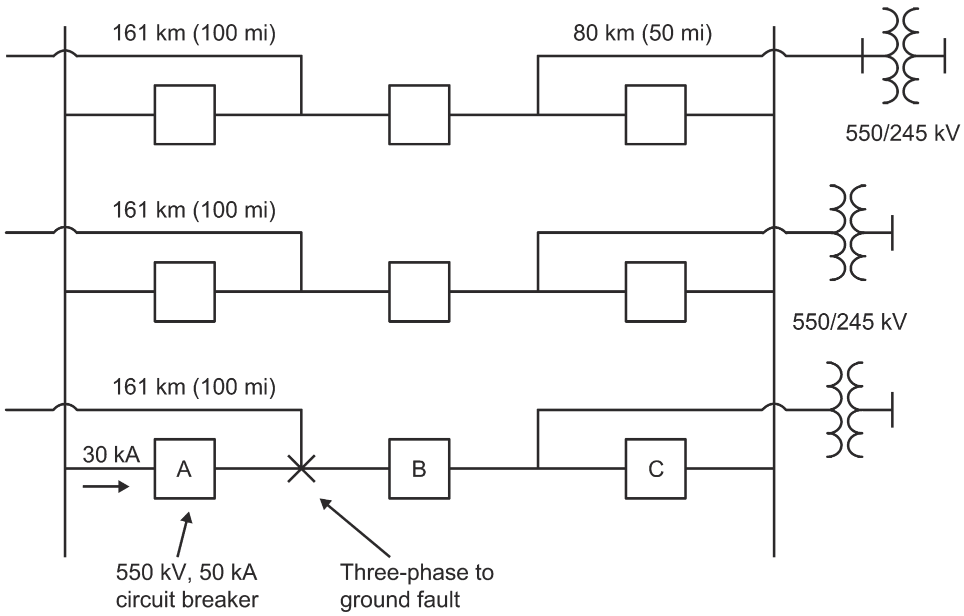

Figure 27—System configuration

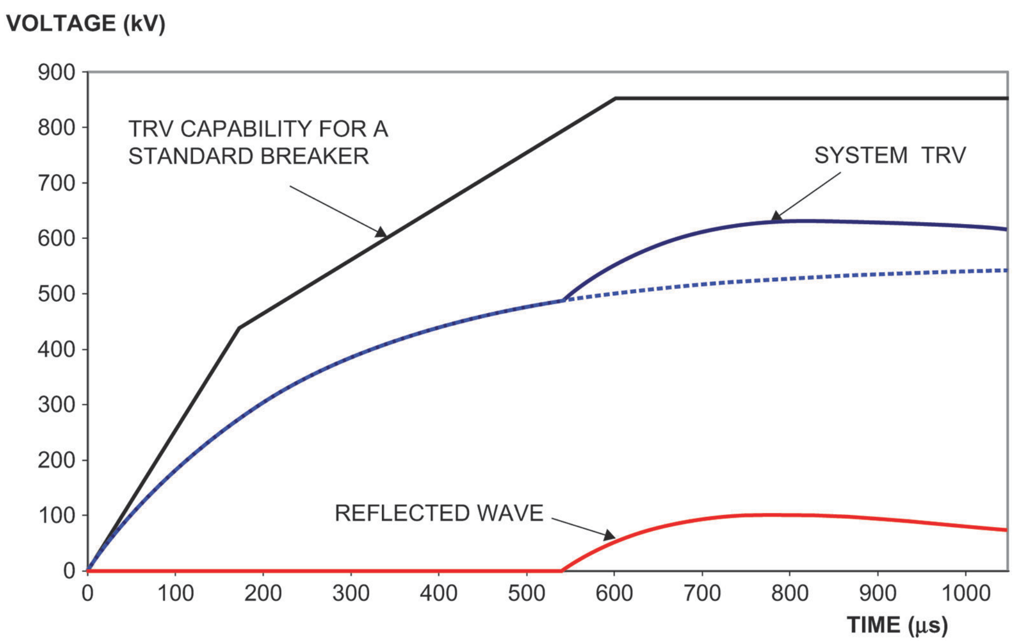

Figure 28—Comparison of TRV capability for a circuit breaker with rated voltage 550 kV (at 75% of its rated interrupting-current capability) and system TRV

