

# 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.

G. W. Becker and M. Waclawiak are with The United Illuminating Company, Shelton, CT 06484 USA

M. F McGranaghan is with The Electric Power Research Institute, Knoxville, TN 37932 USA.

S. Santoso is with The University of Texas, Austin, TX 78712 USA

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.

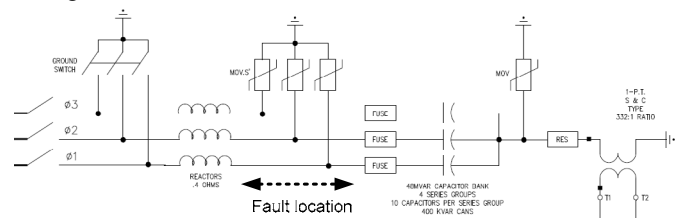


Fig. 1 – A 42 Mvar three-phase capacitor bank at a 115-kV Bus

The East Shore 115-kV capacitor configuration is similar

to the Hydro One Richview Transformer Station capacitor configuration [2-3]. They are both connected in a ungrounded-wye manner and inrush current limiting reactors are installed at the source side of the capacitor bank. On January 30, 2007 an extreme event occurred at the Rich View TS. A double phase-to-neutral fault occurred at the terminal of a 230 kV, 400 Mvar capacitor bank during an energizing operation. The double phase-to-neutral fault then evolved into a three-phase to neutral fault. The circuit breaker used to energize and de-energize the capacitor bank failed to clear the fault in time and the rate of rise of the recovery voltage was thought to have exceeded the breaker withstand transient recovery voltage capability. Because of this incident and given the fact that the capacitor bank configuration at the East Shore 115-kV substation is similar, the United Illuminating Company called for a study to evaluate the TRV withstand capability of capacitor circuit breakers when a three-phase fault occurs at the capacitor terminals.

### III. EVALUATION AND SOLUTION METHODS

TRV withstand capabilities of a circuit breaker are evaluated using standard practices described in IEEE Std. C37.011-2005 [4-5]. The prospective system TRV profiles are estimated for the most unfavorable short-circuit condition through the use of the time-domain modeling and simulation approach. 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. Since the resulting prospective system TRV is greatly influenced by the design of the circuit breaker, an idealized circuit breaker is used. Therefore, when the breaker conducts, it has zero impedance. At current zero, the breaker impedance changes from zero to infinity.

Since there are two three-phase capacitor banks in the same substation, energizing a capacitor bank with another bank already energized will cause significant inrush capacitive switching current to flow from the energized bank to the one being energized for a fraction of a cycle. Similarly, 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. Therefore, a good solution is one that addresses the capacitor breaker TRV concern while maintaining capacitive switching currents to rated switching and momentary current capabilities of both line and capacitor circuit breakers. In other words, the following criteria must be satisfied.

1. 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.
2. 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.

3. The line breakers must be able to withstand outrush capacitive switching and momentary currents during close-in faults.

### IV. TIME-DOMAIN MODEL OF 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 system wide model is preferred compared to a reduced network with a few buses away from the bus of interest. This is so because it can be reused for evaluating TRV performance of breakers at other buses and provides a more realistic representation of the system underground cable capacitance. The time-domain model was developed using the PSCAD/EMTDC platform.

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 line model essentially represents the L and C elements of a PI section in a distributed manner along the line and emulates the effect of an infinite number of PI sections. 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 built-in cable models are solved using the frequency-dependent phase approach.

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. Because effective capacitance values of East Shore 115-kV apparatus are not readily available, they are approximated using data available from IEEE Std. C37.011-2005 Annex B. Capacitance values are specified for outdoor bushings, inductive instrument transformers, capacitive voltage transformers, bus work, circuit breakers, and transformers.

### V. TRV ANALYSIS FOR THE EXISTING CONFIGURATION

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 (see Fig. 1) and the other capacitor was offline.

