PQSoft Case Study

Impact of Capacitor Bank Outrush Reactors
on Circuit Breaker Transient Recovery Voltages

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Abstract:

Current limiting outrush reactors are often installed with utility transmission capacitor banks. These reactors limit the high-magnitude, high-frequency currents that flow when the capacitor bank discharges into a nearby fault. While an outrush reactor reduces the magnitude and frequency of the current during close-in faults, it may cause excessive transient recovery voltages (TRVs) for the capacitor bank circuit breaker due to the very high frequency component of the recovery voltage associated with the reactor. Excessive TRVs may cause the capacitor bank circuit breaker to fail to clear during certain fault conditions. An engineering study was completed to evaluate the TRVs for various capacitor bank circuit breaker operations, system contingencies, and mitigation alternatives. This case study presents a summary of the model development and simulations completed during the outrush reactor TRV study.

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RELATED STANDARDS

IEEE Std. C37.06, IEEE Std. C37.04, IEEE Std. C37.011

INTRODUCTION

Due to the concern for excessive transient recovery voltages (TRVs) during capacitor bank circuit breaker operations, an engineering study was performed to determine the impact of capacitor bank outrush reactors on circuit breaker transient recovery voltages. The study evaluated the concerns and possible solutions, including adding various amount of capacitance to reduce the rate-of-rise of the recovery voltage.

The analysis of high-frequency transient recovery voltages frequently requires the use of sophisticated digital simulation programs. Simulations provide a convenient means to characterize transient events, determine resulting problems, and evaluate possible mitigation alternatives. Occasionally, they are performed in conjunction with system monitoring for verification of models and identification of important power system problems. The complexity of the models required for the simulations generally depends on the system characteristics and the transient phenomena under investigation. The transient analysis for the engineering study was performed using the PSCAD/EMTDC Program (Version 4.2).

STUDY METHODOLOGY

The transient recovery voltage evaluation for various fault conditions was based on the methods provided in IEEE Std. C37.06, IEEE Std. C37.04, and IEEE Std. C37.011. This involved analysis of the most severe conditions, including the clearing of three-phase and single-line-to-ground faults at the capacitor bank circuit breaker and outrush reactor terminals when the system voltage is at a maximum.

The study included normal cases where the system operates with all circuit breakers and lines in service and various contingencies representing different operating conditions. For each case, three-phase ungrounded, three-phase grounded, and single-line-to-ground faults were evaluated.

The transient recovery voltage is the voltage across the terminals of a pole of circuit breaker following current zero when interrupting faults. Transient recovery voltage waveshapes can be oscillatory, exponential, cosine-exponential or combinations of these forms. Transient recovery voltages due to short-line faults (SLFs) are characterized by triangular-shaped waveshapes and a very steep initial rate-of-rise. The triangular shape of the recovery voltage arises from positive and negative reflections of the traveling waves that oscillate between the open circuit breaker and the fault. Due to the short distance involved, the initial rate-of-rise of the recovery voltage (RRRV) can be very steep.

According to IEEE Std. C37.011, the most severe oscillatory or exponential recovery voltages tend to occur across the first pole to open of a circuit breaker interrupting a three-phase ungrounded symmetrical fault at its terminal when the system voltage is at a maximum. When the transient recovery voltage performance meets the withstand criteria when subjected to the fault condition mentioned above, a short-line fault evaluation is not necessary. This is because short-line fault transient recovery voltage capability is higher than that of a three-phase ungrounded fault.

For conditions where the simulated transient recovery voltage exceeded the withstand capability of the circuit breaker, the mitigation option of added capacitance was also evaluated.

MODEL DEVELOPMENT

The model development process included steps for data collection, data approximation, data simplification, and model verification.

The TRV system model was based on short-circuit data that consisted of positive and zero sequence impedance data in the ASPEN Oneliner format. The study area included the substation and the adjacent system (see Figure 1). The boundary of the study area was represented with equivalent sources and transfer impedances such that the electrical representation of the study area (at 60 Hz) was nearly identical to the original representation.

