Performance of a Cost-Effective Design to Prevent Breaker Failures Due to Excessive RRRV During Capacitor Bank Fault Clearing

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***Abstract*—Shunt capacitor banks commonly use series current-limiting reactors (CLRs) to reduce inrush, outrush, and back-to-back switching currents. However, for faults occurring between the CLR and capacitor bank, the reactor can interact with the bus stray capacitance following current interruption and produce a high-frequency recovery voltage with an excessive rate of rise of recovery voltage (RRRV) resulting in failure to interrupt the current. To prevent such failures, phase-to-ground capacitors are typically added. An alternate solution is to add a capacitor connected directly across the CLR, which is an effective and economical means of reducing RRRV. This paper presents a simplified analytical method for evaluating whether an installed transient recovery voltage (TRV) capacitor remains adequate as available system fault current increases due to network expansion or system modifications. The method relates fault current, CLR inductance, effective capacitance, and circuit-breaker RRRV capability and can be used to determine the expected RRRV, minimum required capacitance, or maximum fault current that an existing installation can accommodate.**

I. Introduction

On January 30, 2007, shortly after energization of a 230 kV capacitor bank at the Hydro One Richview Transformer Station, a capacitor-unit bushing flashover initiated within the bank and rapidly cascaded into a three-phase-to-neutral fault at the capacitor-bank terminals, between the capacitor bank and the current-limiting reactor (CLR). The main and backup capacitor-bank breakers operated but failed to interrupt the fault because of arc reignition. The fault was ultimately cleared by bus protection approximately 287 ms after fault inception. The resulting disturbance caused substantial equipment damage and approximately 1500 MW of load loss in southern Ontario. The investigation identified excessive rate of rise of recovery voltage (RRRV), exceeding the breaker rating as the cause of the breaker interruption failure [1].

The Richview installation used CLRs in series with the capacitor bank to control capacitor-bank switching-current duty. Although the CLR limits inrush, outrush, and back-to-back switching currents, it can introduce a severe recovery-voltage duty when clearing a fault between the CLR and the capacitor bank. During such a fault, current through the CLR develops a voltage across the reactor. Following current interruption, the CLR interacts with the relatively small local capacitance primarily associated with the local bus, producing a high-frequency recovery voltage and potentially excessive RRRV [2] [3].

Following the Richview event, the North American Electric Reliability Corporation issued an Industry Advisory in January 2008 addressing excessive RRRV at capacitor-bank installations and the associated risk of breaker failure [4].

The potential exposure is also significant from a utility fleet perspective. At Xcel Energy (hereafter referred to as the energy company), approximately 7 GVAR of capacitor-bank installations, predominantly at 115 kV, used CLR at more than 75 locations [2]. Some 115 kV installations were rated up to 120 MVAR at locations with short-circuit strengths of approximately 10,000 MVA [2].

Subsequent work by the energy company and Michigan Technological University developed a mitigation in which a surge capacitor is connected directly across the CLR rather than from the breaker terminal to ground [3]. This arrangement reduces the frequency of the reactor-side recovery-voltage oscillation and therefore reduces the RRRV, while allowing the use of a substantially lower voltage-rated capacitor than a conventional phase-to-ground transient recovery voltage (TRV) capacitor.

In the joint work, a standard commercially available off-the-shelf capacitor was applied across the CLR as part of the proposed standardized solution [3]. The selected capacitance was substantially greater than the minimum required for many individual installations. This additional capacitance reduced the RRRV and also provided margin for future increases in available fault current. The standardized capacitor arrangement and the margin provided by the selected capacitance are discussed in Section II.

Available short-circuit current at a substation can increase over time because of transmission additions, transformer replacements, new generation, interconnections, or changes in network configuration. For a fixed CLR, increasing fault current increases the voltage developed across the reactor and consequently increases the recovery-voltage duty. Therefore, an installed TRV capacitor that was adequate for the original system condition should be reassessed when the available fault current changes.

This paper presents a simplified analytical method for performing this assessment. The method is applicable to installations in which the TRV capacitor is connected either from phase to ground or directly across the CLR, provided that the capacitance participating in the CLR-side recovery-voltage oscillation is properly represented. The method relates fault

current, CLR inductance, effective capacitance, and circuit-breaker RRRV capability to determine the expected RRRV, the minimum required capacitance, and the maximum fault current that an existing installation can accommodate. The analytical method is then verified using Electromagnetic Transients Program (EMTP) simulation.

