Transient Recovery Voltage Requirements Associated With the Application of Current-Limiting Series Reactors

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***Abstract*— This paper describes transient recovery voltage (TRV) requirements for switching devices used in the application of current-limiting series reactors. For fault current-limiting reactors, the series reactor is used during high fault current conditions. During these conditions, the line breaker is required to interrupt faults that may occur on the line-side of the reactor. For load current-limiting reactors, the series reactor bypass switch is normally closed and is opened to insert the reactor if the load current exceeds the line ampacity. For this situation, the bypass switch must interrupt the load current as it transfers from the switch to the series reactor. The study approach and modeling techniques described in this paper examine TRV requirements for circuit breakers and bypass switches to address (a) TRVs exceeding the rating of the line breaker following the interruption of a fault current, and (b) TRVs exceeding the bypass switch capabilities during reactor insertion. The study results are compared to ANSI/IEEE TRV Standards and corrective actions recommended, including control of series reactor natural frequencies. Effects of variations in the series reactor impedance, variations in bus-fault duty, and impacts of wave-traps and current chopping on TRV are described in the investigation. The results of the study provide guidance for the application of line breakers and bypass switches associated with the installation of current-limiting series reactors.**

***Index Terms*—transient recovery voltage (TRV), current-limiting series reactor, circuit breaker TRV requirements, bypass switch TRV requirements, wave-trap, current chopping**

I. INTRODUCTION

Because of the increase in fault currents and power flows, the application of current-limiting series reactors is increasing in power systems world-wide [1]. This paper focuses on the transient recovery voltage (TRV) associated with the application of these current-limiting reactors. Reference [2] provides information on actual circuit breaker failures caused by excessive TRVs and describes mitigation techniques used to avoid such failures for series reactor-limited faults. References [3] and [4] provide information on a related phenomena regarding current-limiting reactors installed in shunt capacitor banks and their impacts on clearing faults. References [5] through [8] contain the ANSI/IEEE coverage of series reactor-limited TRVs, formulation of TRV-related standards, and general descriptions of TRVs related to high-voltage circuit breakers.

The intent of this paper is to describe the analysis and results for (a) TRVs associated with a line circuit breaker following the interruption of a reactor-limited fault current and (b) TRVs associated with a bypass switch for an insertion event of a series reactor. Details are included related to the control of series reactor natural frequencies and the effects of variations in the series reactor impedance and bus-fault duty on the TRV, along with the impacts of a wave-trap and current chopping on the resulting TRV. The results of the investigation provide general guidance for the application of line breakers and bypass switches associated with the installation of current-limiting series reactors.

II. OBJECTIVES

The following are the specific objectives of this paper on transient recovery voltage requirements associated with the application of current-limiting series reactors:

1. Determine the TRV interrupting requirements associated with bypass switches for representative switching stations for the system under study. Note that for this application the series reactor bypass switch is normally closed, and it is opened to place the series reactor in service to limit the load current whenever line loading exceeds the conductor rating.
2. Determine the TRV requirements associated with protective line circuit breakers for representative switching stations for the system under study for faults located just beyond the series reactor on the line-side.
3. Specify the capacitance needed, and placement of capacitance, to control the TRV to within acceptable limits, as necessary, for the two conditions described above.
4. Determine the above for a generic case considering the following impacts on TRVs:
    - (a) Series reactor impedance from 1 to 10 Ω
    - (b) Series reactor natural frequency up to 200 kHz
    - (c) Bus-fault duties of 40, 63, and 80 kA
    - (d) Single-phase wave-trap located between the series reactor and protective circuit breaker
    - (e) Current chopping up to 10 A [9, 10]

III. INDIVIDUAL CASE STUDIES

Specific analysis are described in this paper for two 138 kV switching stations in the TXU Electric Delivery Company system (referred to as Switching Station A and Switching Station B), which are considered representative of many switching stations in the system. Results for the switching stations are discussed along with the results for a generic case.

