Study of 345 kV Transient Recovery Voltages on the Illinois Power System

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Abstract--Illinois Power will be installing twenty-two new 345 kV breakers at the Baldwin and Prairie State Substations. These breakers are part of an overall system upgrade required to interconnect approximately 1275 MW of new coal fired generation. Prior to the installation, an engineering study was completed to evaluate transient recovery voltages (TRVs) for various breaker operations and system contingencies for these switchyards and other connected and affected substations. The transient analysis for the study was performed using the PSCAD simulation program.

The study found that for a number of cases, the TRV waveshapes exceeded their related TRV capability limits for the first 10-50 μsec. The results also indicated that clearing short-line faults (SLFs) on lines leaving the 345 kV substations would result in an initial rate-of-rise of the recovery voltage (RRRV) that exceeds the breaker's SLF capability. The study evaluated the application of an additional capacitance on the line side of the circuit breakers. This capacitance reduces the initial RRRV to within the related SLF capability.

This paper will present a summary of the model development and simulations completed during the TRV study.

Keywords: transient recovery voltage, TRV, rate-of-rise of the recovery voltage, RRRV, short-line faults, SLF, switching surges, modeling decisions, data simplification, data verification.

I. Introduction

Due to the concern for excessive TRVs during breaker operations, Illinois Power Company (now AmerenIP), and Electrotek Concepts, Inc. (Electrotek) performed an engineering study to evaluate the proposed design, as well as the impact on nearby utility equipment. The study evaluated the concerns and possible solutions, such as adding capacitive devices, to protect against the harmful transients that may damage the surrounding equipment and power system.

The analysis of high-frequency TRVs frequently requires the use of sophisticated digital simulation tools. 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 4.0.2 Professional) [1]. This program can be used for the analysis of circuit switching operations, capacitor switching, lightning transients, and transients associated with the operation of power electronic equipment.

II. Study Methodology

The TRV evaluation for various fault conditions was based on the methods provided in IEEE Std. C37.06 [2], IEEE Std. C37.04 [3], and IEEE Std. C37.011 [4]. This involved analysis of the most severe conditions, including the clearing of a three-phase ungrounded symmetrical fault at the breaker terminal when the system voltage is at a maximum and SLFs.

The study considered normal cases where the system operates with all breakers and lines in service and various contingencies where only one breaker is available to clear a fault. For both of these conditions, three-phase ungrounded and single-line-to-ground faults were evaluated.

TRV is the voltage across the terminals of a pole of circuit breaker following current zero when interrupting faults. TRV waveshapes can be oscillatory, exponential, cosine-exponential or combinations of these forms. TRVs due to 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 breaker and the fault. Due to the short distance involved between the fault location and the open breaker, the initial RRRV can be very steep.

According to IEEE Std. 37.011-1994, 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 TRV performance meets the withstand criteria when subjected to the fault condition mentioned above, a SLF evaluation is not necessary. This is due to the fact that SLF TRV capability is higher than that of a three-phase ungrounded fault.

III. Model Development

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

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The TRV system model was based on short-circuit data provided by Illinois Power. The short-circuit model consisted of positive and zero sequence impedance data prepared in the ASPEN Oneliner format (Version V2001E). The study area included the Baldwin and Prairie State Substations and the adjacent system (see Fig. 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.