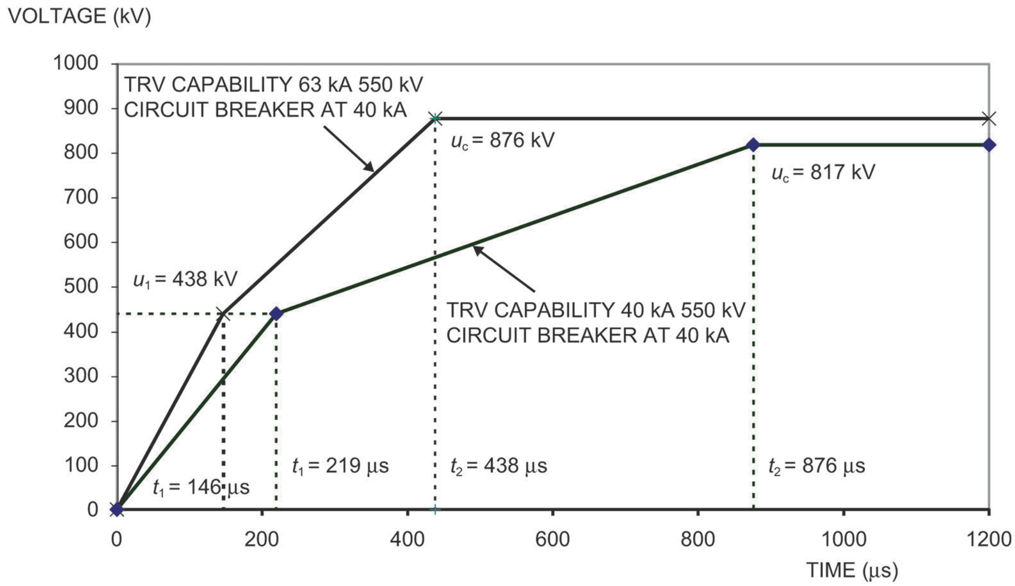

Figure 29—TRV capability curve for 40 kA and 63 kA circuit breakers when interrupting 40 kA at 550 kV

4.4 Oscillatory (underdamped) TRV

4.4.1 Transformer-limited fault

Severe TRV conditions may occur in some cases, for instance when a short-circuit occurs immediately after a transformer without any appreciable additional capacitance between the transformer and the circuit breaker. In such cases, both the peak voltage and rate-of-rise-of-transient-recovery voltage may exceed the values specified in IEEE Std C37.04 (see Figure 31).

In Figure 30 the 40 kA 145 kV circuit breaker has to clear a three-phase fault at 10% of its rating. The resultant TRV is shown in Figure 31. This TRV is determined by the inductance and capacitance of the transformer and the capacitance between the transformer and the circuit breaker (see A.4.3 for the calculation of TRV parameters). It is a high-frequency transient that may exceed the TRV capability envelope defined in IEEE Std C37.04.