A. Switching Station A Analysis

Figure 1 shows the one-line diagram for the three-phase model developed for Switching Station A for use with the Alternative Transients Program (ATP) constructed using ATPDRAW version 3.5 [11, 12]. Figure 1 illustrates the

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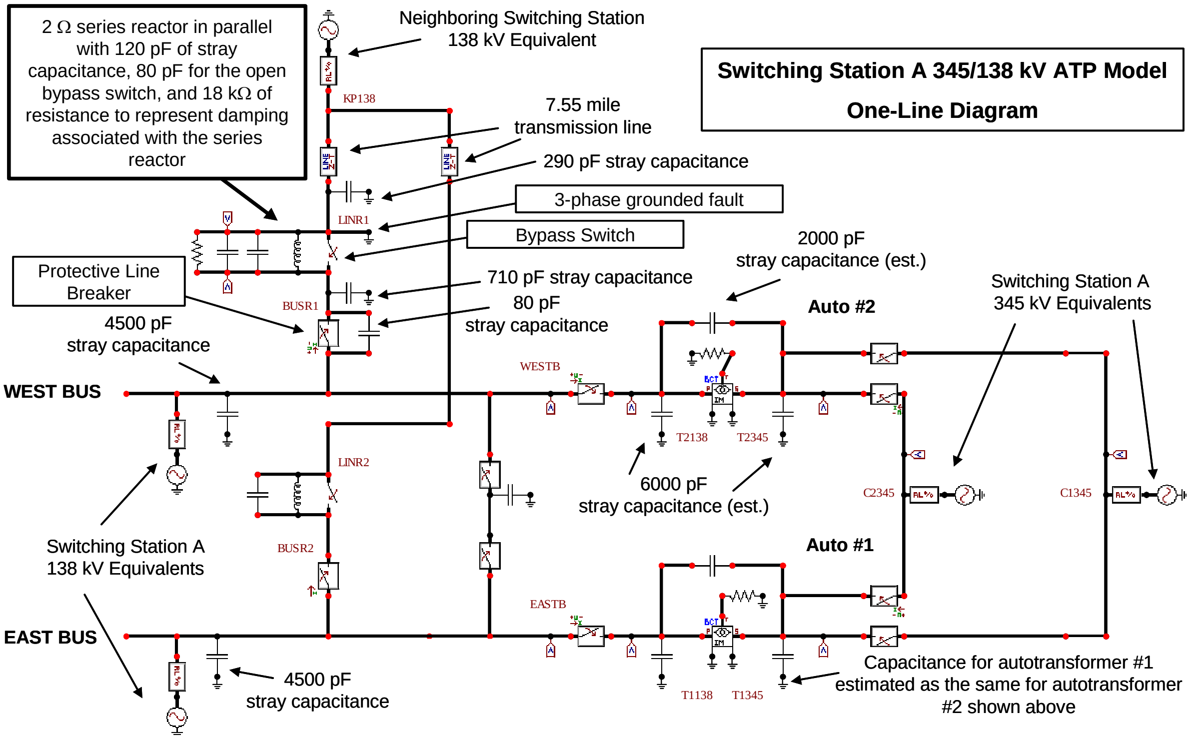

Figure 1. One-line diagram for the three-phase model developed for Switching Station A for use with the Alternative Transients Program (ATP) constructed using ATPDRAW version 3.5.

modeling of a 2 Ω series reactor as a lumped inductance paralleled by 120 pF of capacitance, calculated based on a natural reactor frequency of 200 kHz. Also in parallel are 80 pF for the capacitance associated with the open bypass switch and 18 kΩ of resistance to represent the damping associated with the series reactor (based on a typical over-shoot factor of 1.8 for the line-side voltage transient). The one-line diagram also shows the capacitances modeled on the line-side and bus-side of the series reactor. The transmission lines shown in Figure 1 were represented using a distributed parameter model based on their positive and zero sequence resistance, inductance, and capacitance.

Figure 1 also shows two 345/138 kV transformers modeled with BCTRAN, an impedance matrix representation [11], with capacitance added to their terminals representative of their effective capacitance; 60 Hz short-circuit sources (parallel impedance added for transmission line damping when necessary); and another similar series reactor connected to a parallel transmission line. The far-end of the 7.55 mile transmission line was terminated by a 60 Hz short-circuit equivalent for a neighboring 138 kV switching station. Note that short-circuit equivalents shown in Figure 1 provide required three-phase and single-phase system fault currents.

