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Evaluation of Transient Recovery Voltage Issues Associated with the Grand Avenue 115kV Bus Circuit Breakers

General Description of Transient Recovery Voltage (TRV) for High-Voltage Circuit Breakers

- Recovery voltage appears across the terminals of a pole of the circuit breaker
- The recovery voltage is considered in two consecutive time intervals:
  - One where the transient voltage exists
  - One where the power frequency voltage alone exists

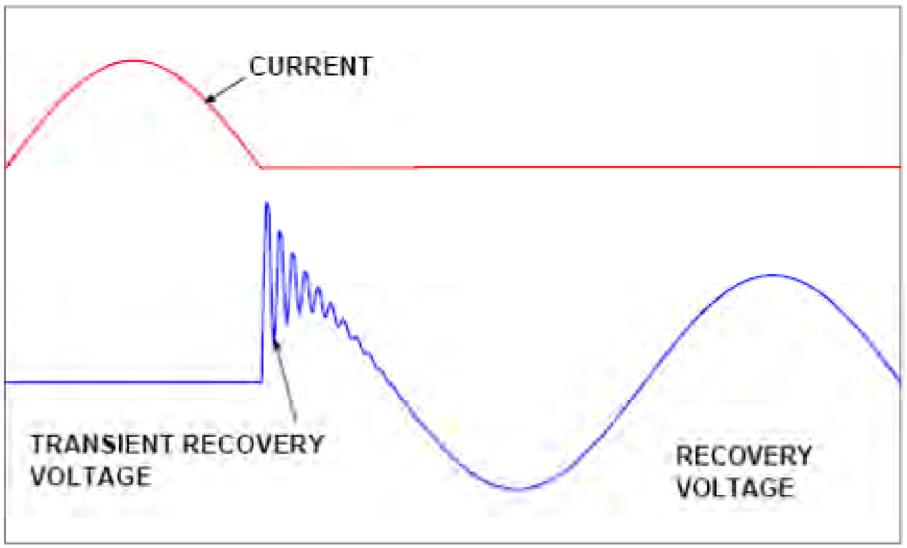


Figure 1 Current, TRV and Recovery Voltage

General Description of Transient Recovery Voltage (TRV) for High-Voltage Circuit Breakers

- During the interruption process several things happen in an extremely short period of time:
  - As the contacts of the circuit breaker part, the arc loses conductivity as the instantaneous current approaches zero.
  - Current stops flowing within a few microseconds.
  - The power system response is what generates the TRV.
  - The difference in the power system response voltage from the source side to the load side of the circuit breaker is the TRV.

General Description of Transient Recovery Voltage (TRV) for High-Voltage Circuit Breakers

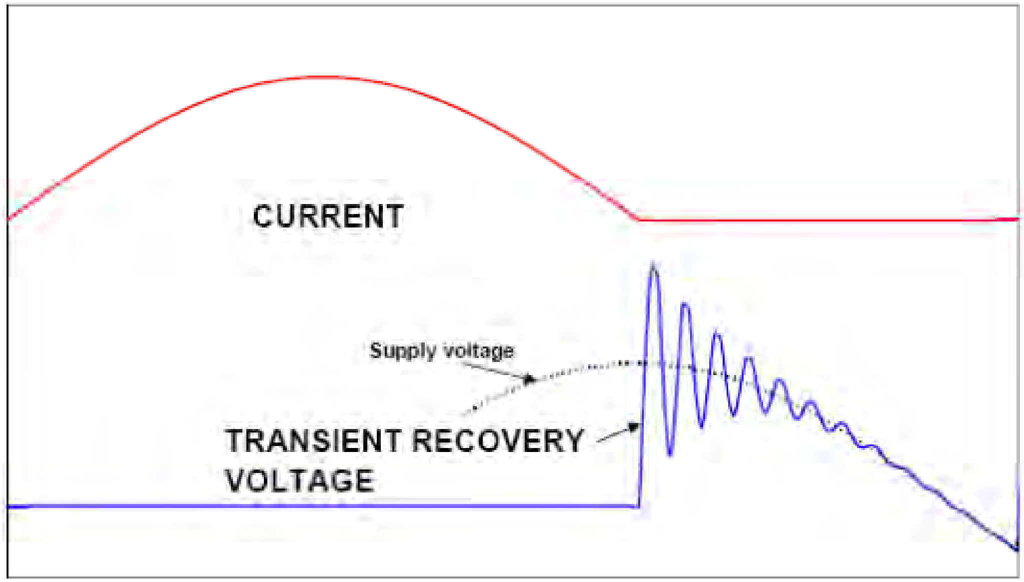


Figure 2 Current and TRV waveforms during interruption of inductive current

When interrupting a fault at the circuit breaker terminals the supply voltage at the current zero is maximum and the supply side terminal reaches the supply voltage in a transient process called transient recovery voltage.

The TRV frequency is $\dfrac{1}{2\pi\sqrt{LC}}$, with L = short-circuit inductance, C = supply capacitance.

General Description of Transient Recovery Voltage (TRV) for High-Voltage Circuit Breakers

So……….What's the problem???

- During the tens of microseconds around current zero, the evolution of arc resistance is a function of the **energy balance in the arc.**

  - Without getting into plasma physics………that is the difference over time between the power input and the power loss due to gas cooling in a gas circuit breaker.

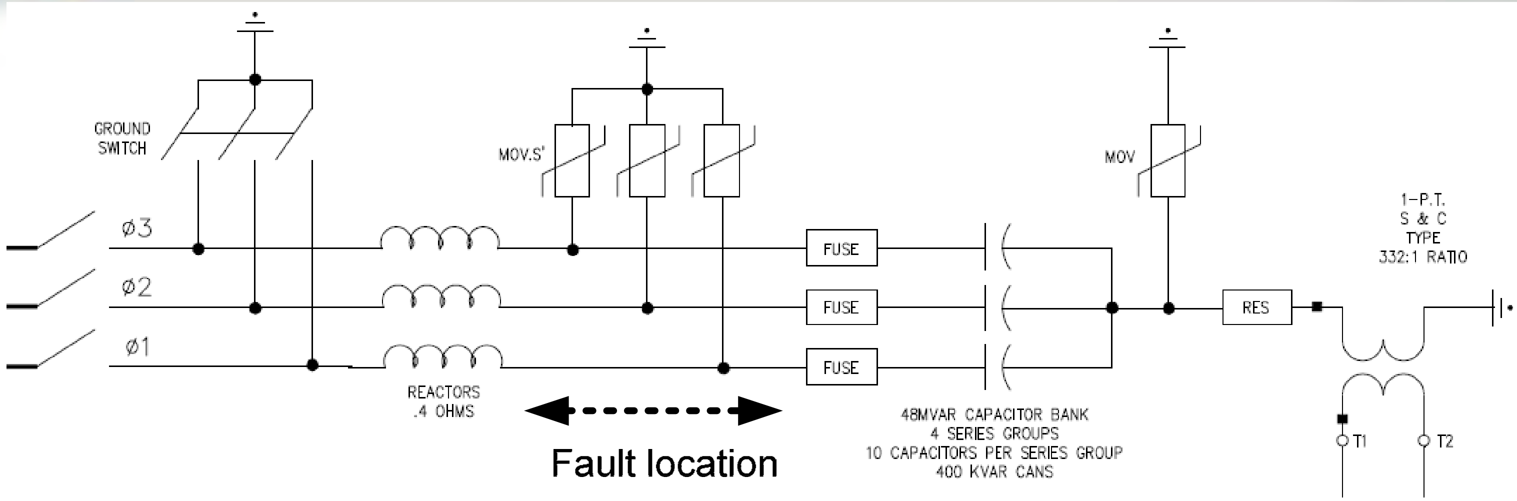
  - If the gas blast is not sufficient, the arc resistance stops increasing after current zero, it decreases to a low value, as a consequence the interval between contacts becomes conductive again and we have……

Thermal Restrike !

Introduction

- Recent failures of transmission capacitor banks documented at the Hydro One Richview Transformer Station.
- The UI transmission network consists of 115-kV overhead lines and underground cables. The network employs two switched capacitor banks at East Shore Substation for voltage and reactive power support. These capacitor banks are equipped with current limiting reactors installed on the source side of the capacitor terminals.
- Based on the study, it was determined that existing 123kV, 50 kA capacitor breakers do not possess sufficient TRV capabilities for clearing a three-phase ungrounded fault at the source-side terminals of the energized capacitor bank.