II. Capacitor-Across-CLR TRV Mitigation

The excessive RRRV described in Section I can be reduced by increasing the capacitance participating in the CLR-side recovery-voltage oscillation. One approach is to connect a TRV capacitor from the breaker terminal to ground. Although effective, this arrangement requires a capacitor insulated for the system phase-to-ground voltage. An alternative developed by the joint project connects the capacitor directly across the CLR [3]. Since the normal voltage across the CLR is only a small fraction of the system voltage, this arrangement permits the use of a substantially lower voltage-rated capacitor while still reducing the recovery-voltage frequency and RRRV.

The lower insulation requirement can significantly reduce equipment cost. Indicative manufacturer estimates obtained in 2024 are summarized in Table I.

Table I
Indicative 2024 Per-Phase Cost Comparison of TRV Mitigation Methods

Voltage Level	Traditional Phase-Ground TRV Capacitors	Alternative Solution "Capacitor Across CLR"
115 kV	$11,500	$2,600 (0.5 μF + MOV)
230 kV	$20,500–$38,500 (5–15 nF)	$2,600 (0.5 μF + MOV)
345 kV	$56,500–$164,500 (5–15 nF)	$2,600 (0.5 μF + MOV)

Application of the capacitor-across-CLR approach at the energy company resulted in an estimated savings of approximately $5 million compared with conventional phase-to-ground TRV capacitor solutions [3].

The joint work developed a standardized arrangement using a standard commercially available off-the-shelf capacitor across the CLR. For applications with CLR values up to approximately 1000 μH and circuit breakers rated up to 63 kA, the proposed package used a 22.8 kV, 50 kVAR capacitor corresponding to approximately 0.25 μF (250 nF), together with 15.3 kV maximum continuous operating voltage surge-arrester protection [3]. As per the 2025 IEEE Standard 18, *IEEE Standard for Shunt Power Capacitors*, the minimum standard kVAR rating is 100 kVAR at 22.8 kV rating (with capacitance of 0.5 μF) and this was used in recent installations.

An important feature of using the 0.5 μF standard capacitor is that its capacitance is considerably greater than the minimum required for many individual installations. The capacitor, therefore, does more than satisfy the RRRV requirement for the fault-current level existing at the time of installation. The additional capacitance also provides margin for increases in fault current while maintaining the CLR-side recovery-voltage rate within the breaker capability. This is particularly useful because system short-circuit strength can increase over the operating life of a substation.

The main concern of this paper is not the original selection of the standardized capacitor, but the remaining RRRV margin as system fault current changes. A simple method is therefore needed to determine whether the installed capacitance remains adequate, how much capacitance is required for a specified fault current, and the maximum fault current that the existing installation can accommodate. Section III develops these relationships.

III. Analytical Method for Evaluating TRV Capacitor Adequacy

A. Analytical Formulation

The purpose of the proposed method is to determine whether the TRV capacitance installed either across the CLR or from phase terminal to ground remains adequate for the available system fault current. The required input data includes the rms symmetrical fault current at the junction of the CLR, the capacitor bank from the applicable short-circuit model, the breaker-rated rms short-circuit interrupting current, CLR inductance, and installed TRV capacitance from applicable equipment nameplate or manufacturer data. The equivalent local stray capacitance includes the capacitance of the buswork, breaker bushings, reactor, and other connected equipment participating in the CLR-side recovery-voltage oscillation. When detailed data are unavailable, this capacitance may be estimated using the typical values provided in IEEE Std C37.011. The breaker-duty ratio, applicable RRRV limit, and effective capacitance are then calculated from these input data. The method is based on the dominant CLR-side recovery-voltage oscillation described in [2] and [3].

The allowable RRRV depends on the current being interrupted relative to the rated short-circuit interrupting current of the breaker. The breaker-duty ratio is defined as shown in (1).

$$T = \frac{I_f}{I_r} \bullet 100\% \tag{1}$$

Where I_f is the rms symmetrical fault current and I_r is the rated rms short-circuit interrupting current of the breaker. For the analytical evaluation used in this paper, the applicable IEEE standard-specified RRRV limits are summarized in Table II [5] [6].