The series reactor-limited fault TRV circuit is shown in the one-line diagram illustrated in Figure 1 (i.e., three-phase grounded fault included in the one-line). Analysis was also performed using the model shown in Figure 1, with the fault removed, to determine the resulting TRV across the bypass switch in parallel with the 2 Ω series reactor for insertion operations.

Table 1 shows a breakdown of the lumped capacitances represented in Figure 1 based on IEEE Std C37.011-1994 [5]. The capacitances listed in Table 1 are critical to the analysis, especially the capacitances connected across the series reactor and on the bus-side and line-side of the series reactor, since they determine the frequency of the TRV imposed on the bypass switch and circuit breaker.

The first part of the analysis for 138 kV Switching Station A examined a three-phase grounded fault on the line-side of the series reactor, which was determined by analysis to impose a more severe TRV duty than the single-line-to-ground fault in this case. Note that the three-phase ungrounded fault was considered too rare of an event for the 138 kV system under study.

The series reactor-limited fault creates high-frequency TRVs that ANSI/IEEE TRV Standards do not specifically address. For this study the focus is on controlling the reactor-side component of TRV to meet known ANSI/IEEE specified short-line fault TRV capabilities for circuit breakers. Both the ANSI/IEEE specified short-line fault and 1-cos TRV capabilities were used for comparison to the imposed TRV, where appropriate [5]. Note that for the series-reactor limited fault the circuit breaker is interrupting reduced current magnitudes (i.e., 35% of rated for the 63 kA rated breaker under study here). Figure 2 shows the reactor-side component of TRV resulting from interrupting a three-phase grounded fault on the line-side of the series reactor, the impact of adding 12 nF of capacitance to ground (on the line-side of the circuit breaker) on the TRV, and the ANSI/IEEE Standard required SLF capability for a 145 kV 63 kA ANSI-rated breaker at 35% fault duty. Figure 2 shows that a minimum of 12 nF is needed to meet ANSI/IEEE TRV Standards.

Table 1- Breakdown of Lumped Capacitances Represented in Figure 1

Location	Equipment	Number	pF	Total pF
Bus-Side of Series Reactor	Buswork	110 ft	2.73 pF / ft	300
	Open circuit breaker (for fault case)	1	150	150
	Closed switch	2	130	260
Total:				**710**
Across Series Reactor	Series reactor	1	120	120
	Open switch (across contacts)	1	80	80
Total:				**200**
Line-Side of Series Reactor	Closed switch	1	130	130
	Buswork	60 ft	2.73 pF / ft	160
Total:				**290**
EAST/WEST Bus (per bus)	Closed circuit breaker	3	300	900
	Closed disconnect switch	5	130	650
	Current transformers	7	300	2100
	Buswork	300 ft	2.73 pF / ft	800
Total:				**4500**
Autotransformers	Effective Capacitance	1	8000	8000
(Per transformer)	Line-to-ground Capacitance	2	6000	6000
	Primary-to-Secondary Capacitance	1	2000	2000

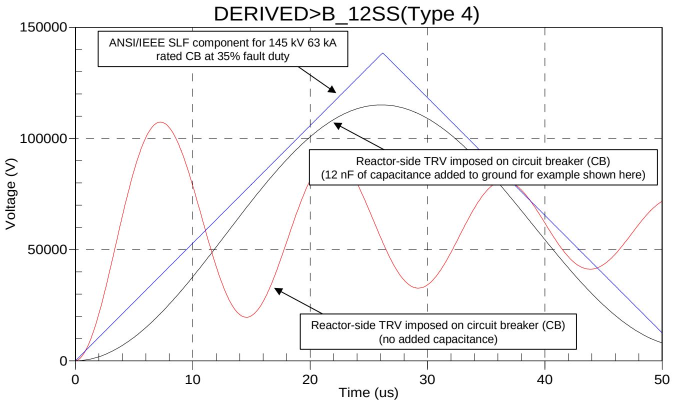

Figure 2. Reactor-side component of TRV on circuit breaker with and without capacitance added compared to ANSI/IEEE TRV Standards.