Fig. 2 shows phase currents and voltages during a three-phase ungrounded fault. When the fault is on the system but before it is cleared by the capacitor breaker (i.e. before 0.0173 msec), the voltage at the neutral point of the energized capacitor bank (refer to Fig. 1 for this neutral point) is zero (or negligible) as shown in Fig. 2D. This is so because the power system remains balanced as a three-phase ungrounded fault is a balanced fault. During this period, the transient recovery voltage (Fig. 2B) is zero because none of the poles have opened. Recall that the transient recovery voltage is the voltage across the contacts of the circuit breaker. The capacitor bank voltage (Fig. 2E) is also zero as the three-phase fault is at the source side of the capacitor terminals. The

voltage across the reactor is large (Fig. 2C) since the current flowing through it is a fault current (35 kArms).

When the first pole of the breaker opens (at 0.0173 msec), the voltage appears across the pole contacts. This is the system TRV voltage associated with the breaker opening (Fig. 2B). Note that the other two poles have not opened yet – thus they have no TRV. The power system beyond 0.0173 msec is unbalanced. The voltage at the neutral point of the capacitor bank (Fig. 2D) is no longer zero but it oscillates. For the purpose of evaluating the performance of the breaker TRV withstand capability; the first few microseconds following the first pole opening are most critical. The voltage across the reactor drops abruptly from about +20 kV to zero in 2  $\mu$ S as the fault current has been interrupted. This abrupt change causes a step voltage change (i.e. to -10 kV) at the neutral of the capacitor bank. Even without the step voltage change, the neutral voltage is moving away significantly from zero, i.e. to -80 kV. The shifting of the neutral voltage causes extremely high magnitudes in the system TRV. This is why an ungrounded capacitor bank typically imposes severe TRV duties on a circuit breaker.

The voltage step changes across the reactor and at the neutral point leads to a sudden step change in the TRV profile (i.e. 30 kV in 2  $\mu$ S, or an initial step change of 15 kV/ $\mu$ S). The RRRV is obviously unacceptable. Fig. 3 shows the first 150  $\mu$ S of the TRV profile. The sudden step jump can be clearly seen near the point of origin of the plot.

The system TRV profile is then compared with the existing breaker related TRV withstand capability at 71% of the rated interrupting current. Fig. 4 clearly shows that the system TRV profile greatly exceeds the breaker related TRV withstand capability in terms of the initial step jump, rate of rise of the recovery voltage and the peak voltage. Note that the step jump immediately following the breaker opening is clearly visible.

Current-limiting reactors have been used successfully over the years to reduce the peak magnitude and frequency of outrush currents experienced by a line breaker during close-in faults. Unfortunately, the presence of a current-limiting reactor places tremendous transient recovery voltage stress on a capacitor breaker when clearing a three-phase ungrounded fault at the source side terminals of the capacitor bank [6-7]. Depending on the size of the reactor, the transient recovery voltage across the contacts during the first pole opening may greatly exceed the TRV withstand capability of the capacitor breaker. When this condition occurs, the capacitor breaker is unlikely to open successfully

## VI. SOLUTION TO ELIMINATE THE INITIAL STEP CHANGE

The above analysis indicates that 0.4 ohm/phase reactors cause an abrupt initial step voltage change immediately after the first pole of the breaker opens. This step change then causes a step voltage change in the neutral of the capacitor bank.