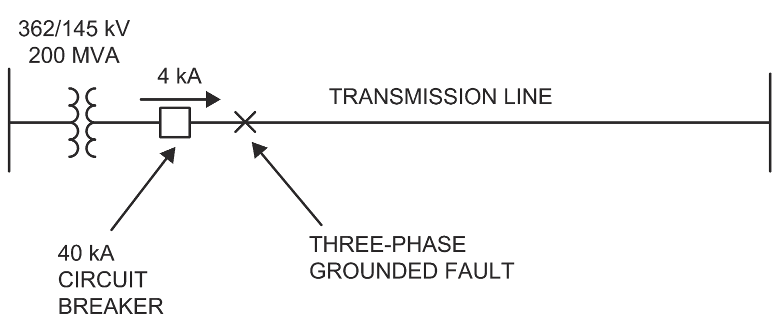

Figure 30—Fault location

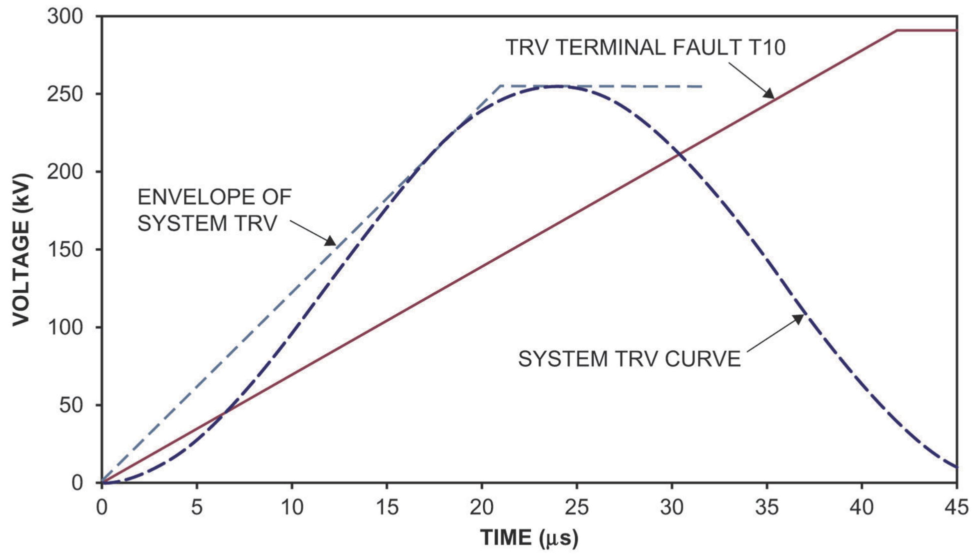

Figure 31—Comparison of standard TRV for terminal fault test duty T10 (10% of rated short-circuit current) for rated voltage 145 kV and system TRV with transformer-limited fault

It should be noted that the transformer-limited fault can occur in a well-developed substation, not just the radial system shown in Figure 30. A similar condition could occur in the system of Figure 27 if transformer breaker C were the last one to clear a bus fault with breaker B open.

The user can choose to specify a circuit breaker for fast transient recovery voltage rise times, as defined in IEEE Std C37.06.1™. In most cases, its higher TRV withstand capability will be sufficient without the need of additional capacitance. These values should be specified only when the rate of rise of the system TRV is higher than the rate of rise of the standard capability curve defined in IEEE Std C37.04. The TRV has a first part that is due to the recovery voltage across the transformer and a second part due to the recovery voltage across the short-circuit reactance of the supply circuit. The first part is a high-frequency voltage oscillation across an impedance representing 90% or 70% of the total short-circuit impedance when I_{TLF} is respectively 10% or 30% of rated short-circuit breaking current (see note 1, below). This first part of the TRV is covered by IEEE Std C37.06.1, the amplitude factor is 1.8, and the voltage drop across the transformer (or reactor) is 90% and 70% of the phase-to-ground supply voltage multiplied by the first-pole-to-clear factor, respectively, for test duties TLF1 and TLF2. The second part of the TRV up to its highest peak has the lower frequency of a terminal fault. It is covered by terminal fault test duty T30 specified in IEEE Std C37.09 that for single-phase tests is based on 100% of the phase-to-ground supply voltage multiplied by the first-pole-to-clear factor.

NOTE 1—The calculation of the voltage drop across the transformer (or reactor) as a function of the fault current is given hereafter.

Supply voltage:

$$U_{\mathrm{s}} = X_{\mathrm{s}} \times I_{\mathrm{sc}} = \left(X_{\mathrm{s}} + X_{\mathrm{T}}\right) \times I = \left(X_{\mathrm{s}} + X_{\mathrm{T}}\right) \times M \times I_{\mathrm{sc}}$$

where

X_{s} is the short-circuit reactance of the supply
X_{T} is the reactance of the transformer (or reactor)
I_{sc} is the rated short-circuit breaking current
I is the fault current

M is the ratio I/I_{sc}

It follows that $(1-M)X_s = M\times X_T$. The voltage drop across the transformer (or reactor) is: $X_T\times I = X_T\times M\times I_{sc} = (1^\circ-^\circ M)X_s\times I_{sc} = (1-M)U_s$.

When the fault current is 30% of rated short-circuit breaking current ($M = 0.3$), the voltage drop is 0.7 U_s.

When the fault current is 10% of rated short-circuit breaking current ($M = 0.1$), the voltage drop is 0.9 U_s.

The system TRV curve can be modified by a capacitance and then be within the standard TRV capability envelope. Figure 32 illustrates the modified system TRV for the condition of Figure 30, but with additional capacitance assumed between the transformer and the circuit breaker.