Arrangement of the Transmission Capacitor Banks



- There exists a step jump in the TRV profile immediately following the breaker opening.
- This phenomenon is contributed by the presence of the inrush current limiting reactors between the breaker terminals and the fault location.

Evaluation and Solution Methods

- TRV withstand capabilities of a circuit breaker are evaluated using standard practices described in IEEE Std. C37.011-2005
- The most severe system TRVs tend to occur across the first pole to open when the circuit breaker interrupts a symmetrical three-phase ungrounded fault at or near the breaker terminals during which the system voltage is at maximum.
- When a close-in line or bus fault occurs near an energized capacitor bank, capacitive current will flow from the bank to the fault location.
- Circuit breakers will fail to close or open when inrush or outrush currents exceed the capacitive current switching duties of the breakers.
- Current limiting reactors are usually required to limit the magnitude and frequency of the capacitive switching current to an acceptable level.

Evaluation and Solution Methods

The following criteria must be satisfied:

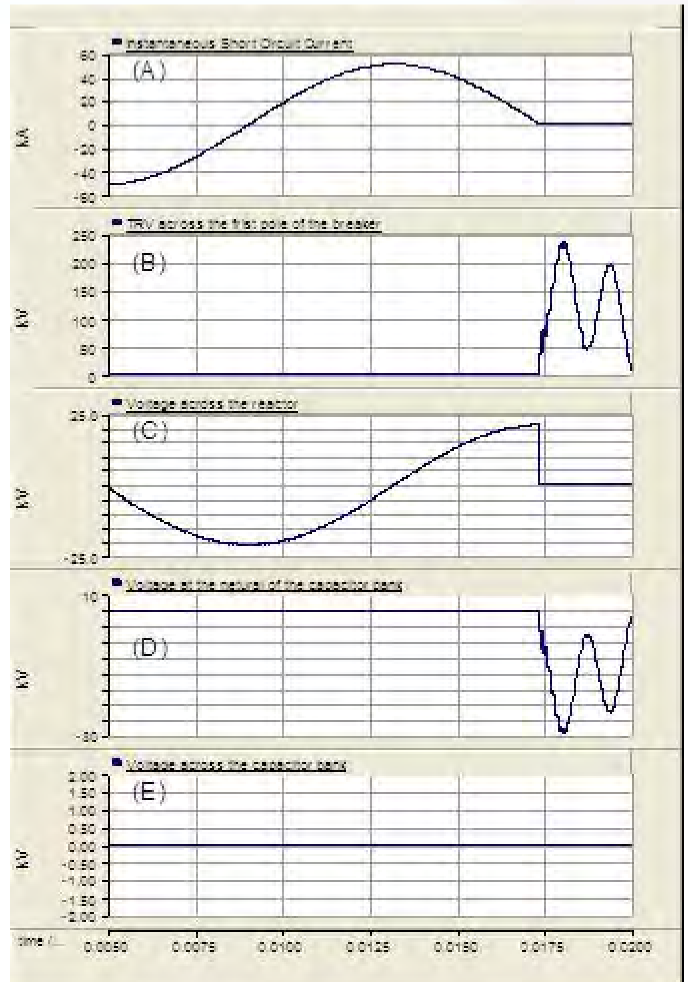
- The capacitor bank circuit breakers must be able to withstand transient recovery voltage resulting from a three-phase ungrounded fault at the source-side of the capacitor terminals.
- The capacitor circuit switchers or breakers used to energize and de-energize capacitor banks must be able to withstand inrush capacitive switching and momentary currents during back-to-back capacitor switching.
- The line breakers must be able to withstand outrush capacitive switching and momentary currents during close-in faults.

Time Domain Model of the Electrical Circuit

- A time-domain equivalent circuit covering the entire New Haven 115-kV system including its overhead lines and underground cables was developed.
- The overhead lines are represented with a Bergeron line model based on a distributed LC parameter travelling-wave line model with a lumped resistance.
- The underground cable model is developed based on the cable cross-section and laying-formation data, as well as cable electrical properties of conductors and insulators (resistivity, permittivity, and permeability).
- The internal apparatus capacitances on the source side of the circuit breaker must be taken into account because they influence the rate of rise of the transient recovery voltage.

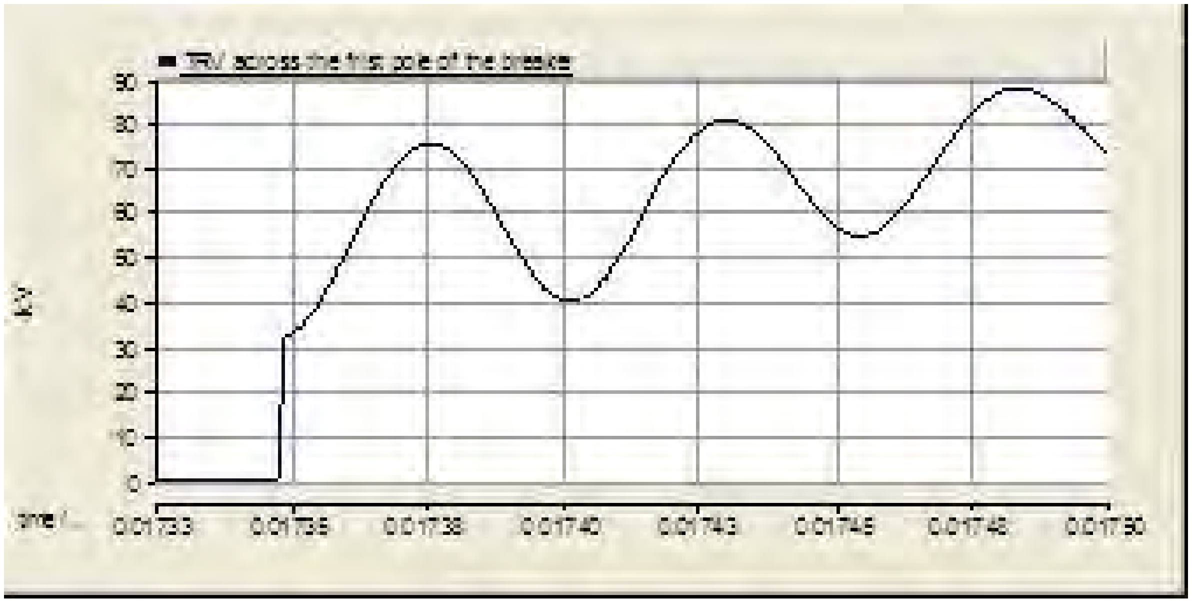
TRV Analysis for the Existing Condition

- TRV capabilities of existing capacitor breakers were evaluated for the most conservative conditions.
- A three-phase ungrounded fault was applied at the source side of the energized capacitor and the other capacitor was offline.



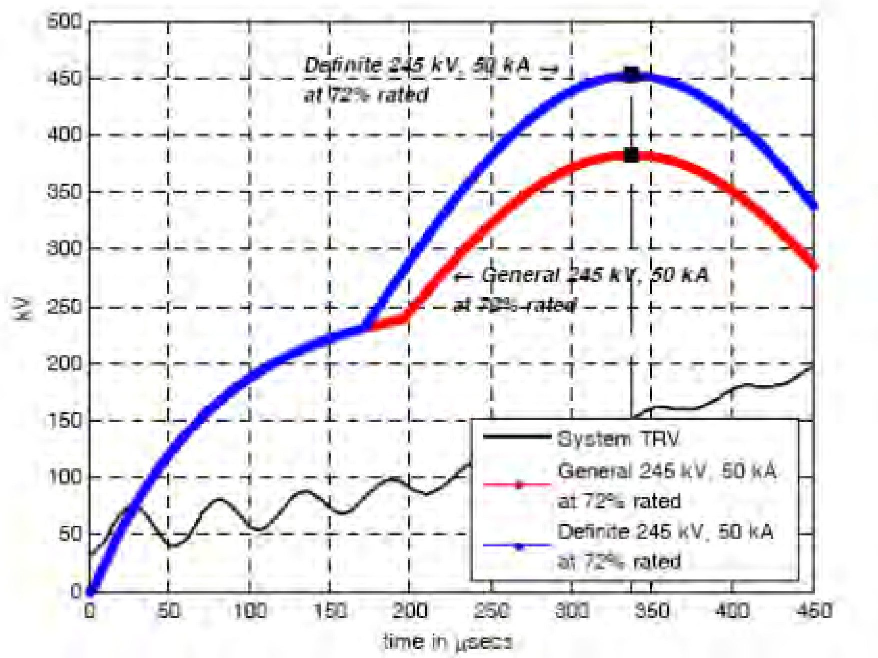
TRV Analysis for the Existing Condition

- The first 150 µS of the TRV profile.
- The sudden step jump can be clearly seen near the point of origin of the plot.



