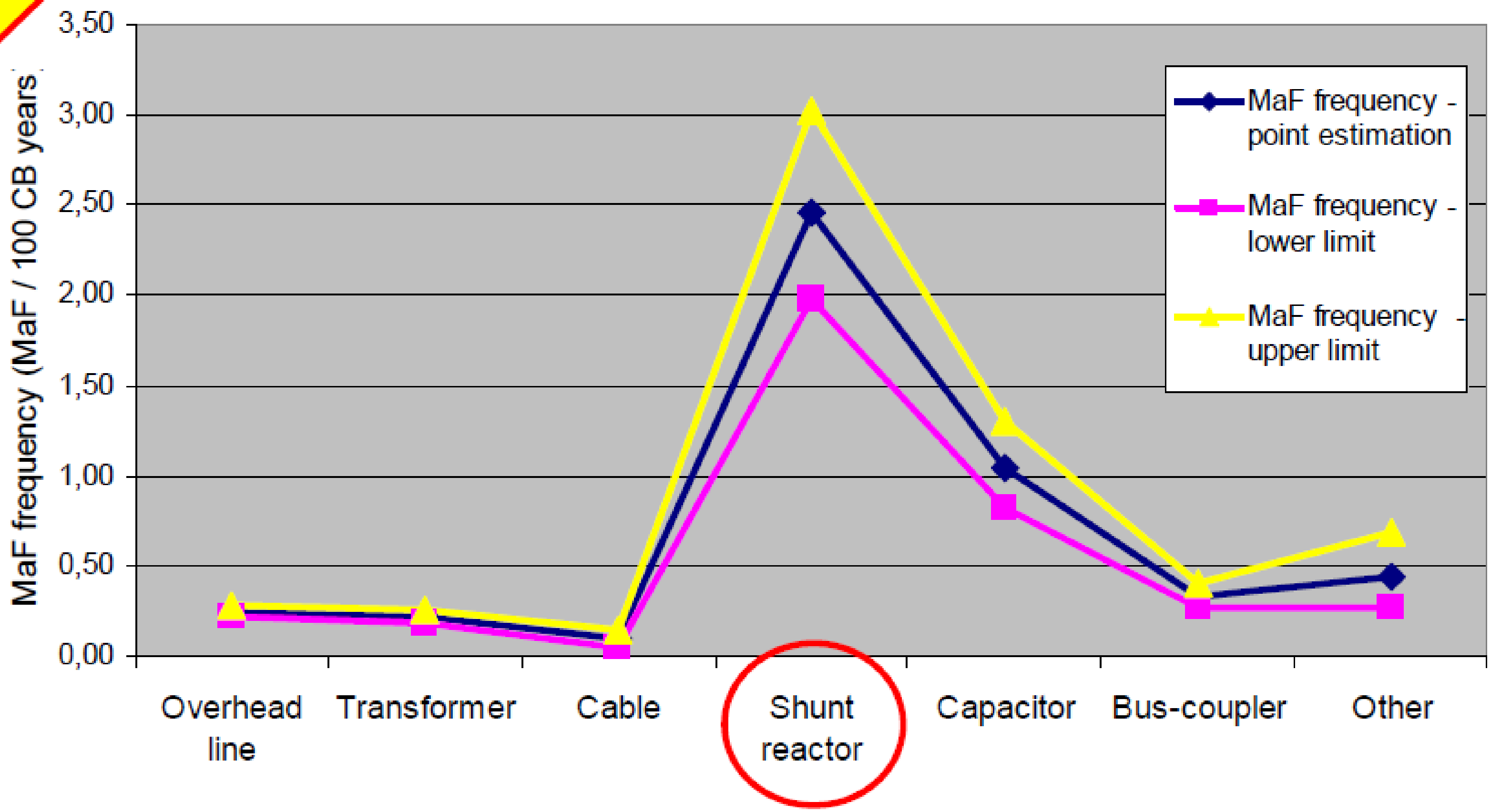
WG A3.06 Reliability of High Voltage Equipment

Final Results **CIRCUIT BREAKERS**



Failure data

Major failure frequencies / Kind of Service



Vienna 2011

Major failure frequency

Shunt Capacitor Bank Switching

What is a Shunt (Power) Capacitor Bank?

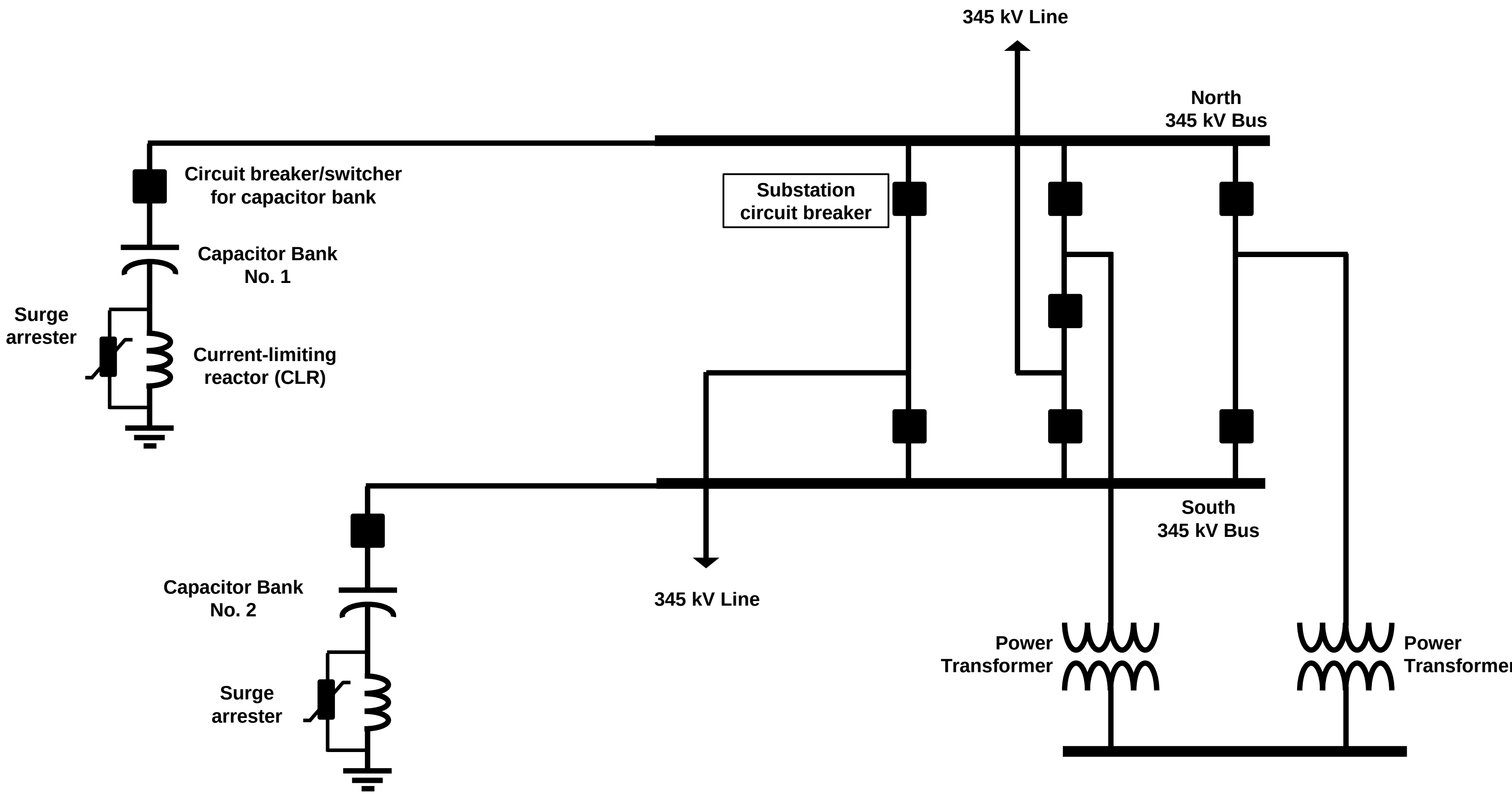
Why Do We Install Shunt Capacitor Banks?

- Voltage/VAR Support
  - Often sized and located based on power flow/stability analysis
  - Located at Transmission or Distribution voltage level
  - Increase voltage by reducing the VAR flow in the system and the resulting voltage drop

- Harmonic Filtering
  - Tuned to reduce level of system harmonic distortion
  - Often associated with power electronic devices

- Power Factor Correction at Customer Level
  - Sized to increase power factor to desired level

Example One-Line Diagram of Substation with a Shunt Capacitor



Applicable Standards and Criteria

- C37.06: "IEEE Standard for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis-Preferred Ratings and Related Required Capabilities for Voltages Above 1000 V)"
- C37.06.1: "Guide for High-Voltage Circuit Breakers Rated on Symmetrical Current Basis Designated "Definite Purpose for Fast Transient Recovery Voltage Rise Times"
- IEEE Std 1036: "IEEE Guide for Application of Shunt Power Capacitors"
- C37.99: "IEEE Guide for the Protection of Shunt Capacitor Banks"
- C37.012: "IEEE Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers"
- IEEE Std 519: "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems"
- IEEE Std 80: "IEEE Guide for Safety in AC Substation Grounding"
- IEEE 1313.2: "IEEE Guide for the Application of Insulation Coordination"
- C62.22: "IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems"

Potential Concerns for Installing a Shunt Capacitor Bank

Steady-State Change In Voltage

- Energizing the capacitor bank will result in an increase in the fundamental frequency voltage at the capacitor bank.
- To minimize the impact of the voltage change on customer loads, it is often limited to 2-3%, where:

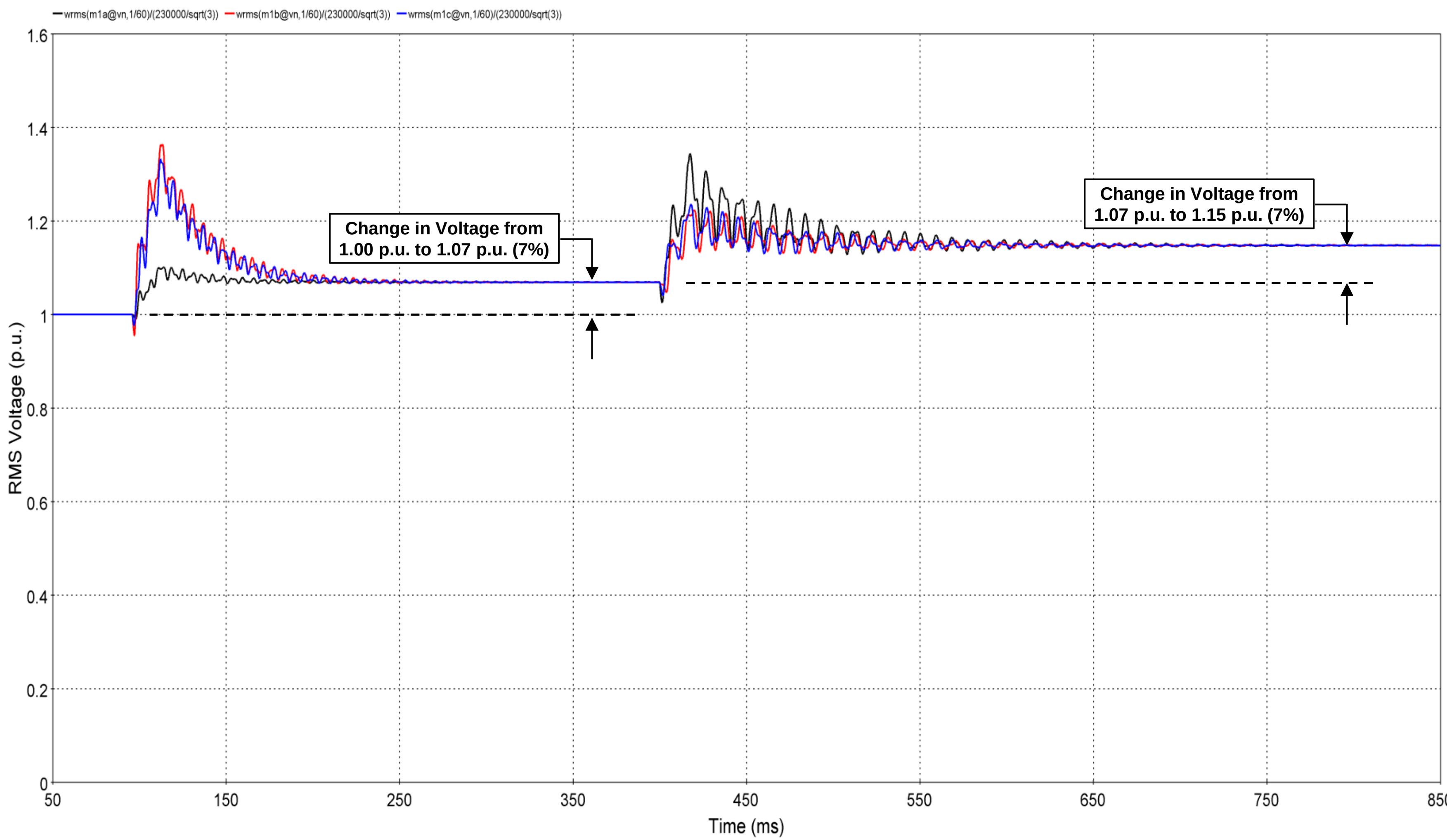
$$\Delta V = \left(\frac{Mvar}{MVA_{SC}}\right) \times 100\%$$

- *Where:*

  Mvar = shunt capacitor bank rating (Mvar)

  MVA_{SC} = the available 3-phase short-circuit current MVA at capacitor bank

What Does the Voltage Change Look Like?