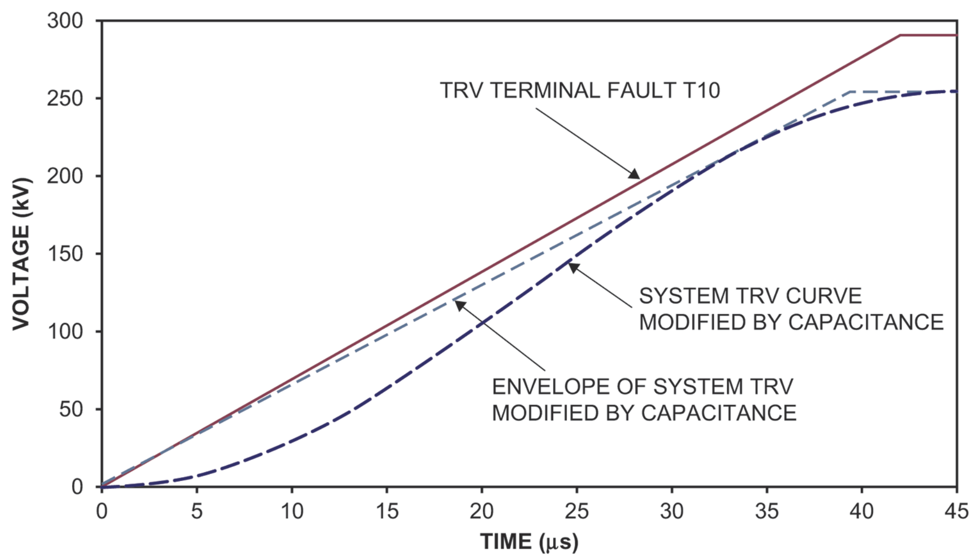

Figure 32—Comparison of standard TRV for terminal fault T10 (10% rated short-circuit current) for rated voltage 145 kV and system TRV with transformer-limited fault when a capacitance is added between the circuit breaker and the transformer

As an alternative, the user can choose to specify a definite purpose circuit breaker for fast transient recovery voltage rise times, as defined in IEEE Std C37.06.1. In most cases, its higher TRV withstand capability will be sufficient without the need of additional capacitance. The definite purpose TRV parameters for fast transient recovery voltage rise times are given in Table 2 and Table 3 of IEEE Std C37.06.1. These values should be specified only when the rate of rise of the system TRV is higher than the rate of rise of the standard capability curve defined in IEEE Std C37.04. For currents between 10% and 30% of rated short-circuit current, values of u_c and t_3 in IEEE Std C37.04 can be obtained by linear interpolation (see 4.2.2).

The TRV for terminal fault T10 shown in Figure 32 and Figure 33 is defined by a two-parameter envelope where u_c and t_3 are defined in Table 19 of IEEE Std C37.04 for 10% short-circuit breaking capability, maximum voltage (U_r = 145 kV), and a first-pole-to-clear factor of 1.5.

u_c = 291 kV

t_3 = 42 µs

The contribution of transformers to the short-circuit current may be relatively large at smaller values of short-circuit current as in T30 and T10 conditions. However, most systems have effectively grounded neutrals at ratings of 100 kV and above. With the system and transformer neutrals effectively grounded, the first-pole-to-clear factor of 1.3 is applicable for all terminal fault test duties. In some systems for rated voltages of 100 kV up to and including 170 kV, transformers with ungrounded neutrals are in service, even though the rest of the system may be effectively grounded. Such cases are covered in Table 19 of IEEE Std C37.04 where test duties T30 and T10 are based on a first-pole-to-clear factor of 1.5. For rated voltages above 170 kV, all systems and their transformers are considered to have effectively grounded neutrals.

IEEE Std C37.06.1 is assumed to cover the large majority of all cases for this switching duty. However, sometimes test reports showing the required values by the guide may not be available because the test laboratory may have had some limitations, and therefore the maximum available *du*/*dt* has been tested (this may be the case especially for higher ratings), or the switching capability of the circuit breaker may not reach the required values.

Depending on the information available concerning the components of the circuit (transformer natural frequency, additional available capacitances) and/or test results, different possibilities exist to check whether a circuit breaker may be usable even if it is not tested according to the inherent specified values mentioned in IEEE Std C37.06.1.