The second part of the analysis associated with Switching Station A examined the bypass switch TRV duty for power flow limiting series reactor insertion operations (to limit the power flow to 2000 A for this application) on the line connecting Switching Station A to a neighboring 138 kV bus. The main concern here is the rapid rise of the TRV for the first few microseconds following the opening of the bypass switch. Based on prior concerns for the bypass switch, curves were to be obtained to supply to the switch manufacturer to ensure that the TRV capability of the bypass switch was adequate. The initial findings indicated that the slope of the TRV for the first few microseconds associated with the bypass switch during insertion events was approximately 1 kV/μs without current chopping. The analysis described in this section focuses on simulations with current chopping, where much higher initial slopes of the TRV were identified than for simulations with no current chopping.

Limiting conditions for the bypass switch TRV analysis were identified under conditions with a 10 A current chop with a wave-trap (also commonly referred to as a line-trap) in the circuit (connected between the circuit breaker and the series reactor on phase B for the circuit under study). When the current chop occurs, the energy stored in the inductance transfers to the parallel capacitance, creating the TRV associated with the bypass switch. The stored energy in the series inductance of the wave-trap increases the severity of the resulting TRV across the bypass switch. Note that for this circuit, the wave-trap has a 5 nF capacitive-coupled voltage transformer (CCVT) associated with it that has an estimated 15 mH drain coil with overvoltage bypass protection. Figure 3 shows the TRV imposed across the bypass switch for a simulation of an insertion event with a 10 A current chop for this circuit.

Figure 3 shows that the simulation with the wave-trap, CCVT, and drain coil in the circuit results in nearly the same TRV across the bypass switch compared to the simulation with a wave-trap and no CCVT. The resulting TRV is also shown for a simulation with a CCVT and no drain coil (assuming that the drain coil overvoltage protection has operated) where the resulting TRV is less severe than with the drain coil in the circuit. Results are also included in Figure 3 for a simulation with no wave-trap and no CCVT in the circuit, where the least severe TRV was observed. Here, “severity” refers to the initial slope (magnitude and rise-time) of the TRV, and thus a more severe TRV has a higher magnitude and shorter rise-time.

To summarize, Figure 3 illustrates that if for some reason the drain coil overvoltage protection does not operate, the resulting TRV imposed across the bypass switch is essentially the same as if there were no CCVT in the circuit. Figure 3 also shows that the TRV across the bypass switch is more severe from the circuit with the wave-trap and CCVT in the circuit compared to the TRV from the circuit with no wave-trap and no CCVT in the circuit. Thus, for the analysis described in this paper, it was assumed that the wave-trap, CCVT, and drain coil are all in the circuit to allow for results representative of the upper bounds for the imposed TRV duty on the bypass switch.

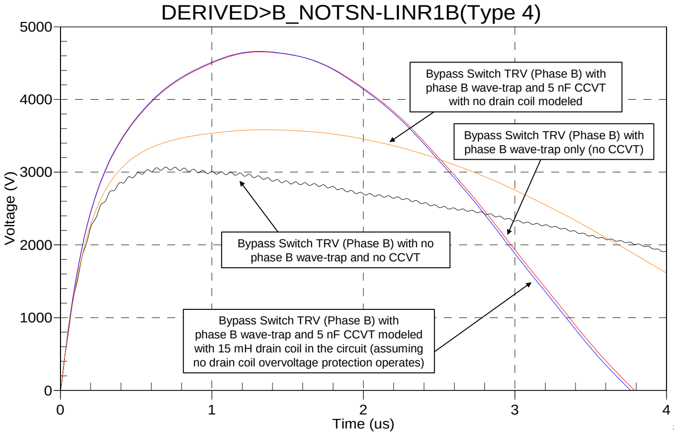

Figure 3. Plots showing the impacts of the drain coil for a 5 nF CCVT associated with the wave-trap on the bypass switch TRV under conditions with a 10 A current chop.

Figure 4 illustrates the results for the bypass switch TRV analysis for insertion of the series reactor under 10 A current chop conditions. Results are shown for the TRV with the wave-trap in the circuit, with the wave-trap in the circuit and 5 nF added across the series reactor, and with the wave-trap in the circuit and 14 nF added across the series reactor. Figure 4 shows that, with no additional capacitance added to the circuit, the resulting TRV has an initial slope of 10 kV/μs for the first few microseconds, which may be of great concern for the interrupting device. Figure 4 shows that the addition of 5 nF across the series reactor mitigates the initial slope of the resulting TRV to approximately 1.5 kV/μs during the first few microseconds of interruption. Figure 4 also shows that 14 nF limits the initial slope of the TRV to less than 1 kV/μs.