What are Mitigation Options for the Voltage Change?

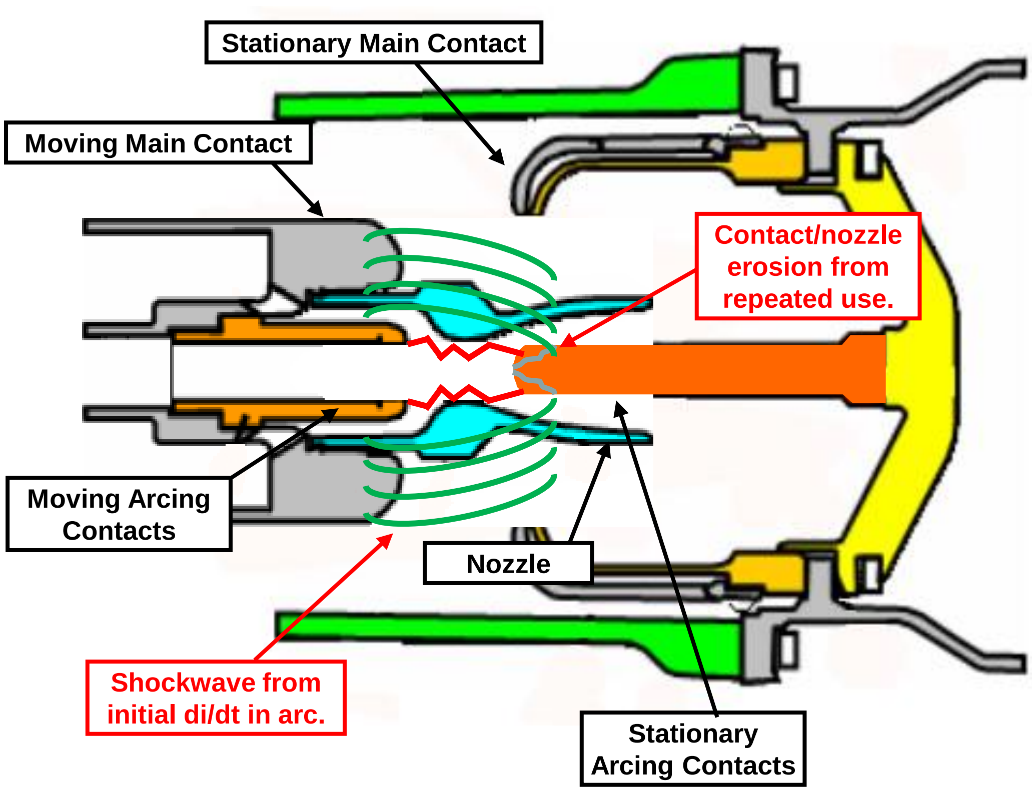
Potential Solutions:

- **Switching in smaller increments** decreases the Mvar switched and reduces the voltage change when energizing the capacitor bank.

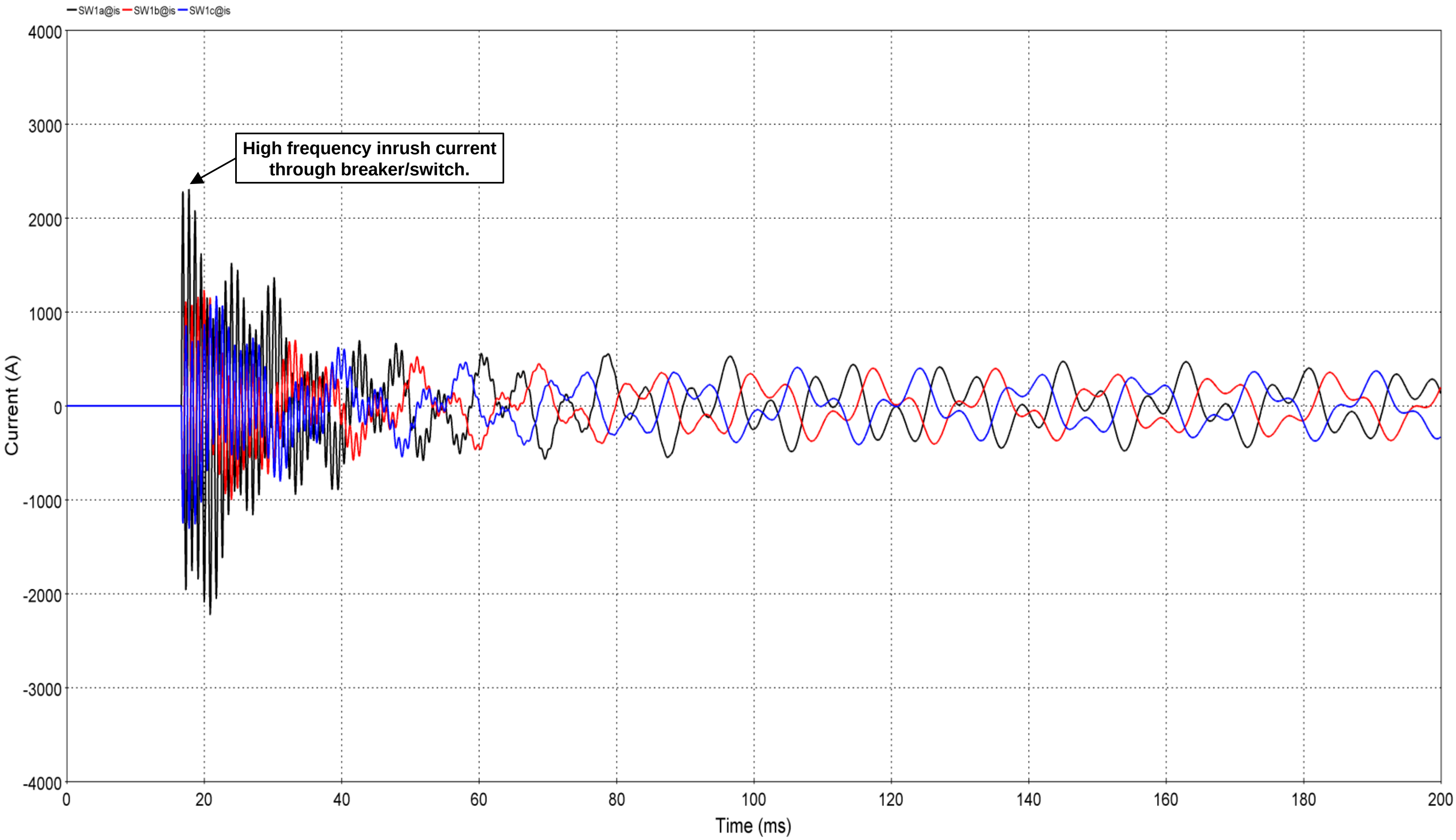
Inrush Current

- When a capacitor bank is energized, a high frequency inrush current will flow through the capacitor bank and anything in series (i.e., circuit breaker/switcher, current-limiting reactor, buswork, etc.).
- Severity of the inrush current is proportional to the number of capacitor banks at the substation that are online during switching and the mitigation equipment used to limit the currents.
- What are potential concerns for inrush current:
  - Circuit breaker/switcher damage
    - Rupture (oil)
    - Contact and nozzle degradation (gas, air, vacuum)
  - Increased circuit breaker maintenance
  - Control circuit interference
  - Transient ground potential rise

Potential Concerns for Capacitor Bank Switching (Inrush Current)



What Does Inrush Current Look Like?



What are Mitigation Options for Inrush Current?

Potential Solutions:

- **Current-limiting reactors** increase series inductance, therefore lower peak and frequency.
- **Pre-insertion resistors** lower the voltage dropped across the breaker/capacitor, therefore lower the peak but not frequency.
- **Pre-insertion inductors** lower the voltage dropped across the breaker/capacitor and increase series inductance, therefore lower peak and frequency
- **Synchronous-close control** lowers the voltage dropped across the breaker/capacitor, therefore lower the peak but not frequency. However, the added benefit of synchronous control is consistent (reduced) arcing times and less breaker wear.

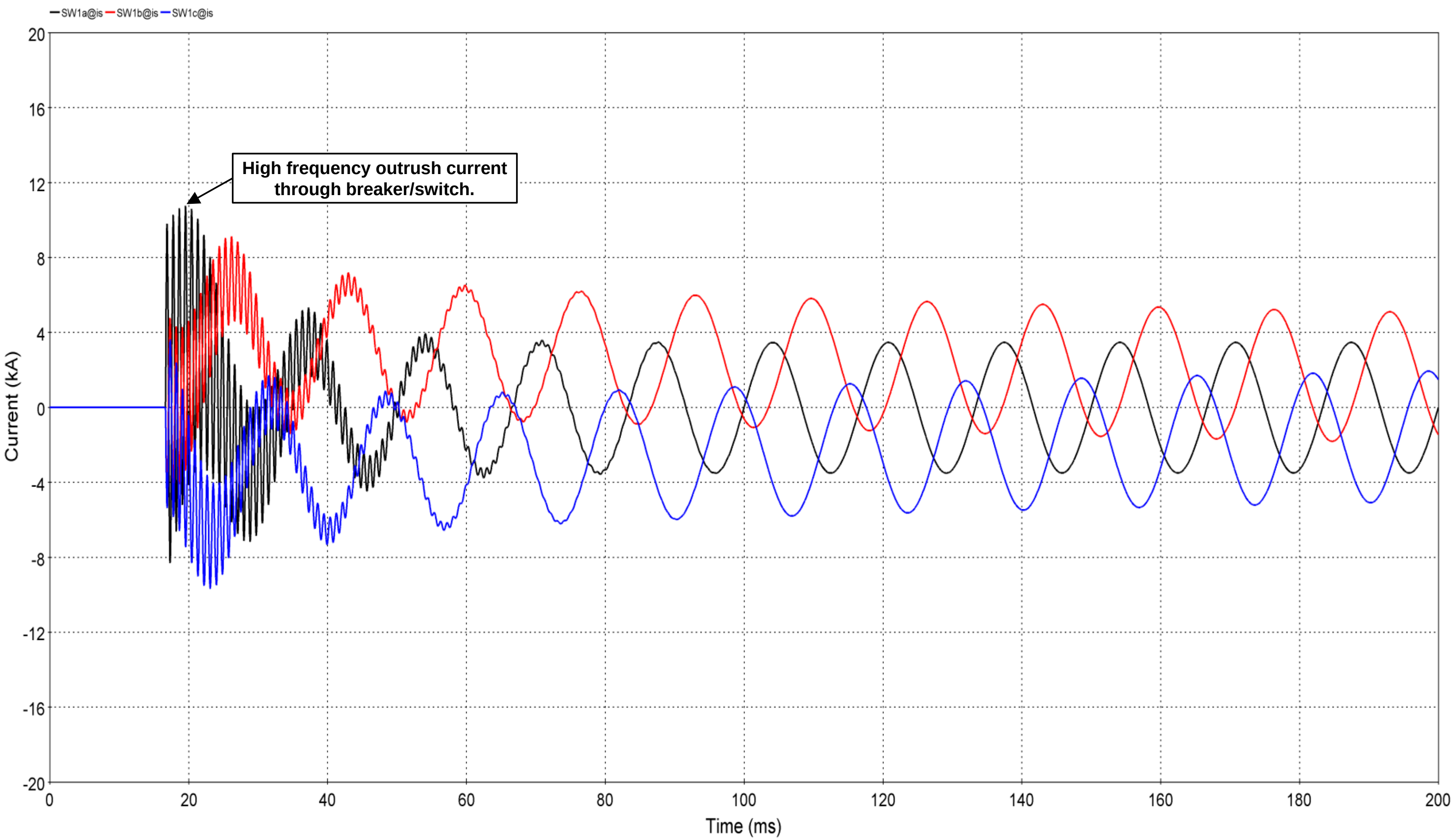
Outrush Current

- When a close-in fault occurs near a substation with a shunt capacitor bank, if a line/bus breaker re-closes into the fault or has a re-strike during opening a high frequency outrush current will flow through the breaker.