Case 1:

Check the actual TRV time, t_3, in the installation using the Equation (33) or the result from available network simulation.

$$t_3 = \frac{1}{1.15 \times 2 \times f_{\text{nat}}} \tag{33}$$

where

t_3 is the time to TRV peak divided by 1.15
f_{nat} is the natural frequency of transformer

If the outcome of this calculation shows a longer time, t_3, than in IEEE Std C37.06.1, it may be cross-checked with available test results.

Case 2:

Take into account additional available capacitances or additional added capacitances, i.e., line-to-ground capacitors, capacitor voltage transformers (CVTs), grading capacitors, etc.

This additional capacitance increases the time to TRV peak and correspondingly $t_{3\text{mod}}$ resulting in a reduced stress for the the circuit breaker according to the following equations.

$$t_{3\,\text{mod}} = 0.87 \times \pi \times \sqrt{L \times (C_{\text{nat}} + C_{\text{add}})} \tag{34}$$

where

$$L = \frac{\frac{k_{\text{pp}}}{\sqrt{3}} \times U_{\text{r}}}{2\pi \times f_r \times I_{\text{sc}}} \times \left(\frac{I_{\text{sc}}}{I} - 1 \right) \tag{35}$$

and

$$C_{\mathrm{nat}} = (2\times 1.15\times t_3)^2 / (4\pi^2 \times L) \tag{36}$$

where

k_{pp} is the first-pole-to-clear factor
U_{r} is the rated maximum voltage
I_{sc} is the rated short-circuit current
I is the transformer-limited fault current
f_{r} is the power frequency
L is the inductance of the transformer
C_{nat} is the effective capacitance (surge capacitance) of the transformer

Example of application:

Rated maximum voltage: 362 kV

Rated short-circuit breaking current: 63 kA

Rated transformer-limited fault (TLF) breaking current: 20 kA

Fault at 30% of rated short-circuit breaking current: 18.9 kA

TRV parameters as defined in Table 3 (line 15) of IEEE Std C37.06.1

Test duty TLF2	$I_{\mathrm{TLF2}} = 20$ kA	$u_{\mathrm{c}} = 559$ kV	$t_3 = 32$ µs
Test duty TLF1	$I_{\mathrm{TLF1}} = 6.3$ kA	$u_{\mathrm{c}} = 718$ kV	$t_3 = 41$ µs

The TRV parameters corresponding to a fault current of 18.9 kA is derived by linear interpolation:

I = 18.9 kA	$u_{\mathrm{c}} = 572$ kV	$t_3 = 32.7$ µs

NOTE 2—A value of 32.6 µs for t_3 would be obtained by using the following equation taken from Annex A of IEEE Std C37.06.1:

$$t_3 = \frac{3.18 \times \sqrt{U_r}}{I_{TLF}^{\;0.21}}$$ with $U_{\mathrm{r}} = 362$ kV and $I_{\mathrm{TLF}} = 18.9$ kA.

The inductance and effective capacitance of the transformer are derived using Equation (35) and Equation (36):

$L = 30.7$ mH

$C_{\mathrm{nat}} = 4.67$ nF

Assuming a value of C_{add} equal to 1.5 nF, and using Equation (34), the modified time, $t_{3\mathrm{mod}}$, is equal to 37.6 µs (and a time-to-peak TRV of 43.2 µs). This $t_{3\mathrm{mod}}$ would be the shortest time that the breaker has to withstand. Consequently, this increased time to peak may allow the use of a circuit breaker which may not be able to cope, or which may not have been tested according to the required values of IEEE Std C37.06.1.

Case 3:

Test reports may be available for the circuit breaker showing a certain t_3 value which is higher than the t_3 value given in IEEE Std C37.06.1.

Such a breaker could be used for this application by adding a capacitor to ground that changes the actual t_3 to a value where a proof for the circuit breaker capability exists.

$$C_{\text{add}} = \frac{(1.15 \times t_{3\ \text{test}})^2}{L \times \pi^2} - C_{\text{nat}} \tag{37}$$

where

$t_{3\ \text{test}}$ is the time of tested TRV

If, for example, a circuit breaker has been tested with a time, $t_{3\ \text{test}}$, of 61 µs, a rated TLF breaking current of 20 kA and a rated maximum voltage of 362 kV as in the example above, this would require an additional capacitance of 11.6 nF in order to make the breaker feasible for this application with a fault current of 18.9 kA.