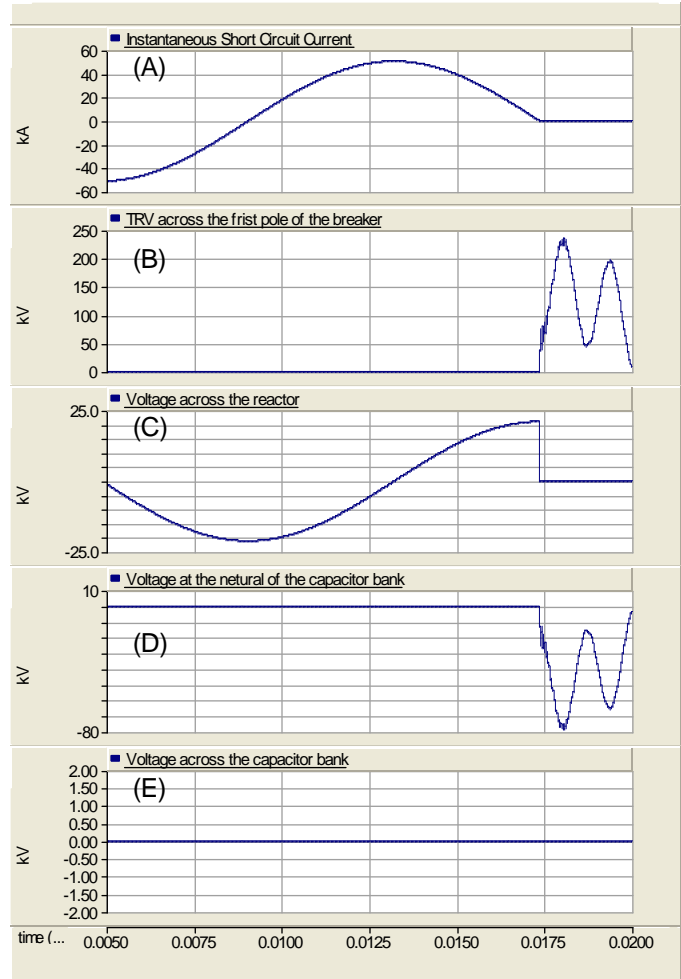


Fig. 2. Short circuit current and voltages at the phase with the first open pole during the three-phase ungrounded fault at the source side of the capacitor terminals.

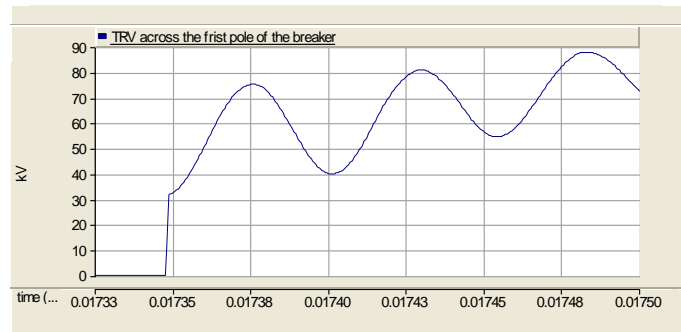


Fig. 3. Comparison between the prospective system TRV associated with the capacitor breaker and the related TRV capability of a general purpose breaker at 71% of interrupting rating.

The initial step jump in the system TRV can be eliminated by completely removing these reactors from the capacitor configuration. Alternatively, the reactors can be bypassed once a back-to-back energizing operation is completed. Unfortunately, these mitigation measures are not desirable as a three-phase ungrounded fault may occur before reactors are bypassed. Furthermore, these reactors must be present in the circuit for the outrush current limiting purpose.

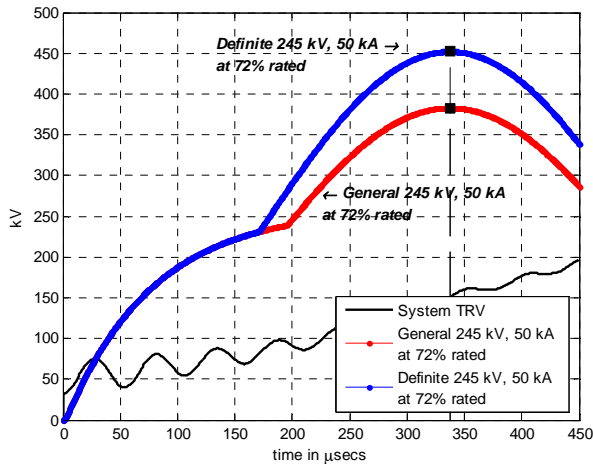


Fig. 4. Comparison between the prospective system TRV associated with the capacitor breaker and the related TRV capability of a general purpose breaker at 71% of interrupting rating.

A sound engineering solution to this problem is to relocate these reactors to the neutral side of the capacitor bank as shown in Fig. 5. 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.

