C37.011™

IEEE Application Guide for Transient Recovery Voltage for AC High-Voltage Circuit Breakers

IEEE Power Engineering Society

Sponsored by the
Switchgear Committee

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Abstract: Procedures and calculations necessary to apply the standard transient recovery voltage (TRV) ratings for ac high-voltage circuit breakers rated above 1000 V and on a symmetrical current basis are covered. The capability limits of these circuit breakers are determined to a great degree by the TRV. TRV ratings are compared with typical system TRV duties.
Keywords: high-voltage circuit breakers, transient recovery voltage

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Introduction

This introduction is not part of IEEE Std C37.011-2005, IEEE Application Guide for Transient Recovery Voltage for AC High-Voltage Circuit Breakers.

This application guide has been revised to align the new transient recovery voltage (TRV) requirements introduced in IEEE Std C37.04, ANSI C37.06, and IEEE Std C37.09, which are being revised concurrently.

Specifically this revision is necessary for the following two reasons:

a) The TRV requirements have changed in the latest editions of IEEE Std C37.04, ANSI C37.06, and IEEE Std C37.09 and further changes are under consideration.
b) The part on TRV associated with transformer limited faults must be aligned with the requirements of ANSI C37.06.1 "Guide for High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis Designated Definite Purpose for Fast Transient Recovery Voltage Rise Times."

The major changes implemented in this guide include the following:

- The TRV capability of circuit breakers that, according to the present version of IEEE Std C37.04, is described by two or four parameters. For breakers rated 100 kV and above, the TRV envelope is defined by four parameters where the short-circuit currents are above 30% of the breaker's capability. At 30% and below, the TRV envelope is described by two parameters. For breakers rated 72.5 kV and below, the TRV envelope is described by two parameters over the entire current range.
- Three-phase to ground faults are the basis for rating, in accordance with the present and revised IEEE Std C37.04. For circuit breakers applied on systems 72.5 kV and below, the TRV ratings assume that the systems can be operated ungrounded. For circuit breakers applied on systems 245 kV and above, the TRV ratings assume that the systems are all operated effectively grounded. For systems 100 kV through 170 kV, the systems can be operated either ungrounded or effectively grounded so two TRV ratings are available for these systems. See Annex C.
- Evaluating a circuit breaker TRV capability is illustrated by a new Figure 1 by comparing circuit breaker rated TRV against that of system TRV envelope.
- In 4.2.3, a new Figure 14 shows how the TRV withstand capability of a circuit breaker can be defined by the combination of SLF and Terminal Fault TRV withstand capabilities, in the case of circuit breakers rated 100 kV and above.
- The case of long line fault interruption that may not be covered by rated TRV capability is treated in a new subclause 4.2.4.
- Special applications where interruption of three-phase ungrounded faults may be required are covered in a separate subclause 4.2.5.
- Effect of asymmetry on TRV is explained by a new Figure 2.
- A.1 has been revised to cover both three-phase grounded and three-phase ungrounded faults.
- Additional explanations on short-line fault TRV are given in A.1.3 to justify the value of the peak factor (1.6) introduced in IEEE Std C37.04.
- The rated maximum voltages have been updated, to be consistent with the values in ANSI C37.06. Calculations in Annex A have been redone with the new values of supply voltages.
- The relation between parameter t_3 (used in the two parameter description of TRV) and the time to peak T_2 is given in a new table A.3.
- A.3.3 has been corrected.
- Annex B has been revised to better explain the terms *equivalent capacitance*, *positive or zero sequence capacitance*, and *effective capacitance*. An example of calculation of transfomer capacitance, derived from Figure B.1, is added.

— A new Annex C gives explanations and guidance on the selection of the first pole to clear factors and the corresponding values for the second and third pole to clear. Figure C.1 gives the relevant pole-to-clear factor, as function of arcing time, in the following three cases: three-phase to ground fault in effectively grounded system, three-phase faults in ungrounded systems, and three-phase ungrounded faults in effectively grounded systems.

Further changes to this guide may be required for three-phase line faults, terminal faults, and the short line fault. They will be included in the next revision of IEEE Std C37.011.

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Contents

IEEE Application Guide for Transient Recovery Voltage for AC High-Voltage Circuit Breakers

1. Overview

1.1 Scope

This application guide covers procedures and calculations necessary to apply the standard transient recovery voltage (TRV) ratings for ac high-voltage circuit breakers rated above 1000 V. The capability limits of these circuit breakers are determined to a great degree by the TRV. This application guide is not included in other existing circuit breaker standards. In this document, the TRV ratings are compared with typical system TRV duties. An example TRV calculation is given in Annex A.

1.2 Purpose

The purpose of this guide is to provide an application guide on the TRV ratings given in IEEE Std C37.04[1] for ac high-voltage circuit breakers rated on a symmetrical current basis. Definitions, rating structure, test procedures, and preferred transient voltage ratings and related required capabilities are included in IEEE Std C37.04, ANSI C37.06, ANSI C37.06.1, and IEEE Std C37.09. IEEE Std C37.010 applies in other respects to these circuit breakers.

2. References

The following standards contain provisions that, through reference in this text, constitute provisions of this guide. When the following specifications are superseded by an approved revision, the revision shall apply.

ANSI C37.06-2000, American National Standard for Switchgear—AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis—Preferred Ratings and Related Required Capabilities.[2]

ANSI C37.06.1-2000, Guide for High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis Designated Definite Purpose for Fast Transient Recovery Voltage Rise Times.

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[1] Information on references can be found in Clause 2.

[2] ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

IEEE Std C37.04™-1999, IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.[3, 4]

IEEE Std C37.09™-1999, IEEE Standard Test Procedure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

IEEE Std C37.010™-1999, IEEE Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

IEEE Std C37.081a™-1997, Supplement to IEEE Guide for Synthetic Fault Testing of AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

3. Transient recovery voltage (TRV)

3.1 General

The recovery voltage is the voltage that appears across the terminals of a pole of a circuit breaker after interruption. This voltage may be considered in two successive time intervals: one during which a transient voltage exists (TRV), followed by a second during which a power frequency voltage alone exists.

During the interruption process the arc rapidly loses conductivity as the instantaneous current approaches zero. Within a few microseconds after current zero, current stops flowing in the circuit. The power system response to current interruption is what generates the TRV. TRV is the difference in the power system response voltages on the source side and on the load side of the circuit breaker. The nature of the TRV is dependent on the circuit being interrupted, whether primarily resistive, capacitive or inductive (or some combination). Additionaly, distributed and lumped circuit elements will produce different TRV waveshapes.

In principle, the response of the load side and source side of the circuit breaker can be analyzed separately and the results subtracted point by point on a time line. The driving voltage is the instantaneous power frequency voltage across the circuit elements at the instant of current interruption.

The breaking operation is successful if the circuit breaker is able to withstand the TRV and the power frequency recovery voltage.

TRVs can be oscillatory, triangular, or exponential and can occur as a combination of these forms. 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 symmetrical fault at its terminal when the system voltage is maximum. (See Annex C for more information on the TRV and power frequency recovery voltage applied on each pole while interrupting a three-phase terminal fault.)

The triangular recovery voltages are associated with line faults. The initial rate of rise of the recovery voltages for line faults becomes greater the closer the fault is to the circuit breaker; however, the magnitude of this line side triangular wave decreases as the rate of rise increases. Generally, the source recovery voltage is much slower and only the triangular recovery voltage is effective in the early time period of the TRV. The amplitude of the recovery voltages for these line faults are determined on a single-phase basis during their early time periods.

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By definition, TRV values defined in the standards are inherent i.e., values that would be obtained during interruption by an ideal circuit breaker without arc voltage (its resistance changes from zero to an infinite value at current zero).

3.2 Effect of circuit breaker on transient recovery voltage

The circuit TRV can be modified by the arc of the circuit breaker. Therefore, the TRV measured across the terminals of two different types of circuit breakers under identical conditions can be different. Recognizing the modifying abilities of each of the various circuit breakers would be an immense task when either calculating a TRV or specifying a related value for the circuit breaker.

To simplify both rating and application, the power system electrical characteristics are defined or calculated ignoring the effect of the circuit breaker. Thus, the TRV, which results when an ideal circuit breaker interrupts, is used as the reference for both rating and application. This TRV is called the inherent TRV. An ideal circuit breaker has no modifying effects on the electrical characteristics of a system and, when conducting, its terminal impedance is zero; at current zero, its terminal impedance changes from zero to infinity.

3.3 Method of rating and application

3.3.1 Selection of a circuit breaker

The TRV ratings for circuit breakers are applicable for interrupting three-phase to ground faults at the rated symmetrical short-circuit current and at the maximum rated voltage of the circuit breaker. For values of fault current other than rated and for line faults, related TRV capabilities are given. Rated and related TRV capabilities are described in IEEE Std C37.04 and given in detail in ANSI C37.06.

While three-phase ungrounded faults produce the highest TRV peaks, the probability of their occurrence is very low (see discussion in Wagner and Smith [B14][5]). Therefore, as described in IEEE Std C37.04, the TRV ratings are based on three-phase grounded faults with the TRV peaks established based on the grounding arrangements prevalent at the respective system voltages.

For circuit breakers applied on systems 72.5 kV and below, the TRV ratings assume that the systems can be operated ungrounded. For systems over 72.5 kV through 170 kV, the systems can be operated either ungrounded or effectively grounded so two TRV ratings are available for these systems. For circuit breakers applied on systems above 170 kV, the TRV ratings assume that the systems are all operated effectively grounded. See Annex C.

In the draft revisions of IEEE Std C37.04 and ANSI C37.06, the TRV capability of a circuit breaker is defined by a two-parameter or four-parameter envelope (see Figure 1, Figure 6, and Figure 7) IEEE PC37.04b [B16], IEEE PC37.06 [B17].

A circuit breaker TRV capability is sufficient if the two- or four-parameter envelope drawn with the rated parameters as specified in ANSI C37.06 is higher than the two- or four-parameter envelope of the system TRV at the point of application (see Figure 1). Consideration should be given for future system growth.

The TRV ratings define a withstand boundary. A circuit TRV that exceeds this boundary at rated short-circuit current, or the modified boundary for currents other than rated, is in excess of the rated or related capabilities of the circuit breaker. If the withstand boundary of the circuit breaker is exceeded, either a different circuit breaker should be used, or the system should be modified in such a manner as to change its

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[5] The numbers in brackets correspond to those of the bibliography in Annex D.

TRV characteristics. The addition of capacitors to a bus or line is one method that can be used to improve the recovery voltage characteristics of the system.

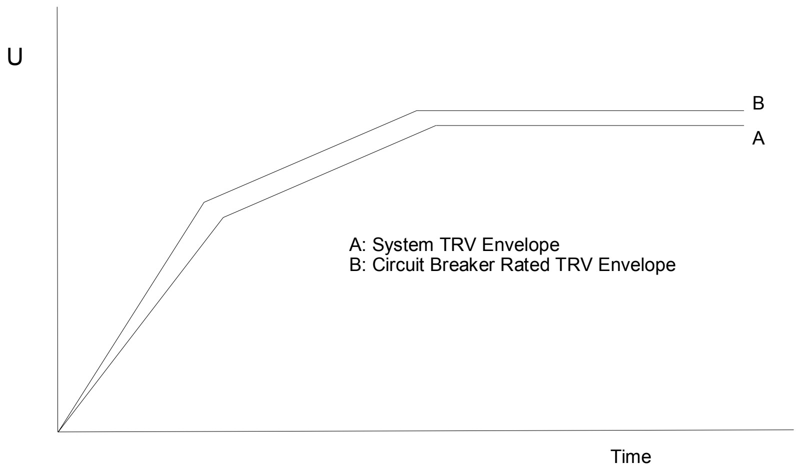
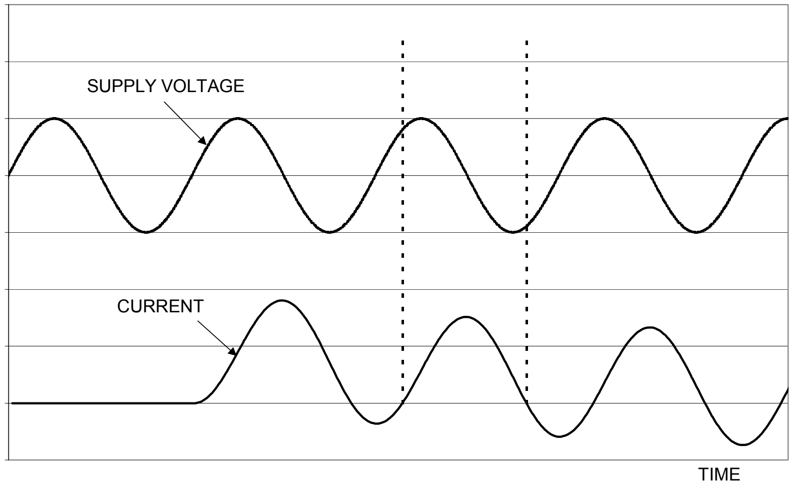


Figure 1—System TRV envelope and circuit breaker rated TRV envelope

3.3.2 Effect of asymmetry on transient recovery voltage

The TRVs that occur when interrupting asymmetrical current values are generally less severe than those that occur when interrupting the related symmetrical current because the instantaneous value of the supply voltage at the time of interruption is less than the peak value (see Figure 2). Circuit breakers have the capability of interrupting these asymmetrical currents provided that the circuit breakers are applied within their rating.