- Severity of the outrush current is proportional to the number of capacitor banks at the substation that are online during switching, the mitigation equipment used to limit the currents, and the location of the fault.

- What are potential concerns for outrush current:
  - Circuit breaker/switcher damage (more concern for oil circuit breakers).
    - Rupture (oil)
    - Contact and nozzle degradation (gas, air, vacuum)
  - Transient ground potential rise

What Does Outrush Current Look Like?



What are Mitigation Options for Outrush Current?

Potential Solutions:

- **Current-limiting reactors** increase series inductance, therefore lower peak and frequency.
- Note that pre-insertion devices and synchronous-close control for the capacitor bank breakers will not mitigate the outrush current because the line breaker is the breaker re-closing into the fault or having a re-strike during opening.

Transient Overvoltages

- When a shunt capacitor bank is energized the voltage at the capacitor bank is forced from zero to system voltage by collapsing ~1.0 p.u. voltage across the circuit breaker/switcher which could result in ~2.0 p.u. at the capacitor bank from the resulting overshoot.
- Traveling waves propagating throughout the system can stress equipment at remote stations as well.
- Potential resonance conditions can also be a cause for concern such as voltage magnification.
- What are potential concerns for the transient overvoltages:
  - Flashovers of equipment
  - Damaged surge arresters and other equipment
  - Power quality/voltage distortion

Transient Overvoltages (continued)

- When a shunt capacitor bank is energized with a nearby capacitor at a lower voltage, the potential for voltage magnification may exist when the following condition is true:

$$L_1 x C_1 = L_2 x C_2$$

- Furthermore, when $C_1 >> C_2$, and $L_1 << L_2$ the condition can be exaggerated.

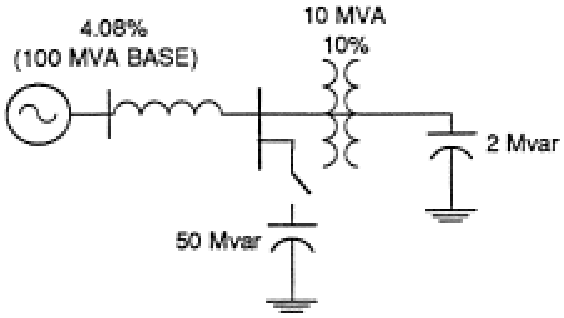


Figure 10—System diagram for magnification condition

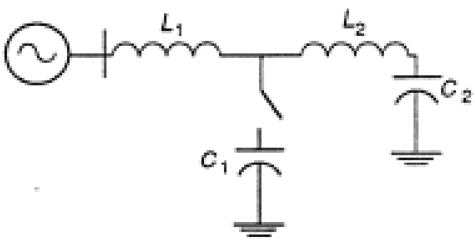
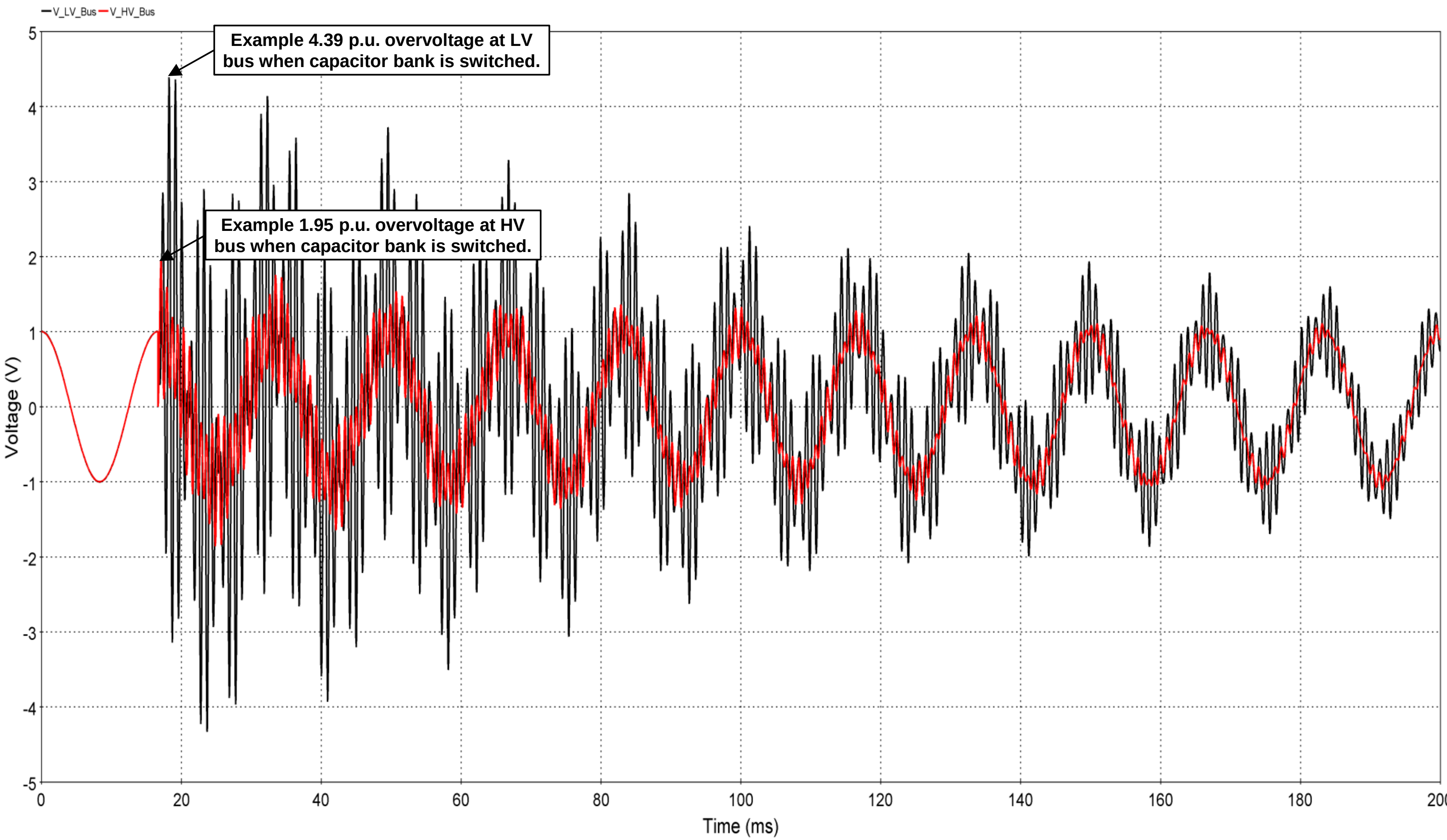


Figure 11—Equivalent circuit for magnification condition

What Does Voltage Magnification Look Like?



What are Mitigation Options for Transient Overvoltages?

Potential Solutions:

- **Current-limiting reactors, pre-insertion resistors/inductors, and synchronous-close control**: Reduce the inrush current and the voltage collapsed across the circuit breaker helping to reduce the voltage surge generated during switching.

- **Surge Arresters**: Mitigate the overvoltages generated by the switching operation.

Re-Strikes During De-Energization

- When a shunt capacitor bank is de-energized a trapped DC charge is left on the capacitor, which results in a near 2.0 p.u. voltage across the breaker/switcher a half cycle later when the system voltage is at an opposite polarity peak.

- If a re-strike occurs at a voltage peak (~2.0 p.u.) across the breaker/switcher, transient overvoltages with nearly twice the severity as normal energizing may occur.

- One of the primary causes of re-strikes is poor contact health.

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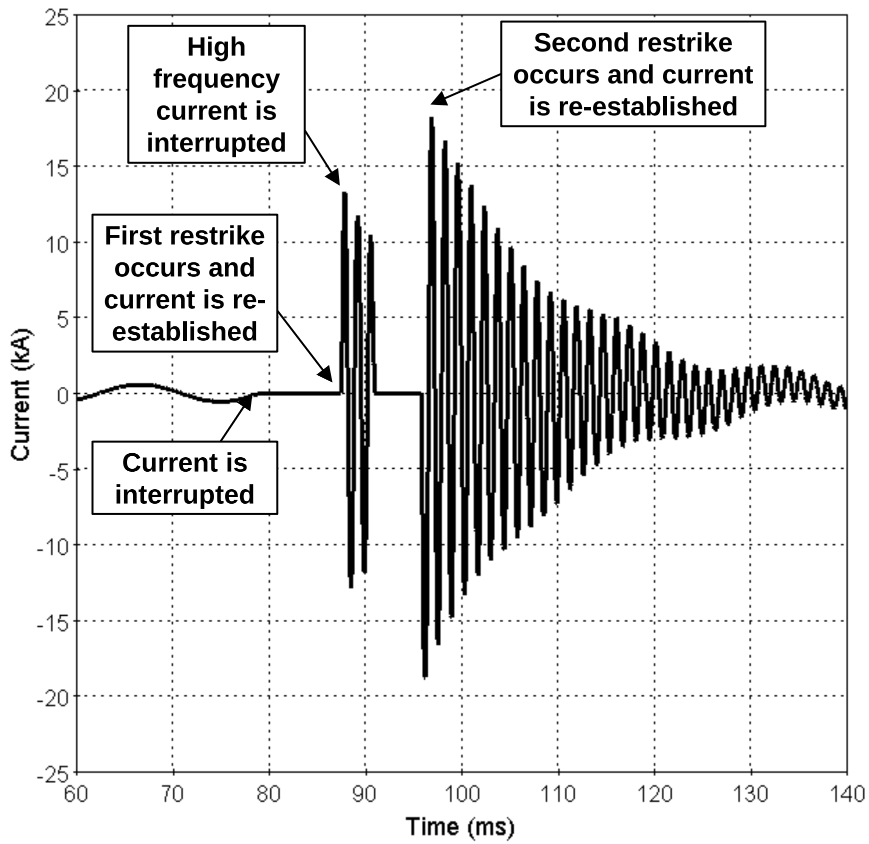
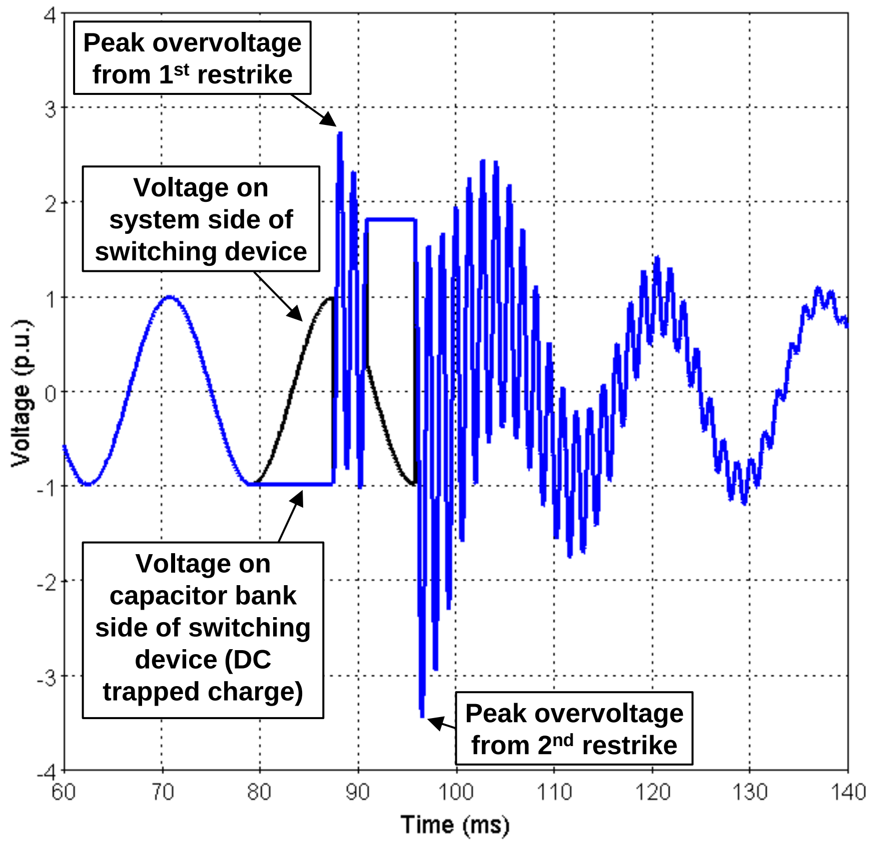
Re-Strikes During De-Energization (continued)

Current Through Switching Device



Voltage on Each Side of Switching Device



What are Mitigation Options for Re-Strikes?