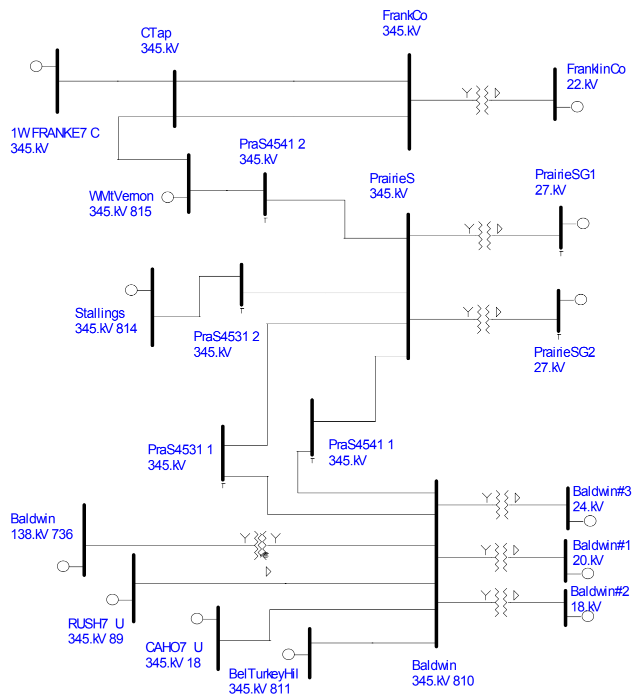

Fig. 1. System Model for the 345 kV TRV Study

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 I.

TABLE I
STEADY-STATE FAULT SIMULATIONS COMPLETED FOR MODEL VERIFICATION

Case ID	Fault Location	Full Model	Reduced Model	PSCAD Model
F1 F2	Baldwin Sub. 345 kV Bus	$I_{3\phi} = 40515$ $I_{\phi G} = 46077$	$I_{3\phi} = 40281$ $I_{\phi G} = 45811$	$I_{3\phi} = 40995$ $I_{\phi G} = 46313$
F3 F4	PrairieS Sub. 345 kV Bus	$I_{3\phi} = 37039$ $I_{\phi G} = 39797$	$I_{3\phi} = 36826$ $I_{\phi G} = 39569$	$I_{3\phi} = 38113$ $I_{\phi G} = 40311$
F5 F6	W. Mt. Vernon Sub. 345 kV Bus	$I_{3\phi} = 19141$ $I_{\phi G} = 15252$	$I_{3\phi} = 18986$ $I_{\phi G} = 15128$	$I_{3\phi} = 18836$ $I_{\phi G} = 15253$

The data provided by Illinois Power 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.

A. Circuit Breaker Data

In evaluating the TRV withstand capability for the 345 kV breakers, the following references were used:

1. ANSI C37.06-2000 Tables 3 and 6 (Note 6 for Table 3)
2. IEEE C37.04-1999, Section 5.9, Table 2 and Figure 5

The new 345 kV breakers will have the following ratings:

Rated Maximum Voltage: .... 362 kV
Rated Continuous Current: .... 3000 A
Rated Short-Circuit Current: .... 63 kA
Rated Interrupting Time: .... 2 Cycles
Rated Transient Inrush Current: .... 25 kA
Rated Transient Inrush Current Frequency:.........4250 Hz

TRV-related data is shown in Table II and Table III.

TABLE II
RATED TRV CAPABILITY OF 362 KV, 3000 A, 63 KA BREAKER

T2 (µsec)	R (kV/µSec)	T1 (µsec)	E1 (kV)	E2 (kV)
775	2	2	1.06 V	1.49 V

TABLE III
MULTIPLIERS FOR VARIOUS INTERRUPTING LEVELS FOR TERMINAL FAULTS (LINEAR INTERPOLATION USED FOR OTHER NUMBERS)

Percent Rating (%)	R	E2	T2
100	1	1	1
60	2	1.07	0.5
30	0	1.13	0.2
10	0	1.17	0.2

The waveshape of the exponential component E1 for terminal faults below 30% of the breaker rating is 1-cosine. Based on Tables II and III 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. Fig. 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.

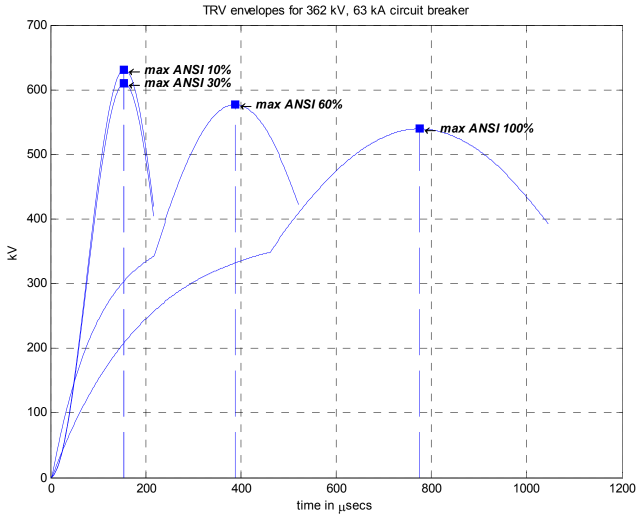

Fig. 2. TRV Withstand Capability for a 362 kV, 3000 A Continuous, 63 kA Short-Time Circuit Breaker