Figure 1 - System Model for the 138kV TRV Study

In the study, all transmission lines were represented with a frequency dependent line model to account for traveling wave phenomena. Generating units were represented with ideal sources behind sub-transient impedances. The accuracy of the transient model was verified by comparing three-phase and single-line-to-ground fault currents at all buses. A subset of the fault cases is summarized in Table 1.

Table 1 - Steady-State Fault Simulations Completed for Model Verification

Case ID	Fault Location	Full Model	Reduced Model	PSCAD Model
F1 F2	9050 Substation 138 kV	$I_{3\phi}$ = 22143 $I_{\phi G}$ = 21553	$I_{3\phi}$ = 22143 $I_{\phi G}$ = 21553	$I_{3\phi}$ = 22079 $I_{\phi G}$ = 21519
F3 F4	9021 Substation 138 kV	$I_{3\phi}$ = 18724 $I_{\phi G}$ = 15275	$I_{3\phi}$ = 18724 $I_{\phi G}$ = 15266	$I_{3\phi}$ = 18707 $I_{\phi G}$ = 15411
F5 F6	9509 Substation 138 kV	$I_{3\phi}$ = 27980 $I_{\phi G}$ = 21337	$I_{3\phi}$ = 27980 $I_{\phi G}$ = 21333	$I_{3\phi}$ = 27955 $I_{\phi G}$ = 21852

The model represented a reduction of the entire system to determine the system equivalents and corresponding fault levels. It should be noted that the corresponding PSCAD model did not include mutual coupling between transmission lines. In addition, typical X/R ratio values were used where the short-circuit model did not include resistance (e.g., lines, transformers, etc.), and relatively large transfer impedances were ignored. Considering these factors, accuracy within 3% was considered acceptable for the 60 Hz short-circuit model verification.

Circuit Breaker Data

The circuit breaker ratings and transient recovery voltage data included:

Rated Maximum Voltage: ....145 kV
Rated Continuous Current: .... 3000 A
Rated Short-Circuit Current: ....40 kA
Rated Interrupting Time: .... 3 Cycles
Line Charging: ....160 A
Isolated Bank Switching: ....315 A
Back-to-Back Switching: ....315 A

Table 2 - Rated TRV Capability of 145kV, 3000 A, 40kA Breaker

T2 (μsec)	R (kV/μSec)	T1 (μsec)	E1 (kV)	E2 (kV)
310	2	2	1.06 V	1.49 V

The waveshape of the exponential component E1 for terminal faults below 30% of the breaker rating is 1-cosine. Based on Table 2 and the discussion in Section 5.9 of IEEE Std. C37.04-1999, the TRV limit envelopes were derived and graphically represented using a MATLAB program. Figure 2 shows the TRV envelopes (or withstand capabilities) for several fault levels. Capability envelopes when interrupting fault currents below 30% of its rated short-circuit current have a waveshape of 1-cosine, while for fault currents above 30% of breaker rating, the waveshape has an exponential-cosine form.
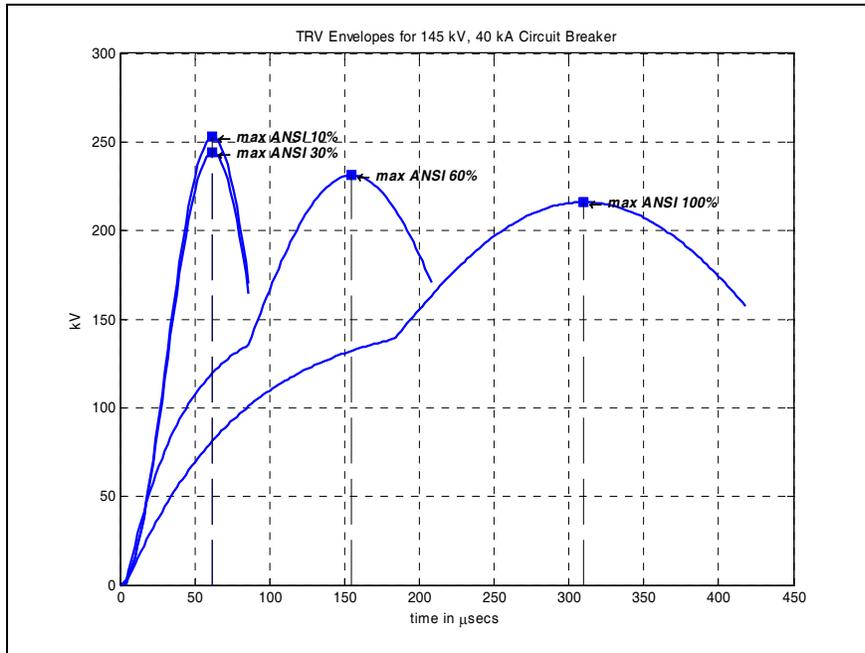
Figure 2 - TRV Withstand Capability for a 145kV, 3000 A, 40kA Breaker