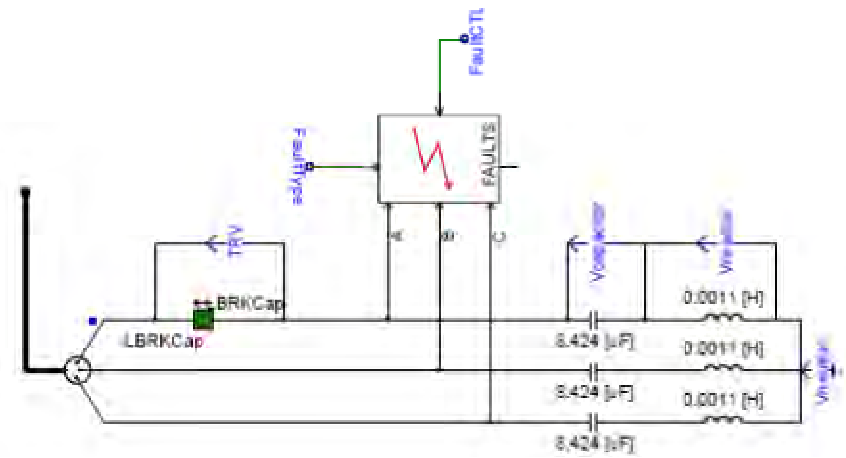
TRV Analysis for the Existing Condition

Comparison between the prospective system TRV associated with the capacitor breaker and the related TRV capability of a general purpose breaker at 71% of interrupting rating.



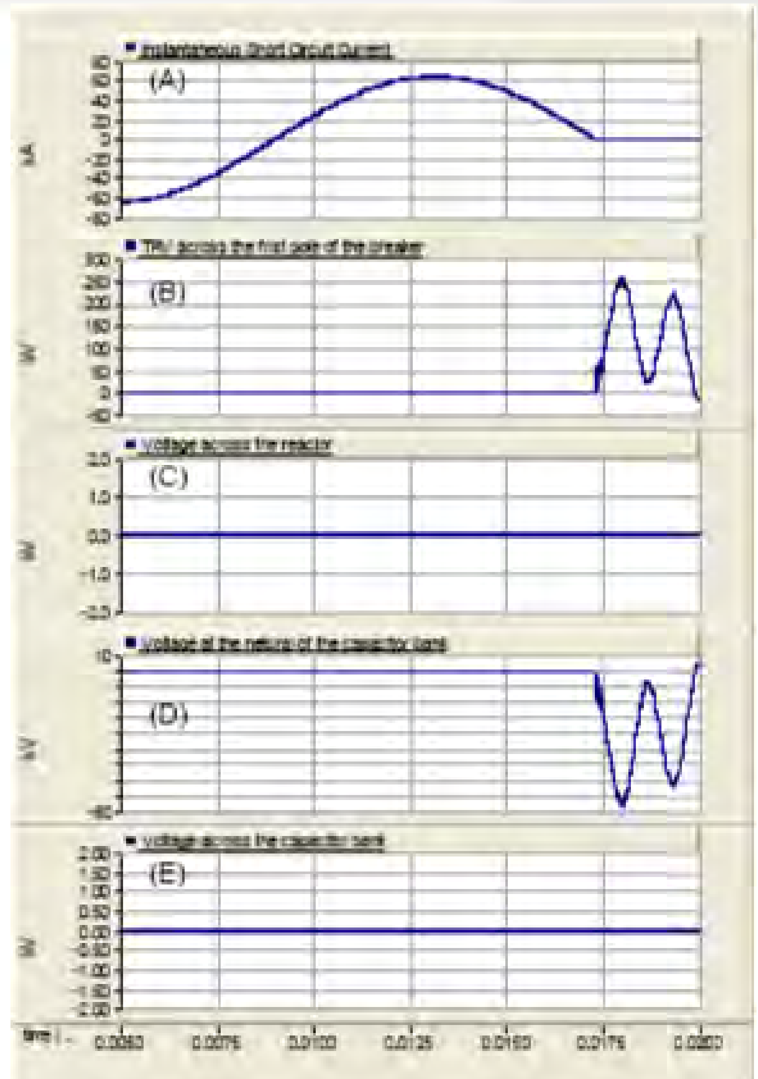
Solution to the Initial Step Change in TRV

- A sound engineering solution to this problem is to relocate these reactors to the neutral side of the capacitor bank.
- With this solution, an appropriately sized reactor for each phase can be used for current limiting purposes without causing an initial step change in the system TRV. Note that this solution alone will not reduce the peak of the TRV profile.



Solution to the Initial Step Change in TRV

- The voltage step change between before and after the first pole opening is negligible. For this reason, the system TRV does not experience an initial step jump immediately after the first pole opening.
- The peak TRV exceeds the breaker withstand capability; however, the initial step jump in the system TRV is clearly eliminated.



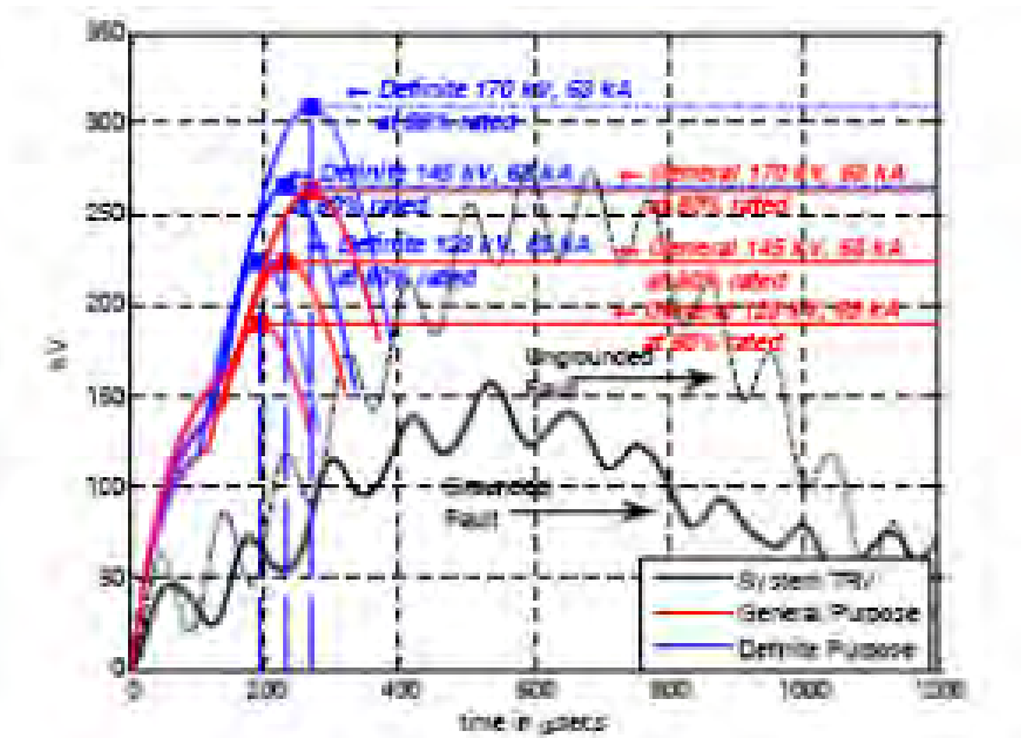
Methods to Reduce the Rate of Rise and Peak TRV

There are three basic approaches to reduce the rate of rise and the peak value of the transient recovery voltage:

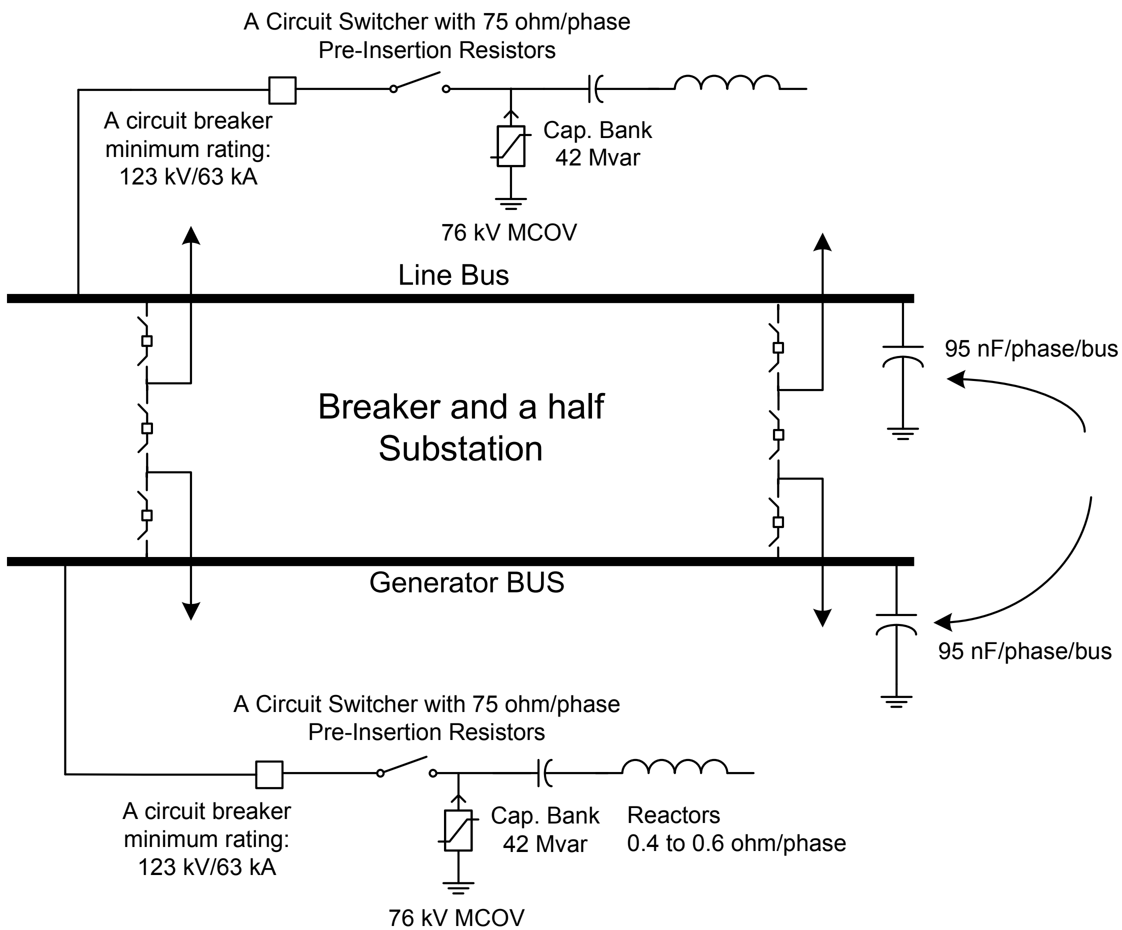
- Approach 1. Provide additional capacitances to the source side of the capacitor circuit breakers without modifying the configuration of existing capacitor banks. Additional capacitances can be in the form of bushing capacitances, capacitive voltage transformers, and capacitance banks.
- Approach 2: Modify the existing capacitor configuration in such a way to reduce the rate of rise and peak value of the system TRV. This approach includes replacing existing capacitor breakers with those having higher TRV duties and providing an intentional ground to the neutral of the capacitor bank configuration.
- Approach 3: Combine the above two approaches.

Methods to Reduce the Rate of Rise and Peak TRV

- These three approaches were analyzed for three-phase grounded and ungrounded faults, neutral reactors grounded and ungrounded, different values of bushing capacitances, and different circuit breaker ratings.



Recommended Capacitor Configuration



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Paper on Methods to Reduce the Rate of Rise and Peak TRV

Mitigation of Transient Recovery Voltage Issues Associated with Transmission Capacitor Banks

G. W. Becker, *Senior Member*, M. F McGranaghan, *Member, IEEE* S. Santoso, Senior Member *IEEE* and M. Waclawiak, *Member, IEEE*

***Abstract*—The failure of several transmission capacitor banks prompted The United Illuminating Company to perform an engineering study to evaluate the transient recovery voltage capabilities of existing 123-kV, oil-filled capacitor bank circuit breakers at the East Shore 115-kV substation. The study determined if the transient recovery voltage capability of existing bus and capacitor bank circuit breakers is sufficient for the present system configuration. Furthermore, the study determined the required design and application changes related to the circuit breakers and capacitor bank component equipment, required to ensure that the bus and capacitor bank circuit breaker transient recovery voltage capabilities are not exceeded. The study recommended a future capacitor bank configuration to mitigate transient recovery voltage issues. The results of the study also lead to an expansion of the study area to include an adjacent substation, Grand Avenue Substation, due to concerns about the required transient recovery voltage capabilities of new gas-insulated switchgear to be installed.**

***Index Terms*—Transient Recovery Voltage (TRV), pre-insertion (closing) resistors, three phase grounded fault, three phase ungrounded fault, re-strike, inrush current, outrush current, reactor, circuit breaker, circuit switcher, rate of rise of recovery voltage (RRRV).**

I. Introduction

Recent failures of transmission capacitor banks documented in [1-3] prompted The United Illuminating Company (UI) to evaluate the transient recovery capabilities of existing bus and capacitor breakers. The UI transmission network consists of 115-kV overhead lines and underground cables. The network employs switched capacitor banks for voltage and reactive power support. These capacitor banks are equipped with current limiting reactors installed on the source side of the capacitor terminals.

The objective of this paper is to present key approaches and findings of our on-going studies to evaluate the transient recovery voltage (TRV) capabilities of existing capacitor and bus breakers. In this paper, we focus on capacitor breakers at the East Shore 115-kV substation. The study determined the required design and application changes related to the circuit breakers and capacitor bank component equipment required to ensure that the capacitor bank breaker TRV capabilities are not exceeded.

This work is the result of a joint study involving The United Illuminating Company and The Electric Power Research Institute.

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Based on the study, it was determined that existing 245 kV, 50 kA capacitor breakers do not possess sufficient TRV capabilities for clearing a three-phase ungrounded fault at the source-side terminals of the energized capacitor bank. There exists a step jump in the TRV profile immediately following the breaker opening. This phenomenon is contributed by the presence of the inrush current limiting reactors between the breaker terminals and the fault location. As a practical permanent solution to this problem, current limiting reactors are relocated to the neutral side of capacitor terminals. Additional capacitances of 95 nF/phase/bus or larger, in the form of two 47.5-nF three-phase sets of CVTs, at the bus side of the capacitor bank circuit breakers are also recommended to further reduced the rate of rise of the recovery voltage.

II. Arrangement of Transmission Capacitor Banks

The East Shore 115-kV substation is a breaker-and-a-half switching station with two main buses identified as Generator and Line Buses. The New Haven Harbor Generating Station is connected to the Generator Bus through a 475 MVA, 22/115 kV delta wye-grounded transformer. Under a normal operation condition, all breakers in the substation are closed and both buses are energized. The substation has a total of two 42 Mvar three-phase capacitor banks, one connected to each bus. SF6 circuit breakers are used to energize and de-energize the capacitor banks. Each 42 Mvar capacitor bank is equipped with 0.4 ohm/phase reactors to limit the inrush current during a back-to-back energizing and the outrush current during a close-in fault. In addition, the capacitor configuration is also equipped with MOV arresters to reduce transient overvoltages. The inrush current limiting reactors are installed at the source side of the capacitor bank. Each capacitor bank is connected in an ungrounded-wye configuration. Figure 1 illustrates a capacitor bank arrangement in the East Shore 115-kV substation.

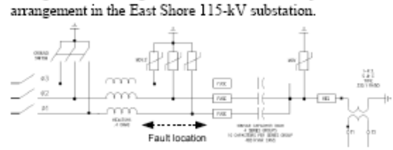


Fig. 1 – A 42 Mvar three-phase capacitor bank at a 115-kV Bus

The East Shore 115-kV capacitor configuration is similar

General Description of Transient Recovery Voltage (TRV) for High-Voltage Circuit Breakers

While three-phase ungrounded faults produce the highest TRV peaks, the probability of their occurrence is very low. Therefore, as described in ANSI/IEEE Std C37.04, the TRV ratings are based on three-phase grounded faults with the TRV peaks established based on the grounding arrangements prevalent at the respective system voltages.