NOTE 3—The added capacitance will result in a higher TRV peak under test. Take care about this behavior for all other test duties.

4.4.2 Reactor-limited fault

4.4.2.1 General

A current-limiting reactor (CLR) is used to reduce the fault current magnitude. It is also used as a damping reactor to limit inrush currents in capacitor bank applications. Due to the very small inherent capacitance of a number of current-limiting reactors, the natural frequency of transients involving these reactors can be very high. A circuit breaker installed immediately in series with this type of reactor will face a high-frequency TRV when clearing a terminal fault (reactor at supply side of circuit breaker) or clearing a fault behind the reactor (reactor at load side of circuit breaker). The resulting TRV frequency generally exceeds by far the standardized TRV values.

When the system TRV exceeds a standard breaker capability, the user has two possibilities:

— Add a capacitance in parallel to the reactor in order to reduce the TRV frequency and have a system TRV curve within the standard capability envelope. A phase-to-ground capacitance could also be added, it can be provided by a capacitor, a capacitive voltage transformer, or by an HV cable.

— Specify a definite purpose circuit breaker for fast transient recovery voltage rise times, as defined in IEEE Std C37.06.1. In some cases, their higher TRV withstand capability will be sufficient. If this is not the case, a capacitance can also be added in parallel or phase-to-ground.

The additional capacitance should be adequately sized to decrease the rate of rise of the TRV below the rated value defined for the circuit breaker utilized. In the case of circuit breakers of rated voltages less than 100 kV, the RRRV can be reduced below the value specified for circuit breakers class S2. If a shielded cable is used to connect a current-limiting reactor to the circuit breaker, the cable capacitance to ground may be sufficient.

NOTE—During close-in external faults (outrush) and back-to-back bank energization, high transient voltages are imposed across the CLR. When the surge capacitor is connected in parallel to the CLR, it should be protected by a surge arrester across the CLR-surge capacitor arrangement (IEEE Std C57.16™-2011 [B23]).

The addition of a capacitor is very effective and cost efficient. It is therefore recommended, unless it can be demonstrated by tests that a circuit breaker can successfully clear faults with the required high-frequency TRV.

4.4.2.2 TRV calculation by system simulation

As an example, Figure 33 illustrates the case of a 38 kV circuit breaker class S2 that clears a three-phase ungrounded fault in a 60 Hz system with a short-circuit current limited by a reactor (CLR). It is considered that the supply circuit has the inherent TRV defined for overhead line systems in IEEE Std C37.04 and a terminal fault current (without current-limiting reactor) of 50 kA. The reactor limits the short-circuit current in the feeder to 12.5 kA.

The parameters of the equivalent single-phase circuit shown in Figure 33 are determined to give the standard value of TRV for the supply side (u_c = 71.7 kV and RRRV = 1.21 kV/μs) corresponding to a first-pole-to-clear factor of 1.5. The determination of the components in the equivalent circuit for a three-phase fault is explained in A.2.2. The resistance R_s is such that the time constant of the supply side is 45 ms, the capacitance to ground of the current-limiting reactor is 680 pF.

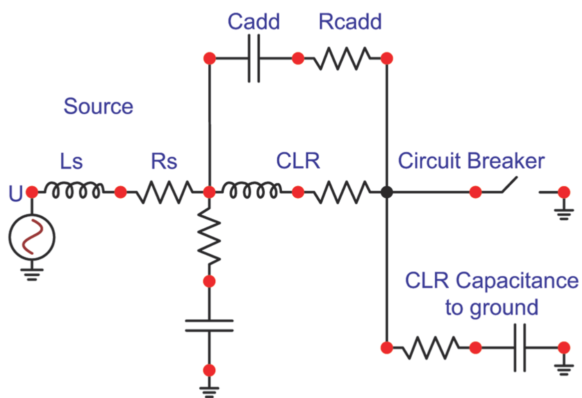

Figure 33—Example of reactor-limited fault (equivalent single-phase representation)

In a first step, the TRV seen by the circuit breaker is calculated without the branch $C_{add} - R_{cadd}$ in parallel to the current-limiting reactor. Figure 34 shows the calculated TRV, which is characterized by the following parameters: u_c = 63.1 kV and RRRV = 11.4 kV/μs. The RRRV greatly exceeds the standard value of RRRV for a class S2 circuit breaker with a rated short-circuit current of 12.5 kA (1.21 kV/μs in case of a fault with 100% rated short-circuit current).