NOTE—IEEE Std C37.081a gives the reduction factors of TRV peak and rate of rise of recovery voltage (*RRRV*) when interrupting asymmetrical currents.[6]



NOTE—Dashed lines show the supply voltage at current zero.

Figure 2— Supply voltage and asymmetrical current

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[6] Notes in text, tables, and figures are given for information only, and do not contain requirements needed to implement the standard.

4. Application considerations

4.1 General

The system TRV characteristic is often complex, and a computer simulation may be necessary for evaluation. In many cases, however, the predominant TRV characteristic may be represented by an exponential, oscillatory, or triangular response as shown in Figure 3, Figure 4, and Figure 5, respectively.

A typical exponential TRV is shown in Figure 3. This exponential TRV typically occurs when at least one transformer and one line are on the unfaulted side of the circuit breaker when a three-phase fault is cleared at the breaker terminals.

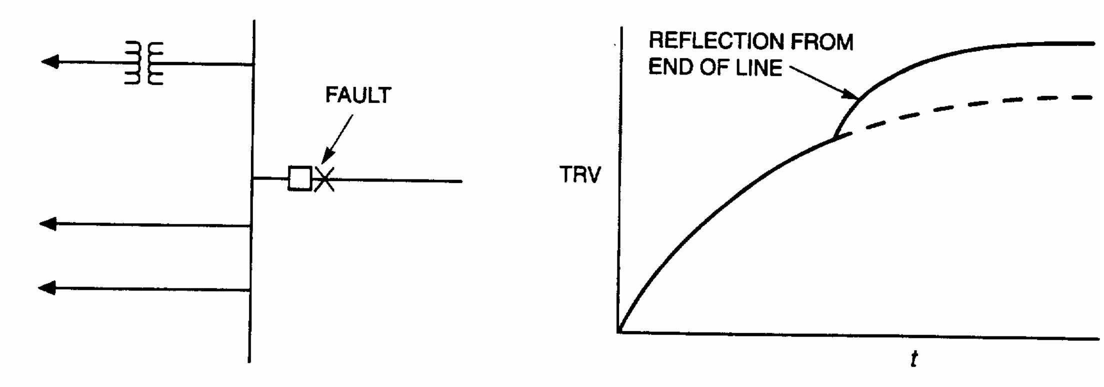


Figure 3—Exponential TRV characteristic

The oscillatory TRV shown in Figure 4 occurs when a fault is limited by a transformer or a series reactor and no transmission line or cable surge impedance is present to provide damping.

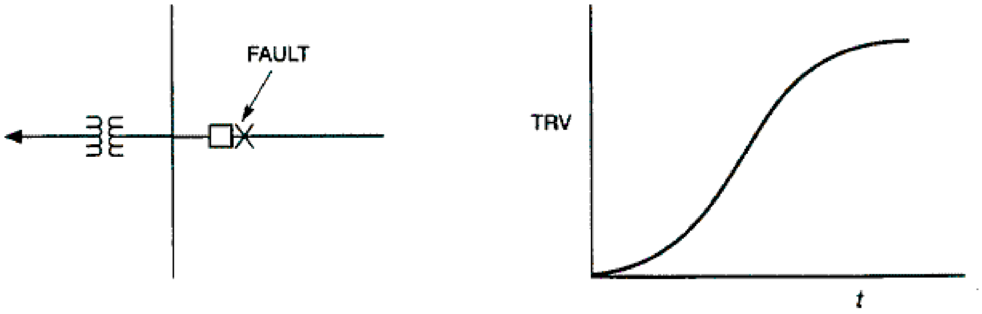


Figure 4— Oscillatory TRV characteristic

Short-line faults (SLF) exhibit the characteristic shown in Figure 5. The transmission line surge impedance, *Z*, determines the nature of the TRV. The rate-of-rise of the saw-tooth shaped TRV is generally higher than that experienced with exponential or oscillatory TRVs.

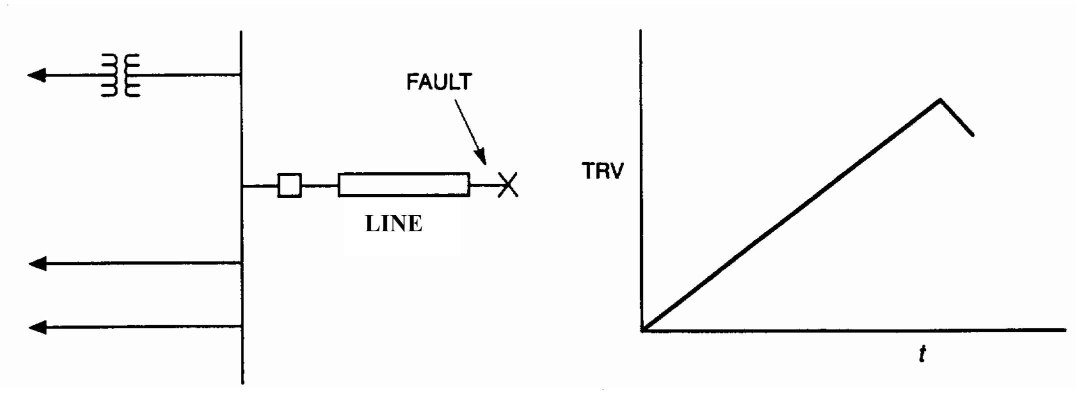


Figure 5—Short-line fault TRV characteristic

The two-parameter and four-parameter envelopes, illustrated in Figure 6 and Figure 7, have been introduced in the draft revision of IEEE PC37.04b [B16] to facilitate the comparison between a TRV obtained during testing and a specified TRV. As shown in Figure 6, the envelope of inherent test TRV must be higher than the reference line of specified TRV. In a similar way it is possible to compare a circuit breaker specified TRV capability and a system TRV obtained by calculation.

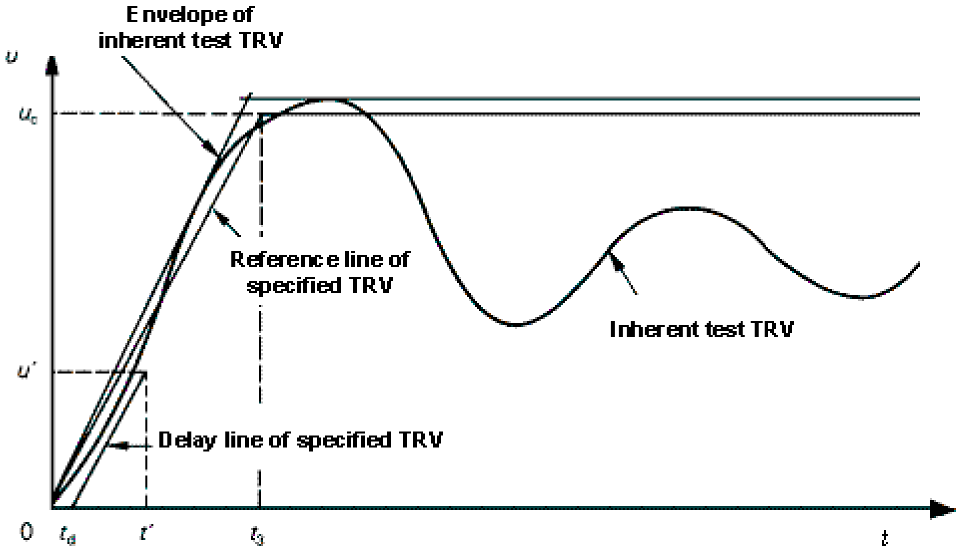


Figure 6—Example of inherent test TRV with two-parameter envelope that satisfies the conditions to be met during type test

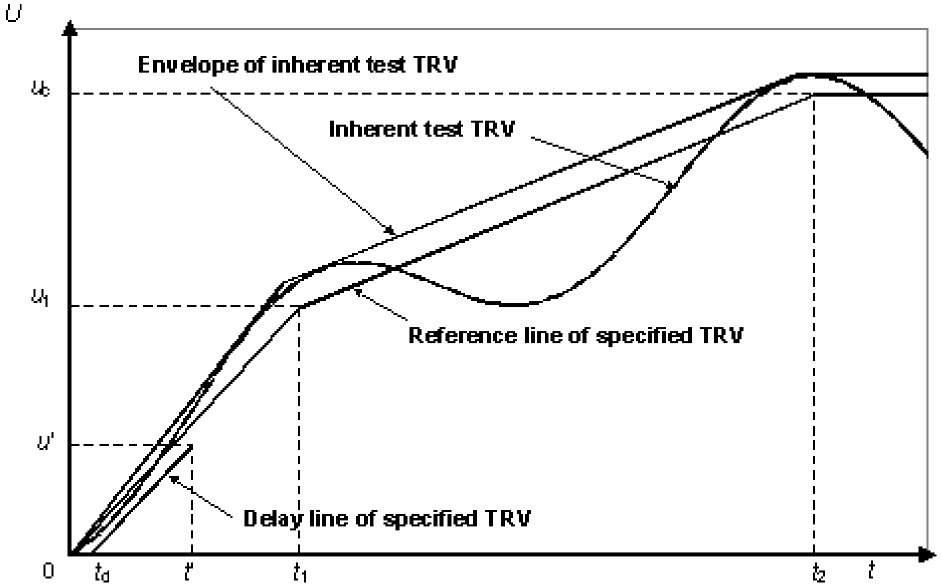


Figure 7—Example of inherent test TRV with four-parameter envelope that satisfies the conditions to be met during type test

A circuit breaker TRV capability is considered to be sufficient if the two or four parameter envelope drawn with rated parameters is higher than the two or four parameter envelope of the system TRV. This procedure provides a comparison between the circuit breaker TRV capability and a system TRV in the two regions where a reignition is likely i.e., during the initial part of the TRV where the RRRV is maximum and in the vicinity of the peak voltage (u_c).

The three-phase fault is usually the most severe terminal fault type and is used as the basis of rating (see Annex C). Short-line faults generally have higher rates-of-rise of recovery voltage than do terminal fault TRVs, but have lower crest voltage magnitudes.

Examples given in this subclause illustrate the use of the standard for some typical simplified system applications. Actual system TRVs may be complex and are often calculated using digital or analog computers with more detailed representations. An IEEE working group in the HVCB subcommittee of the IEEE Switchgear Committee is currently investigating the differences between the simplified system applications and the range of actual applications including some conditions not considered in this guide.

Consequently, the details of the calculations for the examples in this subclause are not included. An example of a detailed TRV calculation, including the first reflection, is given in Annex A. It is based on the calculation of transients in the equivalent circuit shown in Figure A.2. In addition, typical equipment capacitance values are given in Annex B. Some of these values may also be changed or additional values listed, based on the work of an HVCB task force determining natural frequencies of transformers.

4.2 Circuit breaker capability

Rated and related circuit breaker transient recovery voltage capabilities are defined by parameters given in ANSI C37.06. The following text is aligned with the concurrent revisions of IEEE PC37.04 [B16] and IEEE PC37.06 [B17].

Based upon the evaluation of many actual system configurations, standards assume, for systems above 72.5 kV, that clearing terminal fault currents higher than 30% of rating will result in a TRV characteristic that has a four-parameter envelope defined by four parameters (u_1, t_1, u_c, t_2) (see Figure 7).

For terminal fault currents between 10% and 30% for systems above 72.5 kV, and for all terminal fault currents for systems 72.5 kV and below, the standard assume a TRV envelope described by two parameters (u_c, t_3) as illustrated in Figure 6.

For breakers rated 72.5 kV and below, the TRV envelope is described by two parameters over the entire current range.

4.2.1 Three-phase terminal fault

As an example, Figure 8 shows the three-phase to ground fault related transient recovery voltage capability for a 550 kV circuit breaker at 100% of its symmetrical current rating (first-pole-to-clear factor k_{pp} = 1.3). It shows also the TRV capability for the optional case with k_{pp}= 1.5.