B. Capacitance Values for Substation Equipment

Equivalent values of capacitance for substation equipment were the lumped values at the breaker terminals. Since the capacitance values for the 345 kV equipment at the studied substations were not supplied by Illinois Power, it was agreed that typical capacitance ranges based on Annex B of IEEE Std. C37.011-1994 would be used. Three equivalent capacitance values (minimum, maximum, and average) were determined. Table IV shows an example of the collection of typical capacitance values for each bus section in the model.

TABLE IV
TYPICAL CAPACITANCE VALUES
BASED ON ANNEX B OF IEEE STD. C37.011-1994

Baldwin Substation **C_{eq} for the 345 kV East Bus**	**Qty**	**Min (ρF)**	**Max (ρF)**	**Avg (ρF)**
Disconnect Switch	4	60	200	130
CT 6-MR 600/1	4	150	450	300
Bus CVT	1	2000[1]	11000	6500
345 kV Bus (983 Feet)	1	2458	5407	3932
Total:		**5298**	**19007**	**12152**

[1] *Note: 2000 ρF for CVTs provided by Illinois Power*

This process was repeated for all of the 345 kV substation equipment in the system model. The minimum values of equivalent capacitance were used throughout the simulation process for both normal and contingency cases.

C. Basecase Model Development

Fig. 3 shows a portion of the overall PSCAD circuit model used to determine the prospective TRV withstand capabilities for the 345 kV breakers when clearing a three-phase ungrounded fault at the line terminals under normal and contingency conditions. TRV, peak current interrupted, and the percentage of interrupted current (based on the short-time rating for the breakers) was observed for each simulation case. Prospective TRV 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 TRV envelope capability. This process was then repeated for each 345 kV breaker at the Baldwin and Prairie State Substations for both three-phase and single-line-to-ground faults under both normal and contingency conditions.

The contingency cases involved clearing the fault with one breaker being out of service. This condition represents breaker delay in clearing faults, stuck breakers, or breakers taken out of service for maintenance. When one breaker is out of service, the TRV experienced by the clearing breaker tends to be higher. This is due to the fact that there is only one breaker that performs fault clearing instead of two breakers as in normal operating conditions.

The cases for evaluating SLF clearing involved applying a three-phase ungrounded fault 2 km away from the line terminal. A distance of 2 km was chosen to determine the effects of SLF conditions on the RRRV. This process was repeated for each of the 345 kV transmission lines.

The evaluation of both normal and SLF fault cases resulted in approximately 150 simulation cases being completed.