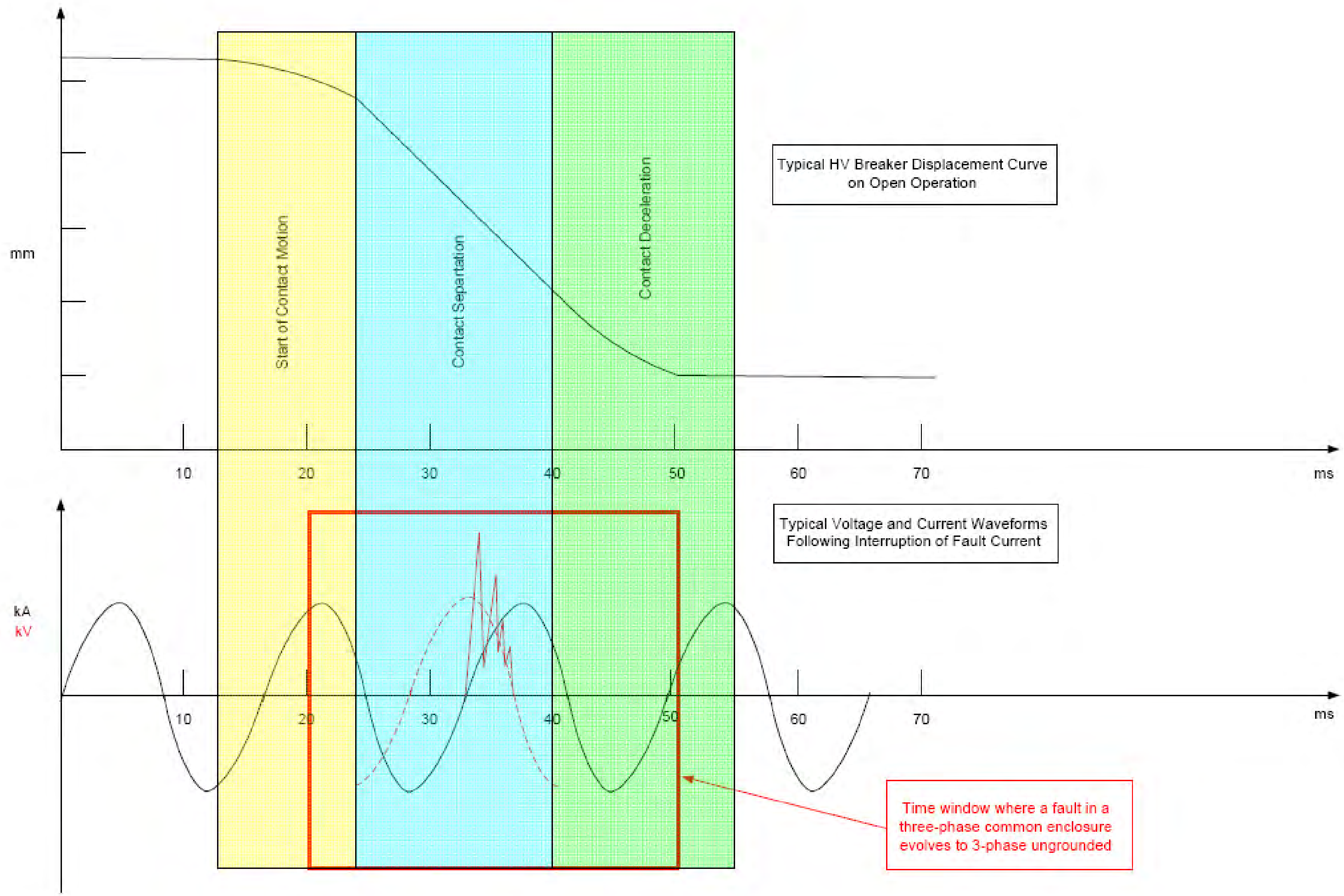
This is true of air-insulated systems and single phase gas-insulated systems.

So why did we care about this at Grand Avenue?

Initial proposal was to use a 3-phase in one enclosure design

In a 3-phase in one enclosure design a single phase to ground fault inside the enclosure will evolve to a 3-phase ungrounded fault in a few milliseconds, due to the rapid breakdown of the dielectric distance between the three phases, which is then causes the single phase to ground fault to extinguish.

General Description of Transient Recovery Voltage (TRV) for High-Voltage Circuit Breakers



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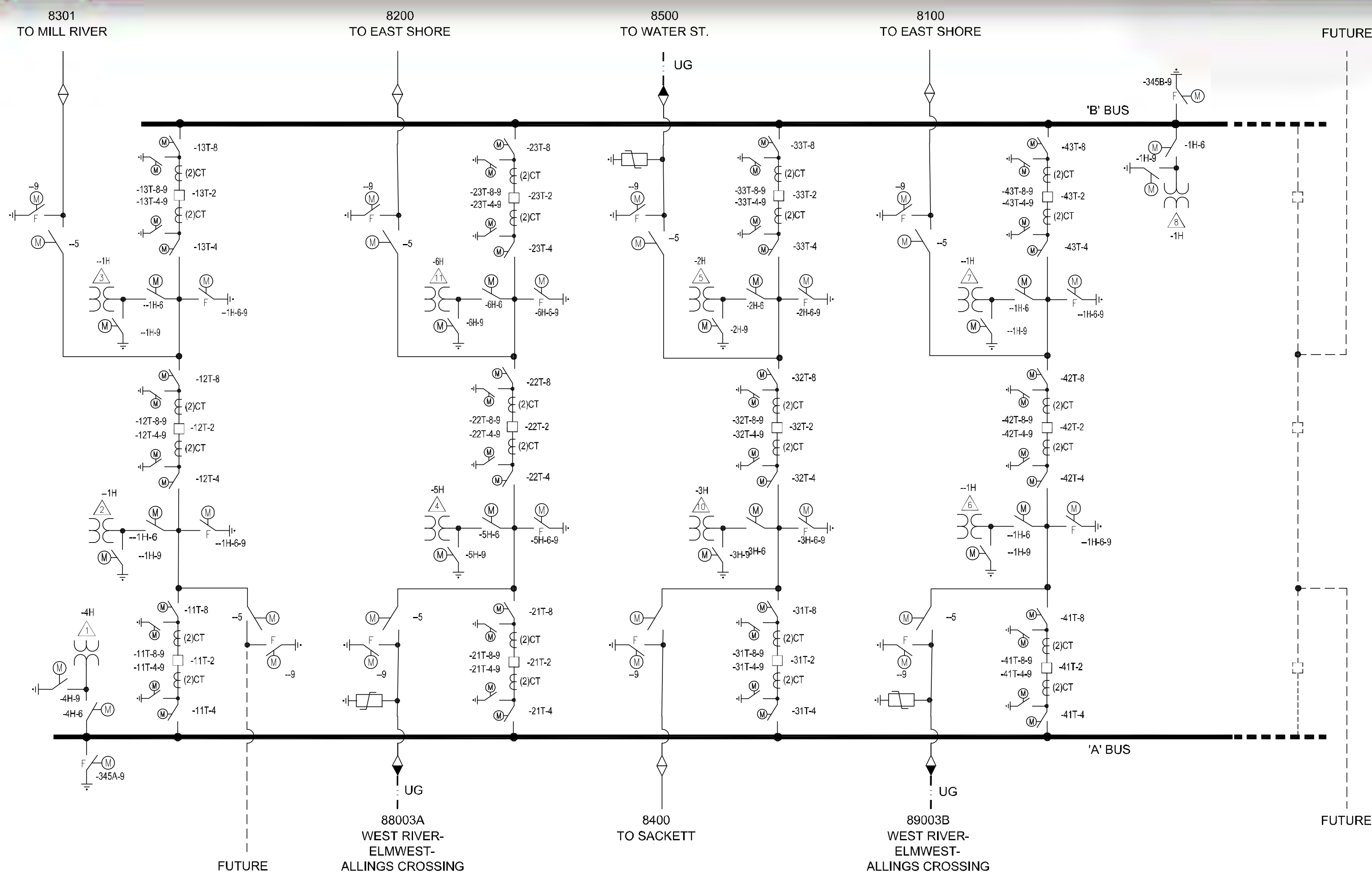
Grand Avenue Circuits