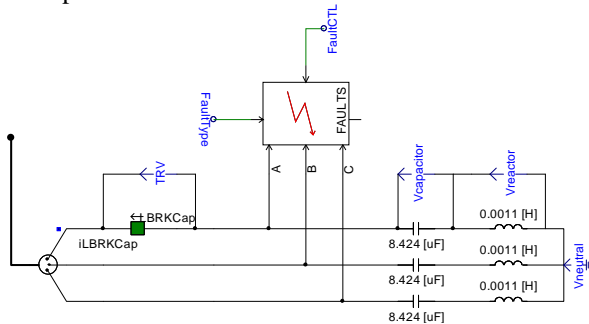


Fig. 5. Proposed solution to Eliminate Step Jump in the System Transient Recovery Voltage.

The proposed solution is evaluated through simulations with conditions described earlier. Fig. 6 shows the resulting short-circuit current, the neutral voltage, and voltages across the reactor, breaker, and capacitor at the phase in which the first pole opens. While the fault is on the system but before the first pole opens (i.e., before  $t = 0.0173$  msec), the voltage across it is zero because the pole has not yet opened. Voltages across the capacitor and reactor are zero because the fault is exactly at the source side of the capacitor terminals. The neutral voltage is zero because the power system is still balanced as this is a balanced fault.

Immediately after the first pole of the breaker opens ( $t > 0.0173$  msec), the power system becomes unbalanced. As expected, the neutral voltage (Fig. 6D) shifts significantly away from zero. In addition, its magnitude is larger than that shown in Fig. 2D. This is attributed to the presence of the reactor at the neutral side of the capacitor. Note that the capacitor configuration is ungrounded.

It is interesting to note that the voltage across the reactor (Fig. 6C) is insignificant compared to the neutral voltage.

Therefore, 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. If the size of the reactor is sufficiently large, the voltage across it would be larger. An initial step change immediately after the first pole opening would be observed. The larger the size of the reactors and the larger the magnitude of the fault current, the higher the initial step jump will be. The size of the capacitor bank has an insignificant effect on the magnitude of the initial step jump since the voltage across (Fig. 6E) is even smaller as compared to that of the reactor.

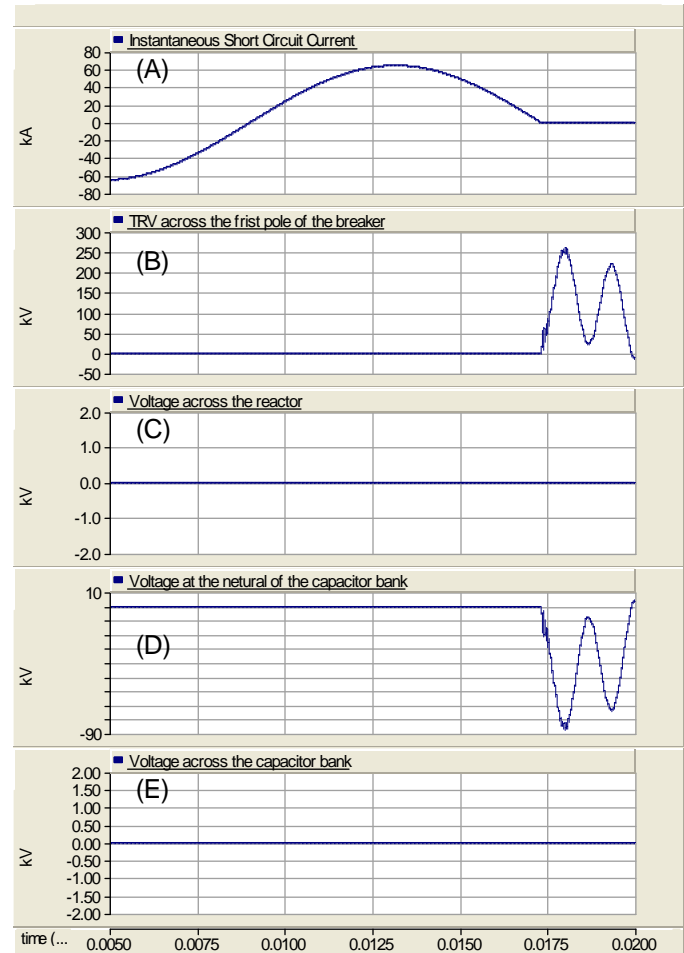


Fig. 6. Short circuit current and voltages at the phase in which the first pole opens during the three-phase ungrounded fault at the source side of the capacitor terminals.