Table II
Breaker-Duty Ratios and RRRV Limits Used in This Study

Breaker-Duty Ratio, T	Allowable RRRV
T ≤ 10%	7 kV/μs
10% < T ≤ 30%	5 kV/μs
30% < T ≤ 60%	3 kV/μs
60% < T ≤ 100%	2 kV/μs

For a fault between the CLR and the capacitor bank, the rms voltage developed across the reactor is calculated as shown in (2).

$$V_{L,\mathrm{rms}} = I_f \omega L \tag{2}$$

And the corresponding peak voltage is calculated as shown in (3).

$$V_{L,\mathrm{pk}} = \sqrt{2} I_f \omega L \tag{3}$$

Where L is the CLR inductance and $\omega = 2\pi f_s$. Equation (3) shows that, for a fixed CLR, the voltage developed across the reactor increases directly with fault current. Therefore, an increase in system short-circuit current also increases the voltage driving the postinterruption CLR-side oscillation [2] [3].

Following an interruption, the CLR oscillates with the effective capacitance connected across it. For an installation having a TRV capacitor, the effective capacitance is given by (4).

$$C_{\mathrm{eff}} = C_{\mathrm{TRV}} + C_s \tag{4}$$

Where C_{TRV} is the installed TRV capacitance and C_s is the equivalent local stray capacitance on the reactor side of the breaker participating in the CLR-side recovery-voltage oscillation. It includes contributions from the buswork, breaker bushings, reactor, and other connected equipment. When detailed data are unavailable, C_s may be estimated using the typical capacitance values provided in IEEE Std C37.011.

The resulting natural frequency is calculated by (5).

$$f_n = \frac{1}{2\pi\sqrt{LC_{\mathrm{eff}}}} \tag{5}$$

Without an added TRV capacitor, C_{eff} may consist mainly of a few hundred picofarads of local capacitance, resulting in a very high oscillation frequency. Increasing the capacitance across the CLR or from phase to ground lowers this frequency and slows the recovery voltage.

For the analytical calculation, the CLR-side recovery voltage is approximated as a sinusoidal oscillation having a peak magnitude of $V_{L,\mathrm{pk}}$. The voltage levels –0.5 $V_{L,\mathrm{pk}}$ and +0.5 $V_{L,\mathrm{pk}}$ correspond to phase angles of –30 degrees and +30 degrees, respectively. The resulting 60 degree phase interval is one-sixth of a complete 360 degree cycle. Therefore, the RRRV over this interval is given by (6).

$$RRRV = \frac{V_{L,\mathrm{pk}}}{T_n/6} = 6V_{L,\mathrm{pk}} f_n \tag{6}$$

Where $T_n = 1/f_n$. Substituting (3) and (5) into (6) gives (7), when consistent International System of Units (SI) are used.

$$RRRV = 6\sqrt{2} f_s I_f \sqrt{\frac{L}{C_{\mathrm{eff}}}} \tag{7}$$

For a 60 Hz system, the equation can be written in convenient engineering units as (8).

$$RRRV = 509.1 \bullet 10^{-6} I_f \sqrt{\frac{L}{C_{\mathrm{eff}}}} \tag{8}$$

Where I_f is in kA rms, L is in µH, C_{eff} is in µF, and $RRRV$ is in kV/µs.

Equation (8) is the principal relationship used in this paper. It shows directly that RRRV increases with fault current and decreases as the effective capacitance is increased. This relationship provides a simple way to reassess an existing installation when a short-circuit study indicates that the available fault current has changed.