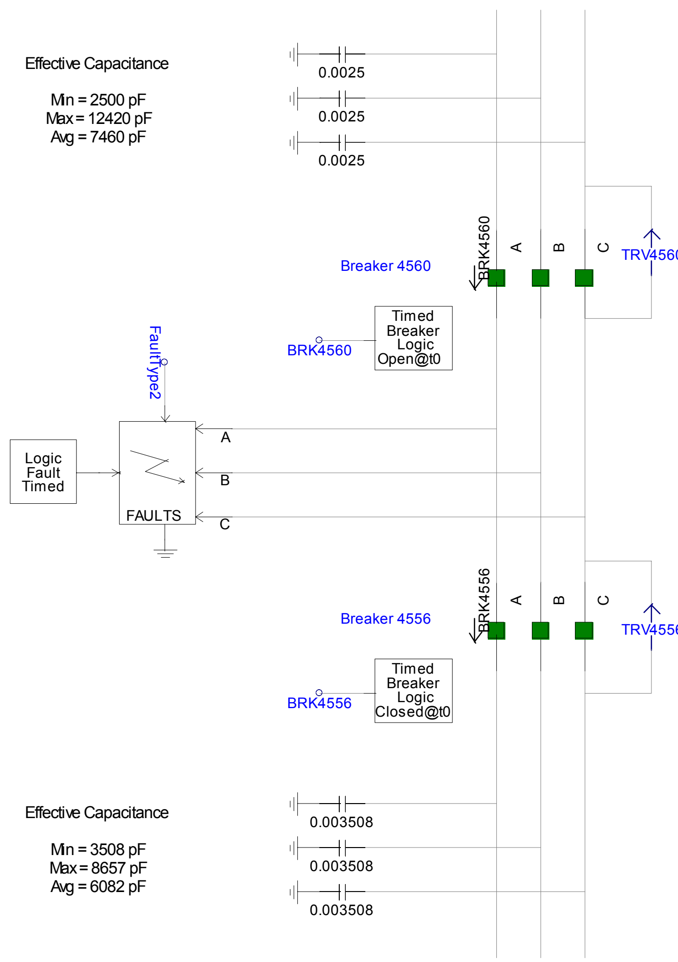

Fig. 3. Circuit for Applying a Three-Phase Fault at the Breaker Terminal

IV. Simulation Results

The TRV evaluation was conducted for the most severe operating conditions, including both three-phase ungrounded faults at the breaker terminal and SLFs. The study considered both normal cases where the system operates with all breakers and lines in service and contingency cases where the only one breaker is available to clear the fault.

A. Three-Phase Ungrounded Terminal Faults

The simulation results for the three-phase ungrounded fault clearing cases were summarized in tables similar to Table III. The table shows the respective case identifier, the breaker number, the peak current that the breaker interrupted, this peak current as a percentage of the rated value (63 kA), the peak TRV in kV, and a note to report whether the TRV was within the breaker's capability envelope. A "YES*" note signifies that the TRV waveshape slightly exceeded the TRV capability for the first 10-50 μsec, but it met the TRV SLF capability. A "NO" note signifies that the TRV waveshape did not meet the TRV capability limit.

TABLE III
TRV Evaluation of Three-Phase Ungrounded Terminal Faults
(Normal System Condtions)

Case ID	Breaker ID	Peak Current (kA)	Percent Rated (%)	Peak TRV (kV)	Within Envelope (Y/N)
A1	4564 4560	33.96 21.44	38.18 24.07	512.66 512.67	YES* YES*
A2	4560 4556	25.34 31.93	28.45 35.84	484.85 484.86	YES* YES*
A3	4592	58.58	66.09	541.73	NO
Continued…					

Fig. 4 and Fig. 5 show several examples of the simulation results for the three-phase ungrounded fault clearing cases summarized in Table III. Fig. 4 shows the recovery voltage for breaker 4560 for Case A1 and Fig. 5 shows the recovery voltage for breaker 4592 for Case A3. Each graph of TRV includes an overlay of the withstand capability.

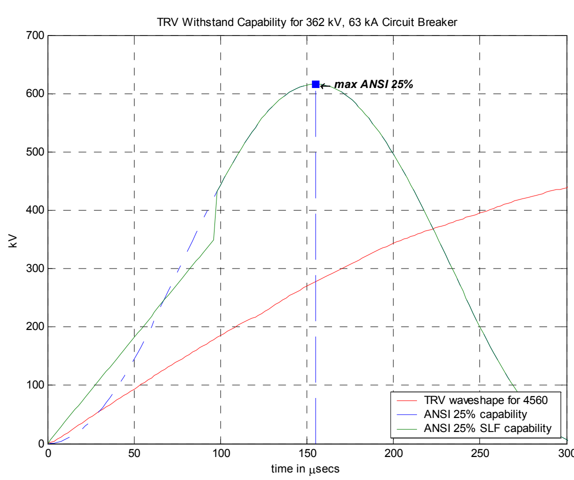

Fig. 4. TRV Withstand Capability for Breaker 4560 for a Three-Phase Ungrounded Fault at the Breaker Terminals on the Cahokia Line Side