Potential Solutions:

- **Current-limiting reactors, pre-insertion resistors/inductors, and synchronous-close/open control**: Reduce the inrush current and the voltage collapsed across the circuit breaker helping to reduce the voltage surge generated during switching.

- **Surge Arresters**: Mitigate the overvoltages generated by the switching operation.

Transient Recovery Voltages (TRV)

- When a fault occurs at a capacitor bank with a current-limiting reactor where the capacitor bank is shorted out and the breaker interrupts current limited by the current-limiting reactor, a TRV with a high rate-of-rise is imposed on the breaker.

- What are potential concerns for the transient overvoltages:
  - Failure of circuit breaker to interrupt

- Some common misconceptions:
  - Installing the CLR on the bus-side of the breaker eliminates the problem
  - Installing the CLR in the capacitor neutral eliminates the problem
  - Very large TRV capacitors are required (hundreds of nF)

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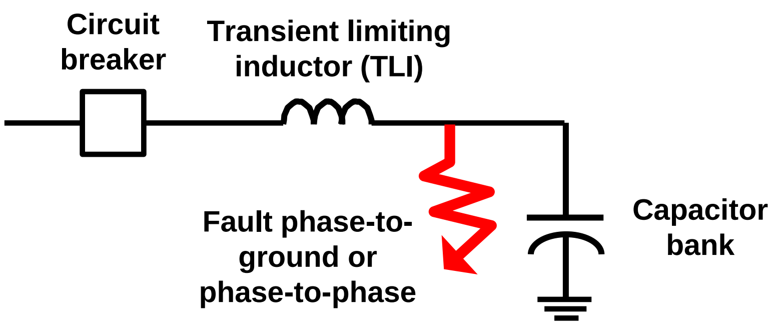
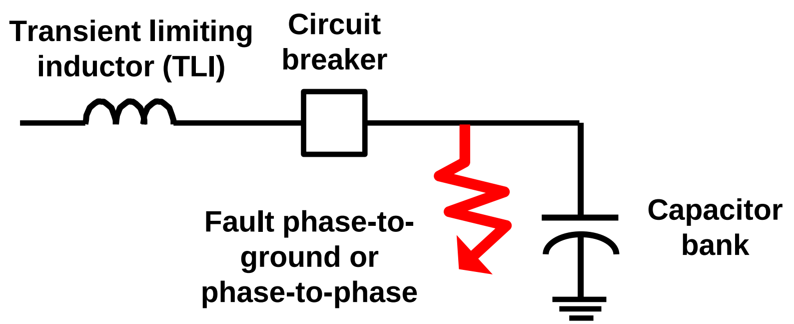
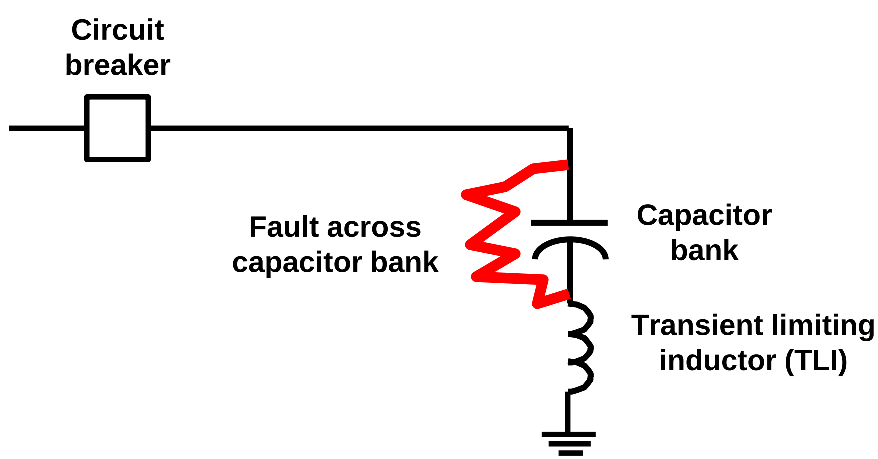
Transient Recovery Voltages (continued)



Example with circuit breaker before TLI

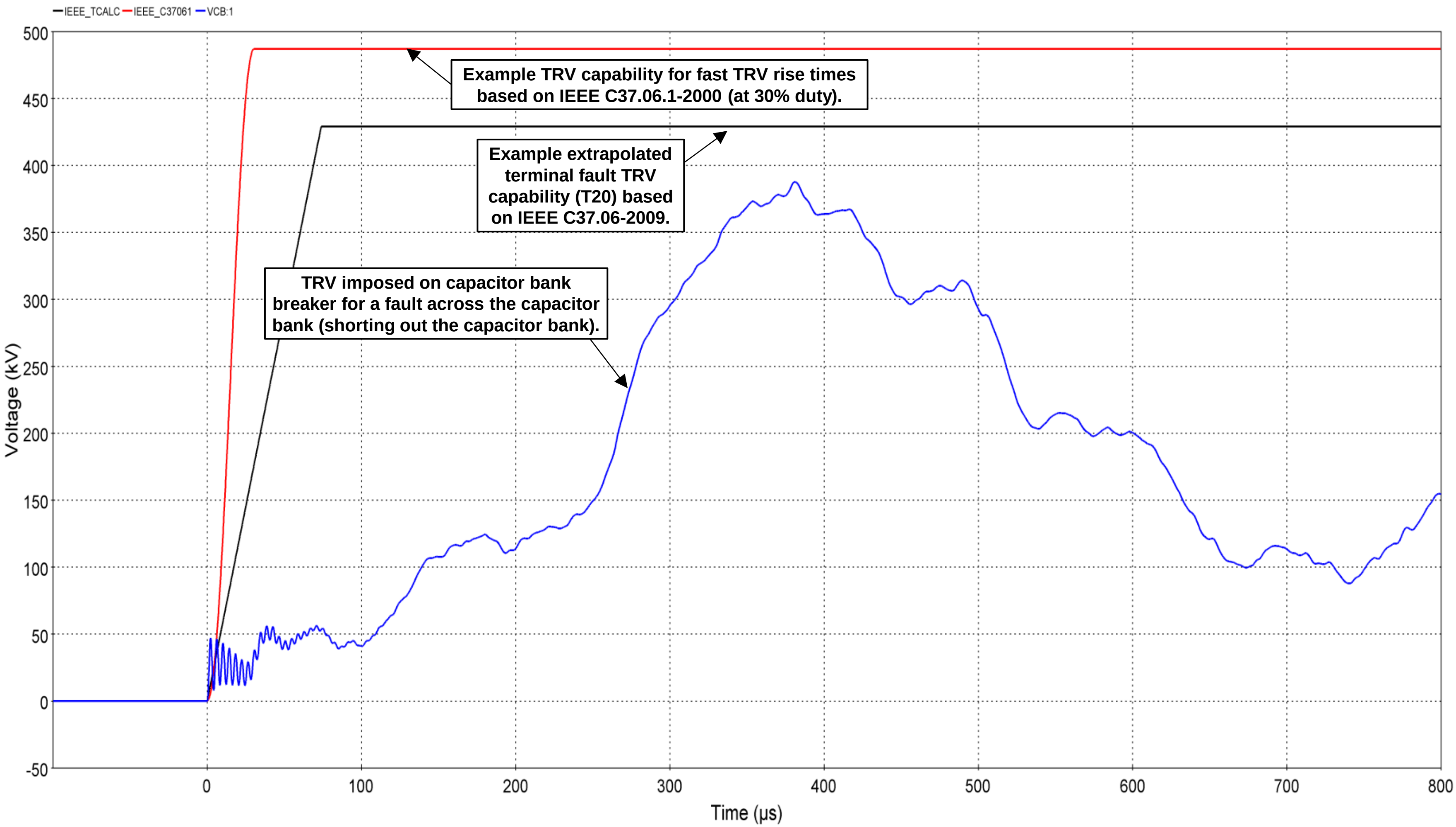


Example with circuit breaker after TLI



Example with TLI in the capacitor bank neutral

What Does the TRV Look Like (Reactor-Limited Fault)?



What are Mitigation Options for Transient Recovery Voltages?

Potential Solutions:

- **TRV Control Capacitors**: Reduce the frequency and the rate-of-rise of the TRV.
- **Eliminating the CLR**: Eliminates the reactor-limited fault TRV.
- **Synchronous-Open Control**: Helps for normal de-energizing but not the reactor-limited fault TRV.

Harmonics

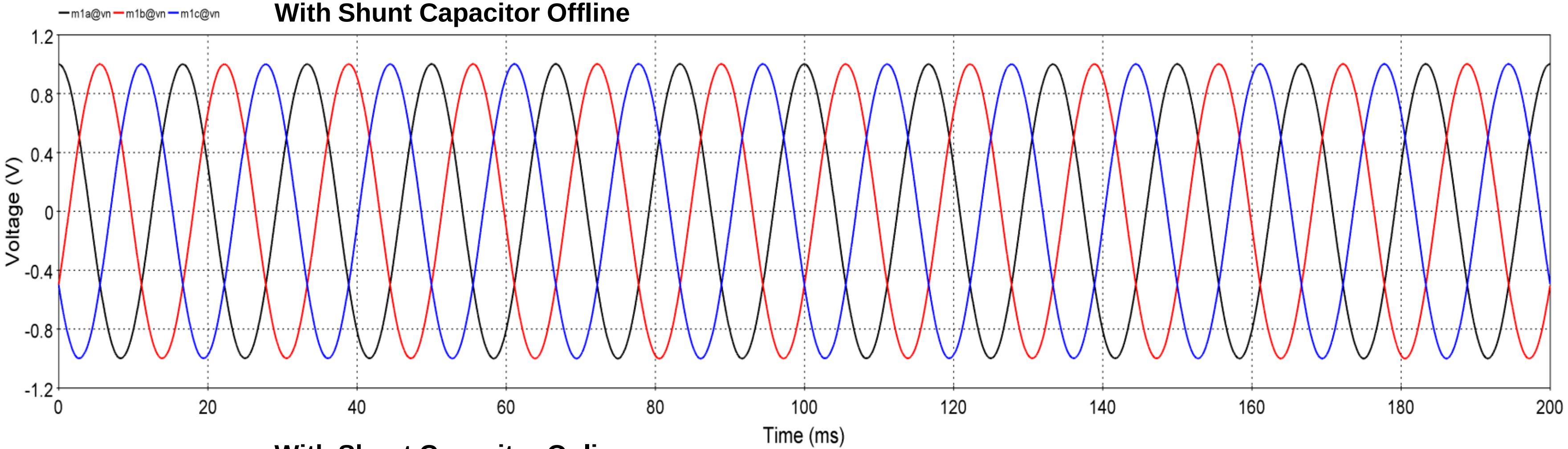
- Shunt capacitors do not generate harmonics, however they can create paths for harmonic currents to flow which could result in increased stress to the capacitor bank.

- Capacitor banks can shift the equivalent harmonic impedance as viewed from the bus which may result in higher harmonic distortions.

