Effects of Phase-Shifting Transformers, and Synchronous Condensers on Breaker Transient Recovery Voltages

Waruna Chandrasena, Bruno Bisewski, and Jeff Carrara

Abstract-- This paper describes several system configurations that could lead to very high TRV/RRRV in the presence of a phase shifting transformer, and synchronous condensers. The special considerations involved in determining the most limiting TRV and RRRV are presented. Mitigation measures required for 15 kV and 115 kV breakers that are applied in the above system configurations are also presented.

Keywords: circuit breakers, electromagnetic transients, phase-shifting transformer, switched capacitors, synchronous machines

I. Introduction

The voltage that appears across the contacts of a circuit breaker during the transient period immediately after the interruption of current is always more severe than the steady state power frequency voltage that appears across the open contacts of the breaker. For a successful opening operation, the transient imposed on the breaker must be within the breaker capability. The capability of the breaker to withstand the opening transient is dependent on the magnitude of the transient recovery voltage (TRV) and the rate of rise of recovery voltage (RRRV). If the voltage across the open breaker builds up faster than the rate at which dielectric strength can build up or the maximum voltage exceeds the maximum withstand capability of the interrupter, a dielectric breakdown occurs and an arc is re-established within the interrupter. In addition to the possible failure of the interrupter, these breakdowns can lead to failure of other power system equipment. Thus dielectric breakdown across the breaker contacts is a concern for both the circuit breaker designer and the power system designer. The power system designer needs to ensure that the duties imposed by the switching application are within the circuit breaker capabilities either by limiting the magnitude of the TRV and/or RRRV or by selecting breakers with adequate capability [1] – [5].

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Very severe rate of rise of recovery voltage (RRRV) can occur at breaker opening when a lumped inductive network feeds the fault current, especially when there is little stray capacitance between the inductor and the breaker. While the ANSI standard C37.06 recognizes this situation by defining the definite purpose breaker for fast transient applications, there are configurations where even the capability of a definite purpose breaker would be exceeded [6],[7].

This paper describes several system configurations that could lead to very high TRV/RRRV in the presence of phase shifting transformers (PST), synchronous condensers, and switched capacitor banks. Simulation results presented are part of a design study carried out for the proposed extension to Granite Station in Vermont.

The proposed additions at Granite Station will include two autotransformers, two phase-shifting transformers; six shunt capacitor banks, four synchronous condensers, and associated switchgear at 230 kV, 115 kV and 13.8 kV voltage levels. Six 115 kV breakers are arranged in a ring bus. The ring bus accommodates the two phase-shifting transformers, two transmission lines, and shunt capacitor banks as shown in Fig. 1. Six additional 115 kV breakers will be used to switch capacitor banks equipped with inrush limiting reactors. The synchronous condensers are connected to the tertiary winding of autotransformers with each transformer having two condensers. Each condenser will have a 15 kV breaker. For an outage of an autotransformer, the condensers from one side can.be switched to the other transformer via a tie breaker.

The TRV duty of the twelve 115 kV breakers, and seven 15 kV breakers were evaluated. Special considerations involved in determining the most limiting cases of TRV/RRRV and in defining mitigation measures for 15 kV and 115 kV breakers at Granite Station are presented.

II. Simulation Model

A detailed three phase time domain simulation model was developed using PSCAD (Fig. 1.). TRV was evaluated for the 15 kV and 115 kV breakers taking into consideration the station buswork, transformers, breakers, arresters, shunt capacitors, voltage transformers, cables, surge capacitors and the associated stray capacitances of all equipment.

The phase shifting-transformers and the autotransformers were modeled using data provided by the transformer manufacturer, which included the leakage inductances and inter-winding capacitances.