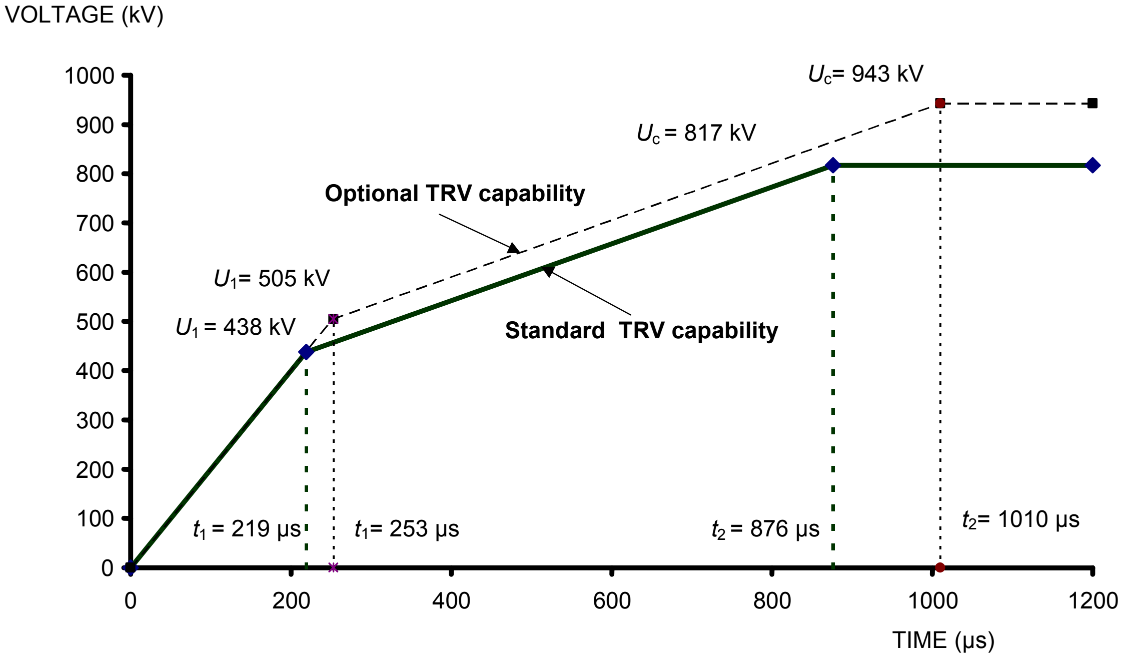


Figure 8—TRV capability envelope for a 550 kV circuit breaker at 100% of its rated fault current capability

The TRV envelope is defined by the four parameters (u_1, t_1, u_c, t_2) given in IEEE PC37.06 [B17]. The parameters that define the envelope of a TRV vary with the short-circuit current level. Multipliers are used to obtain by interpolation the proper parameter values, corresponding to a given short-circuit current, from the rated parameters defined for 100% short-circuit current. IEEE PC37.06 [B17] defines the values of the rated parameters and multipliers.

Table 1 is reproduced here from IEEE PC37.06 [B17] for readers' convenience. These multipliers may be changed as ANSI C37.06 is updated. Readers should refer to the current version of ANSI C37.06 for the multiplier values.

NOTE—Rating values from IEEE PC37.06 [B17] are used in this guide for examples. While revisions to ANSI C37.06 may occur in the future, the same fundamental applications apply.

Table 1—Related required transient recovery voltage capabilities of circuit breakers at various interrupting levels for terminal faults

	Multipliers for rated parameters							
Percent of interrupting capability[a] **(Note 1)**	**72.5 kV and below indoor / cable system**		**72.5 kV and below outdoor / line system**		**100 kV and above**			
	Ku_c	**Kt_3**	**Ku_c**	**Kt_3**	**Ku_1**	**Kt_1**	**Ku_c**	**Kt_2 or Kt_3**
100	1	1	1	1	1	1	1	1 —
60	1.07	0.44	1.07	0.67	1	0.67	1.07	0.5 —
30	1.14	0.22	1.13	0.4	—	—	1.13	— 0.211
10	1.21	0.22	1.17	0.4	—	—	1.17 / 1.26 (Note 2)	— 0.156 / 0.168 (Note 3)

NOTE 1—For other percentage of interrupting capability, interpolation can be done as shown in Figure 9.

NOTE 2—Multiplier for Ku_c is 1.17 for applications with $k_{pp} = 1.5$ and 1.26 for applications with $k_{pp} = 1.3$.

NOTE 3—Multiplier for Kt_3 is 0.156 for applications with $k_{pp} = 1.5$ and 0.168 for applications with $k_{pp} = 1.3$.

[a] Ratio of the symmetrical current component of the current being considered to the related required symmetrical interrupting capability (defined in IEEE Std C37.04) is stated in percent.

The following example is given to illustrate the use of Table 1.

Take, for example, the case of an outdoor (line system) 72.5 kV circuit breaker, the TRV peak withstand capability at 10% of interrupting capabillity is:

$$u_c(T10) = u_c(T100) \times Ku_c = \frac{U_r \times \sqrt{2}}{\sqrt{3}} \times k_{pp} \times k_{af} \times Ku_c \qquad (1)$$

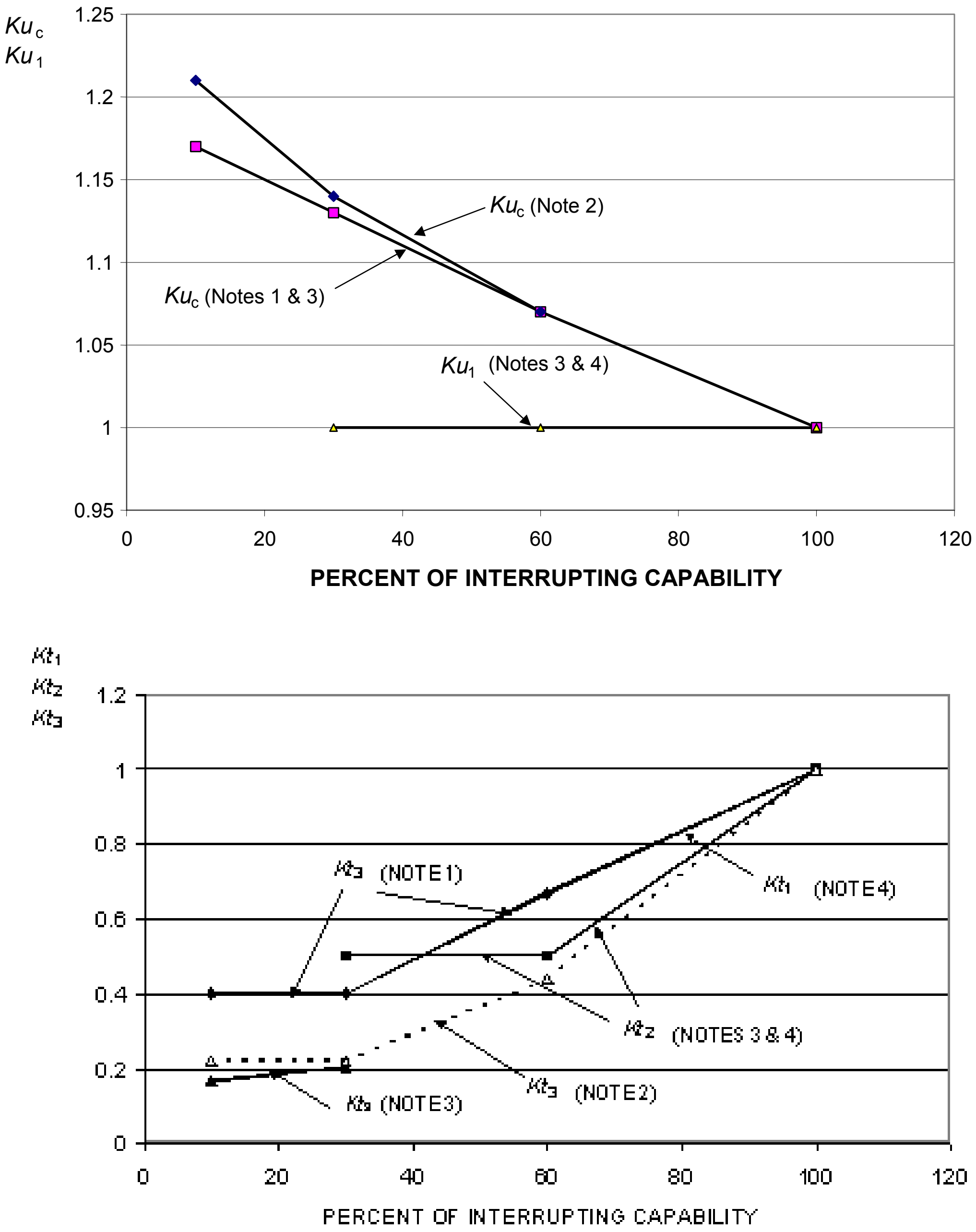
where

$U_r = 72.5$ kV,
$k_{pp} = 1.5$,
$k_{af} = 1.54$, (from Table 2A of IEEE PC37.04b [B16])
$Ku_c = 1.17$.

$$u_c(T10) = \frac{72.5 \times \sqrt{2}}{\sqrt{3}} \times 1.5 \times 1.54 \times 1.17 \quad \text{kV} = 160 \text{ kV}$$

In a similar way, the TRV peak withstand capability at 10% of interrupting capability for a 72.5 kV circuit breaker in a cable system is:

$$u_c(T10) = \frac{72.5 \times \sqrt{2}}{\sqrt{3}} \times 1.5 \times 1.4 \times 1.21 \quad \text{kV} = 151 \text{ kV}$$



NOTE 1—For outdoor circuit breakers and/or line systems 72.5 kV and below.

NOTE 2—For indoor circuit breakers and/or cable systems 72.5 kV and below.

NOTE 3—Rated voltages above 72.5 kV (values shown are those corresponding to $k_{pp} = 1.5$, see Table 1 for values corresponding to $k_{pp} = 1.3$).

NOTE 4—Kt_1 , Ku_1 and Kt_2 are applicable to currents higher than 30% of interrupting capability.

NOTE 5—TRV parameters u_C (or u_1) and t_3 (or t_1 or t_2) are obtained by multiplying the values given in ANSI C37.06 by the corresponding *Ku* and *Kt* multipliers.

Figure 9—TRV parameters multipliers for fractions of rated breaking current

As a further example, the TRV related capability envelope for a 550 kV circuit breaker at 75% of its rated fault current capability can be calculated as follows:

From ANSI PC37.04b [B16], TRV parameters for rated current and rated maximum voltage ($E_{\max}$) = 550 kV:

u_1 = 438 kV
t_1 = 219 µs
u_C = 817 kV
t_2 = 876 µs

From Table 1, the following multipliers are obtained by interpolation for 75% of rated fault current capability :

Ku_1 = 1
Kt_1 = 0.794
Ku_c = 1.044
Kt_2 = 0.687

where

Ku_1	is the multiplier for u_1
Kt_1	is the multiplier for t_1
Ku_c	is the multiplier for u_c
Kt_2	is the multiplier for t_2

TRV capability for 75% current:

u_1 = 438 kV
t_1 = 174 µs
u_c = 853 kV
t_2 = 602 µs

The shape of the TRV capability curve adjusted by the factors as given in Figure 9 is illustrated in Figure 10.

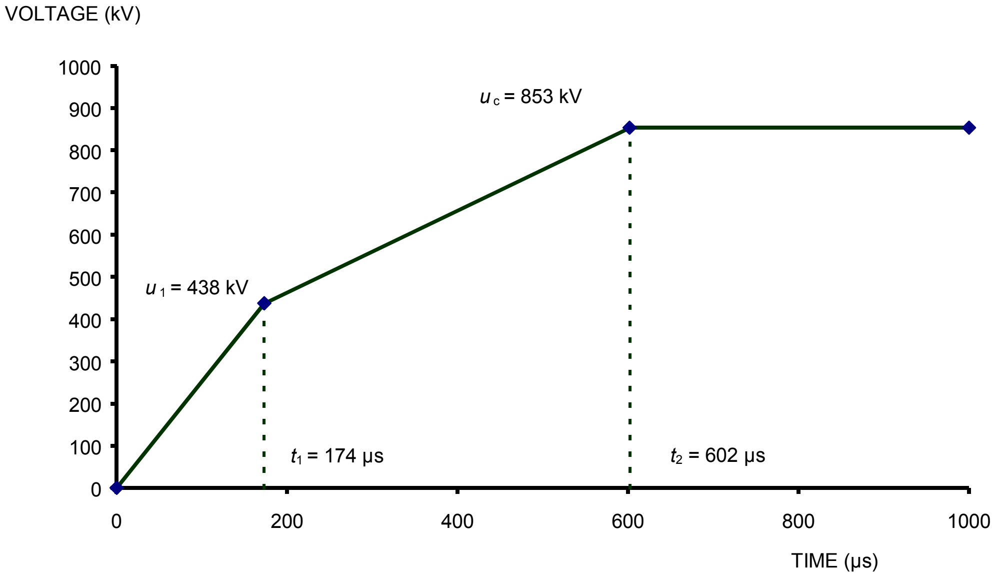


Figure 10 —TRV related capability envelope for 550 kV circuit breaker at 75% of its rated interrupting capability

The general characteristics of the TRV envelopes defined by IEEE PC37.04b [B16] are illustrated in Figure 11 and Figure 12 as a function of the fault current magnitude.