If the calculated RRRV exceeds the applicable breaker limit, (8) can be rearranged to determine the minimum total effective capacitance required, as shown in (9).

$$C_{\mathrm{eff,min}} = L\left(\frac{509.1 \bullet 10^{-6} I_f}{RRRV_{\mathrm{allow}}}\right)^2 \tag{9}$$

Subtracting the existing stray capacitance from the minimum effective capacitance gives the minimum additional TRV capacitance required, as shown in (10).

$$C_{\mathrm{TRV,min}} = C_{\mathrm{eff,min}} - C_s \tag{10}$$

An existing installation satisfies the simplified RRRV criterion when (11) is true.

$$C_{\mathrm{TRV,installed}} + C_s \geq C_{\mathrm{eff,min}} \tag{11}$$

For installations that already have a TRV capacitor, it is often more useful to determine how much additional fault-current increase can be accommodated. Rearranging (8) for fault current gives (12).

$$I_{f,\mathrm{max}} = \frac{RRRV_{\mathrm{allow}}}{509.1 \bullet 10^{-6}} \sqrt{\frac{C_{\mathrm{eff}}}{L}} \tag{12}$$

Where $I_{f,\mathrm{max}}$ is in kA rms and $RRRV_{\mathrm{allow}}$ is the allowable RRRV as per the IEEE documents. The present or projected fault current can then be compared directly with $I_{f,\mathrm{max}}$. If the available fault current remains below this value, the installed capacitance satisfies the simplified RRRV criterion. If it exceeds this value, additional capacitance or a detailed transient study should be considered.

One point needs to be considered when applying (12). The allowable RRRV itself changes with the breaker-duty ratio in Table I. Therefore, if the calculated $I_{f,\mathrm{max}}$ crosses into a higher breaker-duty range, the calculation should be repeated using the RRRV limit applicable to that range. In addition, $I_{f,\mathrm{max}}$ determined from the RRRV criterion does not replace the breaker short-circuit interrupting-current requirement: both conditions must be satisfied.

The equations above provide the complete screening procedure used in this paper. Section IV applies the method to a 115 kV installation and then compares the analytical results with EMTP simulation.

B. Application Example

A numerical example is used to demonstrate the proposed calculation procedure and is subsequently modeled in EMTP in Section IV. The example represents a 115 kV, 60 Hz, 80 MVAR capacitor-bank installation having a 1000 µH CLR. A single-line-to-ground fault is applied between the CLR and the capacitor bank. The available rms fault current is 30 kA and the circuit breaker has a rated short-circuit interrupting

capability of 63 kA. An equivalent reactor-side stray capacitance of 0.5 nF is assumed. The example system configuration is shown in Fig. 1.

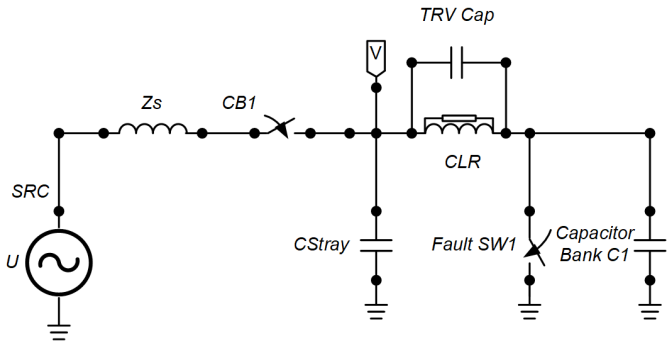


Fig. 1. Typical capacitor-bank installation with the CLR.

1) Case 1: Without Added TRV Capacitance

For the 30 kA fault and 63 kA breaker, the breaker-duty ratio from (1) is calculated as shown in (13).

$$T = \frac{30}{63} \bullet 100 = 47.619\% \quad (13)$$

The applicable RRRV criterion from Table II is therefore 3 kV/µs. Using (3), the peak voltage developed across the 1000 µH CLR is calculated as shown in (14).

$$V_{L,pk} = \sqrt{2}(30)(2\pi 60)(1000 \bullet 10^{-6}) = 15.99 \text{ kV} \quad (14)$$

With only the assumed 0.5 nF local stray capacitance, the effective capacitance is 0.5 nF. Using (5), the analytical oscillation frequency is calculated as shown in (15).

$$f_n = \frac{1}{2\pi\sqrt{(1000 \bullet 10^{-6})(0.5 \bullet 10^{-9})}} = 225.079 \text{ kHz} \quad (15)$$

Using (8), the analytical RRRV is calculated as shown in (16).

$$RRRV = 509.1 \bullet 10^{-6} \bullet 30 \bullet \sqrt{\frac{1000}{0.0005}} = 21.599 \text{ kV/µs} \quad (16)$$

The calculated value is more than seven times the allowable 3 kV/µs criterion. The installation therefore requires additional capacitance.