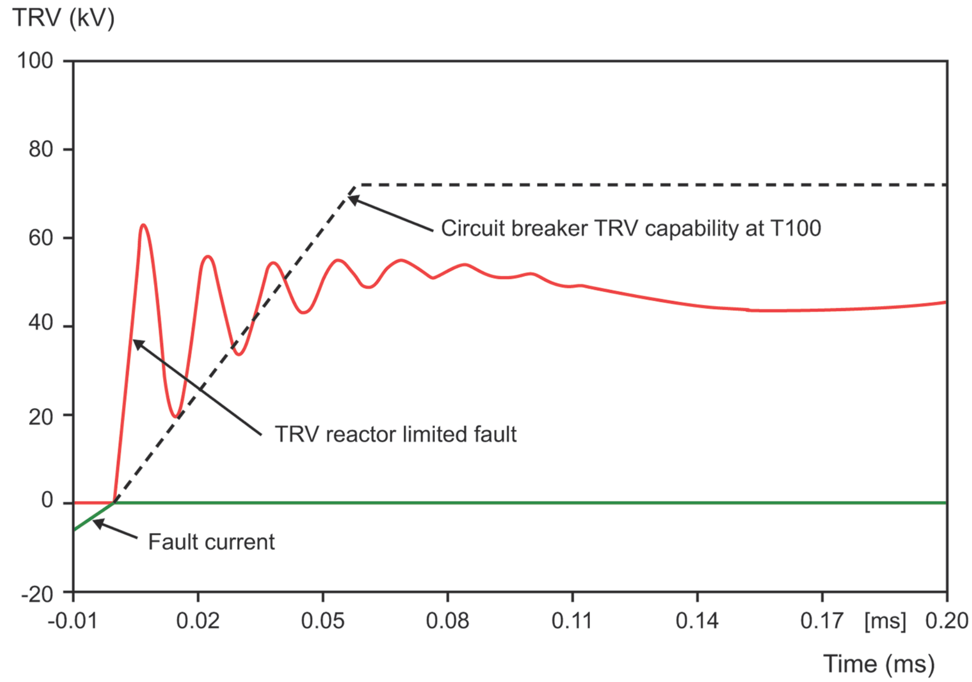

Figure 34—Calculated TRV of reactor-limited fault without added capacitance, comparison with TRV capability for class S2 circuit breaker 38 kV 12.5 kA

Figure 35 shows the calculated TRV obtained in the example of Figure 33 when a capacitor C_{add} of 195 nF is added in parallel to the current-limiting reactor, the series resistance R_{cadd} gives a tan δ of 0.01%. The TRV is characterized by the following parameters: u_c = 86.1 kV and RRRV = 1.1 kV/µs. If the capacitor of 195 nF is connected phase-to-ground, the modified TRV is characterized by u_c = 87.1 kV and RRRV = 0.88 kV/µs. The reduction of RRRV is more effective with phase-to-ground capacitance than when the capacitance is connected in parallel to the CLR.

As can be seen in this example, the modified RRRV can be reduced significantly below the slope of the TRV withstand capability specified for class S2 circuit breakers. The addition of a capacitor increases the peak value of TRV; the value obtained in this example is higher than the TRV withstand specified for terminal fault T100 (u_c = 71.7 kV for class S2 circuit breakers). In such cases, a resistor connected in series with the additional capacitor will be necessary.

Alternatively, a higher peak value of TRV may be specified or a circuit breaker with a higher rated voltage (48.3 kV) or a higher rated short-circuit current may be used. As an example, Figure 36 shows that the reactor-limited fault TRV modified by a phase-to-ground capacitance of 12 nF is covered by the TRV capability of a 38 kV 40 kA circuit breaker interrupting a fault current (12.5 kA) that is approximately equal to 30% of its rated short-circuit current. The examples illustrated by Figure 35 and Figure 36 show that a circuit breaker with a higher short-circuit rating allows the reduction of the added capacitance, an optimum choice of circuit breaker rating and value of added capacitance can be found on a case-by-case basis.