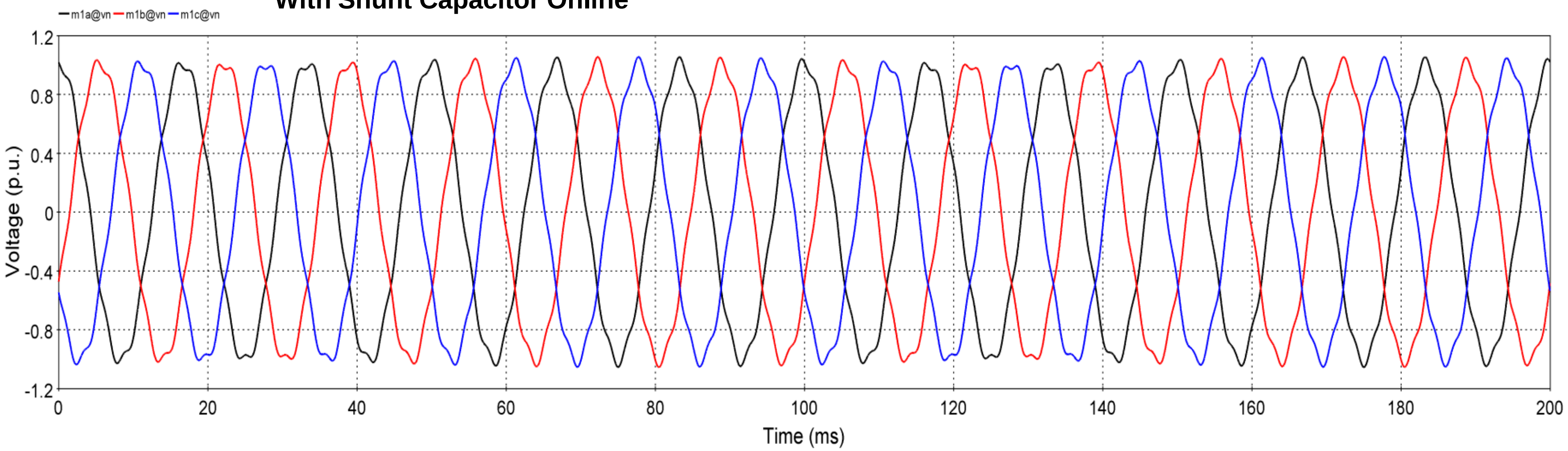
- If capacitors are tuned to harmonics existing in the system, excessive heating and damaged fuses/cans can occur.

What Does Harmonic Distortion Look Like?

With Shunt Capacitor Offline



With Shunt Capacitor Online



What are Mitigation Options for Harmonics?

Potential Solutions:

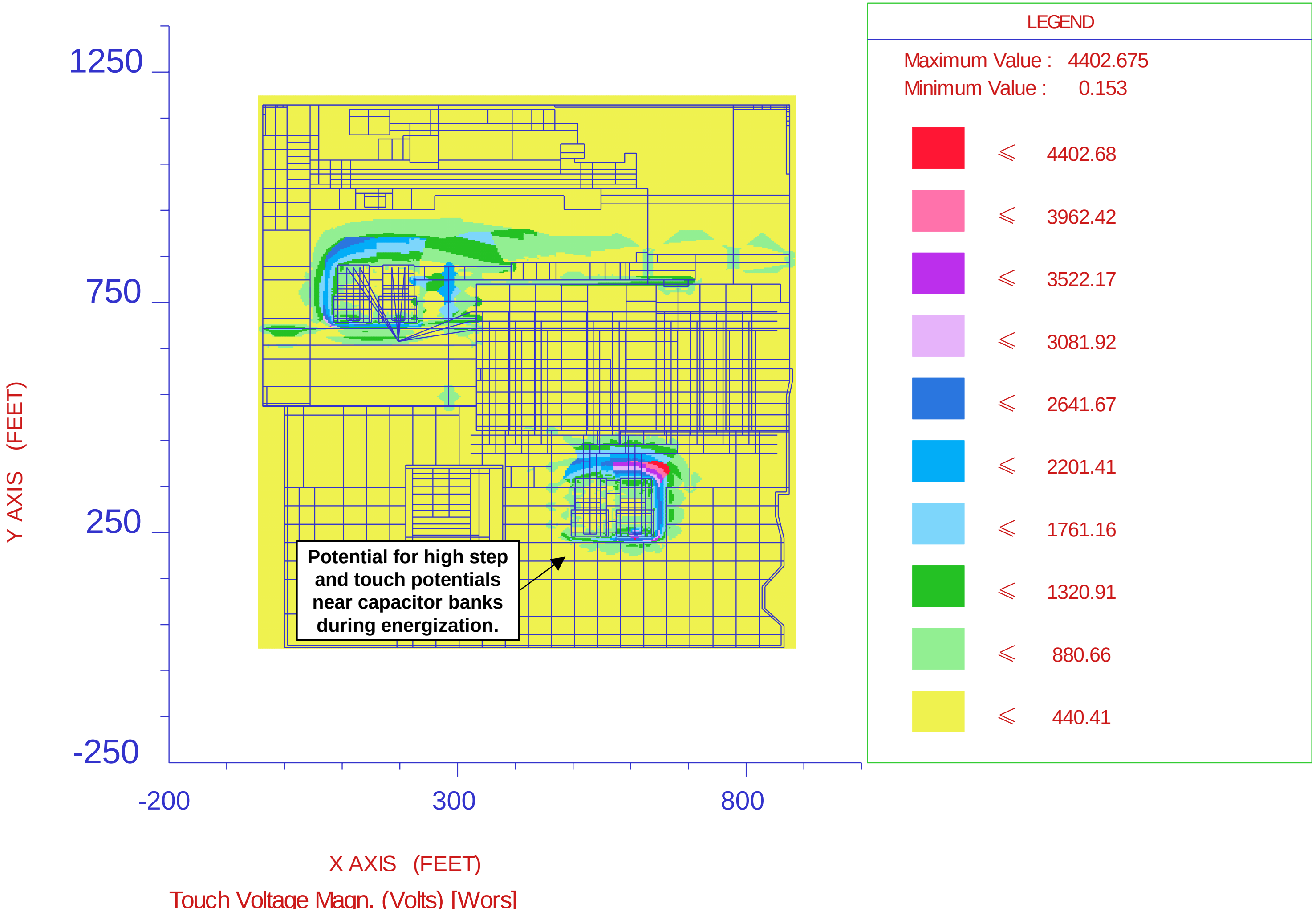
- **Modifying Size of Capacitor/Reactor**: De-tuning the capacitor bank from a specific harmonic.

- **Increasing Ratings**: Increase ratings to handle additional current and dielectric stress from harmonics.

Transient Ground Potential Rise (TGPR)

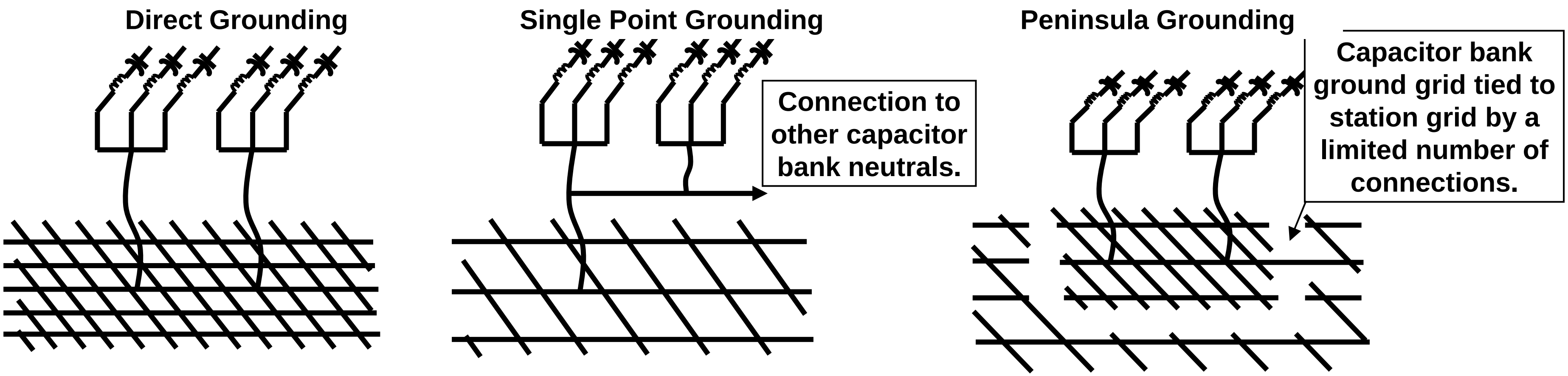
- When a capacitor bank is energized, the inrush current can flow through the ground grid resulting in transient ground potential ride which may lead to high step and touch voltages as well as induced voltage/current into control circuits.
- Substations ground grids are often designed and based on 60 Hz fault current calculations, and when capacitor banks are added to a substation the grounding system may need evaluated.
- Installing capacitor banks significant distances apart in a substation can exaggerate transient ground potential rises.

What Does Transient Ground Potential Rise Look Like?



What are Mitigation Options for TGPR?

Potential Solutions:



- **Current-limiting reactors, pre-insertion resistors/inductors, synchronous-close control**: Reducing inrush current will improve transient ground potential rise because there is less current injected into the grounding system.

- **Improved grounding**: Increasing the density of the ground grid near the capacitor banks for direct grounding, Increasing insulation level of neutral for single-point grounding, Isolating capacitor banks from the rest of the substation for peninsula grounding to avoid high touch voltages.

Shunt Reactor Bank Switching

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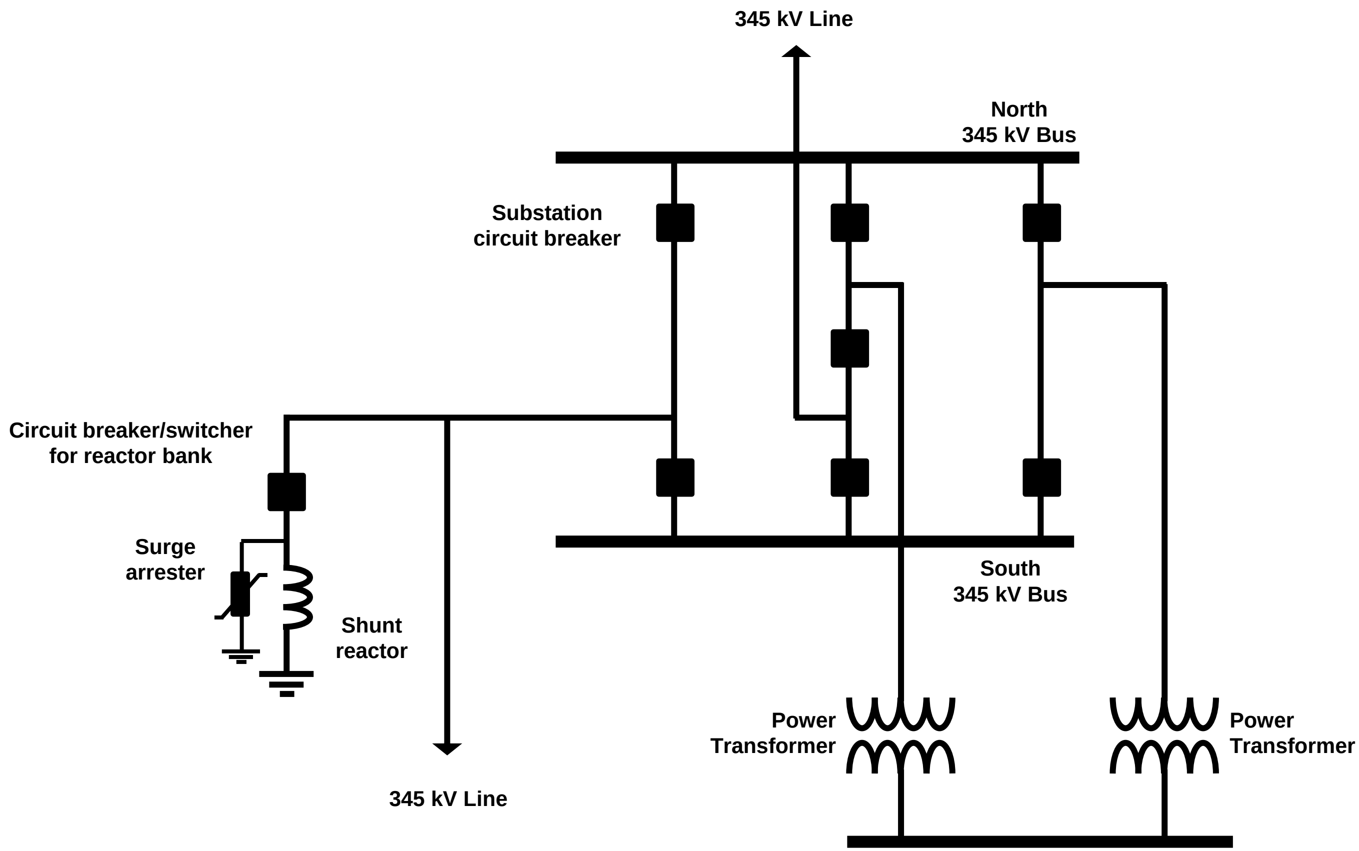
What is a Shunt Reactor Bank?