2) Case 2: With Minimum Required TRV Capacitance

For the same 30 kA fault duty, (9) gives the minimum total effective capacitance required to meet the 3 kV/µs criterion and is calculated as shown in (17).

$$C_{eff,min} = 1000\left(\frac{509.1 \bullet 10^{-6} \bullet 30}{3}\right)^2 = 25.9 \text{ n}F \quad (17)$$

Subtracting the assumed 0.0005 µF stray capacitance gives the minimum additional TRV capacitance as shown in (18).

$$C_{TRV,min} = 0.025918281 - 0.0005 = 0.025418281 \text{ µ}F = 25.418\, nF \quad (18)$$

If conventional installation is chosen, we need 25.418 nF TRV capacitance rated to system maximum voltage (121 kV/124 kV depending on the voltage of the breaker). If the alternate solution is chosen, the same 25.418 nF TRV capacitance is required, but the TRV capacitor rating is based on the maximum voltage across the CLR, which is 15.99 kV peak for this example.

With this capacitor connected across the CLR, the total effective capacitance is 25.9 nF. Using (5), the analytical oscillation frequency becomes (19).

$$f_n = 31.262\, kHz \quad (19)$$

Using (8), the RRRV becomes (20).

$$RRRV = 509.1 \bullet 10^{-6} \bullet 30 \bullet \sqrt{\frac{1000}{0.0259}} = 3.000\, kV/\mu s \quad (20)$$

Thus, increasing the effective capacitance from only 0.5 nF to approximately 25.9 nF reduces the calculated oscillation frequency from approximately 225 kHz to 31 kHz and reduces the RRRV from approximately 21.6 kV/µs to the required 3 kV/µs breaker criterion. Section IV applies the same system parameters in EMTP and compares the simulated fault current, peak reactor voltage, oscillation frequency, and RRRV with the analytical results.

IV. EMTP Verification

The analytical method developed in Section III was verified using an EMTP. The objective of the simulation is not to develop an alternative sizing procedure, but to confirm that the simplified analytical equations accurately predict the principal quantities governing the breaker RRRV: fault current, peak CLR voltage, postinterruption oscillation frequency, and RRRV. The same system parameters and fault condition used in the analytical example are retained so that a direct comparison can be made.

Case 1 represents the installation without an added TRV capacitor and establishes the severity of the unmitigated condition. Case 2 includes the analytically derived minimum TRV capacitance of 25.4 nF across the CLR. The purpose of Case 2 is specifically to verify that the minimum capacitance calculated using (9) and (10) is sufficient to reduce the RRRV to the required 3 kV/µs limit.

A. EMTP Model

A single-phase equivalent model is used to reproduce the dominant CLR-side recovery-voltage oscillation associated with the single-line-to-ground fault considered in Section III. The simplified network is appropriate because the principal quantity of interest is the high-frequency interaction between the CLR and the effective capacitance on the breaker side of the faulted capacitor-bank branch.

The model consists of a 60 Hz equivalent source, source impedance Z_s, circuit breaker, 1000 µH current-limiting reactor, equivalent stray capacitance, capacitor bank, and a controlled fault switch connected between the CLR and the capacitor bank. The source impedance is represented primarily by an inductive Thevenin equivalent and is selected so that the simulated steady-state fault current through the CLR is approximately 30 kA rms. The configuration is shown conceptually in Fig. 1.

The fault switch is connected from the capacitor-bank side of the CLR to ground. After steady-state conditions are

established, the switch is closed to initiate the single-line-to-ground fault. The circuit breaker subsequently opens to interrupt the fault current. The postinterruption voltage at the CLR-side breaker terminal is recorded at sufficiently small simulation time steps to reproduce the high-frequency recovery-voltage oscillation accurately. The EMTP model parameters and switching times used for simulation cases are summarized in Table III.