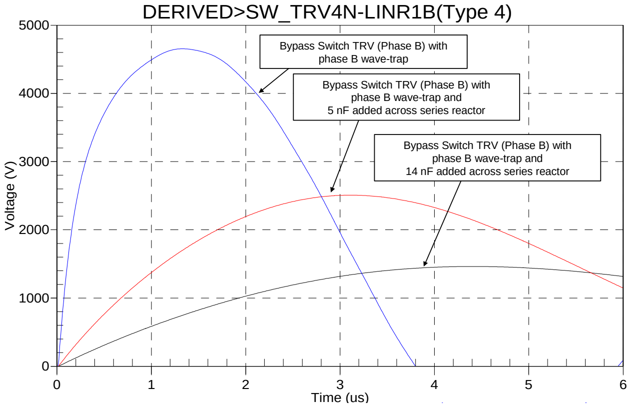

Figure 4. Plot that shows the bypass switch TRV under 10 A current chop conditions, with and without added capacitance.

B. Switching Station B Analysis

For Switching Station B, a similar model was constructed to determine the TRVs associated with the interruption of fault current (for TRVs imposed on the protective line circuit breaker) and insertion of the series reactor (for TRVs imposed on the bypass switch). It was also necessary to examine TRVs for a series reactor in a bus-connected position on the low-side of a 345/138 kV transformer for Switching Station B. Reference Figure 5 for a one-line diagram showing the series reactors analyzed at Switching Station B. Note that there is a 7 Ω series reactor in the line position for this analysis, which replaces the 2 Ω series reactor analyzed for Switching Station A. There is also an additional 2 Ω bus-connected series reactor at Switching Station B.

Figure 6 illustrates the results for the TRV analysis of the series reactor-limited fault circuit for Switching Station B. Figure 6 shows that, for the reactor limited fault for the 7 Ω line-connected series reactor, 15 nF controls the frequency of the reactor-side component of TRV to within a reasonable range with respect to ANSI/IEEE TRV Standards. Figure 6 also shows that 12 nF provides borderline control of the TRV. The generic analysis described in the next section provides more insight into the engineering judgment for the capacitances selected, regarding the imposed TRV duty compared to ANSI/IEEE Standard defined TRV envelopes. Figure 6 shows an added capacitance of at least 12 nF is reasonable and that additional added capacitance will have even further benefits.

An analysis similar to that described for Switching Station A was also performed for the bypass switch TRV associated with series reactor insertion events for the 7 Ω series reactor at Switching Station B. The analysis described for the 2 Ω series reactor for Switching Station A was also repeated for the 2 Ω series reactor for Switching Station B, with the only difference that the Switching Station B 2 Ω series reactor is connected at the bus on the low-side of a transformer and not in a line-termination position. Note that the 7 Ω series reactor limits power flows to 2000 A in the transmission line and the 2 Ω series reactor limits power flows to 3000 A at the bus. No further limiting conditions were identified, i.e., the capacitance determined from the Switching Station A TRV analysis will also limit TRVs to acceptable values at Switching Station B, located as described at the end of Section IV. Thus, the bus-connected series reactor limited fault condition did not cause TRVs that could not be controlled by added capacitance to within acceptable limits outside of those capacitances determined for the line-connected series reactor.

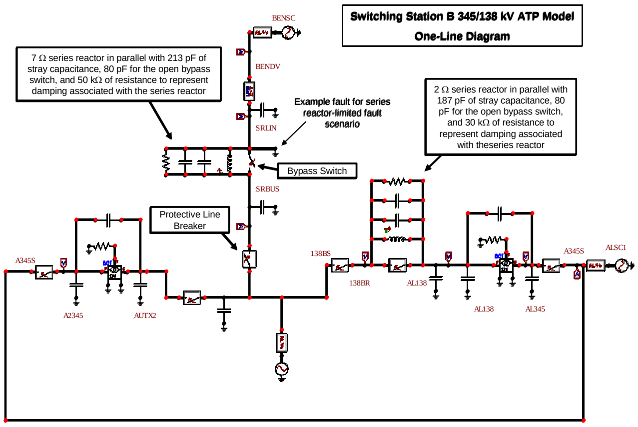

Figure 5. One-line diagram for Switching Station B.