Capacitance Values for Substation Equipment

Equivalent values of capacitance for substation equipment were based on the typical capacitance ranges provided in Annex B of IEEE Std. C37.011-1994. Three equivalent capacitance values (minimum, maximum, and average) were determined. Table 3 shows an example of the collection of typical capacitance values for each bus section in the substation. The minimum values of equivalent capacitance were used throughout the simulation process for both normal and contingency cases.

Table 3 - Typical Capacitance Values Based on Annex B of IEEE Std. C37.011-1994

Capacitor Bank Substation C_{eq} for Capacitor Bank #2	Qty	Min (ρF)	Max (ρF)	Avg (ρF)
Disconnect Switch	1	60	200	130
Current Transformers (CTs)	1	150	450	300
Circuit Breaker (open)	1	25	150	88
138 kV Bus (15 Feet)	1	38	83	60
Total:		273	883	578

Outrush Reactor Model

An outrush reactor was installed with the 138 kV capacitor bank to provide substation circuit breaker protection in the event of reclosing into a close-in fault. The reactor rating of 1.88 mH was based on the 145 kV general-purpose circuit breaker limitation ($Ipk*f < 2x10^7$) in IEEE Std. C37.06-2000.

As shown in Figure 3, the 1.88 mH outrush reactor was modeled as a lumped inductance in parallel with a 51.5 ρF capacitance (value provided by the reactor manufacturer). This results in a natural frequency for the reactor of approximately 511 kHz:

$$f = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(1.88mH * 51.5\rho F)}} = 511.491 kHz$$

> where:
>> f is the natural frequency of the reactor (Hz)
>> L is the inductance of the reactor (H)
>> C is the capacitance of the reactor (F)

Also in parallel with the reactor were the minimum equivalent capacitance values of the connected equipment, including 25 ρF to represent an open circuit breaker, 300 ρF to represent two CTs, and 38 ρF to represent 15 feet of 138 kV bus. Therefore, the total equivalent capacitance included in the simulation model was 363 ρF. This capacitance added to the outrush reactor capacitance yields 414.5 ρF and results in a transient recovery voltage frequency of approximately 180 kHz:

$$f = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(1.88mH * 414.5\rho F)}} = 180.293 kHz$$