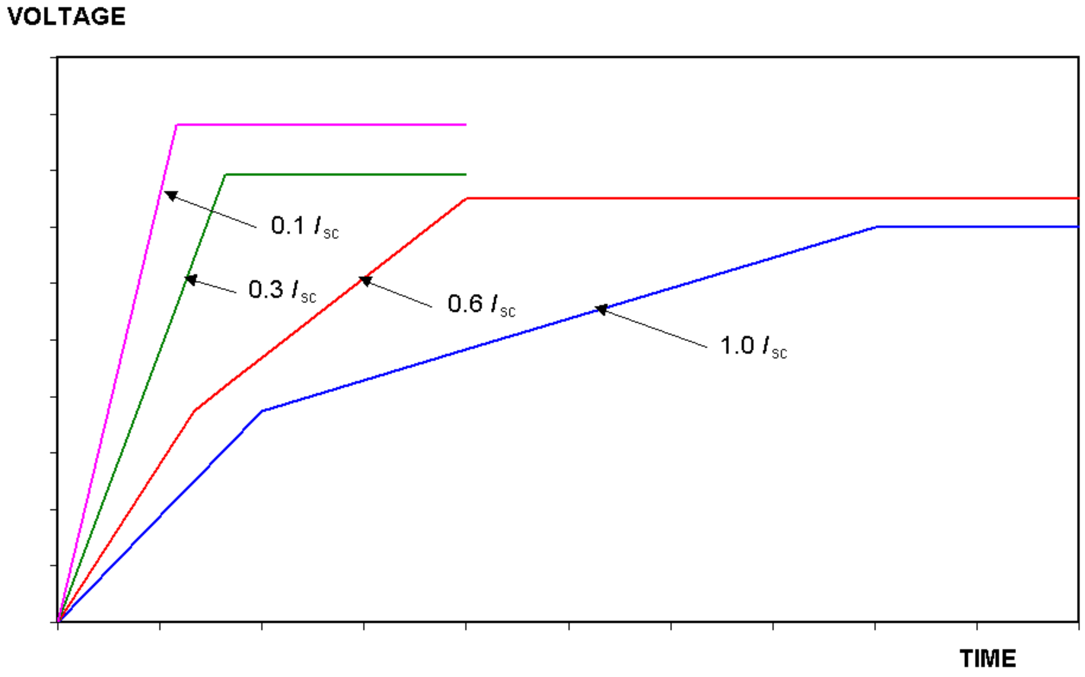


Figure 11—TRV envelopes, systems above 72.5 kV (I is the rated short-circuit current)

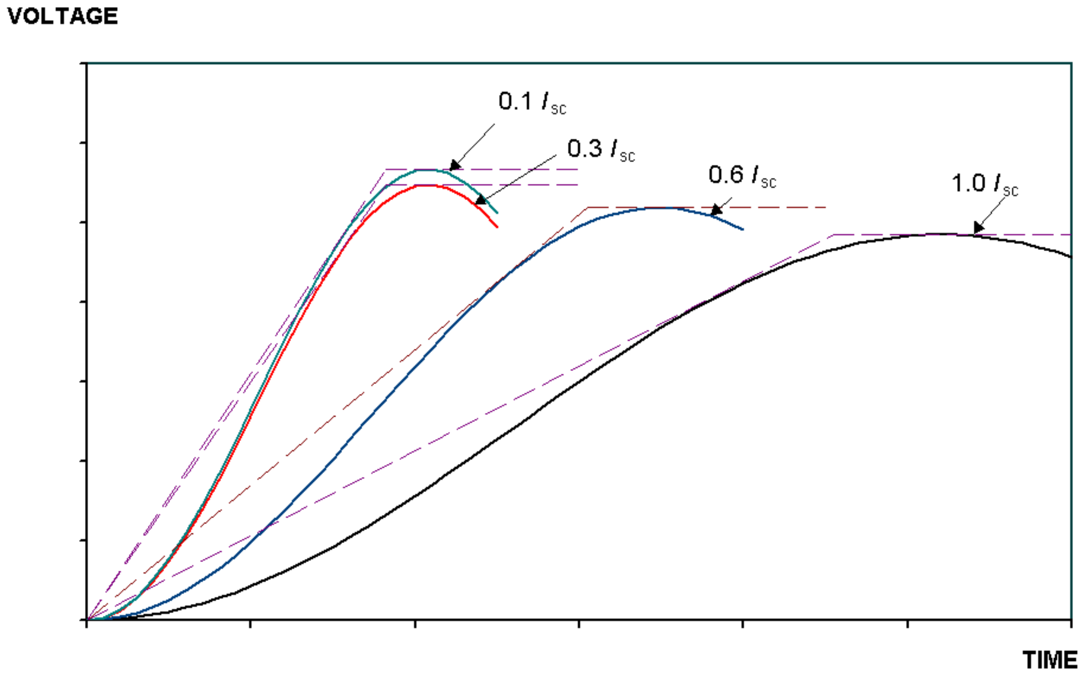


Figure 12—TRV envelopes, systems 72.5 kV and below (I is the rated short-circuit current)

4.2.2 Short-line fault

Short-line fault (SLF) capability, which is a related capability, is described and defined in IEEE Std C37.04. The line side component of the TRV is characterized by a triangular waveshape with a relatively high rate-of-rise, but a low peak magnitude compared to the three-phase terminal fault. A typical SLF waveform is illustrated in Figure 13.

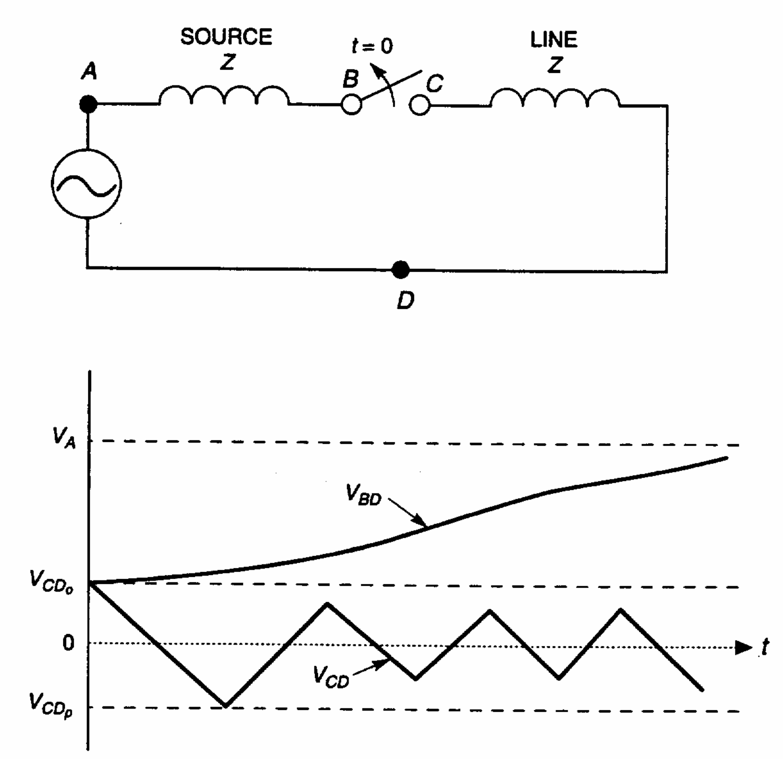


Figure 13—TRV waveshape for short-line fault

In general, it is not necessary to calculate the SLF TRV as long as the terminal fault TRVs are within rating and transmission line parameters are within the values specified in IEEE Std C37.04. The transmission line parameters are given in terms of the effective surge impedance, Z_{eff}, of the faulted line and the amplitude factor, d, defined as:

$$d = 2\omega \frac{Z_{\text{eff}}}{X_{\text{L}}\, v} \tag{2}$$

where

$$X_L = \frac{(2L_{1\omega} + L_{0\omega})\,\omega}{3} \tag{3}$$

$$Z_{\text{eff}} = \frac{(2Z_1 + Z_0)}{3} \tag{4}$$

v is the velocity of light,
X_{L} is the reactance of the line to the fault point per unit length,
$L_{1\omega}$ is the positive sequence power frequency line inductance per unit length,
$L_{0\omega}$ is the zero sequence power frequency line inductance per unit length,

Z_{eff} is the effective surge impedance of the line,
Z_1 is the positive sequence surge impedance,
Z_0 is the zero sequence surge impedance,
ω is 2 π × system power frequency (377 rad/s for a 60 Hz system).

Annex A gives equations for the calculation of the peak factor *d* as function of system parameters.

For standardization purposes, short-line faults correspond to cases where the interrupting pole is the last pole to clear a fault. The rated values for Z_{eff} and *d* as defined in IEEE Std C37.04 are as follows:

$Z_{\text{eff}} = 450\ \Omega$

$d = 1.6$

The SLF TRV capability (up to the first peak of TRV) is defined as follows:

$$e = e_{\text{L}} + e_{\text{S}} \tag{5}$$

$$e_{\text{L}} = d(1-M)\sqrt{2/3}\ E_{\max} \tag{6}$$

$$e_{\text{S}} = 2\ M\ (t_{\text{L}} - t_{\text{d}}) \tag{7}$$

$$R_{\text{L}} = \sqrt{2}\omega\ M\ I\ Z_{\text{eff}} \tag{8}$$

$$t_{\text{L}} = \frac{e_{\text{L}}}{R_{\text{L}}} \tag{9}$$

where

e is the first peak value of TRV (kV),
e_{L} is the line side contribution to TRV (kV),
e_{S} is the source side contribution to TRV (kV),
R_{L} is the rate-of-rise of recovery voltage (kV/μs),
t_{L} is the time to peak (μs),
d is 1.6,
I is the rated short-circuit current (kA),
I_{L} is the fault current (kA),
M is the ratio of the fault current to the rated short-circuit current (I_L / I),
t_{d} is the time delay of recovery voltage on the source side (μs),
$E_{\max}$ is the rated maximum voltage (kV),
Z_{eff} is 450 (Ω).

As explained in A.1.3, the fault current is

$$I_{\text{L}} = \frac{V_{\text{LG}}}{X_{\text{L}}\ \lambda + V_{\text{LG}} / I} \tag{10}$$

where

V_{LG} is the system line-ground voltage,
λ is the distance from the opening circuit breaker to the fault.

An example of application is given in A.3.3.

4.2.3 Faults with initial rate of rise of TRV higher than rated

For fault currents less than rated, the prospective system TRV envelope may exceed the maximum envelope defined by the standards only at the very beginning of the waveform. In actuality, the standard defines a higher withstand in this region through the SLF capability. It is often unnecessary, but when it is needed, the user can apply the capability associated with SLFs to bus faults.

In Figure 14, the TRV capability curve for the example in 4.2.1 is shown with the short-line fault capability included. For this example,

E_{max} = 550 kV
I = 40 kA
M = 0.75
ω = 377 rad/s

The initial peak of TRV can be calculated, using Equation (5) to Equation (9) as follows:

- Line side contribution

  e_{L} = 180 kV
  R_{L} = *7.2* kV/µs
  t_{L} = 25 µs

- Source side contribution

  As shown in Figure 15, the contribution of the source side TRV until t_{L} can be calculated, assuming rated values of the time delay (t_{d} = 2 µs) and of the *RRRV* (=2 kV/µs) when interrupting 100% of rated short-circuit current.

  When interrupting a SLF with a reduced fault current, the rate-of-rise of recovery voltage on the supply side is reduced to $2\,M = 2 \times 0.75$ kV/µs = 1.5 kV/µs

  The source side contribution to TRV is then $e_{\text{S}} = 1.5\,(25 - 2)$ kV = 34.5 kV

- Initial TRV peak

$$e_{\text{T}} = 180\,\text{kV} + 34.5\,\text{kV} = 214.5\,\text{kV} \text{ (at } t_{\text{L}} = 25\ \mu\text{s)}$$

In a similar way, the TRV withstand capability of a circuit breaker at 60% of its rated fault current capability can be obtained by making the envelope of the TRV capabilities demonstrated by terminal fault test duty T60 and SLF test duty L60.

Figure 14 shows that the combination of SLF and Terminal fault TRV withstand capabilities can be defined by six parameters (e_{T}, t_{L}, u_1 , t_1, u_{c}, *and* t_2) the TRV withstand capability of a circuit breaker rated 100kV and above, at a given percentage of its rated interrupting capability. In a similar way, the TRV withstand capability for a circuit breaker rated 72.5 kV and below can be defined by a four-parameter envelope (e_{T}, t_{L}, u_{c}, *and* t_3) of its SLF and terminal fault TRV withstand capabilities (where applicable).

NOTE 1—The (e_{T}, t_{L}) point is additional to the four (or two) parameter TRV envelope described in 4.1 and is introduced here to extend the TRV envelope in the region requiring a higher initial rate of rise of TRV.

NOTE 2—For low values of M it may happen that e_{T} is higher than u_1, in that case the TRV withstand after time t_{L} is obtained by the envelope of an horizontal line starting from (e_{T}, t_{L}) and the four-parameter TRV capability for terminal fault. This is justified by the fact that the TRV withstand capability is an increasing function of time.