Why Do We Install Shunt Reactor Banks?

- Reducing Overvoltages
  - Often sized and located based on power flow/stability analysis
  - Installed at line/cable ends to account for charging current and reduce open-ended voltages

Example One-Line Diagram of Substation with a Shunt Reactor



Applicable Standards and Criteria

- C37.015: "IEEE Application Guide for Shunt Reactor Switching"
- C37.06: "IEEE Standard for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis-Preferred Ratings and Related Required Capabilities for Voltages Above 1000 V)"
- C37.06.1: "Guide for High-Voltage Circuit Breakers Rated on Symmetrical Current Basis Designated "Definite Purpose for Fast Transient Recovery Voltage Rise Times"
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- IEEE 1313.2: "IEEE Guide for the Application of Insulation Coordination"
- C62.22: "IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems"

- ***IEC 62271-110: "High-voltage switchgear and controlgear – Part 110: Inductive load switching"***

Potential Concerns for Installing a Shunt Reactor Bank

Inrush Current

- When a reactor bank is energized, an inrush current with a dc offset will flow through the reactor bank and anything in series (i.e., circuit breaker/switcher, buswork, etc.).

- Severity of the inrush current is proportional to the shunt reactor characteristics (saturated reactance) and the system strength at the shunt reactor.

- What are potential concerns for inrush current:
  - Circuit breaker/switcher stress
  - Relay mis-operation
  - Exciting resonance conditions and overvoltages

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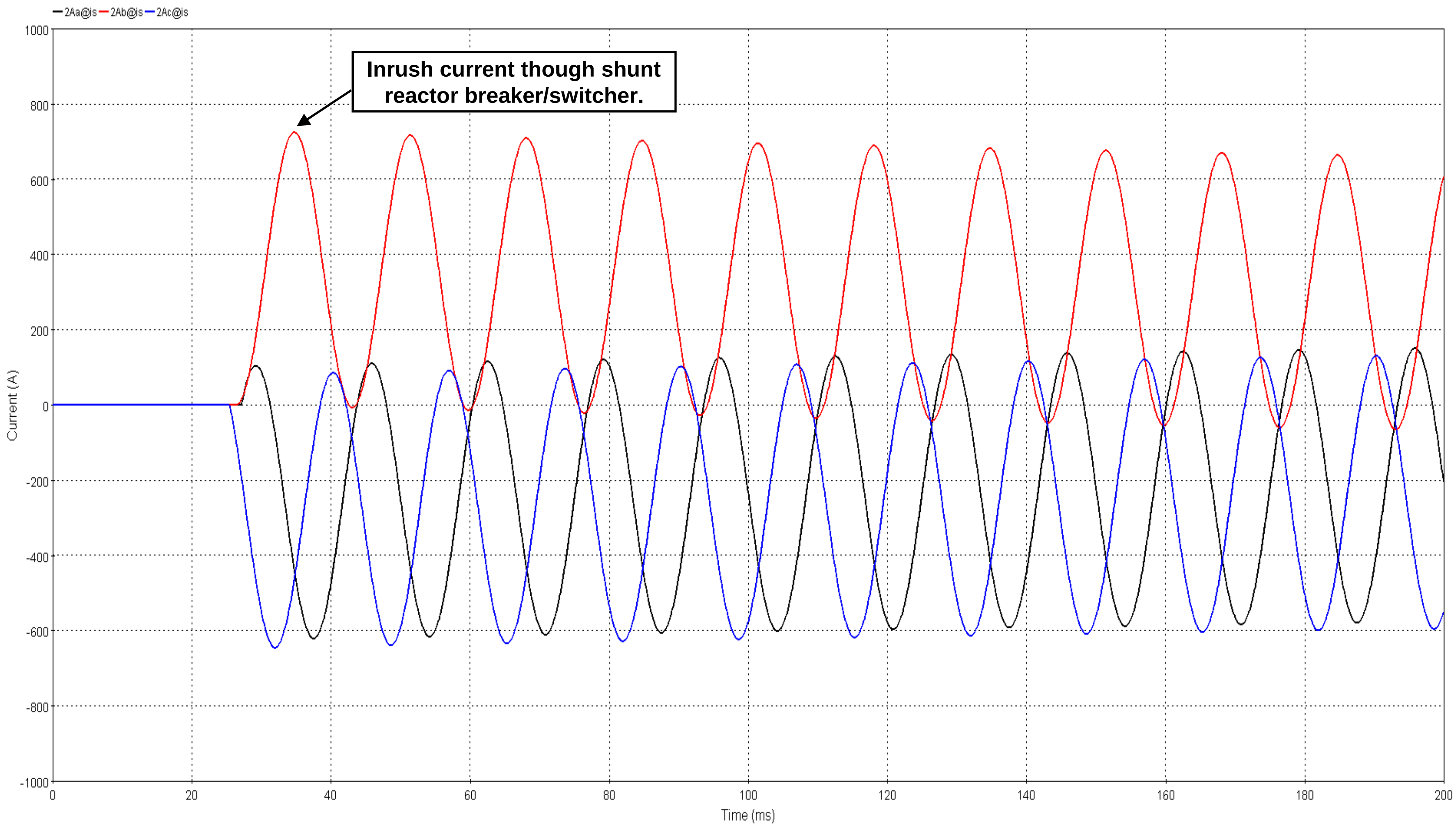
What Does Inrush Current Look Like?



What are Mitigation Options for Inrush Current?

Potential Solutions:

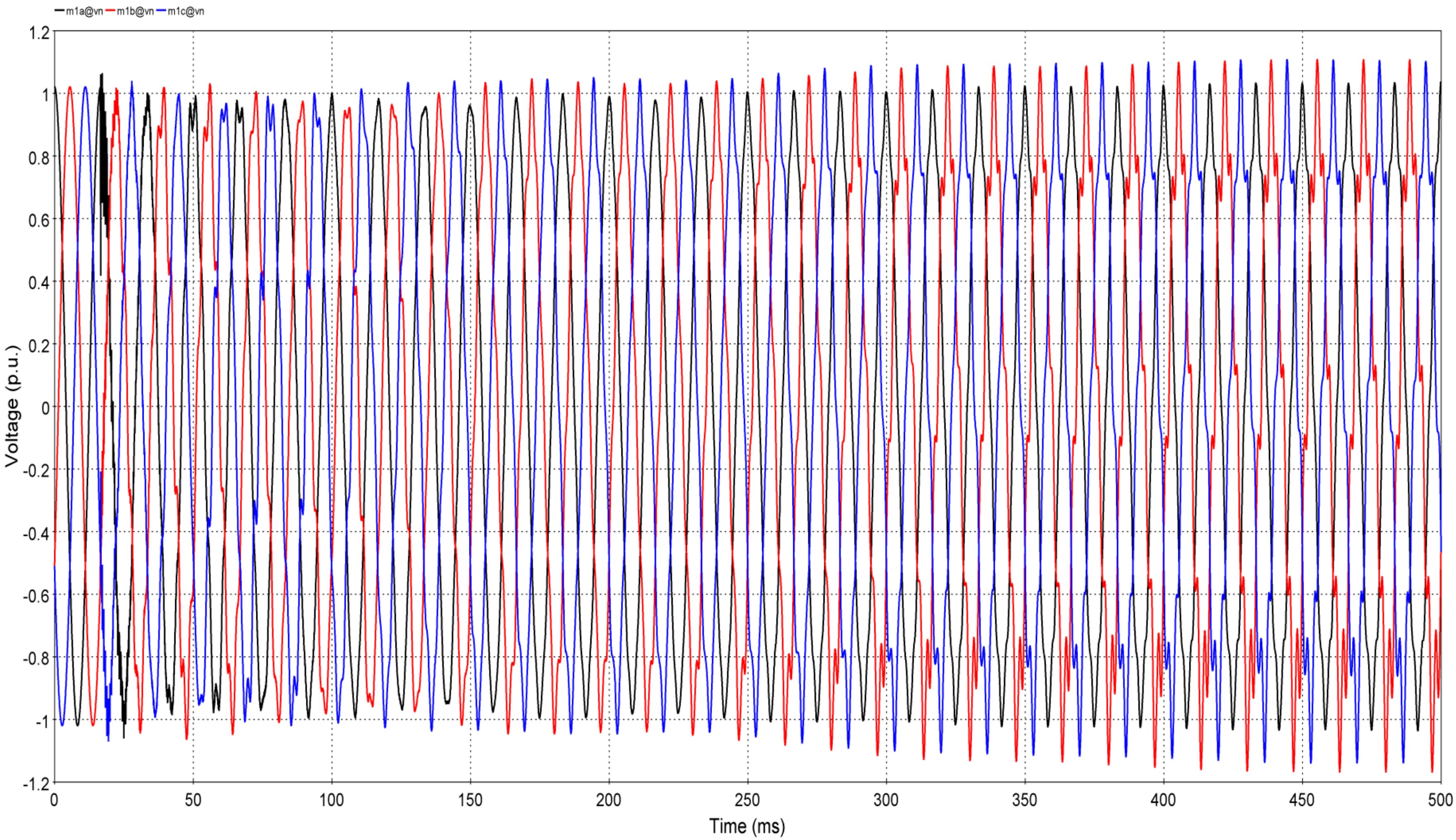
- **Pre-insertion resistors** lower the voltage dropped across the breaker/capacitor, therefore lower the peak but not frequency.
- **Synchronous-close control** lowers the voltage dropped across the breaker/capacitor, therefore lower the peak but not frequency. However, the added benefit of synchronous control is consistent (reduced) arcing times and less breaker wear.

Transient and Temporary Overvoltages

- When a reactor bank is energized the inrush current can excite transient or temporary voltages that can stress equipment insulation and potentially over-duty surge arresters.

- Voltage sags can result from the inrush current during energizing which may result in tripping of sensitive loads in severe cases.

What Do the Overvoltages Look Like?



What are Mitigation Options for Overvoltages?

Potential Solutions:

- **Pre-insertion resistors** lower the voltage dropped across the breaker/capacitor, therefore lower the peak but not frequency.
- **Synchronous-close control** lowers the voltage dropped across the breaker/capacitor, therefore lower the peak but not frequency. However, the added benefit of synchronous control is consistent (reduced) arcing times and less breaker wear.