Finally, a variable resistor was also connected in parallel with the reactor to represent the typical damping associated with the outrush reactor.
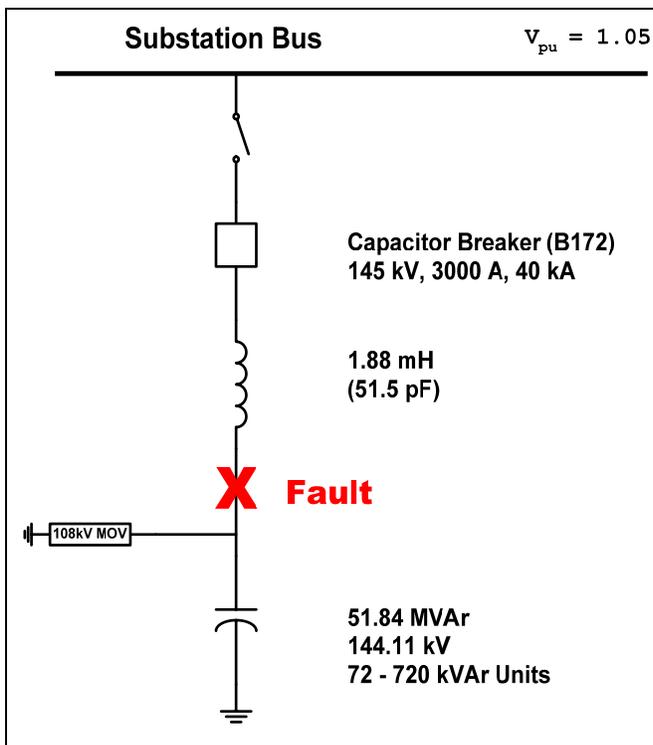

Figure 3 - Outrush Reactor Model

Basecase Model Development

Figure 4 shows a portion of the overall PSCAD circuit model used to determine the prospective transient recovery voltage withstand capabilities for the 138 kV capacitor bank circuit breaker when clearing various faults at the terminals of the outrush reactor under normal and contingency conditions. Transient recovery voltage, peak current interrupted, and the percentage of interrupted current (based on the short-time rating for the circuit breaker) was observed for each simulation case. Prospective transient recovery voltage waveshapes were then compared to their related capabilities by using a user-developed MATLAB program to graph the output from each PSCAD simulation case with an overlay of the transient recovery voltage envelope capability.
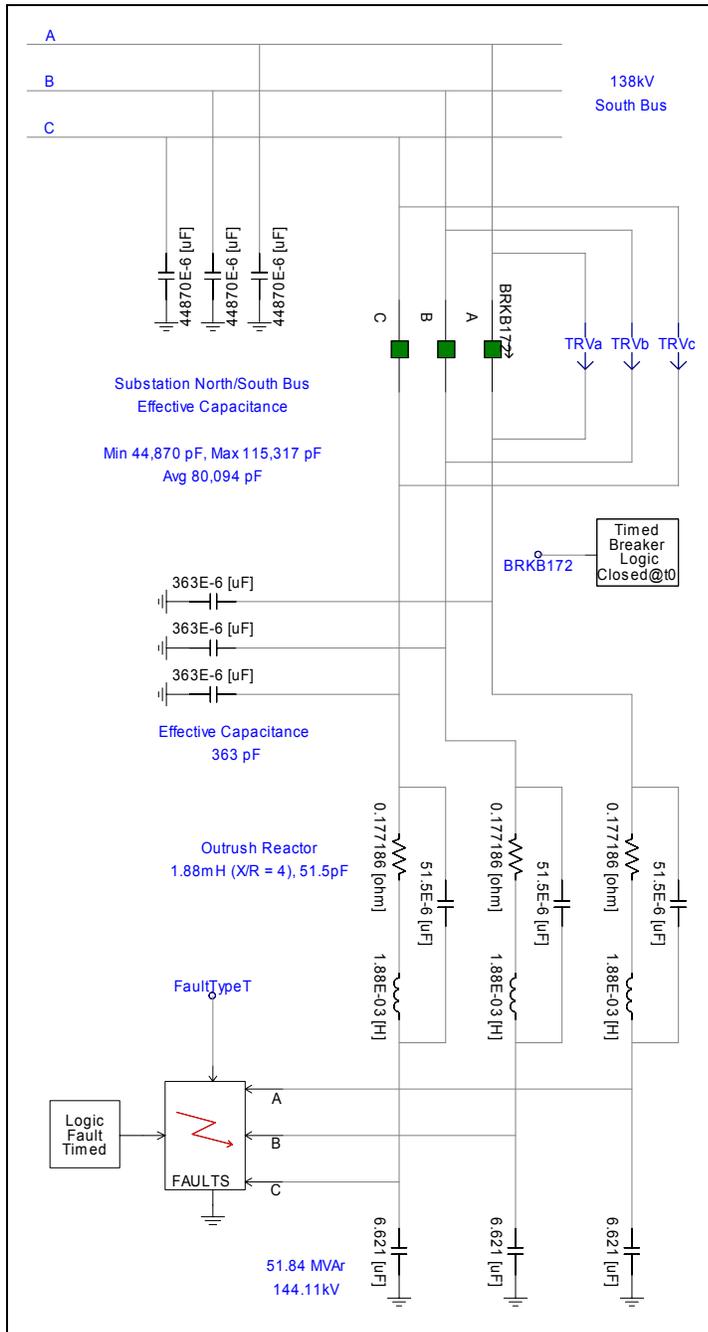
Figure 4 - Circuit for Applying Various Faults at the Outrush Reactor Terminals