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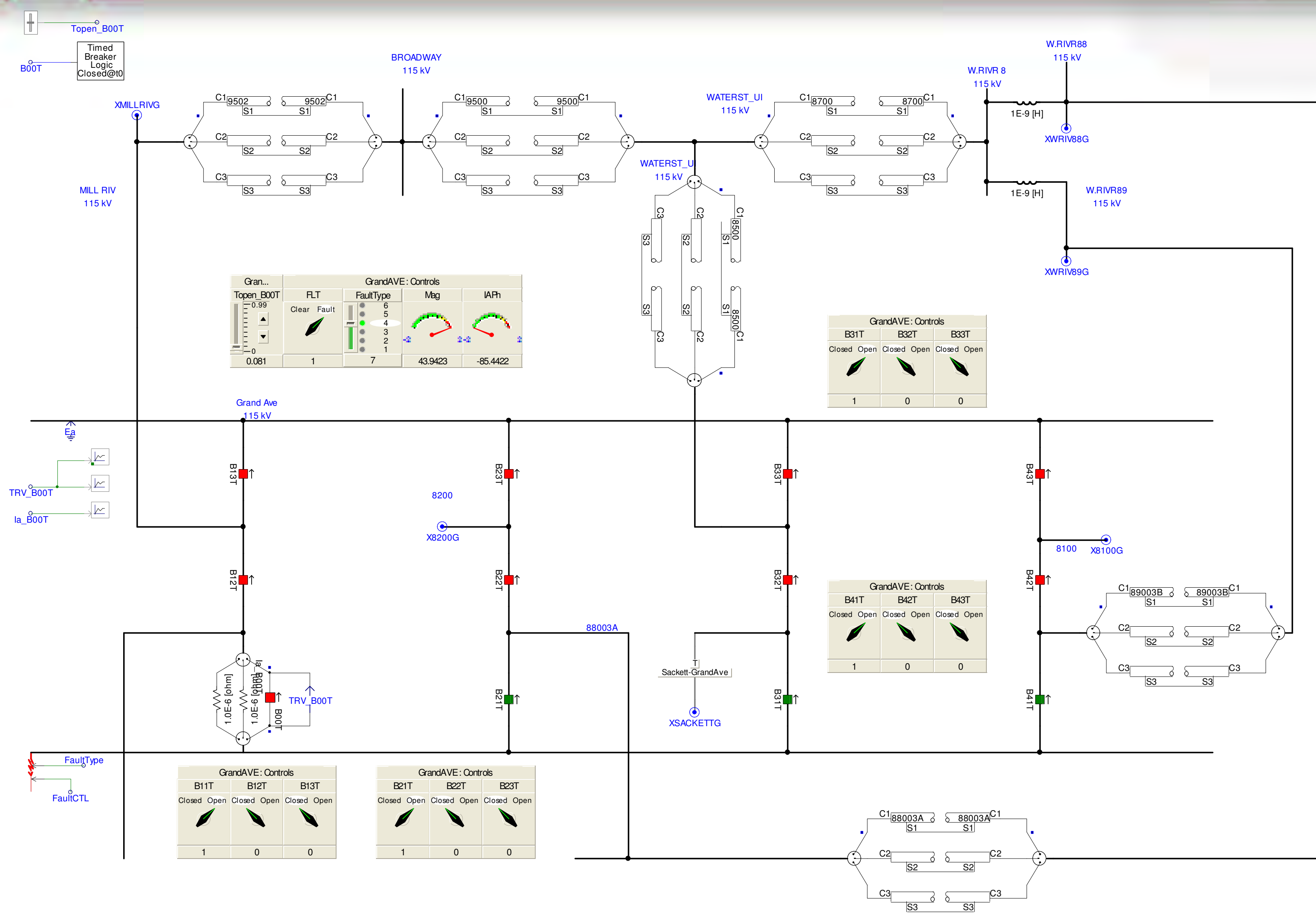
Grand Avenue Circuits



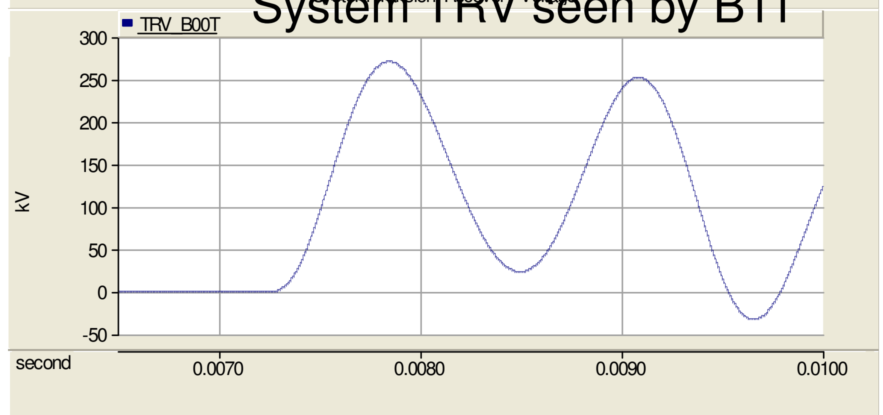
600 nF/phase/bay not shown above

Evaluation of Breaker B11 (-11T-2)

General fault conditions:

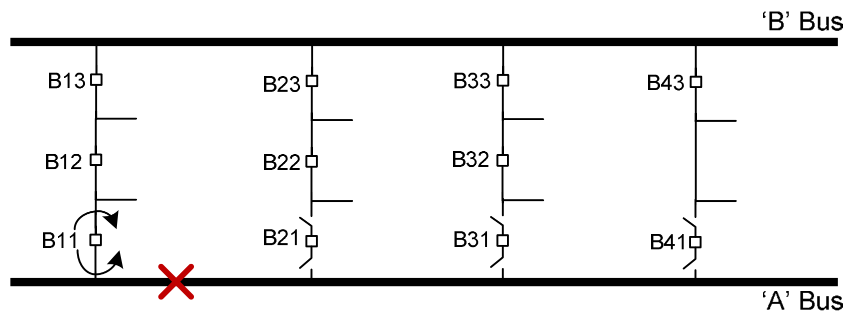
- **A three-phase ungrounded fault** is applied at a bus (i.e. 'A' or 'B' bus).
- The evaluated breaker is the last to trip – all bus breakers on the faulted bus have tripped.
- East Shore, Sackett, and North Haven 115 kV capacitors are offline.

System TRV seen by B11



Evaluation for Breaker B11

- A three-phase ungrounded fault at 'A' Bus
- B21, B31, B41 have tripped.
- B11 is the last to trip.



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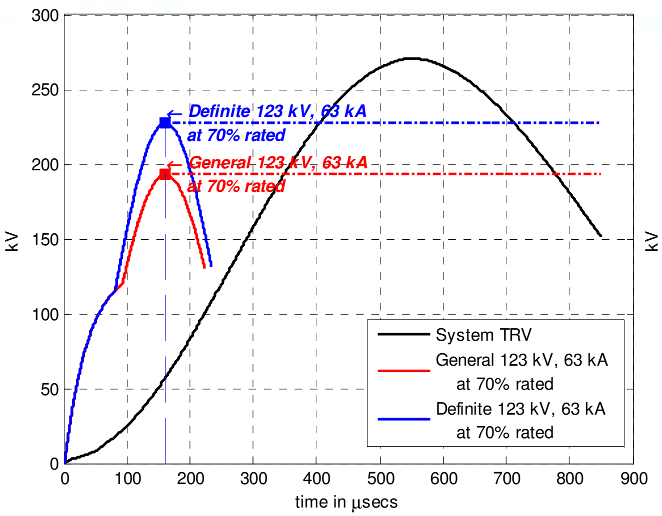
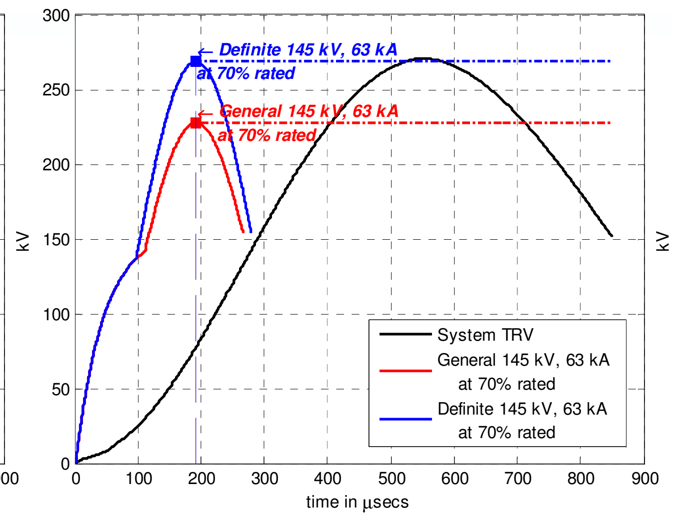
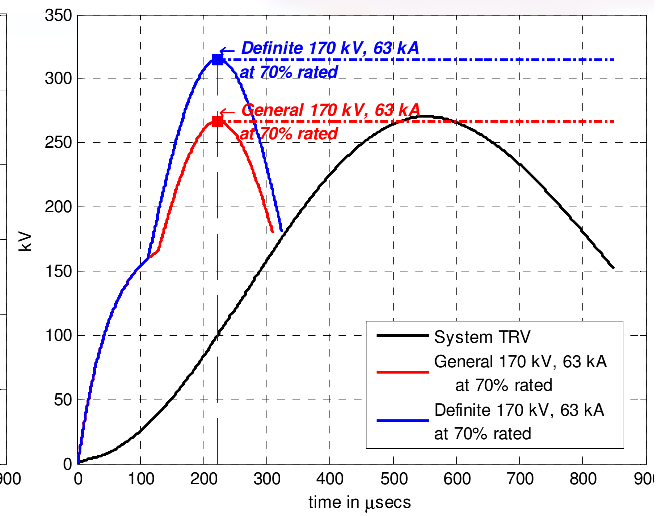
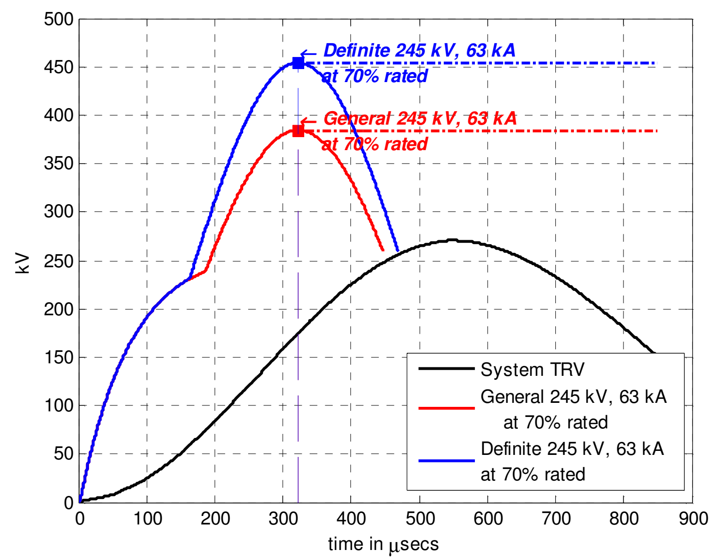
Comparison of System TRV with Breaker TRV Capabilities Evaluation of Breaker B11 (-11T-2)