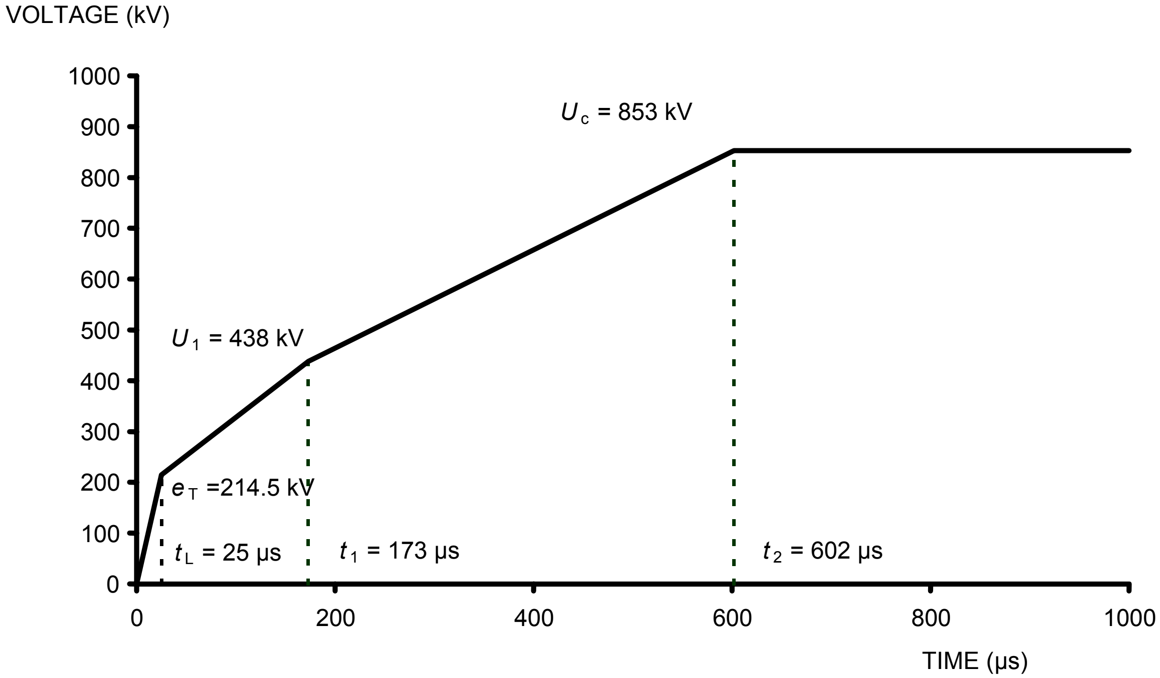


Figure 14—TRV related capability envelope for 550 kV circuit breaker at 75% of its rated fault current capability with SLF component

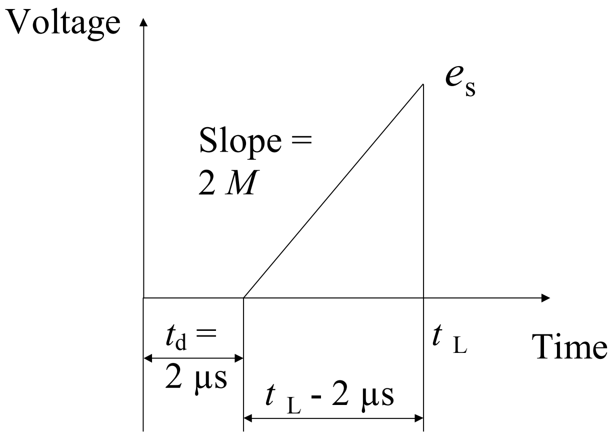


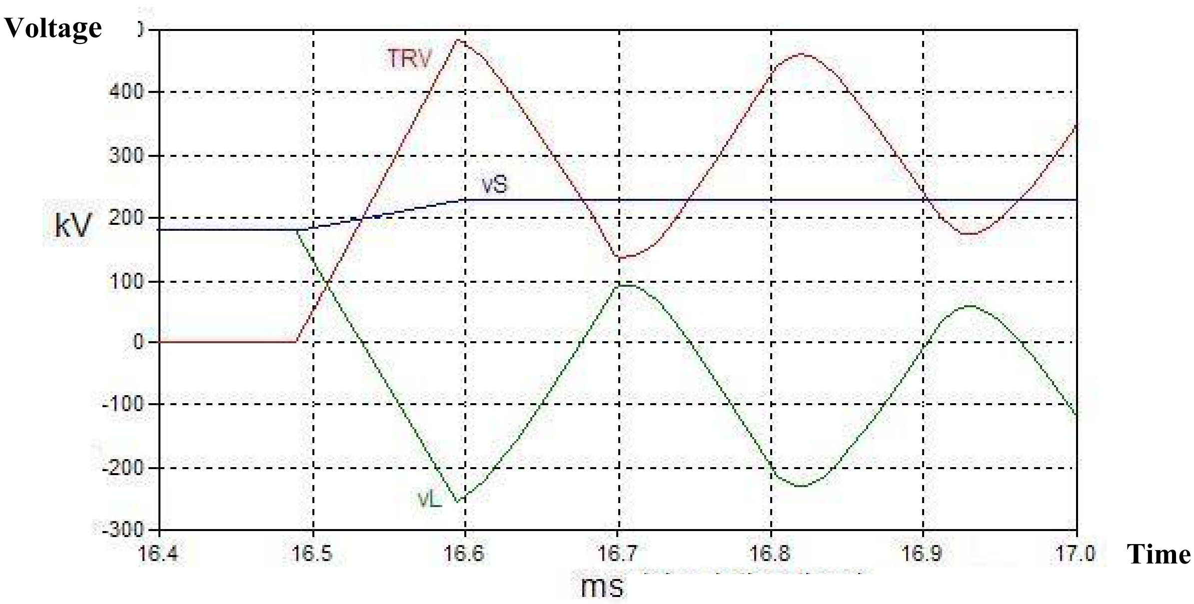
Figure 15—Contribution of the source side voltage to TRV

4.2.4 Line faults

With some line fault conditions, it may occur that the initial part of the TRV is not covered by the standard TRV withstand capability defined for terminal fault and short-line fault, even when both capabilities are combined as explained in 4.2.3. Such situations can occur during interruption of three-phase line faults as mutual coupling of lines between the first interrupted phase and the two other phases can increase the line side contribution of TRV on the first pole-to-clear (short-line faults covered in 4.2.2 correspond to cases where the interrupting pole is the last pole to clear a fault).

4.2.4.1 Example with a L60 fault at 15.6 km (9.66 mi) from the circuit breaker

To illustrate this fault condition, Figure 16 shows the TRV on the first pole-to-clear when interrupting a three-phase 24 kA line fault in a 550 kV system. The short-circuit current for a three-phase terminal fault is 40 kA.



TRV = transient recovery voltage v_S = supply side voltage v_L = line side voltage

Figure 16—TRV, supply-side and line-side voltages when the first pole clears a three-phase 24 kA line fault in a 550 kV system

NOTE—As shown in Figure 16, the contribution of the supply side is calculated only until the first peak of the line side voltage is reached. This is sufficient for the determination of TRV up to its peak value.

The following gives the comparison of the system TRV and the TRV withstand capability of a circuit breaker with a rated short-circuit current of 40 kA.

a) System TRV: The system TRV applied on the circuit breaker, as shown on Figure 16, is characterized by

$$\text{peak value} = 484 \text{ kV}$$

$$RRRV = \frac{484}{105} = 4.6 \text{ kV/}\mu\text{s}$$

b) TRV withstand capability of the circuit breaker:

The fault current is 60% of the circuit breaker rated short-circuit current. As explained in 4.2.3, the first peak of the TRV withstand capability for a 550 kV circuit breaker with SLF component is:

E_{max} = 550 kV
I = 40 kA
M = 0.60

- Line side contribution

  e_L = 287.4 kV
  R_L = 5.74 kV/µs
  t_L = 50 µs

- Source side contribution

$$e_S = 2\,M\,(t_L - t_d) = 1.20\,(50-2)\,\text{kV} = 57.6\ \text{kV}$$

- Initial TRV withstand capability

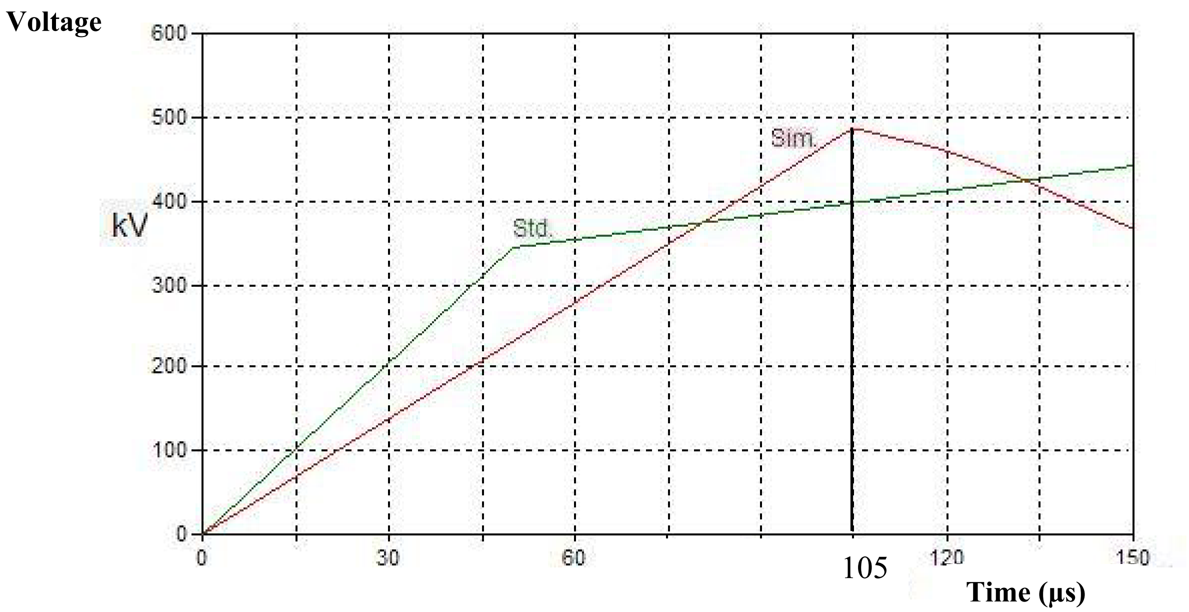
peak TRV $e = 287.4\,\text{kV} + 57.6\,\text{kV} = 345\ \text{kV}$

RRRV $= \dfrac{345}{50}\,\text{kV/µs} = 6.9\ \text{kV/µs}$

As can be seen in this example, the TRV peak withstand capability demonstrated during SLF tests can be exceeded in some conditions of three-phase line faults, depending on the actual short-circuit power of the source. However, this higher TRV peak is associated with an RRRV that is significantly lower than that withstood during the corresponding SLF test duty. In such cases, it has to be checked if the system TRV is covered by the envelope of the TRV capabilities demonstrated by terminal fault test duty T60 and SLF test duty L60. If this is not the case, a specific TRV withstand capability could be required or a circuit breaker with a higher short-circuit rating could be specified. (See the NOTE that follows.) The manufacturer should be consulted for such applications.

NOTE—When the ratio of the fault current to the rated short-circuit current of the circuit breaker is decreased (e.g., from M = 24/40 = 0.60 to M = 24/50 = 0.48), the initial peak TRV withstand capability of the circuit breaker is increased [see Equation (6)].

The composite TRV peak withstand capability, determined as shown in Figure 14 by combining SLF L60 and terminal fault T60 withstand capabilities, is 399 kV at 105 µs. In this particular case, as illustrated in Figure 17, the TRV peak withstand capability is still lower than the system TRV.



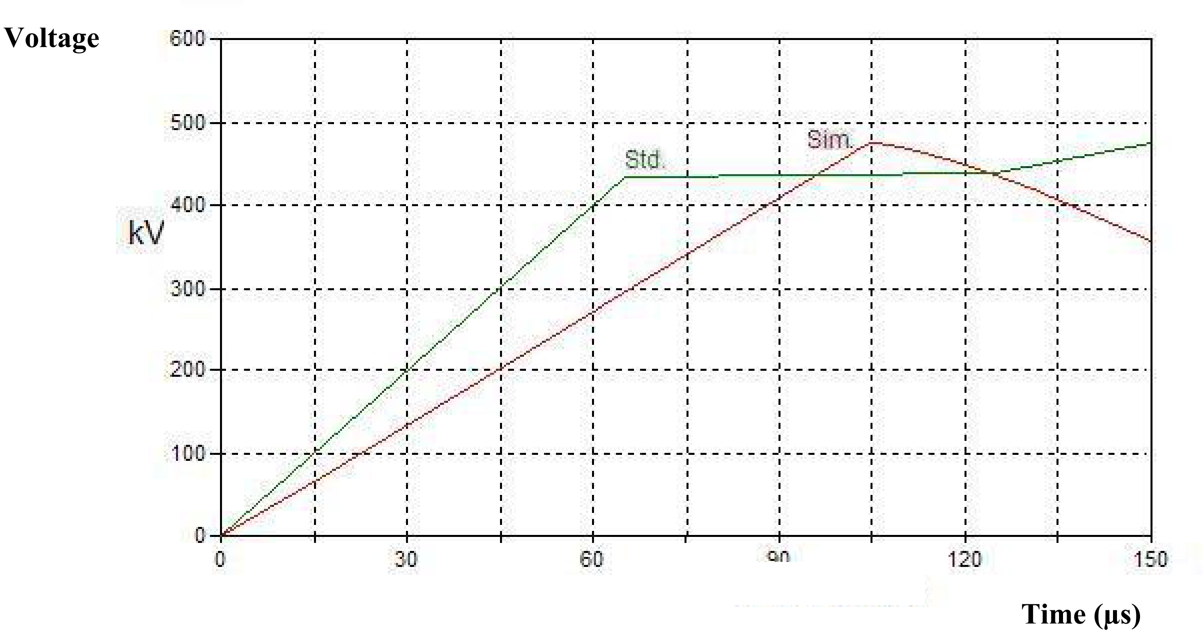
Sim = system TRV Std = composite TRV capability of circuit breaker

Figure 17 —Comparison of system TRV and composite TRV capability of circuit breaker Case of three-phase 24 kA line-fault and 550 kV 40 kA circuit breaker

The calculation shown in b) above can be performed for a circuit breaker rated 550 kV 50 kA 60 Hz. It leads to a TRV withstand capability of 434 kV at 64.9 µs (*RRRV* = 6.7 kV/µs) when interrupting a short-line fault with 24 kA (*M* = 0.48).