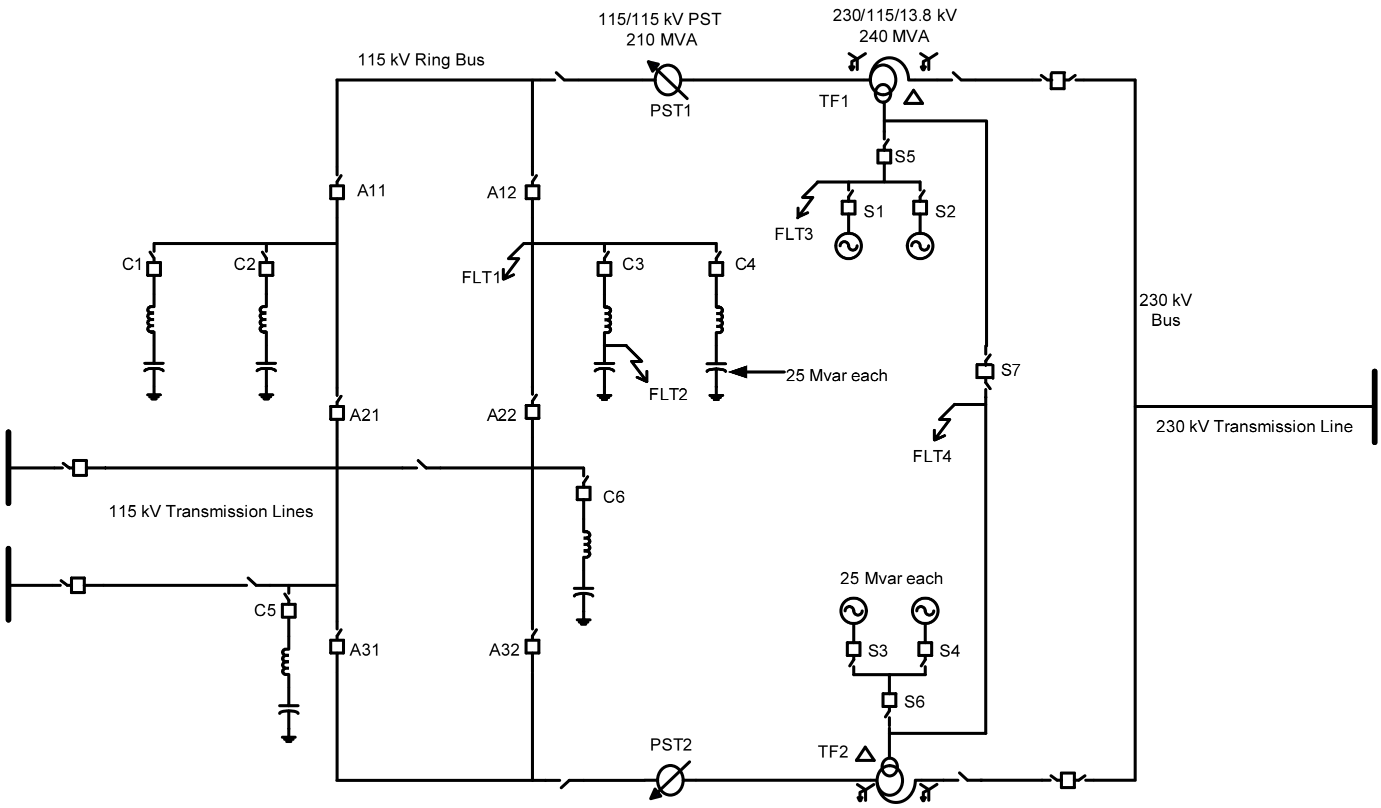

Fig. 1. Conceptual One-Line Diagram of the Granite Station

It was necessary to make a number of assumptions in the course of this work. The intent was to consider reasonable worst-case conditions, which typically include the consideration of the maximum possible short circuit levels and lowest stray capacitance values. Typical values of stray capacitance given in IEEE standard C37.11 were assumed whenever actual values were not available [8].