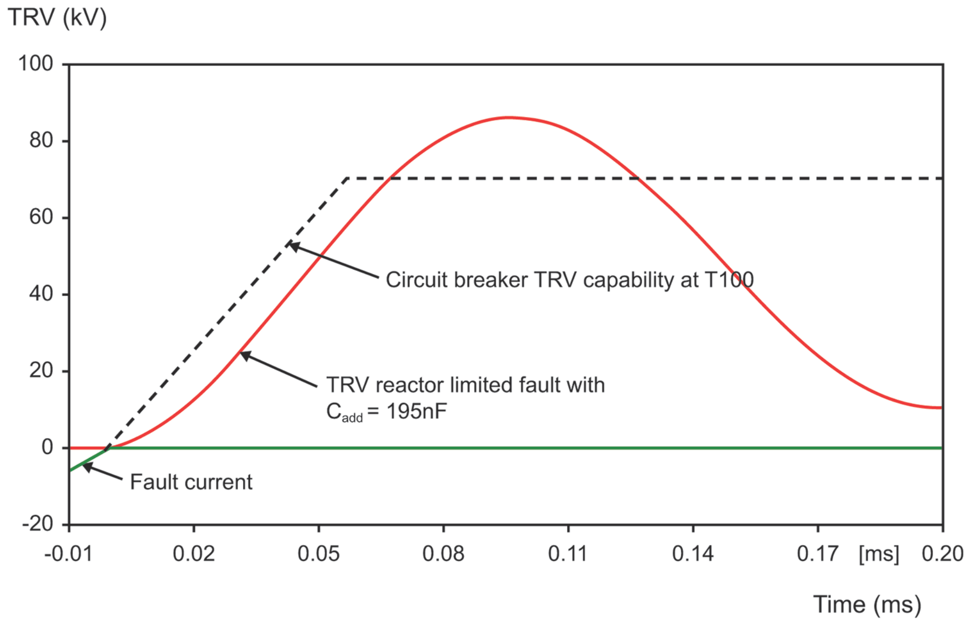

Figure 35—Calculated TRV of reactor-limited fault with 195 nF added capacitance, compared with TRV capability for class S2 circuit breaker 38 kV 12.5 kA

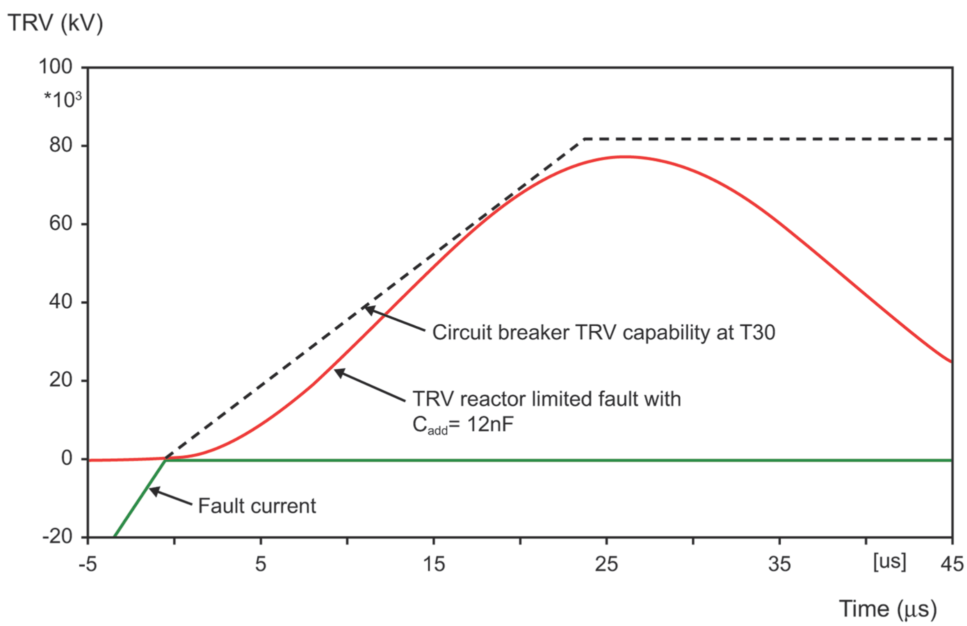

Figure 36—Calculated TRV of reactor-limited fault with 12 nF added capacitance, compared with TRV capability for class S2 circuit breaker 38 kV 40 kA at 30% of rated short-circuit current