TABLE III
EMTP MODEL PARAMETERS AND SWITCHING TIMES

Item	Value
Source type	Single-phase sinusoidal source
Source magnitude	93.9 kV peak, 60 Hz
Source inductance, Zs	4.87 mH
Breaker state	Closed at start; opens at 0.10 s
Fault switch state	Open at start; closes at 0.05 s
Stray capacitance	0.5 nF
CLR	1000 μH
Cap bank	16.05 μF
Total simulation time	0.15 s
Time step, Δt	0.05 μs
TRV capacitor	Case 1: 0; Case 2: 25.4 nF

B. *Verification Results*

1) *Case 1: No Added TRV Capacitor*

The first simulation represents the unmitigated installation. Only the 0.5 nF equivalent stray capacitance is present, and no TRV capacitor is connected across the CLR.

The analytical calculation in Section III predicts a 30 kA rms fault current, a peak CLR voltage of 15.99 kV, an oscillation frequency of 225.08 kHz, and an RRRV of 21.60 kV/μs. The EMTP simulation is used to verify each of these quantities. The simulated fault current is measured through the breaker, in the direction from the source toward the fault location, as shown in Fig. 2.

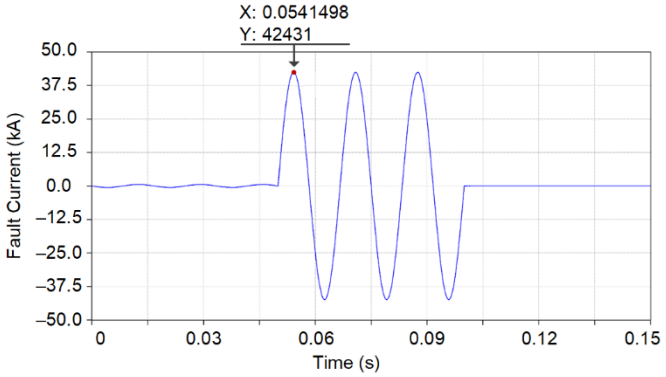


Fig. 2. Case 1 fault-current waveform measured through the breaker.

Fig. 2 shows that $I_{f,pk\ sim}$ is 42.431 kA.

The simulated peak fault current is converted to the corresponding rms value using (21).

$$I_{f,\mathrm{rms\ sim}} = \frac{I_{f,\mathrm{pk\ sim}}}{\sqrt{2}} = 30.003\ \mathrm{kA} \tag{21}$$

The measured fault-current peak of 42.431 kA corresponds to 30.003 kA rms. This confirms that the source equivalent reproduces the 30 kA analytical duty.

Fig. 3 shows the simulated postinterruption voltage across the CLR. The resulting simulated peak reactor voltage is 15.745 kV, compared with the analytical value of 15.99 kV.

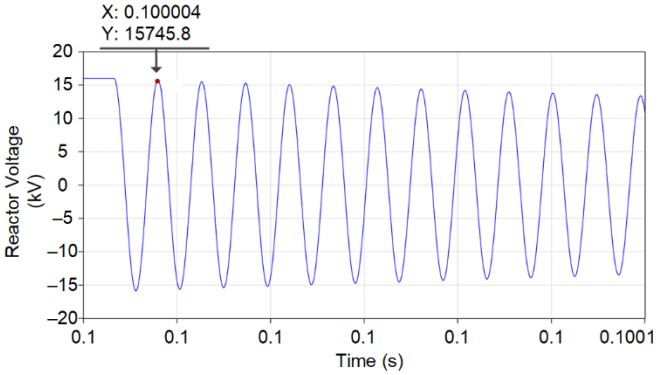


Fig. 3. Case 1 simulated postinterruption voltage across the CLR.

Using the three cursor-marked positive peaks shown in Fig. 4, the oscillation period was obtained directly from the time differences between successive peaks. The extracted times and the resulting simulated period and frequency are shown following and in (22) to (25).