A. 115 kV Breakers

The system fault contributions together with fault contributions from the four synchronous condensers would result in total fault current on 115 kV side of about 12 kA. This is about 30% rating of the 40 kA circuit breakers. If definite purpose breakers were used, a 30% fault current interrupting duty would be at the point where the breakers have the highest RRRV capability. Faults were applied at ten different locations in the ring bus, shunt capacitor banks, and 115 kV transmission lines. During the fault application circuit breakers near the fault, either in the ring bus (A11 to A32) or switched capacitor banks (C1 to C6) were switched and the transient recovery voltage was calculated. As the limiting TRV could occur under normal or certain contingency conditions, the studies were focused on determining the limiting conditions. Therefore, the sensitivity of point on wave of fault application, and phase angle of the phase-shifting transformer, was also considered.

The most critical faults identified in this exercise are shown in Fig. 1. FLT1 was a bus fault fed by phase-shifting transformer/autotransformer when breaker A21 was open. FLT2 was a fault in the shunt capacitor bank, between the reactor and the capacitor bank when breakers A21 and A22 were open.

B. 15 kV Breakers

Synchronous condensers were assumed to be operating at maximum output of 33 Mvars, which results in the highest internal voltage of about 1.45 p.u. Each condenser has 0.25 uF surge capacitors at its terminals, and condensers are connected to the transformers through two cable sections. Faults were applied at three locations under different operating conditions to determine the most limiting conditions.

The most critical faults from a TRV perspective were condenser fed faults shown in Fig. 1. FLT3 was a fault applied at the terminals of the condenser breaker when the internal voltage was assumed to be at 1.45 p.u. FLT4 was a fault applied at the bus-tie breaker. The bus-tie breaker would see the highest short circuit duty if the autotransformer and two condensers feed into the fault. However, this breaker would also see a very high TRV duty if the fault contribution comes from condensers only. i.e. Autotransformer TF1 was out of service.

III. Results and Discussion

The evaluation of the acceptability of breaker TRV is based on the comparison of calculated TRV values with applicable IEEE and ANSI standards. Although IEEE Std. C37.04, ANSI C37.06, and IEEE Std. C37.09 are being revised concurrently [5] current revisions of ANSI C37.06-2000 [6] and ANSI C37.06.1- 2000[7] were considered as applicable references for comparisons with calculated values.

A. 115 kV Breakers in the Ring Bus

The highest TRV duty was calculated for breaker A12 when the breaker A21 was taken out of service, which results in a fault current being directly fed from the phase-shifting transformer/autotransformer. The calculated values would exceed the capability of 145 kV definite purpose breakers as shown in Fig. 2.

The phase-shifting transformer contains a single tank design with a delta connected exciting winding. This arrangement of windings provides very small series impedance at zero phase-shifting angles. A wide variation in the series inductance and the relatively small stray capacitance associated with the equipment would generally result in a high natural frequency of oscillations. The change in series impedance would also cause a significant variation in the fault currents passing through the phase-shifting transformer. Therefore, 115 kV circuit breakers in the ring bus (A11 to A32) would experience severe duties when the fault current is entirely fed by phase-shifting transformers.

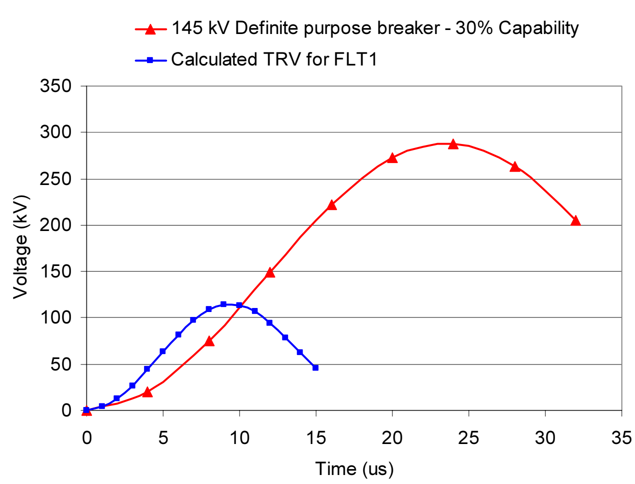

Fig. 2. TRV calculated for breaker A12 for a three-phase to ground fault at FLT1. Comparison of calculated waveform with 145 kV definite purpose breaker capability curve at 30% interrupting duty.