Fig. 7 shows the first 200  $\mu$ s of the system TRV is plotted and compared with the breaker TRV withstand capability curve. Of course, the peak TRV exceeds the breaker withstand capability; however, the initial step jump in the system TRV is clearly eliminated. Based on this analysis, the conclusion is that reactors must be relocated to the neutral of the capacitor banks to get rid of the initial step jump in the system TRV.

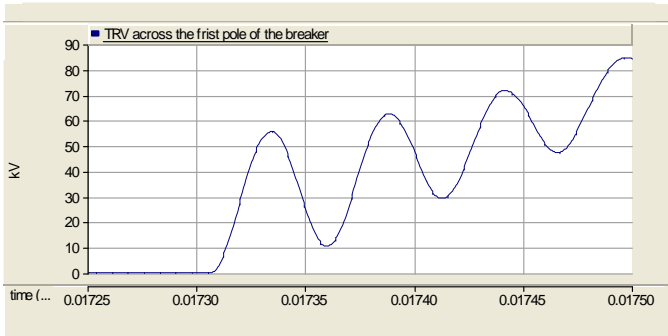


Fig. 7. System transient voltage recovery profile after the reactors are relocated to the neutral of the capacitor bank. The initial step jump in the system TRV is eliminated

## VII. 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.

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.

The prospective system TRV profiles for an ungrounded neutral reactor configuration were evaluated for three-phase ungrounded and grounded faults. On the basis of clearing three-phase grounded faults at the capacitor terminals, a capacitor breaker must be rated 123 kV/63 kA general-purpose or higher. However, it cannot be expected to successfully clear a three-phase ungrounded fault at the same location. Fig. 8 shows system TRV profiles for three-phase grounded and ungrounded faults relative to breaker TRV capabilities. System TRV peaks for three-phase ungrounded and grounded faults are 274.5 kV and 157.1 kV, respectively. In other words, a three-phase ungrounded fault yields 118 kV higher than a three-phase grounded fault. To successfully clear a three-phase ungrounded fault, the capacitor breaker must be rated 170 kV/63 kA definite-purpose or higher. It is important to note that two 47.5-nF three-phase sets of CVTs are added to both main buses.

## VIII. RECOMMENDED CAPACITOR CONFIGURATION

In addition to the TRV evaluation which resulted in the application of 123kV, 63kA circuit breakers for capacitor bank protection (based on a three phase grounded fault), the size of current-limiting reactors were evaluated to ensure that they have adequate inrush and outrush capabilities without adversely affecting the breaker TRV performance.

The effectiveness of circuit switchers with pre-insertion resistors was also evaluated. Therefore, instead of using a circuit breaker to energize and de-energize a capacitor, an appropriate circuit switcher designed for switching and protection of shunt capacitor banks should be used. Such a circuit switcher is equipped with standard pre-insertion closing resistors and has a much higher number of operations between maintenance intervals (i.e. 10,000 operations for the circuit switcher before required major maintenance, versus 2,000 operations for the circuit breaker before required major maintenance). The recommended capacitor configuration for each 42 Mvar capacitor bank is summarized in Fig. 9. The capacitor breakers shown are on the basis of three-phase grounded faults.