Transient Recovery Voltage Evaluation Criteria and Simulation Cases

The outrush reactor limited fault creates a high frequency transient recovery voltage that the related ANSI/IEEE standards do not specifically address. For this study, the focus was on determining, and then reducing the reactor side component of the transient recovery voltage to meet the known ANSI/IEEE specified short-line fault capability for the 145 kV, 40 kA capacitor bank circuit breaker.

Criteria for the transient recovery voltage evaluation were based on IEEE Std. C37.011-1994, which states that evaluations should be conducted for three-phase ungrounded faults at the circuit breaker terminals when the system voltage is at maximum. The maximum voltage is 1.05 per-unit of the nominal voltage. The transient recovery voltage evaluation for the capacitor bank circuit breaker at the capacitor bank substation considered the following conditions:

- during the clearing of a three-phase ungrounded symmetrical fault at the circuit breaker terminal when the system voltage is at the maximum (1.05 per-unit).

- during the clearing of a single-line-to-ground fault at the circuit breaker terminal when the system voltage is at the maximum (1.05 per-unit).

- during the clearing of a three-phase-ungrounded fault at the outrush reactor terminal.

- during the clearing of a three-phase-to-ground fault at the outrush reactor terminal.

- during the clearing of a single-line-to-ground fault at the outrush reactor terminal.

For conditions where the simulated transient recovery voltage exceeded the circuit breaker's withstand capability, the mitigation option of added capacitance was evaluated. This included cases for various standard capacitance ratings, including 1,500 pF, 2,500 pF, 5,000 pF, 7,500 pF, and 10,000 pF. Relevant transient recovery voltage and mitigation cases were repeated for a number of other outrush reactor ratings, such as 3.68 mH, 1.88 mH, 0.94 mH, 0.90 mH, and 0.20 mH. These cases were completed to determine the relationship between the reactor rating and the severity of the capacitor bank circuit breaker recovery voltages. Similarly, cases were completed to determine if a circuit breaker with a higher short circuit rating affected the results.

Finally, a number of transient recovery voltage and mitigation cases were repeated under several contingency conditions, such as the removal of the substation's 345 kV/115 kV transformer.

SIMULATION RESULTS

The transient recovery voltage evaluation included both three-phase and single-line-to-ground faults at the outrush reactor terminals.

Reactor Terminal Faults

The simulation results for the various reactor terminal fault clearing cases were summarized in tables similar to Table 4. The table shows the respective case identifier, the fault type, the capacitance values, the peak current that the circuit breaker interrupted, this peak current as a percentage of the rated value (40 kA), the peak transient recovery voltage in kV, and a note to report whether the transient recovery voltage was within the circuit breaker's capability envelope. A "YES*" note signifies that the transient recovery voltage waveshape slightly exceeded the transient recovery voltage capability for the first 10-50 μsec, but it met the transient recovery voltage short-line fault capability. A "NO" note signifies that the waveshape did not meet the transient recovery voltage capability limit.