Addition of extra capacitance at the bus side of the breaker can reduce high RRRV [3],[5]. However, the amount of extra capacitance required needs to be determined while taking the variation of inductance in the phase shifting transformer into consideration. An efficient means to rapidly analyze this type of problem is to use frequency domain analysis.

Frequency scans have been used to determine the natural frequency of a network [9]. This technique would give the frequency of the system TRV, although it cannot provide any information about the magnitude of TRV. In this analysis, frequency scans were used to determine the amount of capacitance required to reduce the frequency of oscillations based on the rise time of the breaker capability curve. Time domain simulations were carried out using the calculated capacitance, which confirmed that resulting TRV does not exceed the breaker capability. By combining frequency scans with time domain simulations, this technique has reduced the number of iterations required to determine the size of capacitance when the circuit has a variable inductance such as a phase-shifting transformer.

The harmonic impedance of the system as seen from breaker A12 looking into the source side of the station was calculated for a number of phase shifting angles with and without a capacitor (Fig. 3). Harmonic impedance calculated without additional capacitance shows very high impedance around 60 kHz, which corresponds to the rise time seen in Fig.2 for the calculated TRV. The frequency scans indicated that an addition of a 0.06 uF capacitor would be adequate to reduce the frequency of oscillations.

After the required capacitance was identified as 0.06 uF, time domain simulations were carried out to confirm that the calculated values do not exceed the breaker duty. Fig. 4 shows TRV calculated for breaker A12 for a three-phase to ground fault at FLT1 with a 0.06 uF capacitor and a PST phase angle of 32 degrees. At this phase angle, short circuit current was about 7% of the breaker rating of 40 kA. Thus the calculated values were compared with the 7% capability curve, which has a lower RRRV capability than the 30% capability.

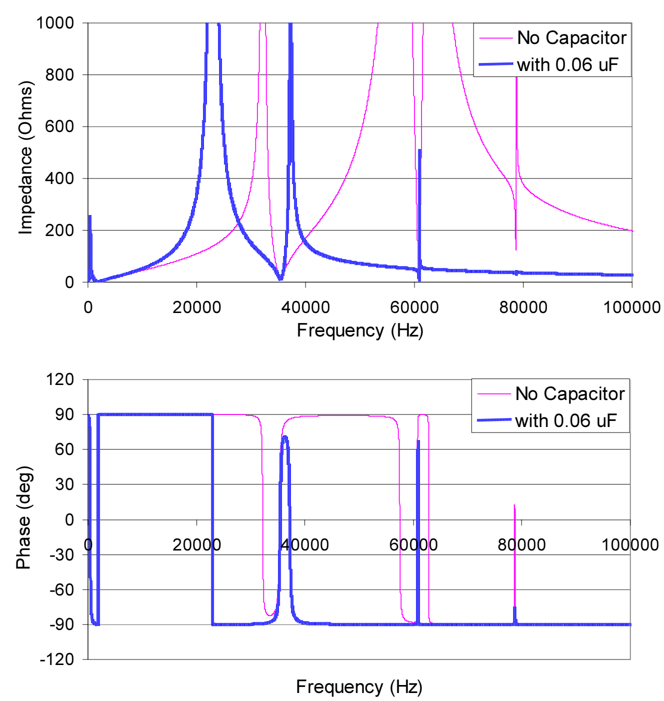

Fig. 3. Calculated values of harmonic impedance seen from breaker A12 into the source side of the station with and without a 0.06 uF capacitor and a PST phase angle of 32 degrees.

B. 115 kV Breakers at Capacitor Banks

The switched capacitor banks have inrush limiting reactors mounted at the top of the capacitor banks. Air core reactors are generally used for these applications, which inherently have a very high natural frequency of oscillation.