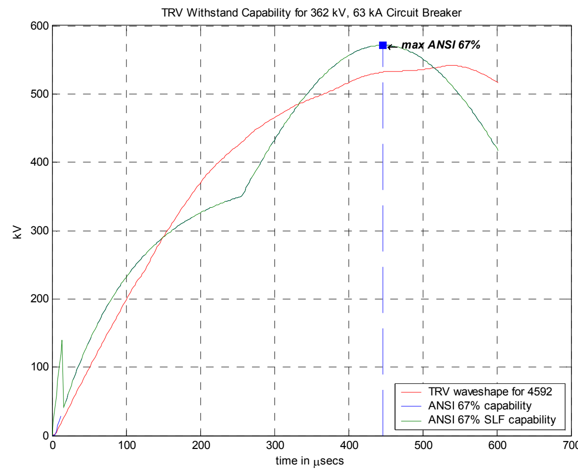

Fig. 5. TRV Withstand Capability for Breaker 4592 for a Three-Phase Ungrounded Fault at the Breaker Terminals on the Turkey Hill Line Side

B. Short-Line Faults

The simulation results for the SLF cases were recorded and compared to their respective TRV withstand and SLF capabilities. Fig. 6 shows an example of the simulation results for a SLF clearing case. When compared to their respective terminal fault case, the magnitude of the peak fault current interrupted was lower due to the additional line impedance between the fault location and the breaker terminals. However, the RRRV was higher due to the traveling waves that oscillate between the fault location and breaker terminals.

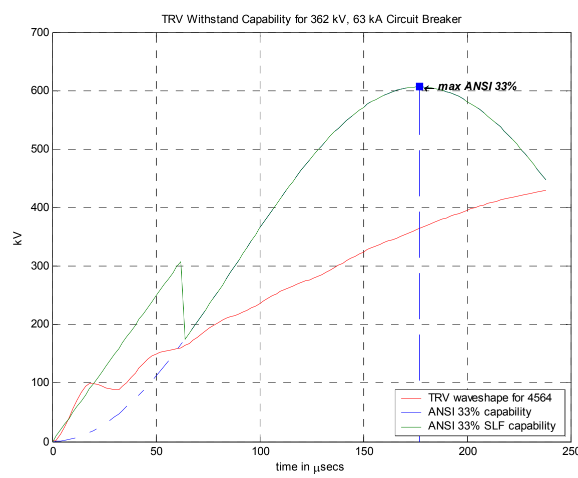

Fig. 6. TRV Withstand Capability for Breaker 4564 for a Three-Phase Ungrounded SLF on the Cahokia Line – (no added capacitance)

As can be seen in Fig. 6, the initial TRV for the case with no added capacitance exceeds the related SLF capability. Additional cases were then completed for each faulted transmission line to evaluate the effectives of various capacitance values for reducing the RRRV for each 345 kV substation breaker. These cases are shown in Fig. 7 (15 ηF), Fig. 8 (30 ηF), and Fig. 9 (45 ηF).

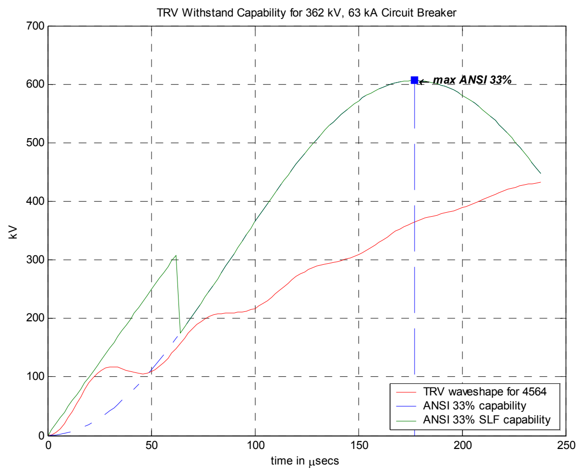

Fig. 7. TRV Withstand Capability for Breaker 4564 for a Three-Phase Ungrounded SLF on the Cahokia Line – (15 ηF added at each line terminal)