The composite initial TRV peak withstand capability is 462 kV at 105 µs (see Figure 18). Although the level demonstrated by SLF testing is lower, but faster, than the system initial TRV peak value, in practical terms and typically with SF_6 single pressure circuit breakers, it would be expected that the TRV capability is sufficient as the deficit in TRV peak is compensated by the higher RRRV demonstrated during SLF tests (6.7 kV/µs to be compared with 4.4 kV/µs). Users should exercise judgment in cases where the system TRV is higher but the system RRRV is less than the breaker withstand capability.

NOTE—Due to the short arc time-constants in SF_6, single-pressure circuit breakers are more sensitive to the RRRV than to the first peak value of TRV obtained during SLF interruption. It is generally accepted that, as a first approximation, the SLF interrupting capability of single pressure SF_6 circuit breakers can be expressed as RRRV versus the fault current derivative.



Sim = system TRV

Std = composite TRV capabilty of circuit breaker

Figure 18—Comparison of system TRV and composite TRV capability of circuit breaker

Case of three-phase L60 line-fault in 550 kV system with 40 kA short-circuit current and circuit breaker rated 550 kV 50 kA

It has to be noted that the higher system TRV peak is applicable only to the first pole-to-clear; interruption by other poles is covered by the short-line fault test duty (see 4.2.2).

As explained in the introduction to this guide, this matter needs further study and will be thoroughly covered in the next revision of IEEE Std C37.011.

4.2.4.2 Example with a fault 146 km (90 mi) from the breaker

If the fault is farther away on the line, the peak of TRV increases due to the higher voltage drop on the line and coupling between phases. But as the short-circuit current is lowered by the added line reactance, the RRRV is also decreased.

If the fault is 146 km (90 mi) away on the line, a TRV peak of 1000 kV is applied 970 μs after current interruption of 5.4 kA. The RRRV is relatively slow in this case (1.03 kV/μs).

Such actual cases of interruption of relatively low short-circuit currents with a TRV characterized by a high peak, should be compared with the TRV withstand capability of a circuit breaker demonstrated by the terminal fault test duties T10 and T30, and, where applicable, the out-of-phase test duty of IEEE Std C37.09.

NOTE—The out-of-phase test duty demonstrates a higher TRV peak withstand than terminal fault test duties T10 and T30. However, the out-of-phase test duty cannot be always used for the demonstration of the TRV withstand as it is a non-mandatory test duty.

In the present example of a 550 kV circuit breaker, the TRV capability defined in IEEE PC37.06 [B17] has a peak value of 1123 kV and a RRRV of 1.54 kV/μs.

Therefore, the TRV withstand required by a line fault 146 km (90 mi) down the line is covered by the out-of-phase TRV capability, if the two-parameter TRV is used. Although IEEE PC37.06 [B17] defines a four-parameter TRV, a two-parameter TRV having the same peak TRV and the same RRRV may be used by agreement of the manufacturer as it is more severe.

4.2.5 Three-phase ungrounded faults

For special applications in transmission systems (rated maximum voltage 245 kV to 800 kV) with effectively grounded neutral in cases where the probability of three-phase faults not involving ground cannot be disregarded, the system TRV calculations (see Annex A) may show that the standard circuit breaker capability may be exceeded. If this should occur, a first-pole-to-clear factor of 1.5 may be required and corresponding TRV withstand capability parameters are given in IEEE PC37.06 [B17].

For special cases where an increased TRV withstand capability is required (first pole-to-clear factor k_{pp}= 1.5), the implication for circuit breakers already tested with rated values of TRV corresponding to k_{pp}= 1.3 is that only the withstand of the first pole-to-clear has to be demonstrated because the required withstand for the second and third pole-to-clear is already covered (see Figure C.1 in Annex C). In the case of a 550 kV circuit breaker at 100% of its breaking capability, Annex C shows that the required TRV peak for the second and third pole-to-clear a three-phase ungrounded fault is

$$0.87 \times 550 \times 1.4 \times \frac{\sqrt{2}}{\sqrt{3}}\ \text{kV} = 547\ \text{kV}.$$

This value of 547 kV is covered by the value required during testing of a 550 kV circuit breaker with a first pole-to-clear factor of 1.3:

$$\text{TRV peak} = 1.3 \times 550 \times 1.4 \times \frac{\sqrt{2}}{\sqrt{3}}\ \text{kV} = 817\ \text{kV}$$

To summarize, in the special cases where three-phase ungrounded faults need to be considered, only the TRV withstand of the first pole-to-clear has to be demonstrated with a factor of 1.5 and the associated interrupting window (between minimum arcing time and minimum arcing time + 60° - ε, with ε taken as 18°).

4.3 Exponential (overdamped) TRV

Assuming that a network can be reduced to a simple parallel RLC circuit, the TRV is exponential (overdamped) if $R \leq \frac{1}{2}\sqrt{L/C}$ (see A.1.1.1).

This condition is met in the example shown in Figure 19 of a 550 kV substation where several lines are connected on the supply side of the interrupting circuit breaker A.

Figure 19 shows the one-line diagram of the 550 kV substation. Figure 20 illustrates the TRV seen by circuit breaker A when clearing the three-phase fault shown in Figure 19 (circuit breaker B is open). This waveform is overdamped and exhibits an exponential waveshape. A reflection occurs from the end of the shortest line after approximately 535 μs, causing a slight increase in the TRV crest. The TRV capability curve (Figure 8) is also shown in Figure 20, indicating that the breaker TRV capability exceeds system requirements.

In some cases it may be necessary to use a higher current-rated circuit breaker to obtain the desired TRV capability curve. In Figure 21, the TRV capability curves for a 550 kV, 40 kA, and 63 kA circuit breaker are compared to a 40 kA fault application. It is evident that the 63 kA circuit breaker provides additional capability.

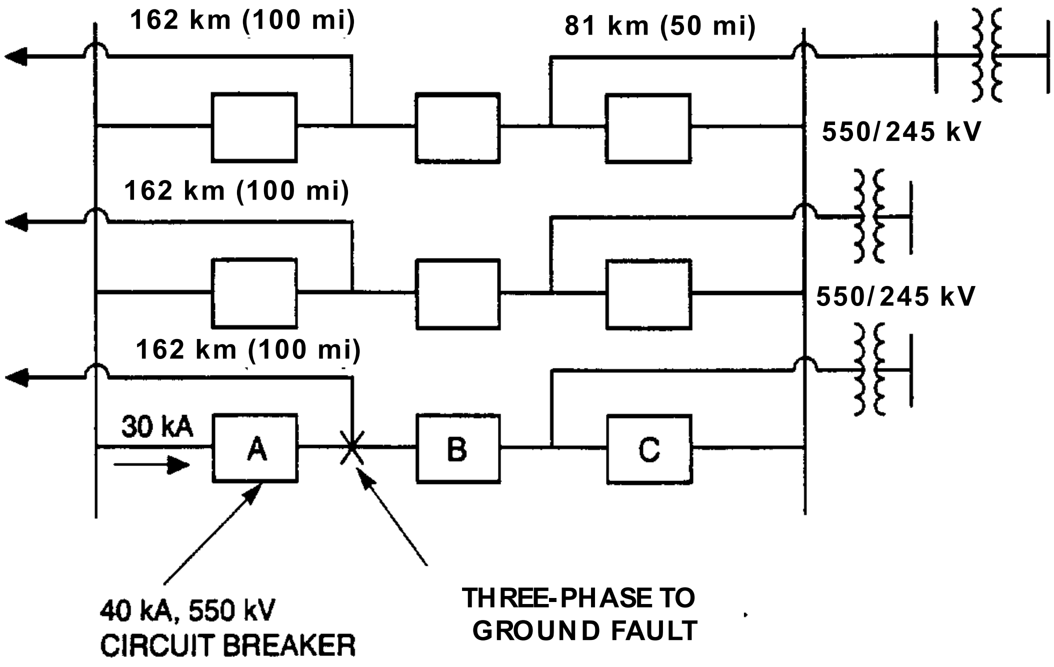


Figure 19 —System configuration

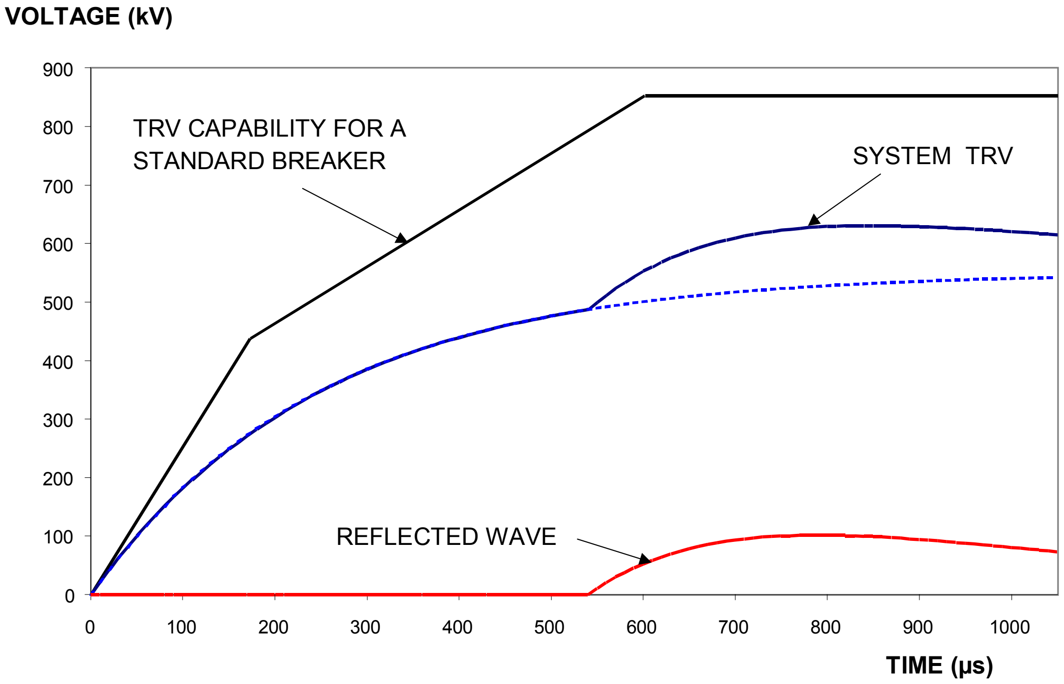


Figure 20—Comparison of TRV capability for a 550 kV circuit breaker (at 75% of its rated interrupting current capability) and system TRV

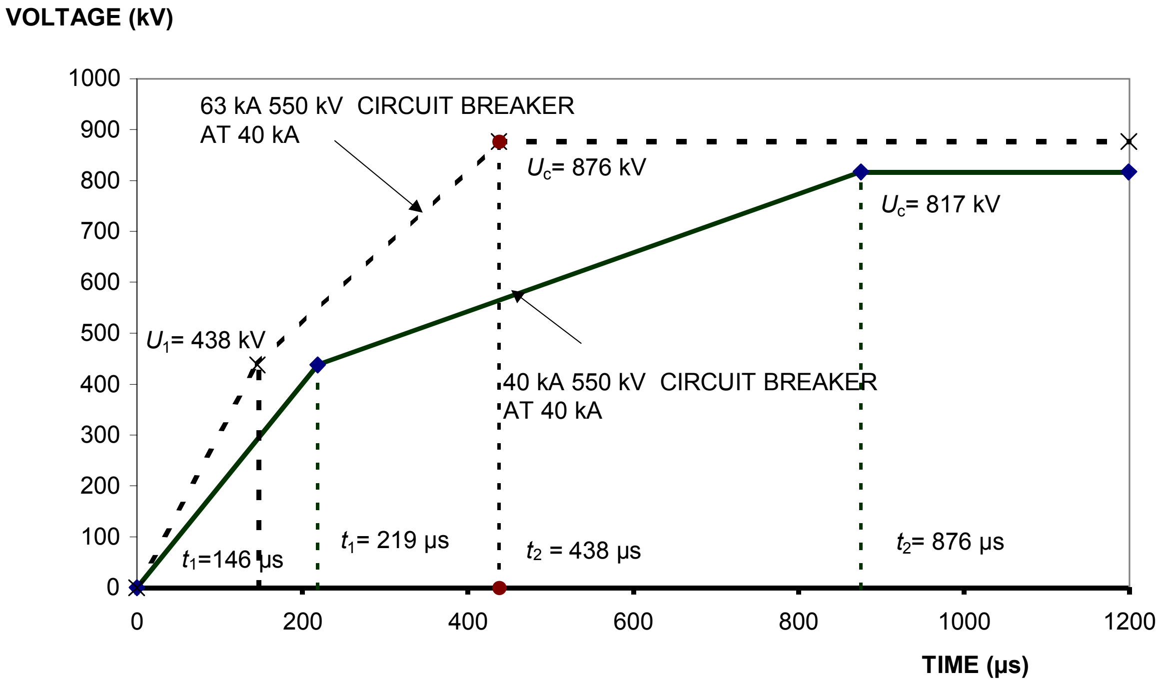


Figure 21—TRV capability curve for 40 kA and 63 kA circuit breakers when interrupting 40 kA under 550 kV

4.4 Oscillatory (underdamped) TRV

4.4.1 Transformer limited fault

In Figure 22, 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 23. This TRV is determined by the inductance and capacitance of the transformer and the capacitance between the transformer and the circuit breaker (see A.3.2 for the calculation of TRV parameters). It is a high-frequency transient that may exceed the capability curve defined in IEEE Std C37.04 and ANSI C37.06.