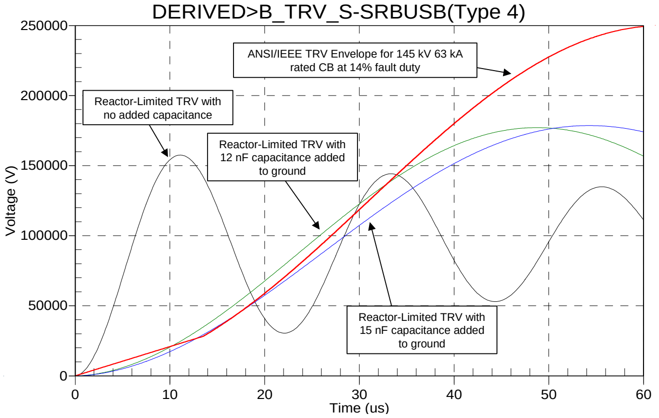

Figure 6. Plot that shows the results for the series reactor-limited fault circuit for Switching Station B.

IV. Generic Analysis

A generic analysis was performed to determine the minimum capacitance required for ANSI-rated circuit breakers to mitigate TRVs resulting from a series reactor-limited fault. Variables included were bus-fault duties of 40, 63, and 80 kA; series reactor natural frequencies up to 200 kHz; and series reactors impedances from 1 to 10 Ω. Table 2 summarizes the relevant parameters and findings of the generic analysis, again performed using the ATP. Table 2 results were obtained based on a reactor natural frequency of 200 kHz, existing stray capacitance of 700 pF on the bus-side of the series reactor, and an overshoot factor of 1.8 for the line-side transient (to determine the parallel resistance to represent the damping associated with the series reactor). A natural reactor frequency of 200 kHz was associated with all reactor impedances studied, although for higher series reactor impedances the natural reactor frequency will generally be lower. Note that this assumption did not significantly impact the results, since the associated parallel capacitance for the reactor did not significantly change for the range of frequencies considered.

Table 2 indicates that for series reactors from 1 Ω to 3 Ω, the reactor-side component of the TRV was compared to ANSI/IEEE Standard SLF capability resulting in up to 18 nF needed to control the reactor-side component of the TRV to the ANSI/IEEE SLF capability curve (for the 3 Ω series reactor case). However, engineering judgment indicates that 14 nF is reasonable for this case. The same analysis was repeated for reactor ohmic sizes from 4 Ω to 10 Ω. Comparing the ANSI/IEEE Standard 1-cos capability to the reactor-side component of the TRV, up to a 24 nF capacitor is needed to control the TRV to the ANSI/IEEE 1-cos capability curve for the limiting case identified, which was for the 4 Ω series reactor.

Figure 7 provides insight into the added capacitance needed to control the TRV. For the limiting 4 Ω series reactor case, Figure 7 shows the reactor-side component of TRV with 14 nF added versus various fault duties for the ANSI/IEEE defined TRV envelope for a 145 kV 63 kA rated circuit breaker. Figure 7 shows the ANSI/IEEE Standard TRV envelope for fault current duties of 24%, 28%, 30%, and 32% compared to the imposed TRV duty with 14 nF of capacitance added in parallel with the 4 Ω series reactor. Figure 7 shows that 14 nF is reasonable to control the reactor-side component of the TRV, considering its magnitude and slope. For such applications it is desirable to choose the minimum satisfactory capacitance necessary, considering the performance of the circuit breakers and the economics of the capacitance chosen to control the TRV. For this particular application, 14 nF was chosen as a practical trade-off, with consideration given to readily available capacitances at that time by the utility's supplier. Thus, based on engineering judgment, it was deemed appropriate to treat 14 nF as a minimum capacitance needed to control the high-frequency TRV. Note that higher values of added capacitance would provide additional "margin."