Figure 5 and Figure 6 show several examples of the simulation results for the outrush reactor terminal fault clearing cases summarized in Table 4. Figure 5 shows the recovery voltage for the capacitor bank circuit breaker for Case C1 and Figure 6 shows the results for Case D1. Each graph includes the corresponding circuit breaker withstand capability.

Table 4 - TRV Evaluation of Reactor Faults

Case ID	Fault Type	Equivalent C Added C (ρF)	Peak Current (kA)	Percent Rated (%)	Peak TRV (kV)	Within Envelope (Y/N)
C1	3φ-UnGnd	C_{min} None	27.2	48.1	205.1	NO
C4	3φ-Gnd	C_{min} None	27.2	48.1	120.0	NO
D1	1φ-Gnd	C_{min} None	26.6	46.9	117.4	NO
E3	1φ-Gnd	C_{min} 5,000 ρF	26.6	46.9	118.1	YES[*]
E8	3φ-UnGnd	C_{min} 5,000 ρF	27.2	48.1	205.1	YES[*]
E9	3φ-Gnd	C_{min} 5,000 ρF	27.2	48.1	120.8	YES[*]
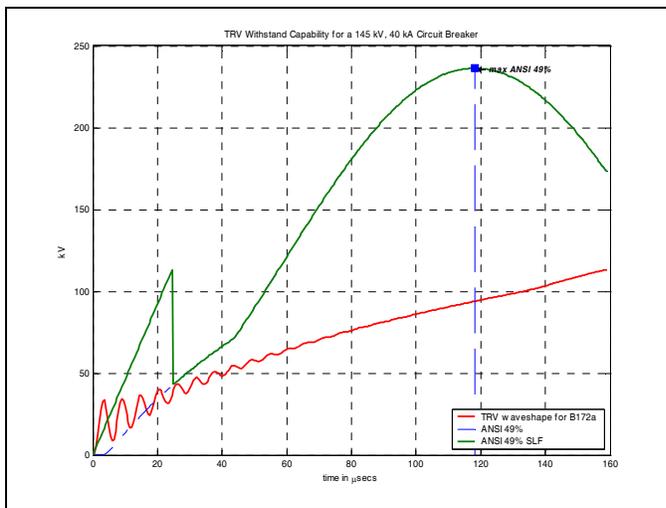
Figure 5 - TRV Withstand Capability for Case C1
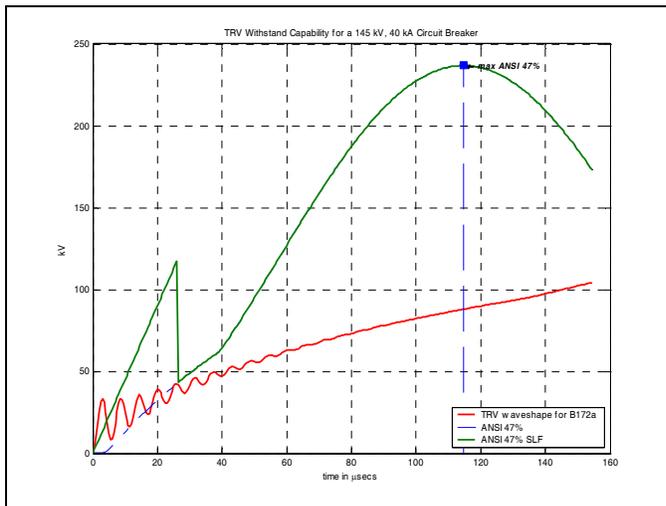
Figure 6 - TRV Withstand Capability for Case D1

Evaluating Effectiveness of Added Capacitance

A number of cases were completed to evaluate resulting transient recovery voltages for the capacitor bank circuit breaker when clearing faults at the outrush reactor terminal under normal conditions with additional capacitances added at the reactor terminals.