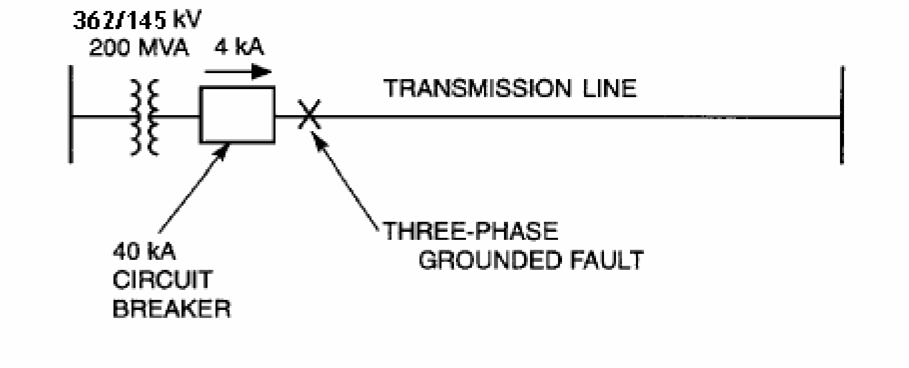


Figure 22—Fault location

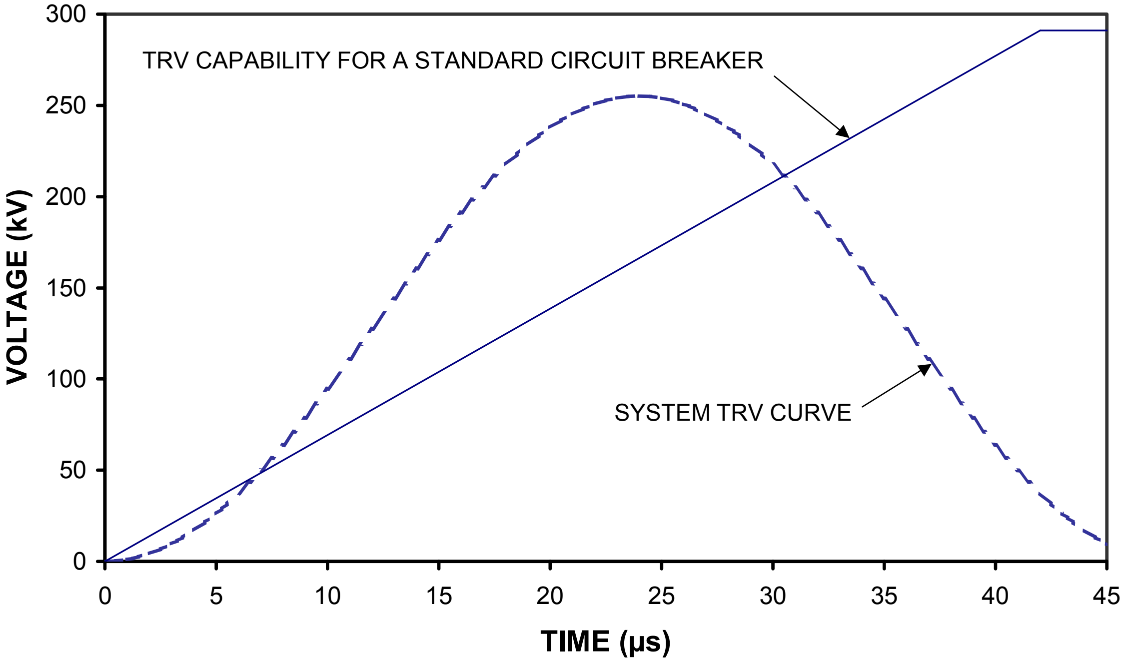


Figure 23—Comparison of TRV capability for 145 kV circuit breaker (at 10% of its rated interrupting current capability) and system TRV with transformer limited fault

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 ANSI C37.06 (see Figure 23).

The system TRV curve can be modified by a capacitance and then be within the standard capability envelope. Figure 24 illustrates the modified system TRV for the condition of Figure 22, but with additional capacitance assumed between the transformer and the circuit breaker.

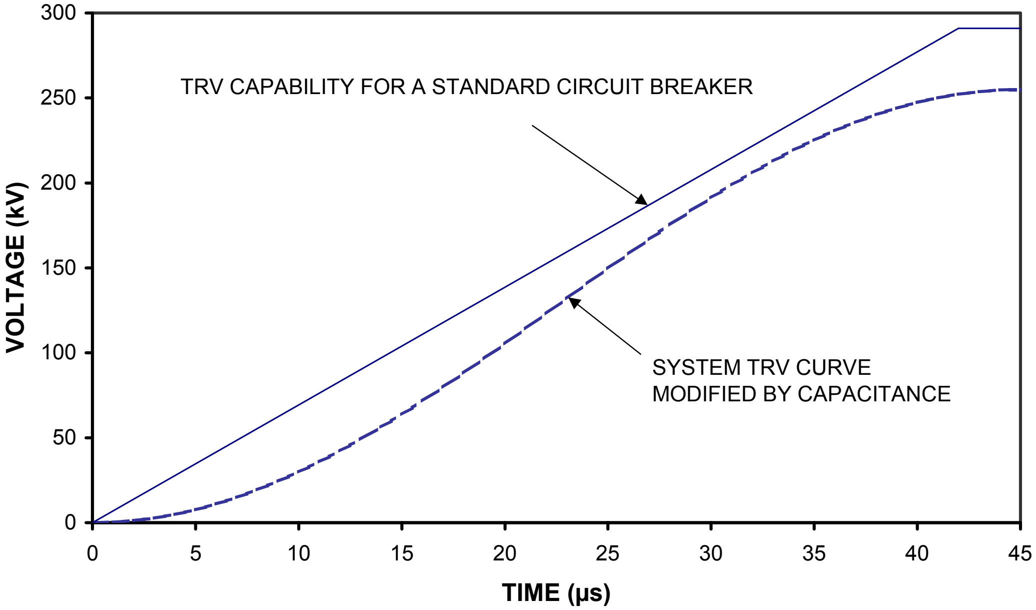


Figure 24—Comparison of TRV capability for 145 kV circuit breaker (at 10% of its rated interrupting current capability) and system TRV modified by additional capacitance between circuit breaker and transformer

As an alternative, the user can choose to specify a definite purpose circuit breaker for fast transient recovery voltage rise times, as defined in ANSI C37.06.1-2000. 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 1B, Table 2B, and Table 3B of ANSI 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 ANSI C37.06.

The standard capability curve shown in Figure 23 and Figure 24 is defined by a two-parameter envelope where u_c and t_3 are defined in Table 3B of IEEE PC37.06 [B17] for 10% short-circuit breaking capability, maximum voltage (E_{max} = 145 kV), and effectively grounded systems.

u_c = 291 kV

t_3 = 42 µs

The contribution of transformers to the short-circuit current is 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 systems are covered in IEEE PC37.04b [B16] and

ANSI C37.06 [B17] 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.

For currents between 10% and 30% of rated short-circuit current, values of u_c and t_3 can be obtained by linear interpolation.

It should be noted that the transformer limited fault can occur in a well developed substation, not just the radial system shown in Figure 22. A similar condition could occur in the system of Figure 19 if transformer breaker "C" were the last one to clear a bus fault with breaker "B" open.

4.4.2 Reactor limited fault

When line side series reactors are used, high rate-of-rise TRVs can result in much the same way as for transformer limited faults discussed in 4.4.1. An example of a series reactor used on a 230 kV system is illustrated in Figure 25. The resultant TRV for the case described is shown in Figure 26.

This system TRV may exceed the standard capability curve, which is described by a two-parameter envelope where u_c and t_3 are defined in Table 3B of IEEE PC37.06 [B17] for 10% short-circuit breaking capability, maximum voltage (E_{max} = 245 kV):

u_c = 492 kV

t_3 = 70 µs

For currents between 10% and 30% of rated short-circuit current, values of u_c and t_3 can be obtained by linear interpolation.

Wavetraps used in transmission line communication systems may also add a high-frequency component to the TRV although of a lesser magnitude than a transformer or a current limiting reactor. However, under some circumstances, wavetraps can substantially increase the TRV over that present without the trap. A wavetrap is usually a parallel L-C device that is placed between the line and circuit breaker.

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

- Specify a definite purpose circuit breaker for fast transient recovery voltage rise times, as defined in ANSI C37.06.1-2000. In some cases their higher TRV withstand capability will be sufficient.
- 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.

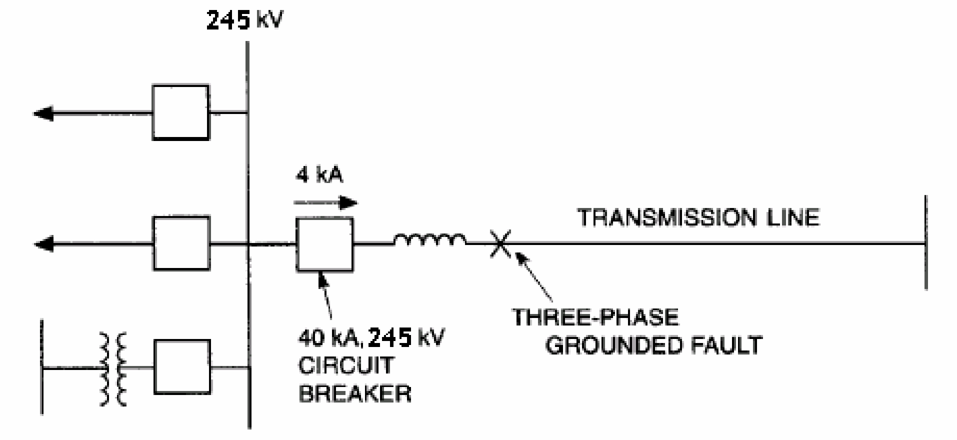


Figure 25—Fault location

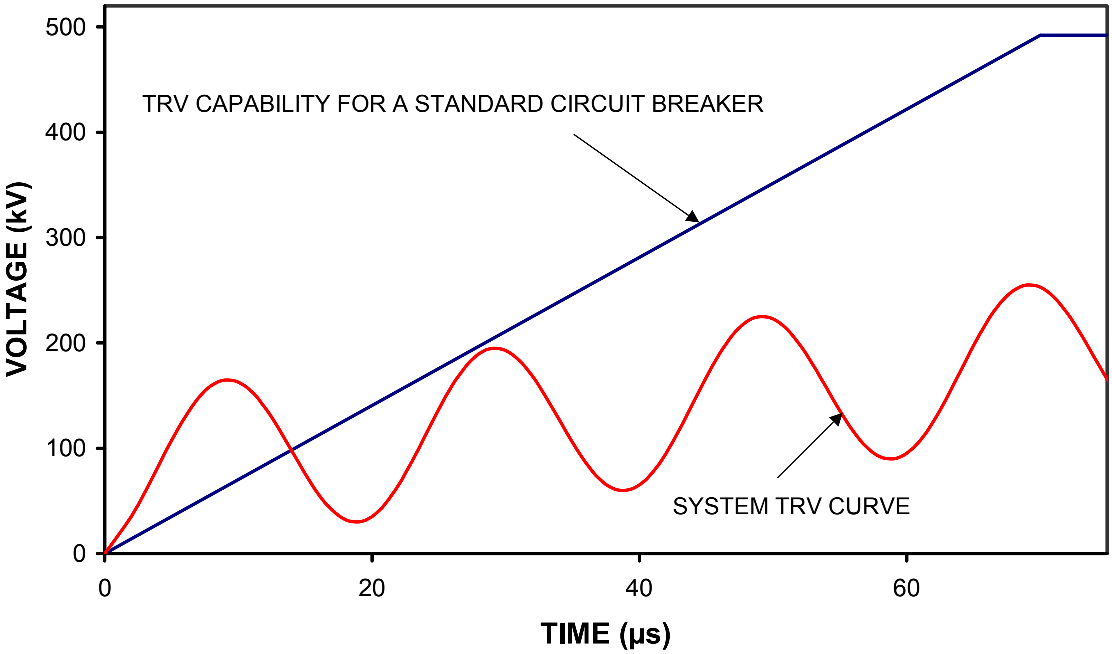


Figure 26—Comparison of TRV capability for 245 kV circuit breaker (at 10% of its rated interrupting current capability) and system TRV with reactor limited faults

4.5 Applications where breaker capability is exceeded

When the inherent TRV of the system exceeds standards, the user has three main alternatives outside of reconfiguring the system. These alternatives are as follows:

a) A breaker with a higher voltage rating, or a modified circuit breaker should be used. In special cases where the terminal fault TRV capability at 60% or 100% of short-circuit capability is higher than rated, a breaker with a higher interrupting capability can be used (see Figure 21).
b) Capacitance should be added to the circuit breaker terminal(s) to reduce the rate of rise of the TRV.
c) The manufacturer should be consulted concerning the application.

As long as a circuit breaker is applied within its symmetrical current and voltage ratings, one of the above methods should result in a satisfactory application.

Annex A

(informative)

TRV calculation techniques

A typical system is shown in Figure A.1 consisting of local sources and remote sources connected through transmission lines. This system will be used to illustrate the TRV types and calculation procedures. Four transmission lines and two transformers (local generation and a tie line transformer) supply the 145 kV station. A number of references are available on calculating TRVs (see Bewley [B1] through Colclaser [B5], Greenwood [B7] through Hedman [B9] , and Naef, et al [B11]) in addition to the information in this annex. *Circuit Interruption* [B2] gives a basic discussion of TRVs, while the papers referenced deal with specific problems and concerns as well as more complex applications.