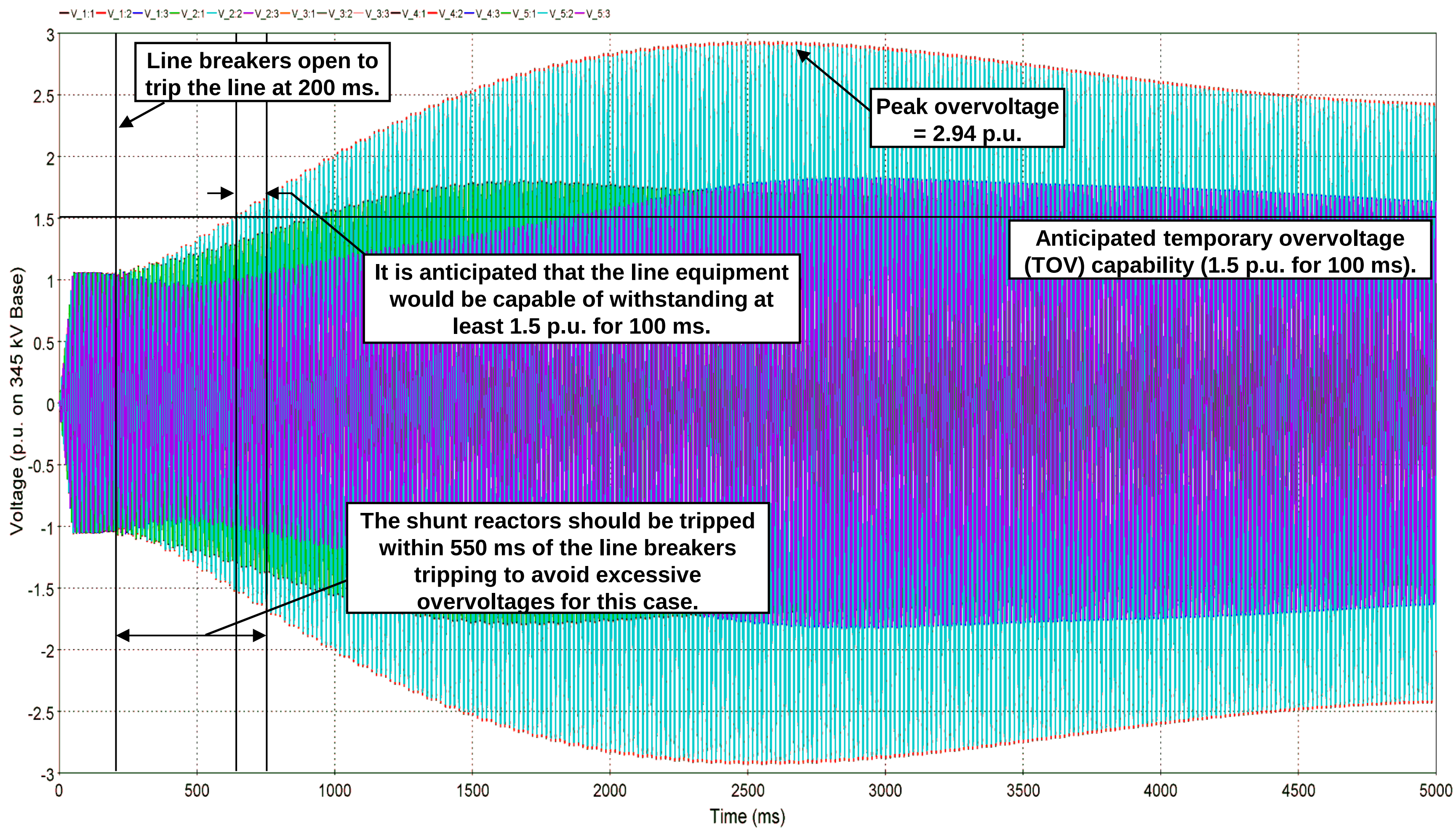
Resonance from Connected to De-Energized Lines

- When a reactor bank is connected to a de-energized line that runs parallel to an energized line, there is a potential for a resonance condition between the shunt reactor and the capacitance between the two lines that could cause high voltages on the de-energized line.

- The high voltages can cause concerns for working on the de-energized line, excessive duty on connected surge arresters, excessive duty on ground switches connected to the de-energized line.

- Note that placing the reactor on the bus can eliminate this concern, however then the shunt reactor cannot be used for controlling open-ended line voltages.

What Do the Resonance Overvoltages Look Like?



What are Mitigation Options for the Resonance?

Potential Solutions:

- **Tripping Reactors:** Removing the reactors from the line when the line is de-energized.
- **Modifying the Reactor Size:** Modifying the reactor size can de-tune the resonance condition.
- **Neutral Reactors**: Adding reactors to the neutral can be used to de-tune the resonance condition.

Transient Recovery Voltages from Normal De-Energizing

- When a reactor bank is de-energized the current flowing through the circuit breaker can be interrupted before a current zero (current chop) which can result in high transient recovery voltages imposed on the circuit breaker.
- If the circuit breaker contact parting is initiated during the re-ignition window of the circuit breaker, the current will be re-established after interruption at the first current zero as shown on the next slide.
- Where frequent operation of the shunt reactor occurs, repeated re-ignitions can result in excessive contact wear and potential circuit breaker failure.

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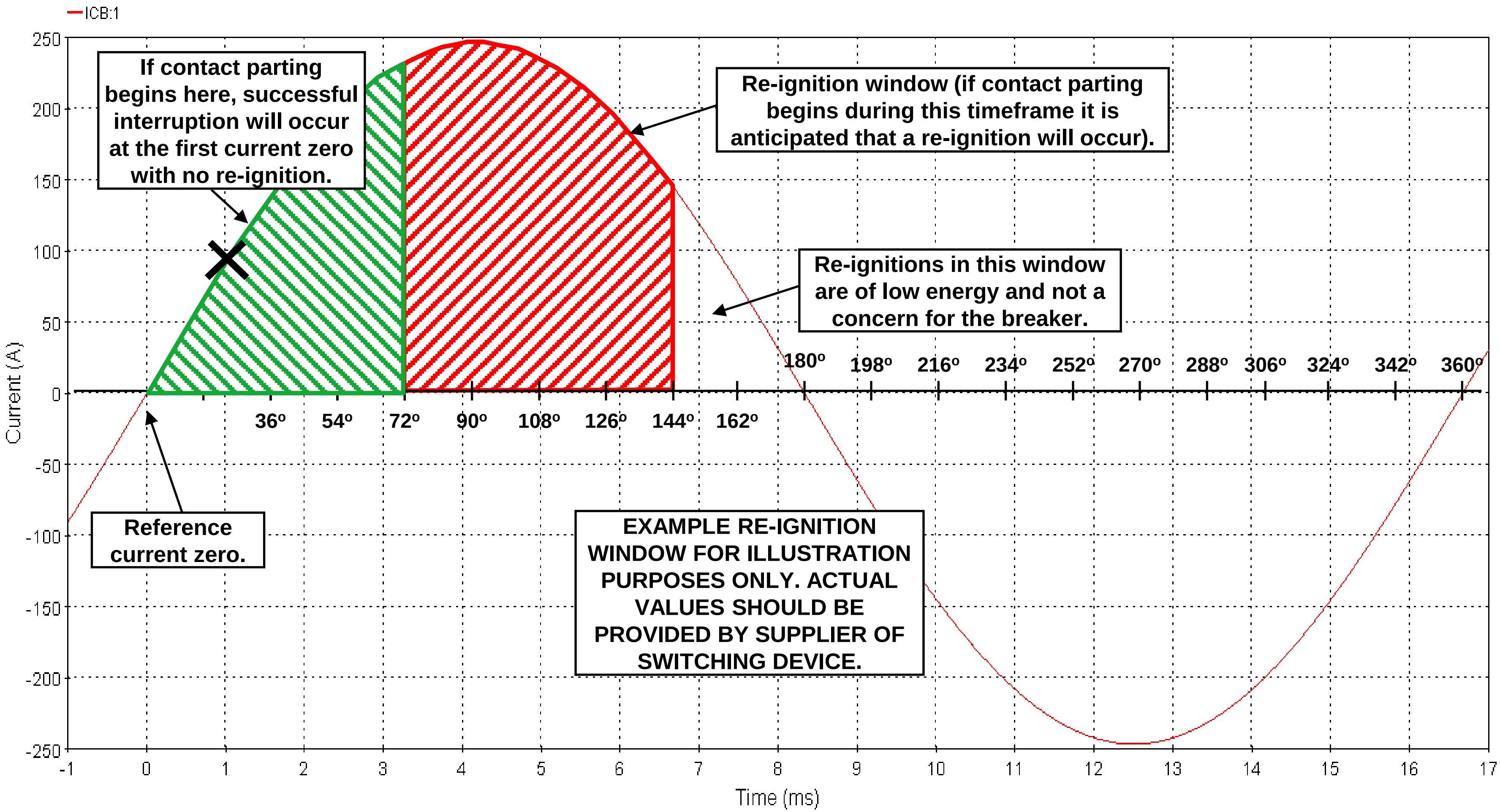
General Concept for Controlled Switching for Reactor Banks



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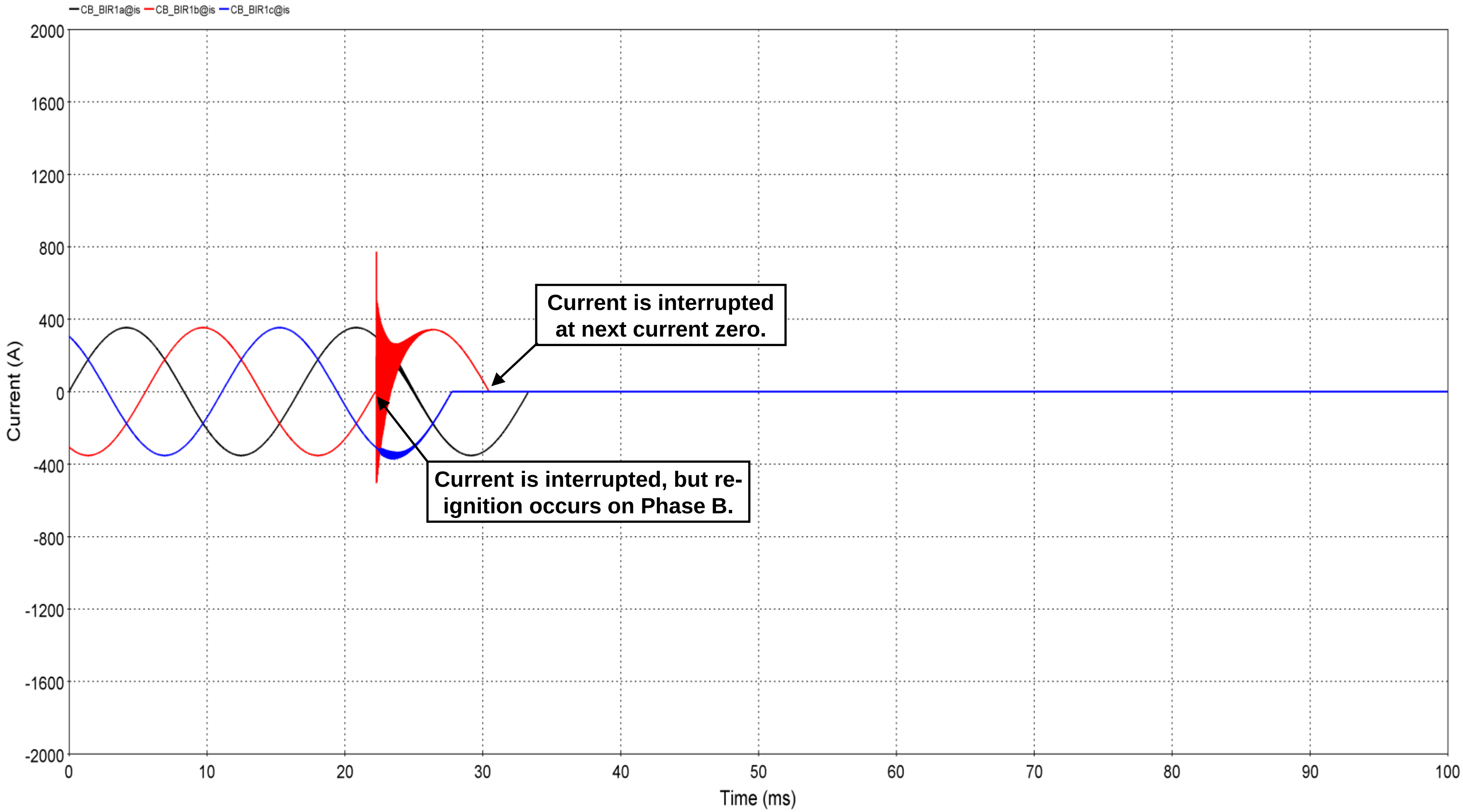
What Does a Re-Ignition Look Like?
Plot of the Current Through the Breaker



What Does a Re-Ignition Look Like?