The ratings of the additional capacitances simulated included standard ratings available from several manufacturers, including 1,500 ρF, 2,500 ρF, 5,000 ρF, 7,500 ρF, and 10,000 ρF. The additional capacitance adds to the outrush reactor and other equipment capacitances. For example, adding a 1,500 ρF capacitance results in a total capacitance of 1914.5 ρF and a transient recovery voltage frequency of approximately 84 kHz.

Figure 7 and Figure 8 show examples of the simulation results for a single-line-to-ground fault on the outrush reactor terminal. Figure 7 shows the recovery voltage for the capacitor bank circuit breaker with 1,500 ρF added and Figure 8 shows the results with 5,000 ρF added.
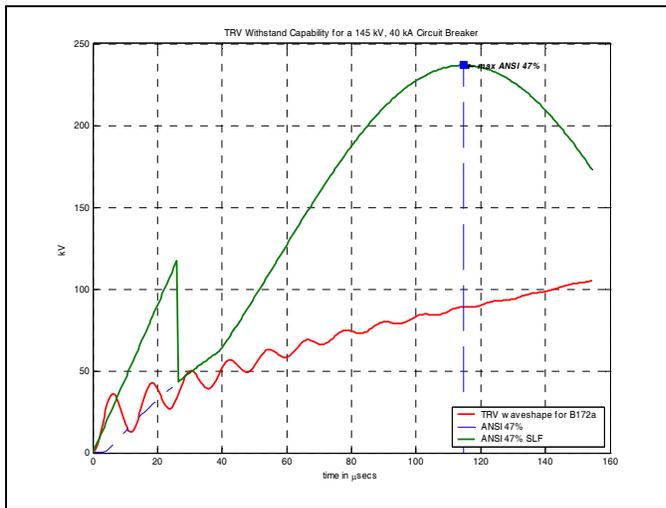

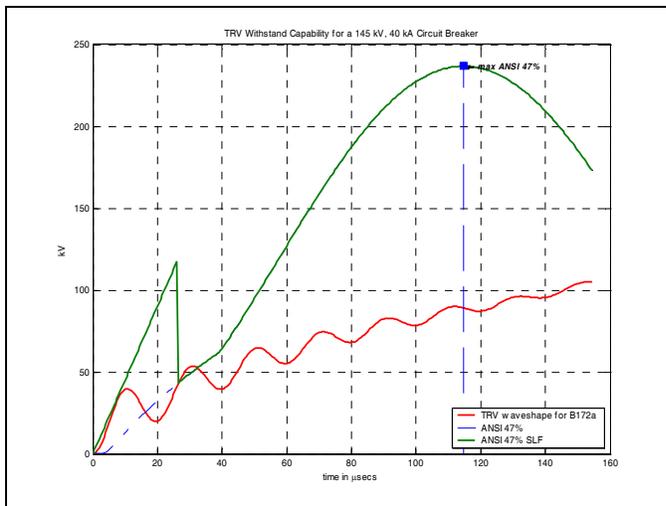**Figure 7 - TRV Withstand Capability for Case D1 with 1,500pF Added (Case E1)**

Figure 8 - TRV Withstand Capability for Case D1 with 5,000pF Added (Case E3)

Evaluating Outrush Reactor Rating

Cases were completed to evaluate resulting transient recovery voltages for the capacitor bank circuit breaker when clearing faults at the outrush reactor terminal for a number of different reactor ratings, including 0.20 mH, 0.90 mH, 0.94 mH, and 3.68 mH.