- Breakers 123 kV/63 kA and 145 kV/63 kA general purpose do not have sufficient TRV capabilities.
- Breaker 145 kV/63 kA (definite) and 170 kV/63 kA (general) have marginal TRV capabilities.
- Breaker 170 kV/63 kA definite and 245 kV/63 kA do have sufficient TRV capabilities.



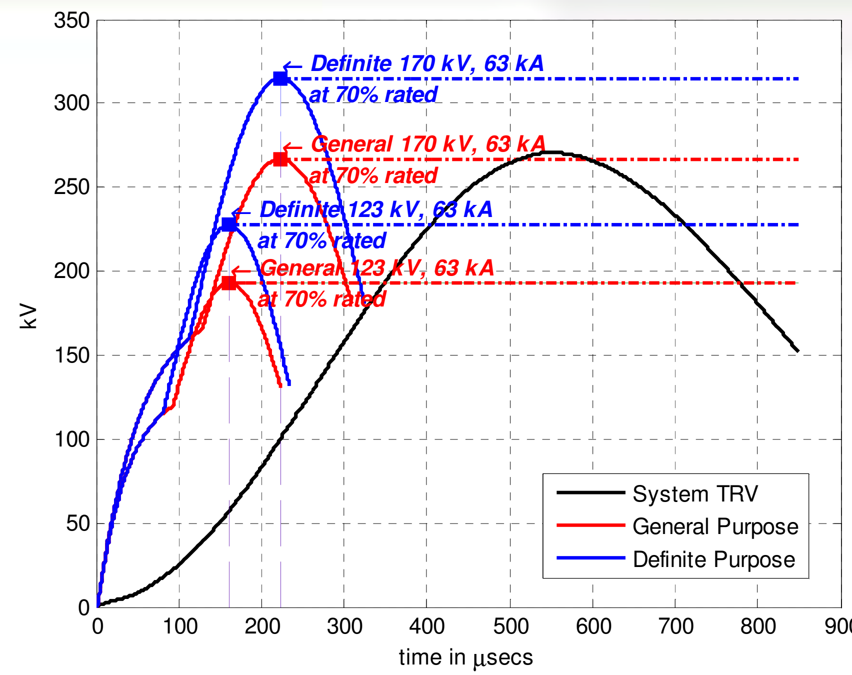
Evaluation of Breaker B21, B31, B41

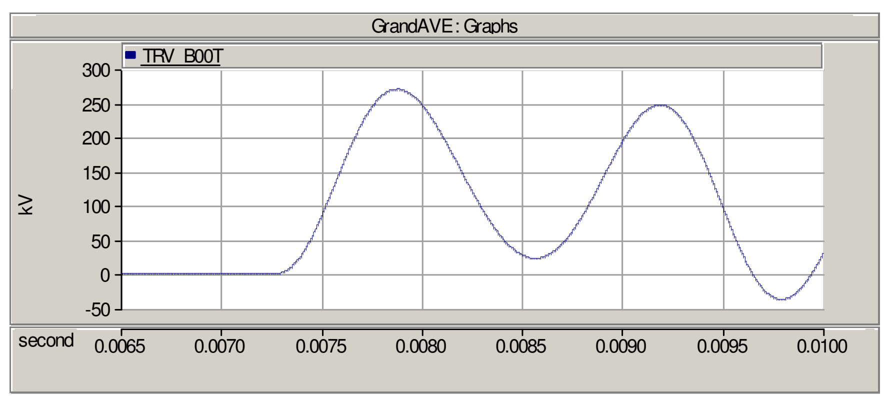
Evaluation for Breaker B21, B31, and B41

- **A three-phase ungrounded fault** at 'A' Bus
- The evaluated breaker is the last to trip; all bus breakers on the faulted bus have tripped
- East Shore, Sackett, and North Haven 115 kV capacitors are offline.

Results for Breaker B21 B31, and B41

- They are identical to B11 results.
- See slide 5.
- Marginal ratings: 170 kV, 63 kA general purpose
- Desired ratings: 170 kV, 63 kA definite purpose





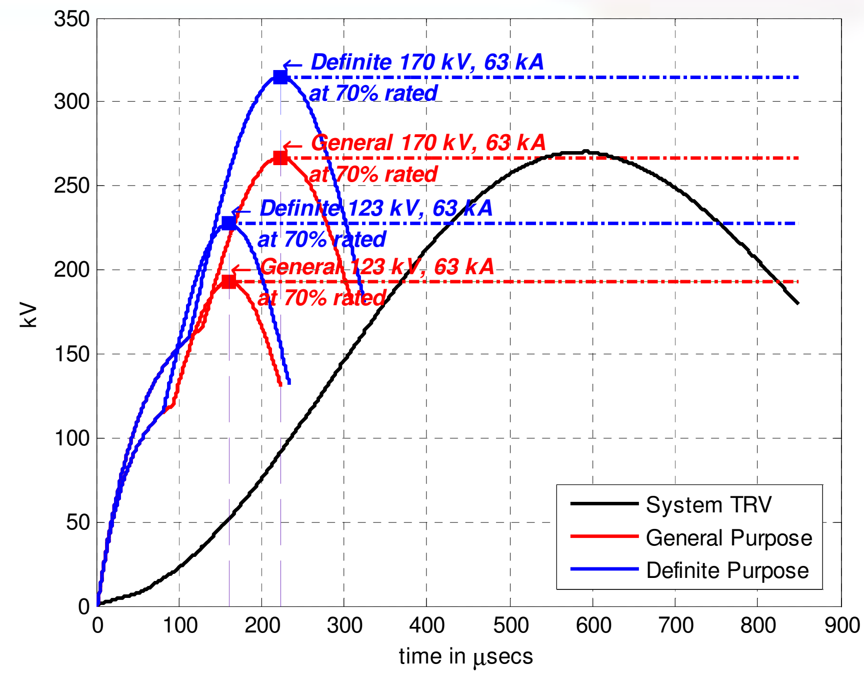
Evaluation of Breaker B13, B23, B33, B43

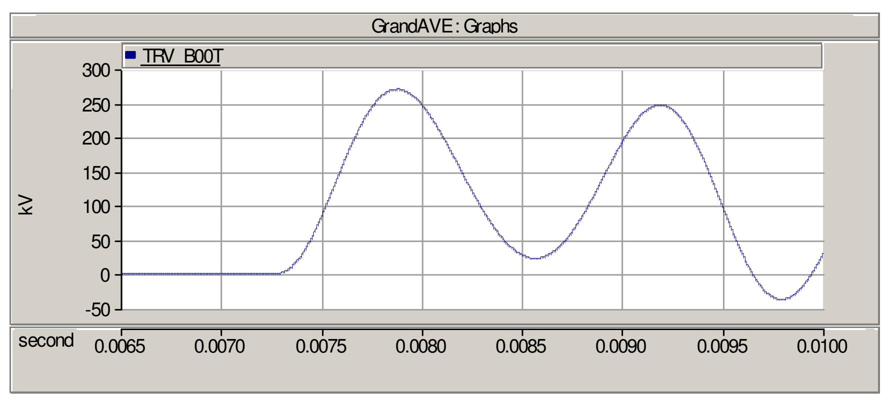
Evaluation for Breaker B13, B23, B33, B43

- **A three-phase ungrounded fault** at B' Bus
- The evaluated breaker is the last to trip;
  all bus breakers on the faulted bus have tripped
- East Shore, Sackett, and
  North Haven 115 kV capacitors are offline.