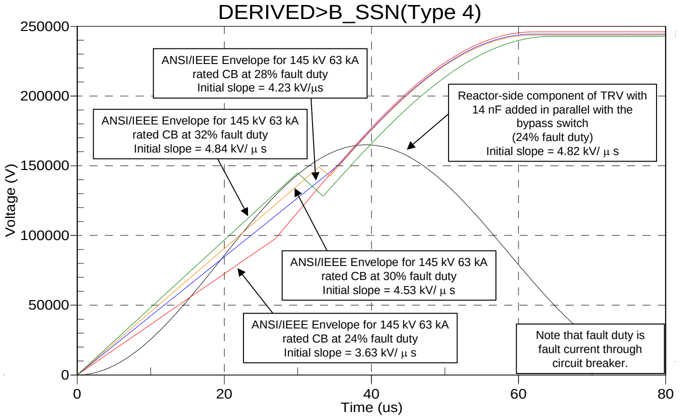

Figure 7. Reactor-side TRV of the circuit breaker with 14 nF added versus various fault duties for the ANSI/IEEE defined TRV envelope for a 145 kV 63 kA rated circuit breaker.

Table 2
Summary of Relevant Parameters and Findings for the Generic Analysis

138 kV Reactor Size (Ohms)	3-Ph Bus Fault Duty (kA)	Impedance for Rated Bus Fault (Ohms)	Max Fault Duty Through Reactor (kA)	Rated Fault Duty Through Breaker (%)	Reactor Inductance (mH)	Reactor Capacitance (pF)	TRV Time-to-Peak (μs)	TRV Magnitude (kV peak)	ANSI Requirements for 145 kV Time-to-Peak (ms)	ANSI Requirements for 145 kV (Magnitude) (kV peak)	Metric for ANSI Requirements (SLF or 1-cos)	Minimum Added Capacitance Needed to Meet ANSI (nF)	Recommended Additional Capacitance for 145 kV ANSI-rated CB (Based on Engineering Judgment) (nF)
1	40	1.992	26.6	66.6	2.65	238.7	4.96	67.8	11.1	71.2	SLF	6	6 to 14
1	63	1.265	35.2	55.8	2.65	238.7	4.96	89.6	11.1	94.1	SLF	6	6 to 14
1	80	0.996	39.9	49.9	2.65	238.7	4.96	101.6	11.1	106.8	SLF	6	6 to 14
2	40	1.992	20.0	49.9	5.31	119.4	6.55	101.6	22.3	106.8	SLF	12	12 to 14
2	63	1.265	24.4	38.7	5.31	119.4	6.55	124.3	22.3	130.6	SLF	12	12 to 14
2	80	0.996	26.6	33.2	5.31	119.4	6.55	135.4	22.3	142.3	SLF	12	12 to 14
3	40	1.992	16.0	39.9	7.96	79.6	7.82	121.9	33.4	128.1	SLF	18	14
3	63	1.265	18.7	29.7	7.96	79.6	7.82	142.7	33.4	149.9	SLF	18	14
3	80	0.996	19.9	24.9	7.96	79.6	7.82	152.3	33.4	160.0	SLF	18	14
4	40	1.992	13.3	33.2	10.61	59.7	8.92	135.4	72.1	242.7	1-COS	24	14
4	63	1.265	15.1	24.0	10.61	59.7	8.92	154.1	62.0	246.7	1-COS	24	14
4	80	0.996	15.9	19.9	10.61	59.7	8.92	162.4	62.0	248.5	1-COS	24	14
5	40	1.992	11.4	28.5	13.26	47.7	9.89	145.0	62.0	244.8	1-COS	21	14
5	63	1.265	12.7	20.2	13.26	47.7	9.89	161.9	62.0	248.4	1-COS	21	14
5	80	0.996	13.3	16.6	13.26	47.7	9.89	169.1	62.0	249.9	1-COS	21	14
6	40	1.992	10.0	24.9	15.92	39.8	10.78	152.3	62.0	246.3	1-COS	18	14
6	63	1.265	11.0	17.4	15.92	39.8	10.78	167.5	62.0	249.6	1-COS	18	14
6	80	0.996	11.4	14.2	15.92	39.8	10.78	173.9	62.0	250.9	1-COS	18	14
7	40	1.992	8.9	22.2	18.57	34.1	11.60	157.9	62.0	247.5	1-COS	16	14
7	63	1.265	9.6	15.3	18.57	34.1	11.60	171.8	62.0	250.5	1-COS	16	14
7	80	0.996	10.0	12.5	18.57	34.1	11.60	177.6	62.0	251.7	1-COS	16	14
8	40	1.992	8.0	19.9	21.22	29.8	12.36	162.4	62.0	248.5	1-COS	14	14
8	63	1.265	8.6	13.7	21.22	29.8	12.36	175.1	62.0	251.2	1-COS	14	14
8	80	0.996	8.9	11.1	21.22	29.8	12.36	180.4	62.0	252.3	1-COS	14	14
9	40	1.992	7.2	18.1	23.87	26.5	13.08	166.1	62.0	249.3	1-COS	13	13 to 14
9	63	1.265	7.8	12.3	23.87	26.5	13.08	177.8	62.0	251.8	1-COS	13	13 to 14
9	80	0.996	8.0	10.0	23.87	26.5	13.08	182.6	62.0	252.8	1-COS	13	13 to 14
10	40	1.992	6.6	16.6	26.53	23.9	13.77	169.1	62.0	249.9	1-COS	12	12 to 14
10	63	1.265	7.1	11.2	26.53	23.9	13.77	180.0	62.0	252.2	1-COS	12	12 to 14
10	80	0.996	7.2	9.1	26.53	23.9	13.77	184.4	62.0	252.8	1-COS	12	12 to 14