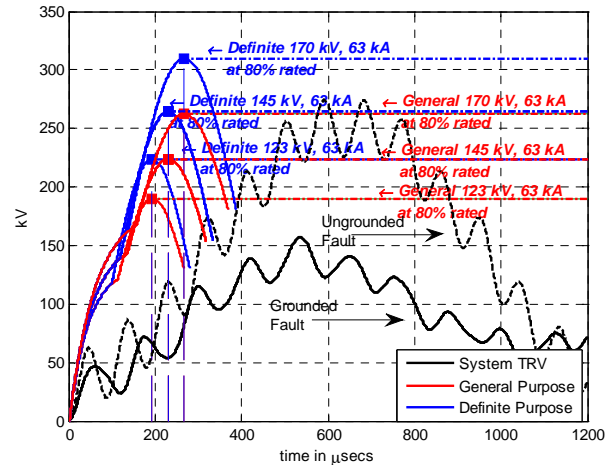


Fig. 8. Comparison between the prospective system TRV associated with grounded and ungrounded faults in an ungrounded capacitor configuration.

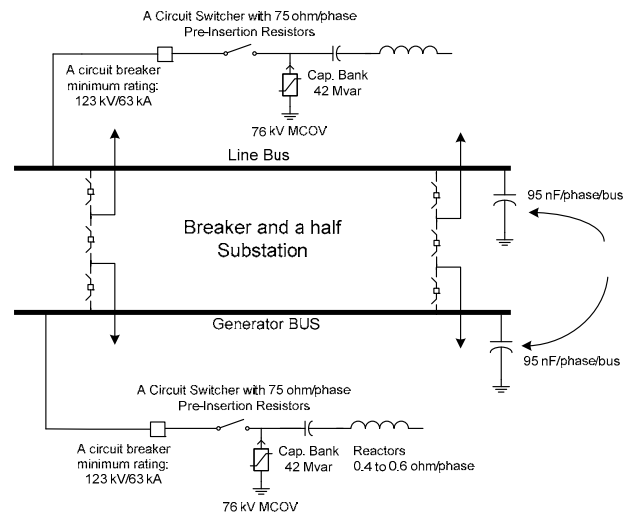


Fig. 9. Future capacitor configuration with the neutral point of the reactors being ungrounded. Capacitor breaker ratings on the basis of three-phase grounded faults are 123 kV/63 kA general-purpose or higher.

## ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions of Daniel Brooks and Wes Sunderman of Electric Power Research Institute, and Christian Bilcheck, Robert Pellegrini, Mark Adams, Alex Boutsoulis, Dave Bradt, and Chuck Eves



of The United Illuminating Company for their work associated with this document.

## IX. REFERENCES

- [1] T. A Bellei, and G. Ransom, "Current-limiting inductors used in capacitor bank applications and their impact on fault current interruption," 2001 IEEE/PES Transmission and Distribution Conference and Exposition, Vol. 1, pp. 603 – 607, Oct. 28 – Nov. 2, 2001..
- [2] L. Marti, Richview TS Capacitor Bank Failure," Special Studies, Transmission System Development, Hydro One Networks, Inc, June 8, 2007.
- [3] IESO, *Richview SC22 Incident – January 30, 2007*, IESO\_REP\_0386, [http://www.ieso.ca/imoweb/pubs/ircp/IESO\\_REP\\_0386-Richview-SC22-20070130.pdf](http://www.ieso.ca/imoweb/pubs/ircp/IESO_REP_0386-Richview-SC22-20070130.pdf), accessed Nov. 23, 2009.
- [4] C. L Wagner, H. M Smith, "Analysis of transient recovery voltage (TRV) rating concepts," *IEEE Trans. Power Apparatus and Systems*, vol. PAS-103, No. 11, Nov. 1984, pp. 3354 – 3363.
- [5] IEEE Std. C37.011-2005, IEEE Application Guide for Transient Recovery Voltage for AC High-Voltage Circuit Breakers, Institute of Electrical and Electronics Engineers, New York, NY.
- [6] J. Rostron, "Outrush reactors for capacitor banks, The Solution or a Problem," in <http://www.southernstatesllc.com/pdf/News-Aug05.pdf>. Accessed October 26, 2008.
- [7] J. R Ribeiro, "Protect circuit breakers from close-in fault," *Transmission and Distribution World Magazine*, May 01, 2008.