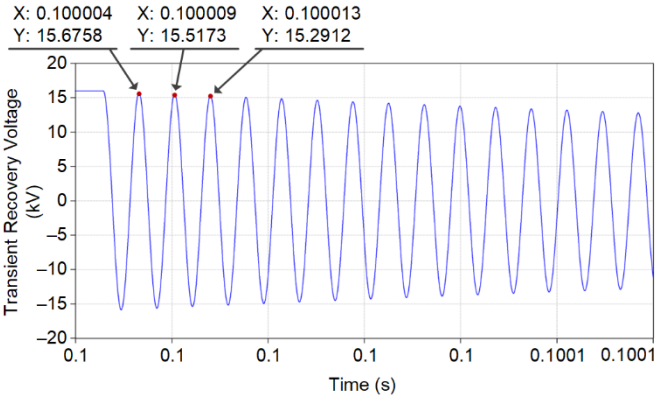


Fig. 4. Case 1 postinterruption reactor-side breaker-terminal voltage waveform used to determine oscillation frequency.

Fig. 4 shows that t_1 is 0.100004 s, t_2 is 0.100009 s, and t_3 is 0.100013 s.

$$\Delta t_{12} = t_2 - t_1 = 5\ \mu\mathrm{s} \tag{22}$$

$$\Delta t_{23} = t_3 - t_2 = 4\ \mu\mathrm{s} \tag{23}$$

$$T_{\mathrm{sim}} = \frac{\Delta t_{12} + \Delta t_{23}}{2} = \frac{5+4}{2} = 4.5\ \mu\mathrm{s} \tag{24}$$

$$f_{\mathrm{sim}} = \frac{1}{T_{\mathrm{sim}}} = 222.22\ \mathrm{kHz} \tag{25}$$

The simulated RRRV is then obtained by applying (6) to the simulated peak reactor voltage and oscillation frequency, as shown in (26).

$$RRRV_{EMTP} = 6 \bullet 15.745 \bullet 222.22 = 20.99\ \mathrm{kV/\mu s} \tag{26}$$

The Case 1 EMTP results therefore confirm the unmitigated condition: the simulated RRRV of 20.99 kV/µs is far above the 3 kV/µs criterion and agrees closely with the analytical value of 21.60 kV/µs.

2) Minimum Calculated TRV Capacitor

The second simulation retains exactly the same source, breaker, fault condition, CLR, capacitor bank, and stray capacitance. The only change is the connection of the analytically calculated C_{TRV} = 25.4 nF capacitor directly across the CLR.

This is the critical verification case for the proposed method. The purpose is to demonstrate that the minimum capacitance derived analytically, rather than an arbitrarily oversized capacitor, reduces the RRRV to the selected breaker capability.

Fig. 5 shows the simulated postinterruption voltage across CLR. The resulting simulated peak reactor voltage is 16.196 kV, compared with the analytical value of 15.99 kV

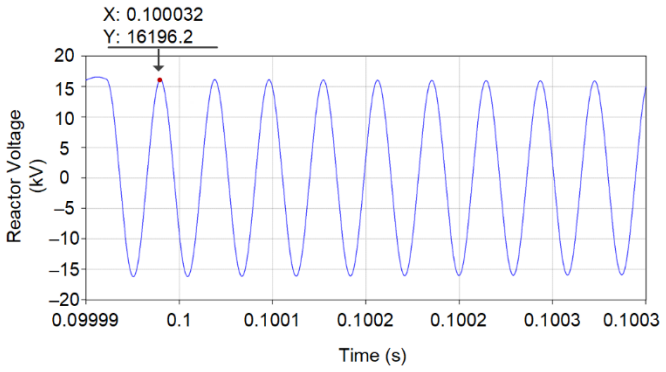


Fig. 5. Case 2 simulated postinterruption voltage across CLR.

Using the three cursor-marked positive peaks shown in Fig. 6, the oscillation period was obtained directly from the time differences between successive peaks. The extracted times and the resulting simulated period and frequency are shown following and in (27) to (30).

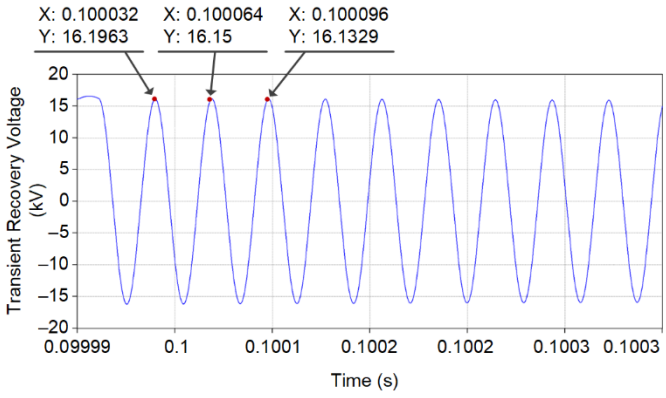


Fig. 6. Case 2 postinterruption reactor-side breaker-terminal voltage waveform used to determine oscillation frequency.