With respect to installation of a capacitance, since the capacitance can be placed in parallel with the series reactor or to ground on the bus-side of the series reactor for the series reactor-limited fault TRV, but must be placed in parallel with the series reactor for the bypass switch TRV; it is recommended that the additional capacitance be installed in parallel with the series reactor. Reference [2] describes other advantages associated with placing additional capacitance in parallel with the series reactor. Note that a coupling capacitor was chosen by the utility for the capacitance.

V. OVERALL SUMMARY OF FINDINGS

The following conclusions specifically address the objectives from Section II:

(1) Without added capacitance, the bypass switches must be capable of interrupting a TRV with an initial slope of 10 kV/μs under conditions with a wave-trap in the circuit and a 10 A current chop. With 5 nF of capacitance added in parallel with the series reactor, the initial slope is reduced to 1.5 kV/μs. A total of 14 nF of added capacitance reduces the initial slope to below 1 kV/μs.

(2) Without added capacitance, the imposed high-frequency TRV caused by the series reactor-limited fault exceeds the circuit breaker TRV capability based on ANSI/IEEE Standard capability curves.

(3) A minimum capacitance of 14 nF reasonably controls the TRV to within acceptable limits for 145 kV ANSI-rated circuit breakers.

(4) The following provides comments on each of the variations studied:
    (a) Limiting case for imposed TRV duty on the series reactor was identified for a 4 Ω series reactor.
    (b) A natural reactor frequency of 200 kHz was used for the range of reactor impedances studied. Note that the capacitance associated with the natural reactor frequency is an order of magnitude lower than that needed to control the TRV.
    (c) Bus-fault duties of 40, 63, and 80 kA did not impact the amount of capacitance needed to control the TRV since the source-side component of the TRV did not significantly impact the results in this study.
    (d) The wave-trap increased the magnitude and shortened the rise-time of the TRV, causing a more severe situation than with no wave-trap in the circuit.
    (e) Current chopping greatly increased the magnitude and shortened the rise-time of the TRV for the bypass switch, and consequently requires increased capabilities of the bypass switch and/or added capacitance. For example, with no current chopping, initial slopes of 1 kV/μs were identified; however, with current chopping, initial slopes of 10 kV/μs were identified.

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VII. BIOGRAPHIES

Donald J. Shoup joined the Mitsubishi Electric Power Products Inc., Warrendale, PA in July 2000. Prior to joining MEPPI, Mr. Shoup was with Robicon's Research and Development Department in Pittsburgh, PA, where he worked during the summers as an engineering assistant, beginning in 1998. In 2000, he earned a MS in Electric Power Engineering from Rensselaer Polytechnic Institute in Troy, NY. Prior to this, he earned his BEE from Gannon University in Erie, PA in 1999.

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