If a fault occurs between the reactor and the capacitor bank (FLT2) when breakers A21 and A22 were out of service, the ensuing TRV across breaker C3 would have a very high oscillation frequency. This is due to the fact that the fault current is entirely fed from the transformers while a fault is applied at behind an air-core reactor. The frequency of oscillations seen in Fig. 5 corresponds to the natural frequency of inrush limiting reactor.

The high frequency transients could be limited by either relocating the reactor to the bottom of capacitor bank or by mounting extra capacitance at the reactor side of the breaker terminals. Frequency scans show that a 0.06 uF capacitance is adequate to reduce the high RRRV to acceptable values. The worst-case fault condition was calculated when the fault current is below 7% of the rated breaker interrupting duty. Fig. 6 shows the comparison of the calculated TRV duty with the breaker interrupting capability.

C. 15 kV Breakers

Each synchronous condenser will have a 15 kV breaker that is expected to clear all faults including three phase to ground and three phase ungrounded faults. Very high transient recovery voltages (TRV) can occur during three-phase ungrounded faults. Special considerations are required in the case of condenser breakers when the breaker opens to clear a condenser-fed fault while the condenser is operating at very high excitation levels, which results in high internal voltage. The high internal voltage would appear across the breaker contacts when the breaker opens, resulting in a very high TRV duty on the breaker. A three-phase ungrounded fault (FLT4) was applied at the bus-tie breaker (S7). Fig. 7 (a) shows a comparison of calculated TRV and TRV peak capability of a 15 kV general purpose breaker for a condenser fed fault.

The very high TRV duty calculated for clearing of condenser fed faults together with very high short circuit currents seen at this station indicated that general purpose breakers could not meet the requirements of this application. However it was found that a generator class 15 kV breaker was available which could meet the duty for this application. Based on several inquiries from circuit breaker manufacturers, a 15 kV, 63 kA generator class vacuum circuit breaker was selected. This circuit breaker has the capability to withstand a TRV magnitude of about 45 kV at 50% interrupting duty. However, the calculated TRV in the most limiting cases would slightly exceed this value. Thus, the high TRV needed to be mitigated.

Fig. 7 (b) shows the voltages calculated at the two contacts of breaker S7 during a three-phase fault at FLT4. These waveforms show the first pole to clear, is exposed to a TRV voltage comprised of two voltage components that are out of phase.

The proposed solution is to use arresters to limit the TRV magnitude. At these voltage levels, 18 kV phase-to-ground surge arresters would marginally conduct. However, peaks values are well into the conduction range of 18 kV arresters, if the arresters were connected phase-to-phase. Fig. 8 shows the comparison of calculated TRV and voltage across the breaker contacts when 18 kV arresters were connected phase-to-phase at the source side of the breaker. Simulation results confirm that a generator class 15 kV, 63 kA breaker combined with phase-to-phase connected surge arresters could meet the very high TRV duty expected in this application.

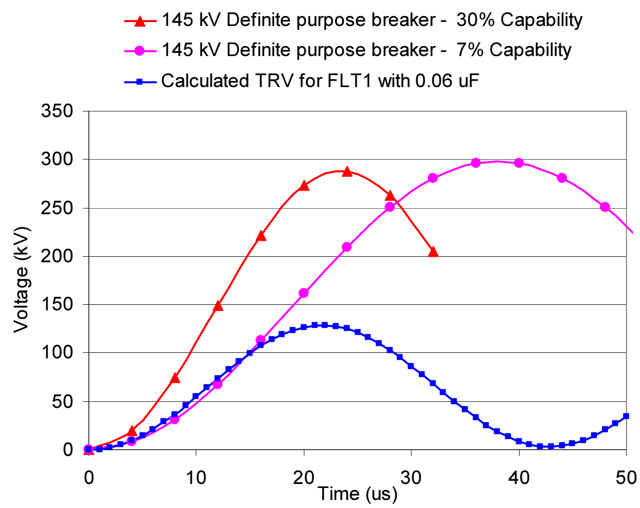

Fig. 4. TRV calculated for breaker A12 for a three-phase to ground fault at FLT1 with a 0.06 uF capacitor and a PST phase angle of 32 degrees. Comparison of calculated waveform with 145 kV definite purpose breaker capability curves.