Fig. 6 shows that t_1 is 0.100032 s, t_2 is 0.100064 s, and t_3 is 0.100096 s.

$$\Delta t_{12} = t_2 - t_1 = 32\ \mu s \tag{27}$$

$$\Delta t_{23} = t_3 - t_2 = 32\ \mu s \tag{28}$$

$$T_{sim} = \frac{\Delta t_{12} + \Delta t_{23}}{2} = \frac{32 + 32}{2} = 32\ \mu s \tag{29}$$

$$f_{\text{sim}} = \frac{1}{T_{\text{sim}}} = 31.25\ \text{kHz} \tag{30}$$

The analytical calculation predicts that the effective capacitance will increase from 0.5 nF to approximately 25.9 nF and that the corresponding oscillation frequency will decrease from 222.22 kHz to 31.25 kHz.

The simulated RRRV is then obtained by applying (6) to the simulated peak reactor voltage and oscillation frequency, as shown in (31).

$$RRRV_{\text{EMTP}} = 6 \bullet 16.196 \bullet 31.25 = 3.06\ \text{kV/µs} \tag{31}$$

The Case 2 simulation therefore closely reproduces the analytical target of 31.27 kHz and 3.00 kV/µs. The 3.06 kV/µs EMTP result differs from the analytical RRRV by 2.00 percent, demonstrating close agreement for the calculated minimum capacitance.

3) Analytical and EMTP Comparison

The analytical and EMTP results for both study cases are compared in Table IV.

TABLE IV
COMPARISON OF ANALYTICAL AND EMTP RESULTS

Parameter	Analytical No TRV Cap	EMTP No TRV Cap	Analytical 25.4 nF TRV Cap	EMTP 25.4 nF TRV Cap
Fault current, rms (kA)	30.00	30.003	30.00	29.97
Peak CLR voltage (kV)	15.99	15.745	15.99	16.196
Oscillation frequency (kHz)	225.08	222.22	31.27	31.25
RRRV (kV/µs)	21.60	20.99	3.00	3.06

The analytical and EMTP results show close agreement for both study cases, with all reported quantities within approximately 3 percent. This confirms that the simplified analytical method adequately captures the dominant CLR-side oscillation and resulting RRRV. The comparison also verifies that the calculated 25.4 nF TRV capacitor produces the intended reduction in RRRV and produces a practical basis for evaluating existing installations as fault level changes.

V. CONCLUSION

CLRs are effective for controlling capacitor-bank switching-current duty, but they can create excessive RRRV when a circuit breaker clears a fault between the CLR and the capacitor bank. The capacitor-across-CLR arrangement developed for this application reduces the recovery-voltage frequency and provides an effective means of limiting the RRRV [3].

This paper presents a simplified analytical method for checking whether the TRV capacitance installed either directly across a CLR or from phase to ground remains adequate as available system fault current increases. The equations relate

fault current, CLR inductance, effective capacitance, and breaker RRRV capability and can be used to determine the expected RRRV, the minimum required capacitance, and the maximum fault current that an existing installation can accommodate.

For the 115 kV application example, the analytical method identified excessive RRRV with only the bus stray capacitance and determined the additional capacitance required to satisfy the selected breaker criterion. EMTP simulation of the same cases showed close agreement with the analytical prediction of the CLR-side oscillation frequency and RRRV. The results support use of the proposed equations as an engineering method for reassessing existing TRV-capacitor installations when system short-circuit levels increase.

VI. Acknowledgment

The authors gratefully acknowledge Dr. Bruce A. Mork of Michigan Technological University for his technical guidance and assistance in developing the preliminary electromagnetic-transient model during the EE 5220 Power System Transients course. The preliminary EMTP model provided a foundation for portions of the analytical simulation methodology presented in this paper.

VII. References

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VIII. Biographies

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