Results for Breaker B13 B23, B33, and B43

- They are identical to B11 results.
- See slide 5.
- Marginal ratings: 170 kV, 63 kA general purpose
- Desired ratings: 170 kV, 63 kA definite purpose





Revisit with a 3-phase ungrounded fault – East Shore Both Capacitors Online Evaluation of Breaker B11 (-11T-2)

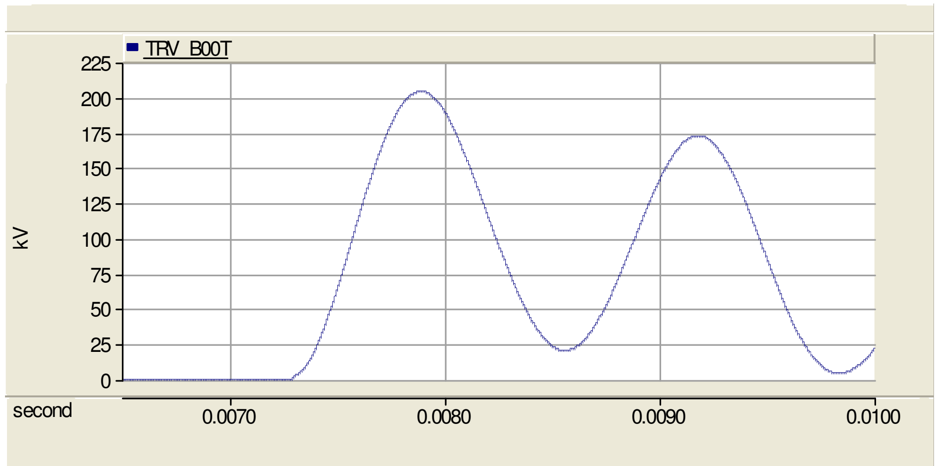
General fault conditions:

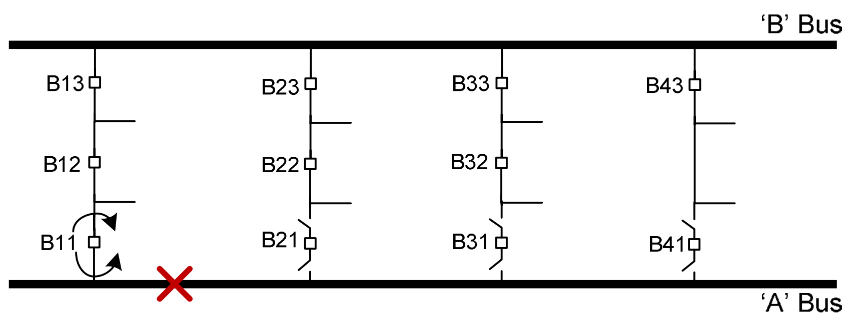
- **A three-phase ungrounded fault** is applied at a bus (i.e. 'A' or 'B' bus).
- The evaluated breaker is the last to trip – all bus breakers on the faulted bus have tripped.
- Both East Shore 115 kV capacitors are online.

Evaluation for Breaker B11

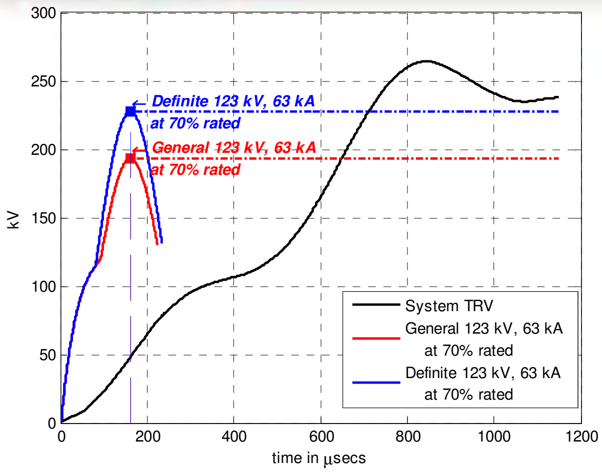
- A three-phase ungrounded fault at 'A' Bus
- B21, B31, B41 have tripped.
- B11 is the last to trip.

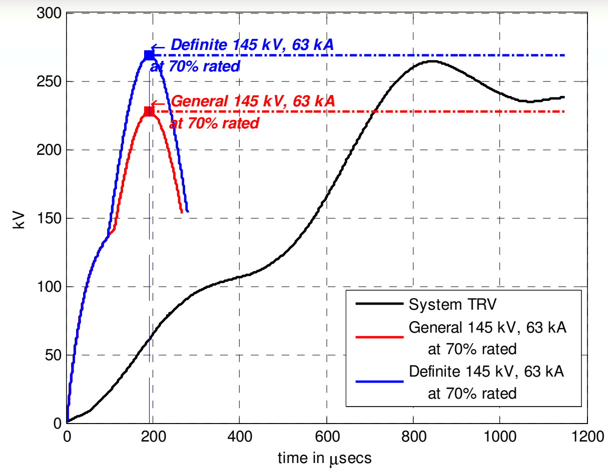
System TRV seen by B11

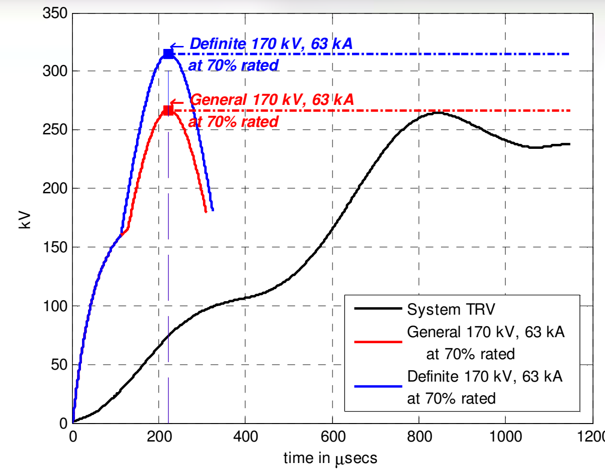




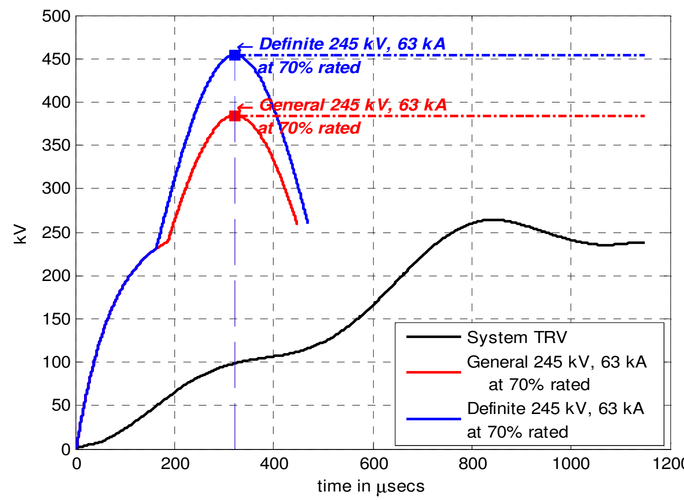
Revisit with a 3-phase ungrounded fault – East Shore Both Capacitors Online Evaluation of Breaker B11 (-11T-2)







- Marginal ratings: 170 kV, 63 kA general purpose
- Desired ratings: 170 kV, 63 kA definite purpose



Remarks/Conclusion

- Breaker ratings based on three-phase ungrounded faults.
  - Bus breakers for Grand Avenue must be rated at minimum 170 kV/63 kA with definite purpose duty.
- We chose to apply 245kV/63kA equipment to satisfy the TRV rating requirements and to use general purpose breakers.

Questions?

?