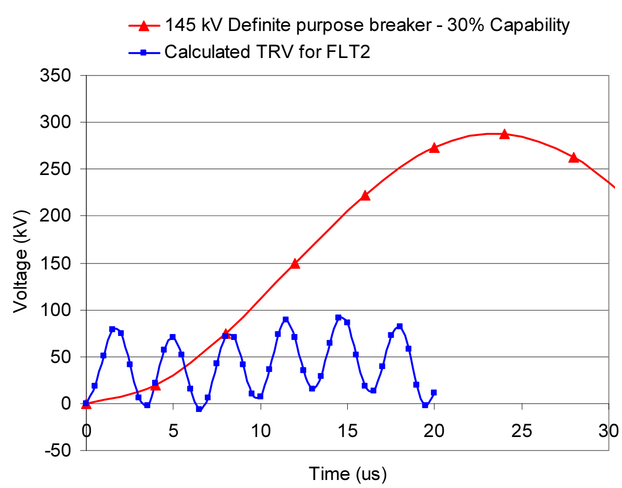

Fig. 5. TRV calculated for breaker C3 for a three-phase to ground fault at FLT2. Comparison of calculated waveform with 145 kV definite purpose breaker capability curves.

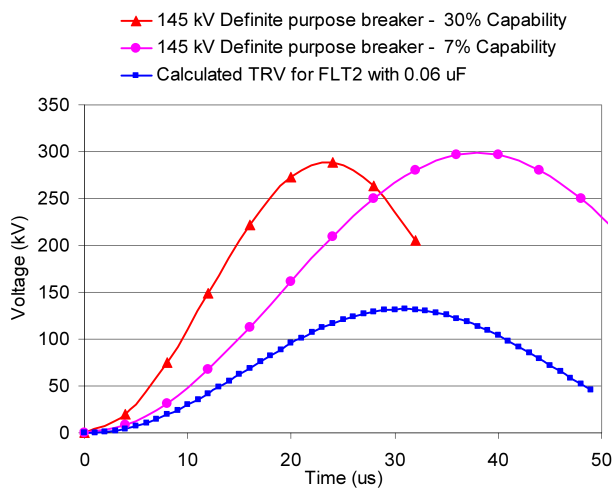

Fig. 6. TRV calculated for breaker C3 for a three-phase to ground fault at FLT2 with 0.06 uF capacitor. Comparison of calculated waveform with 145 kV definite purpose breaker capability curves.

Surge arresters would conduct for few cycles during the transient, however the energy dissipation is well within their capabilities. In addition, energy dissipation in arresters has significantly improved damping.

The condenser breakers generally would not see very high RRRV duty as a result of surge capacitance at the machine terminals, and a number of cables connected to the condensers.

The calculated TRV duty is also applicable for other 15 kV breakers in the station that may need to interrupt condenser fed faults including condenser breakers (S1 to S4) and incomer breakers S5 and S6.

IV. Conclusions

Several system configurations that could lead to very high TRV magnitude and RRRV in the presence of phase shifting transformers, synchronous condensers, and shunt capacitor banks, were presented. The high TRV/RRRV values could even exceed the breaker capability of definite purpose breakers.

If a fault is entirely fed by phase-shifting transformers (PST), a wide variation of inductance in the PST should be taken into consideration. If extra capacitance is considered for mitigation of high RRRV, both frequency scans and time domain simulations can be combined to determine the size of extra capacitance. This technique would significantly reduce the computation effort required, especially when the circuit has variable inductance such as a PST.

Synchronous condenser fed faults could have very high TRV that could even exceed the capability of generator class breakers due to high internal voltages. The most limiting cases found to be in the case of a three-phase ungrounded fault, which was mitigated by connecting phase-to-phase arresters at the condenser side of the breaker.