Plot of the Voltage Across the Breaker

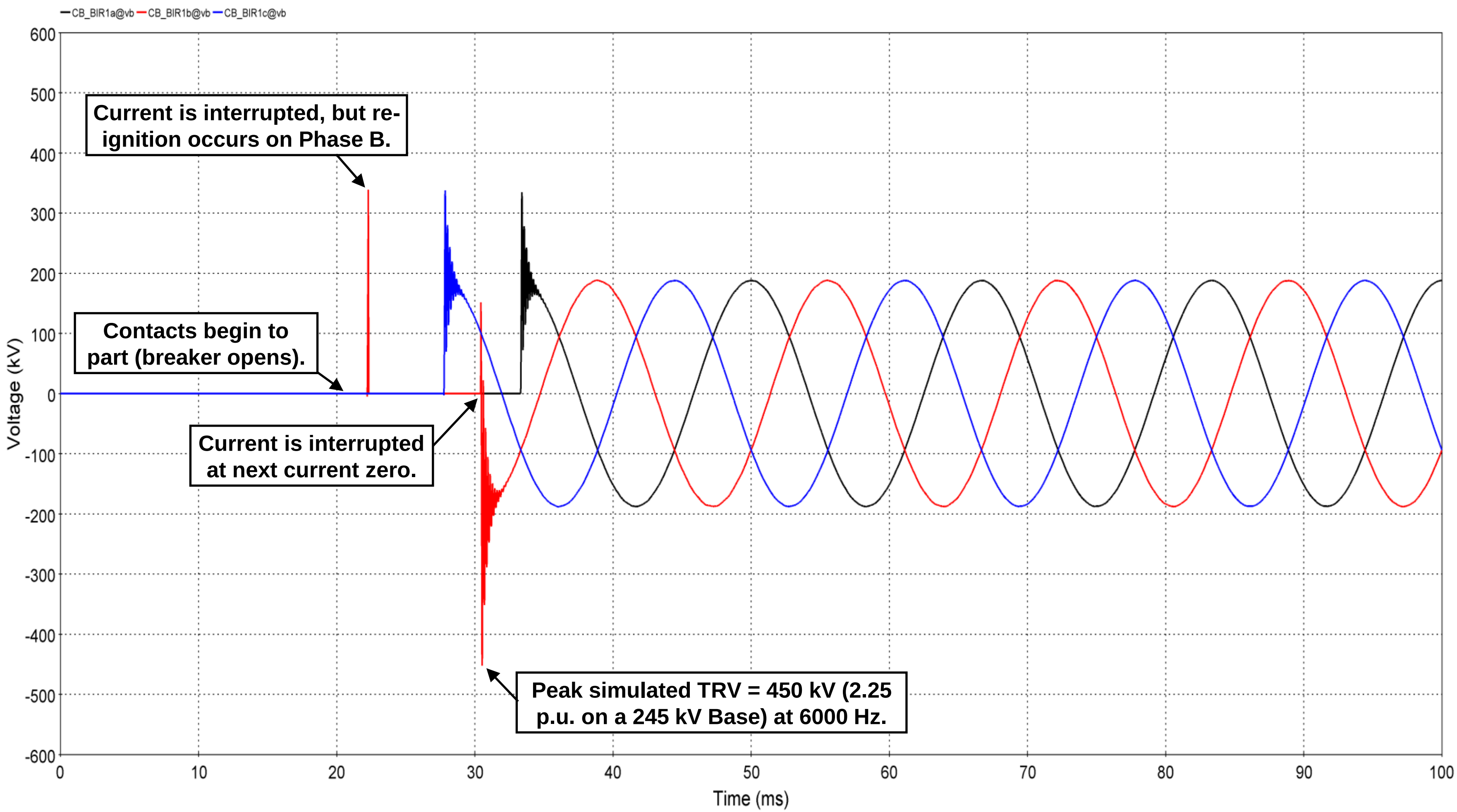
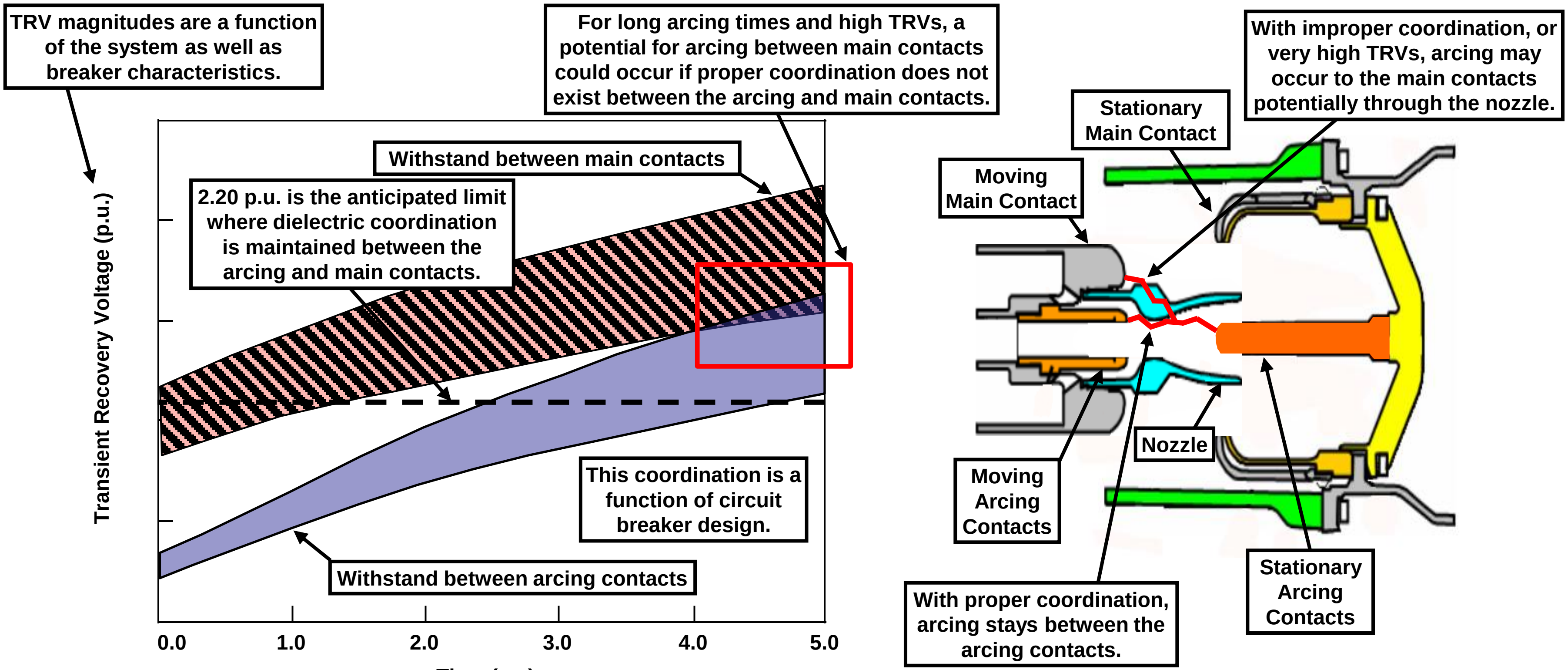


Illustration of Dielectric Coordination Between Arcing and Main Contacts During Switching



EXAMPLE COORDINATION CURVE FOR ILLUSTRATION PURPOSES ONLY. ACTUAL VALUES SHOULD BE PROVIDED BY SUPPLIER OF SWITCHING DEVICE.

What are Mitigation Options for the TRV?

Potential Solutions:

- **Synchronous-open control** controls the arcing time to control the chopping current and ensure contact parting time outside the re-ignition window to achieve successful interruption of the current at the first current zero reducing contact wear.

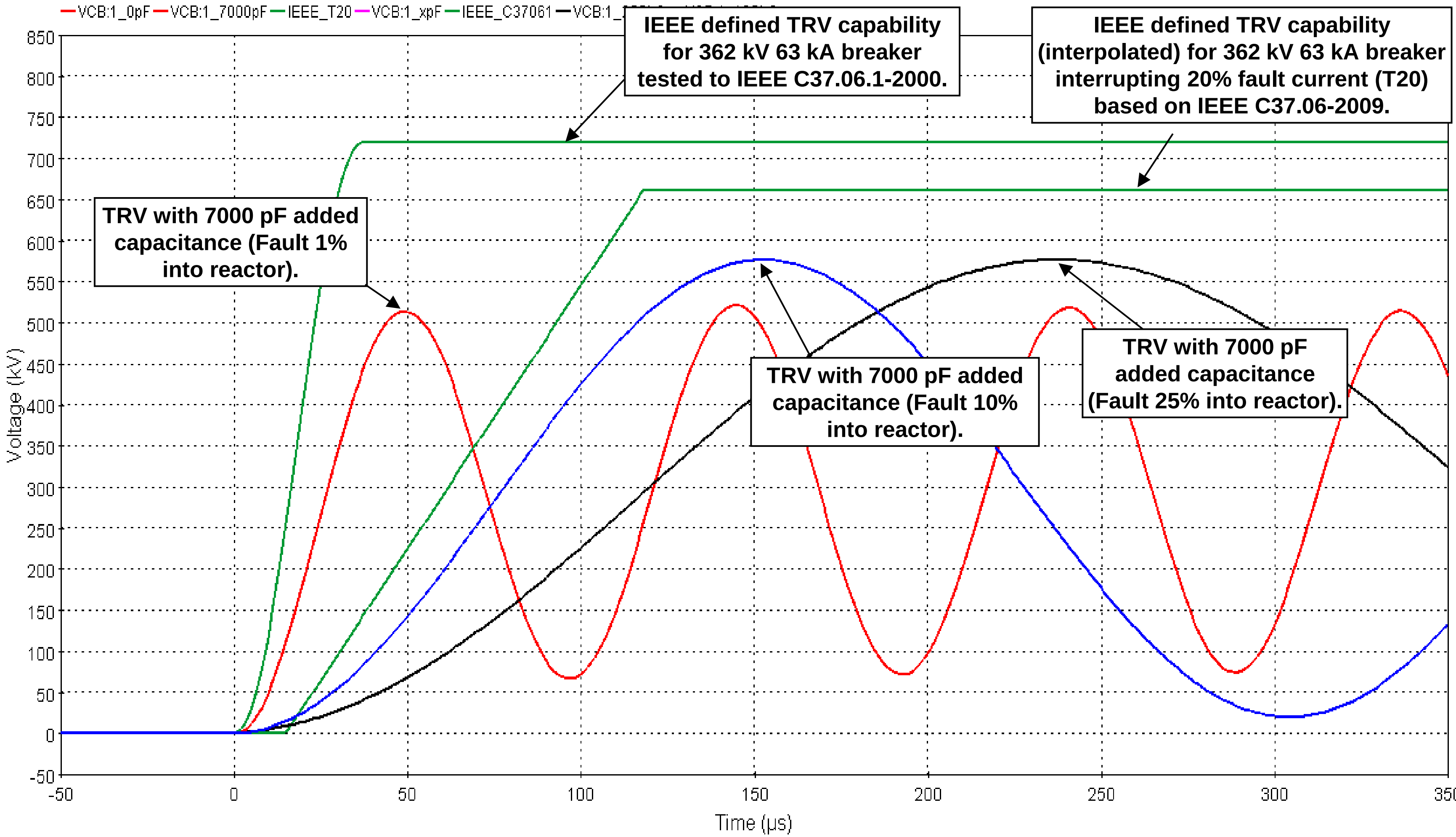
- **Surge arresters** mitigate the transient overvoltages after a re-ignition to reduce the transient recovery voltage imposed on the breaker so that it can interrupt the current at the second current zero (if a re-ignition occurs).

- **TRV control capacitors** can potentially help reduce the transient recovery voltage imposed on the circuit breaker.

Transient Recovery Voltages from Internal Reactor Fault

- When an internal fault occurs on a shunt reactor where a portion of the reactor windings are shorted out, a transient recovery voltage with a high rate-of-rise can be imposed on the circuit breaker interrupting the fault similar to the reactor-limited fault for a shunt capacitor bank.

What Do the Transient Recovery Voltages Look Like?



What are Mitigation Options for the TRV?

Potential Solutions:

- **TRV Control Capacitors**: TRV control capacitors can be added between the circuit breaker/switcher to reduce the rate-of-rise of the TRV.

Overall Summary

- Shunt Capacitor Bank Switching
  - Potential Concerns: Voltage Change, Inrush/Outrush, Overvoltages, TRV
  - Mitigation Solutions: Cap sizes, CLR, Sync-Control, Pre-Insertion Devices, Surge Arresters, TRV Control Capacitors

- Shunt Reactor Bank Switching
  - Potential Concerns: Inrush Currents, Overvoltages, TRV
  - Mitigation Solutions: Sync-Control, Pre-Insertion Devices, Surge Arresters, TRV Control Capacitors

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Questions/Discussion