## X. BIOGRAPHIES

**George W. Becker** earned a Bachelor of Science Degree in Electrical Engineering and a USCG Third Assistant Engineer's License from the State University of New York Maritime College in 1986. In 1992 he earned a Masters Degree in Electric Power Engineering from the Polytechnic Institute of New York. In 1994 he also earned an MBA from the University of New Haven.

Mr. Becker is the Manager of Transmission and Substation Engineering for The United Illuminating Company located in New Haven, Connecticut. He has also held several Engineering and Operations positions over his prior 20 year tenure with Northeast Utilities Service Company in Berlin, Connecticut; these included Manager of Document Control and Design Standards, Manager of Distribution Substation Engineering and Design, Substation Project Engineer, System Protection Engineer and Equipment Test Specialist.

Mr. Becker is a Senior Member of the IEEE and the Vice Chairman of the Gas-Insulated Substations Subcommittee of the IEEE Substations Committee. He is also Chairman of the Working Group charged with developing the IEEE Guide for the Application of Medium-Voltage Gas-Insulated Substations 1kV to 52kV.

Mr. Becker is a registered Professional Engineer in Connecticut and Massachusetts.

**Marek G. Waclawiak** received his Masters Degree in Electrical Engineering from Politechnic of Lodz, Poland in 1976. He is member of Institute of Electrical and Electronics Engineers. He is serving as a member of Power Delivery and Utilization Business Area Council of Electric Power Research Institute since 1995.

Mr. Waclawiak is the Chief Electrical Engineer with the United Illuminating Company in New Haven, CT. He joined the United Illuminating Co. in 1985 after spending four years in Distribution System Network Design for the City Public Service of San Antonio in Texas. Mr. Waclawiak participates in R&D and Strategic Planning for Electric System at UI. Prior to his present assignment, he lead UI's System Integrity Group responsible for Reliability, Power Quality, Distribution Planning and Distribution Standards. Mr. Waclawiak responsibilities also included Distributed Generation Interconnection issues, Power Quality efforts including the power quality monitoring system, various distribution system studies especially in the underground electric network systems.

Mr. Waclawiak has coauthored CIRED papers - "Weather Normalized Load Demand Forecasting for Distribution Planning" and "Using Energy as a Measure of Risk in Distribution Planning", IEEE Transaction Papers – "System impacts evaluation of a single-phase traction load on a 115-kV transmission system", "Substation power quality performance monitoring and the Internet", "Substation power quality monitoring to prioritize system improvements" and "Indices for Assessing Utility Distribution System RMS Variation Performance"; and an article to *Transmission & Distribution World Magazine* – "Utilities Implement Intelligent Monitoring Applications to Improve Reliability

Mr. Waclawiak is a registered professional engineer in the state of Connecticut.

**Mark F. McGranaghan** received the B.S.E.E. and M.S.E.E. degrees from the University of Toledo, Ohio and the M.B.A. degree from the University of Pittsburgh, Pennsylvania. Currently, he is vice president of consulting services at EPRI, Knoxville, Tennessee. He is coauthor of the book *Electrical Power Systems Quality*. He has been influential in developing IEEE and international standards for harmonic limits on power systems and within facilities. He helped to achieve coordination between the IEEE and IEC in a wide range of PQ standards development activities. He has taught seminars and workshops on PQ issues and power system analysis to electric utility engineers from around the world. He is a Member of the IEEE.

**Surya Santoso** received the B.S.E.E. degree from Satya Wacana Christian University, Indonesia, in 1992 and the M.S.E.E. and Ph.D. degrees from the University of Texas at Austin in 1994 and 1996, respectively. He is an Associate Professor with the Department of Electrical and Computer Engineering, The University of Texas at Austin, where he has been since 2003. He was a Senior Power Systems/Consulting Engineer with Electrotek Concepts, Knoxville, TN, between 1997 and 2003. His research interests include power system analysis, modeling, and simulation, and wind power integration. Mr. Santoso is coauthor of *Electrical Power Systems Quality* (McGraw-Hill), now in its 2nd edition. He also authors a recently published college textbook entitled, *Fundamental of Power Quality*, (Createspace/Amazon.com). He is a senior member of the IEEE since 2002.