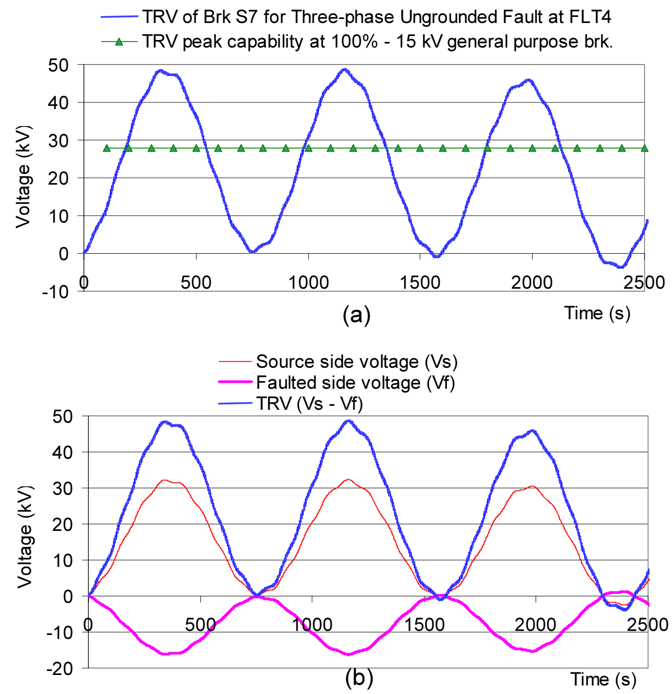

Fig. 7. TRV calculated for breaker S7 for a three-phase ungrounded fault FLT4. (a) Comparison of calculated waveform with TRV peak capability of 15 kV general purpose breaker; (b) Voltage calculated at two breaker contacts (Vs and Vf), and TRV calculated (Vs-Vf)

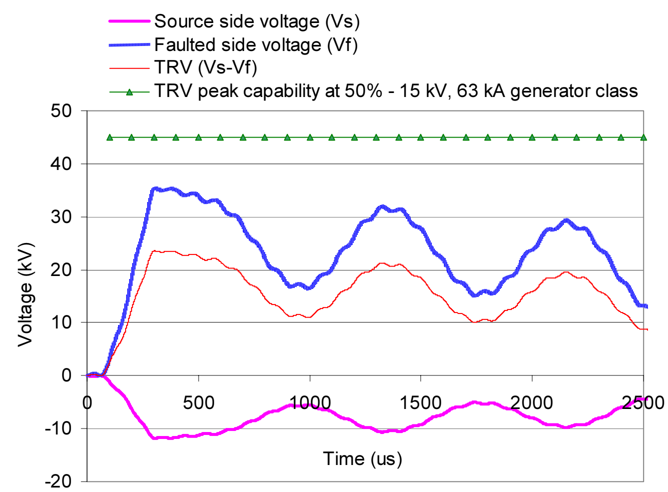

Fig. 8. TRV calculated with phase-to-phase MOV arresters for breaker S7. Comparison of calculated waveform with a 15 kV generator class breaker for a three-phase ungrounded fault FLT4.

V. Appendix

Equipment Data

(1) Phase shifting Transformer

115 kV/ 115 kV, 210 MVA

(2) Autotransformers

230 kV/115 kV/ 13.8 kV, 240 MVA

(3) Switched Capacitor Banks

24.75 Mvars each, 1.5 mH inrush limiting reactor

(4) Synchronous Condensers

25 Mvars (33 Mvars cold temp. rating), Xd" = 0.17 p.u.

TABLE I
SERIES IMPEDANCE OF PHASE-SHIFTING TRANSFORMERS
115 KV/115 KV, 210 MVA

Phase Angle	Impedance (p.u.)
0.0	0.0
16.4	0.6
32.2	2.1
46.8	5.2
60.0	10.2

VI. ACKNOWLEDGMENT

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VIII. BIOGRAPHIES

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