Figure 9, and Figure 10 show examples of the simulation results for a single-line-to-ground fault on the outrush reactor terminal. Figure 9 shows the recovery voltage for the capacitor bank circuit breaker with a 3.68 mH reactor rating (no additional capacitance) and Figure 10 shows the results with a 3.68 mH reactor rating and a 10,000 pF capacitance.
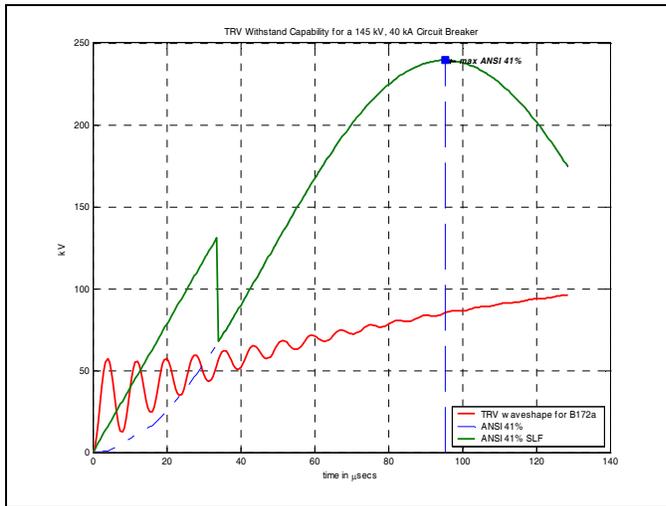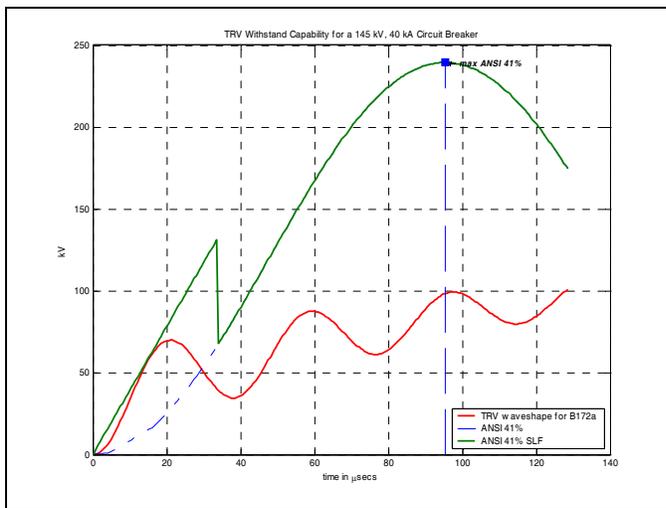

Figure 9 - TRV Withstand Capability for a 3.68mH Reactor

Figure 10 - TRV Withstand Capability for a 3.68mH Reactor with 10,000pF Added

SUMMARY

The engineering study included an evaluation of the transient recovery voltage performance of a 145 kV capacitor bank circuit breaker in a 138 kV substation. A number of observations and conclusions included:

1. The simulated transient recovery voltages exceeded the short-line fault capability limits when clearing three-phase ungrounded, three-phase grounded, and single-line-to-ground faults at the reactor terminals. This is because the recovery voltage severity is worsened by the very high frequency component of the transient voltage on the reactor side of the circuit breaker.

2. One method for improving this condition is with the application of an additional capacitance to ground between the circuit breaker and the outrush reactor. This capacitance reduces the severity of the transient recovery voltage. Standard capacitance ratings, including 1,500 ρF, 2,500 ρF, 5,000 ρF, 7,500 ρF, and 10,000 ρF, were simulated. The simulations indicated that the 5,000 ρF capacitance was the minimum standard capacitance rating that would reduce the recovery voltage to within the beaker's capability for all of the cases.

3. The effect of outrush reactor rating on resulting transient recovery voltages was evaluated for the ratings 0.20 mH, 0.90 mH, 0.94 mH, and 3.68 mH. Only the 0.20 mH reactor rating had a transient recovery voltage waveshape that did not exceed the related short-line fault capability limit. A 10,000 ρF capacitance was required to reduce the recovery voltage to within the circuit beaker's short-line fault capability for the 3.68 mH reactor rating.

4. Supplemental cases were completed to evaluate several contingency operating conditions. The severity of the transient recovery voltages was not changed significantly because the characteristic was dominated by the very high frequency component of the transient voltage on the reactor side of the circuit breaker.

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