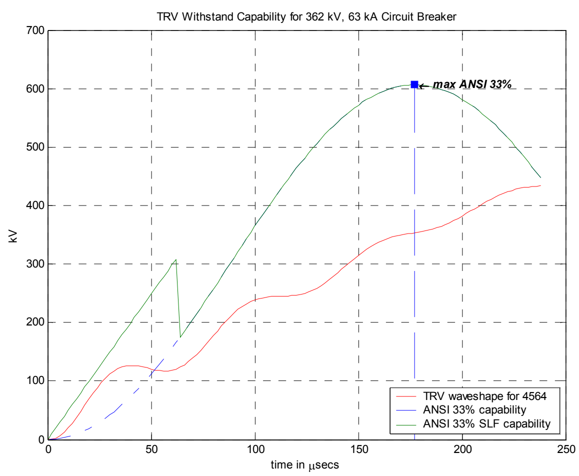

Fig. 8. TRV Withstand Capability for Breaker 4564 for a Three-Phase Ungrounded SLF on the Cahokia Line – (30 ηF added at each line terminal)

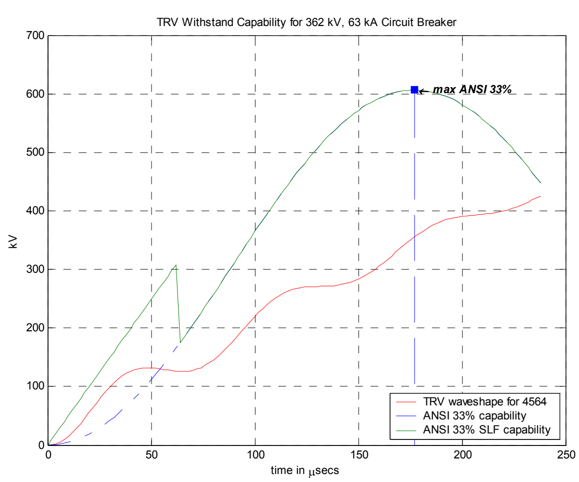

Fig. 9. TRV Withstand Capability for Breaker 4564 for a Three-Phase Ungrounded SLF on the Cahokia Line – (45 ηF added at each line terminal)

For the SLF case shown in Fig. 7, the addition of 15 ηF reduced the RRRV to within the related SLF capability. For a number of cases for other lines that were studied, an additional capacitance of 30 ηF or 45 ηF was required to reduce the RRRV to within the related SLF capability.

The additional capacitance has to be added at the breaker terminals on the line side to effectively reduce the initial RRRV during the SLF conditions. This is because the recovery voltage at the line side being much more severe than that at the bus or source side due to the traveling wave effects.

Once it was determined that additional capacitance would need to be added to the line terminals for the SLF cases, additional simulations were completed to re-evaluate the initial normal and contingency cases that had exceeded their respective withstand capabilities. For example, Fig. 10 shows the effect of adding 45 ηF on each line breaker for the same fault condition that was previously shown in Fig. 4.

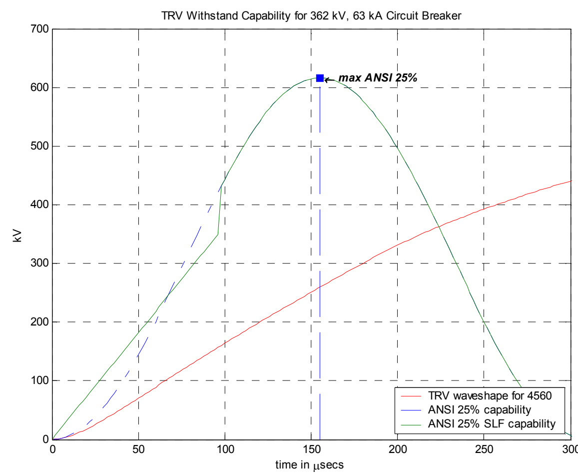

Fig. 10. TRV Withstand Capability for Breaker 4560 for a Three-Phase Ungrounded Fault at the Breaker Terminals on the Cahokia Line Side – (45 ηF added at each line terminal)

V. Conclusions

The engineering study included an evaluation of the TRV performance for various breaker operations for twenty-two new 345 kV breakers on the Illinois Power system. A number of observations and conclusions based on the simulation results included:

1. The TRV evaluation for the new 345 kV circuit breakers in the Baldwin and Prairie State Substations was conducted for the most severe operating conditions, including clearing both three-phase ungrounded faults at the breaker terminal and SLF.
2. Three capacitance values, representing a range of equivalent capacitances for substation equipment, were determined based on information provided by Illinois Power and from Annex B of IEEE Std. C37.011-1994.

3. The TRV evaluation considered both normal cases where the system operates with all breakers and lines in service and contingency cases where only one breaker is available to clear a fault. Both three-phase ungrounded and single-line-to-ground faults were evaluated for these conditions.
4. For a number of cases, the TRV waveshapes exceeded their related TRV capability limit for the first 10-50 μsec after the breaker had opened. These cases were then compared to their corresponding SLF capability.
5. For a number of normal and contingency cases, the TRV waveshapes exceeded their related capability limit. For these cases, the breaker's withstand capability was exceeded due to the peak of the recovery voltage, rather than the initial rate-of-rise.
6. With respect to clearing SLF on lines leaving the 345 kV substations (2 km from the substation), the simulations indicated that the initial RRRV will exceed the related SLF capability. One method for mitigating this condition is with the application of an additional capacitance on the line side of the breaker. This capacitance reduces the initial RRRV to within the related SLF capability.
7. Simulations were completed to evaluate the application of an additional 15 ηF, 30 ηF and 45 ηF of capacitance on the line side of breakers. These cases used the same capacitance values at each of the line terminals.
8. The additional capacitance of 30 ηF/phase generally reduced the initial RRRVs to within the related SLF capability. However, there were a number of cases where the SLF withstand capability was still exceeded. The additional capacitance of 45 ηF/phase is preferred, since it reduced the initial rate-of-rise to within the SLF withstand capability.

VI. Practical Considerations

In this study, the selection of the necessary additional capacitance values may depend on the equivalent capacitance values assumed to be on the bus side of the breakers. Therefore, the selection of the minimum equivalent capacitance values may have resulted in somewhat conservative results.

After the study was completed, the breaker manufacturer was consulted to determine if the actual breakers being purchased would be capable of successfully opening under the simulated fault conditions with the recovery voltage duties that had been identified in the study. A comparison of worst-case simulated recovery voltage duty with the capability of the actual breaker showed that the breakers would of capable of clearing for all of the operating conditions that had been simulated in the study.

In designing the switchyards to a fault current withstand level of 63 kA, at least 8 ηF of capacitance is needed for the circuit breakers to be capable of this fault level. In adding 10 ηF of capacitance at the line and bus terminals, the breakers will indeed meet all requirements and will reduce the RRRVs to within the related SLF capability. Due to the added generation nearby and the probability of a 63 kA fault to occur, the 10 ηF of capacitance that will be added is assumed to be adequate. This capacitance value was also selected due to manufacturer's limit in building capacitive transformers and the impracticality in installing 345 kV capacitor banks for each line terminal and bus position.

VII. References

[1] *PSCAD, Version 4.0.2 Professional*, www.pscad.com.

[2] *IEEE AC High Voltage Circuit Breakers Rated on a Symmetrical Current Basis – Preferred Ratings and Related Required Capabilities*, IEEE Standard C37.06, May. 2000.

[3] *IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers*, IEEE Standard C37.04, June. 1999.

[4] *IEEE Application Guide for Transient Recovery Voltage for AC High Voltage Circuit Breakers Rated on a Symmetrical Current Basis*, IEEE Standard C37.011, September. 1994.

VIII. Biographies

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