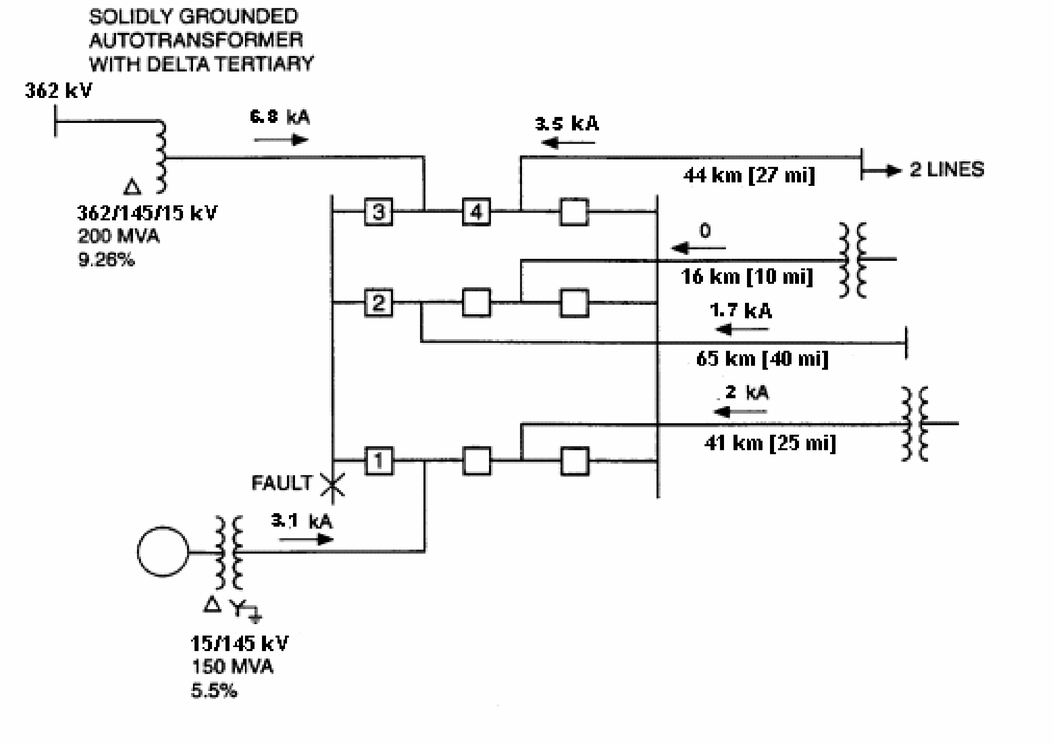


Figure A.1—System diagram

A.1 Transient recovery voltage types

In the case of transmission voltages, three-phase to ground faults are the basis for rating because it is recognized that three-phase ungrounded faults have a very low probability of occurrence, especially in the case of faults with a high short-circuit current. For lower voltages, less than 100 kV, the case of a three-phase ungrounded fault is automatically covered since a first pole-to-clear factor of 1.5 is specified to cover three-phase faults in non-effectively grounded systems.

Three-phase terminal faults and short-line faults are discussed here. The terminal fault discussion is further divided into terminal faults having oscillatory and exponential waveforms. The three-phase terminal fault is usually the most severe terminal fault type and is used to define the breaker rating. Short-line faults generally have higher rates of rise of recovery voltage than do terminal fault TRVs, but have lower crest voltage magnitudes.

A.1.1 Three-phase terminal fault

During the interruption of a three-phase terminal fault, the circuit shown in Figure A.2 defines the general electrical equivalent network for the first phase to clear. The reduced circuits are valid for short time frames until reflections return from remote buses. Reflections are covered in A.1.2.

Figure A.2a) shows the corresponding one-line diagram representation, while Figure A.2b) indicates the three-phase representation.

The equivalent circuit, given by Figure A.2c), shows that it is reduced to a simple parallel RLC circuit with components defined as follows:

a) Equivalent inductance

$$L_{eq} = \frac{3\,L_0\,L_1}{L_1 + 2L_0} \qquad \text{(A-1)}$$

For three-phase to ground faults in effectively grounded systems, i.e., with $L_0 = 3\,L_1$, $L_{eq} = 9\,L_1/\,7 = 1.3\,L_1$

For three-phase to ground faults in ungrounded systems (L_0 infinite), $L_{eq} = 1.5\,L_1$

b) Equivalent surge impedance

$$Z_{eq} = \frac{3}{n}\frac{Z_0 Z_1}{Z_1 + 2Z_0} \qquad \text{(A-2)}$$

where $Z_0 = 1.6\,Z_1$

$$Z_{eq} = 1.14\,\frac{Z_1}{n}$$

c) Equivalent capacitance

$$C_{eq} = C_0 + \frac{2(C_1 - C_0)}{3} = \frac{C_0 + 2C_1}{3} \qquad \text{(A-3)}$$

if $C_0 = C_1$ then $C_{eq} = C_0 = C_1$

where

Z_1 is the positive-sequence surge impedance of the transmission lines terminating at the station,
Z_0 is the zero-sequence surge impedance of the transmission lines terminating at the station,
n is the number of lines,
L_1 is the positive-sequence inductance, representing all other parallel sources terminating at the station (transformation to lower or higher voltage systems, generation, etc.),
L_0 is the zero-sequence inductance, representing all other parallel sources terminating at the station,
C_1 is the positive-sequence capacitance,
C_0 is the zero-sequence capacitance.

For the special case of three-phase ungrounded faults on effectively grounded systems,

$$L_{eq} = 1.5\,L_1, \quad Z_{eq} = \frac{1.5\,Z_1}{n}, \quad C_{eq} = \frac{C_1}{1.5}$$

A.1.1.1 Exponential (overdamped) TRV

Current injection techniques can be used to solve for the circuit breaker TRV and, because the time span of interest is short (microseconds), the interrupted current can be represented by a ramp. The solution for the parallel RLC network (as shown in Figure A.2c) is

$$V_{\mathrm{cb}} = E_1\,(1 - e^{-\alpha t}\,(\cosh \beta t + \frac{\alpha}{\beta}\sinh \beta t))\quad \mathrm{kV} \tag{A-4}$$

where

V_{cb} is the voltage across the open circuit breaker contacts
E_1 is $\sqrt{2} I \omega L_{\mathrm{eq}}$ in kV
ω is $2\pi f = 377$ rad/s for 60 Hz systems and 314 rad/s for 50 Hz systems
I is short-circuit current in kA, rms

α is $\dfrac{1}{2 Z_{\mathrm{eq}} C_{\mathrm{eq}}}$

β is $\sqrt{\alpha^2 - 1/(L_{\mathrm{eq}} C_{\mathrm{eq}})}$

Z_{eq} is in ohms
L_{eq} is in henrys
C_{eq} is in farads

For many systems the circuit will be overdamped by the parallel resistance of the line surge impedances, thus the capacitance can be neglected as a first approximation. The solution to the simple RL circuit is then

$$V_{\mathrm{cb}} = E_1\,(1 - e^{-t/\tau})\quad \mathrm{kV} \tag{A-5}$$

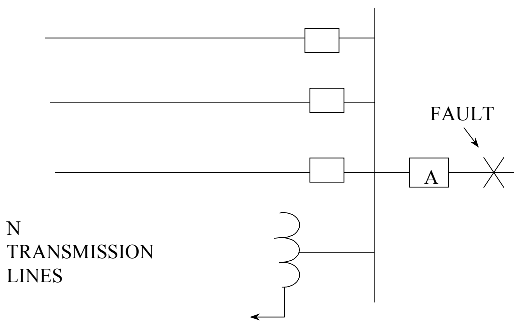
where

τ is $\dfrac{L_{\mathrm{eq}}}{Z_{\mathrm{eq}}}$ s

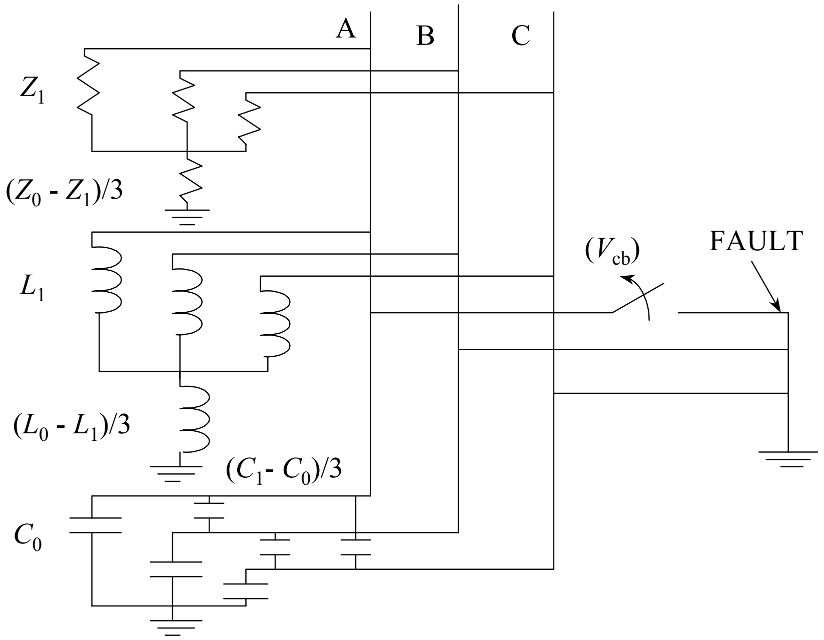
The derivative of equation (A-4) at time zero is the rate of rise of the recovery voltage and is given by

$$\frac{dV_{\mathrm{cb}}}{dt} = R = \sqrt{2}\, I\, \omega\, Z_{\mathrm{eq}}\, 10^{-6}\quad \mathrm{kV/\mu s} \tag{A-6}$$

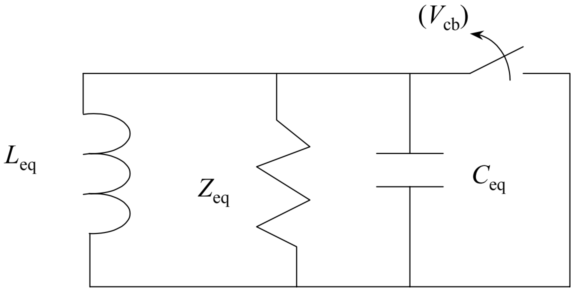
The above exponential expressions [see Equation (A-4), Equation (A-5), and Equation (A-6)] describe the component of the TRV until reflections return from remote stations associated with the transmission lines connected to the faulted station.



a) Single-line diagram



b) Three-phase diagram



c) Equivalent circuit

Figure A.2—Circuit definition—interruption of a three-phase to ground fault

A.1.1.2 Oscillatory (underdamped) TRV

If there are no lines on the bus, then the resistance is removed from the equivalent circuit in Figure A.2 c), and the TRV will be oscillatory. An approximate expression for the voltage is given in Equation (A-7). The expression is approximate because of neglecting the source impedances behind the transformers.

$$V_{\mathrm{cb}} = E_1\,[1 - \cos(t / \sqrt{L_{\mathrm{eq}} C_{\mathrm{eq}}})] \quad \text{kV} \tag{A-7}$$

Even when lines are present, it is possible for the recovery voltage to be oscillatory. To be oscillatory, the surge impedance of a source side line has to be such that

$$Z_{\mathrm{eq}} \geq 0.5\sqrt{L_{\mathrm{eq}} / C_{\mathrm{eq}}}$$

With Z_{eq}, L_{eq} and C_{eq}, as defined in A.1.1.

This equation shows that as the number of transmission lines is increased, the circuit is likely to be nonoscillatory, i.e., overdamped. In most cases, however, even $N = 1$ makes the circuit overdamped.

A.1.2 Reflected waves

The initial wave that was calculated in Equation (A-5) appears across the breaker pole. It also appears as traveling waves on each of the transmission lines. When one of these waves reaches a discontinuity on the line such as another bus or a transformer termination, a reflected wave is produced, which travels back towards the faulted bus. The time for a wave to go out and back to a discontinuity is

$$T = 6.68\, l \sqrt{\mu k} \quad \mu\text{s} \tag{A-8}$$

where

l is the distance to the first discontinuity (in kilometer),
μ is the magnetic permeability,
k is the dielectric constant.

- For overhead lines

$$\sqrt{\mu k} = 1.0$$

It takes 6.68 µs for a wave to go out and back to a discontinuity 1 km away, or 10.74 µs when it is 1 mile away.

- For cables, typically

$$k = 4\,,\ \mu = 1.0 \text{ and } \sqrt{\mu k} = 2$$

At a discontinuity transmitted and reflected waves can be described by Equation (A-9) and Equation (A-10) and Figure A.3 (Bewley [B1] and *Electrical Transmission and Distribution Reference Book* [B6]).

Transmitted wave

$$e_{\mathrm{t}} = e_{\mathrm{i}} \frac{2 Z_{\mathrm{b}}}{Z_{\mathrm{a}} + Z_{\mathrm{b}}} \tag{A-9}$$

Reflected wave

$$e_{\mathrm{r}} = e_{\mathrm{i}} \frac{Z_{\mathrm{b}} - Z_{\mathrm{a}}}{Z_{\mathrm{a}} + Z_{\mathrm{b}}} \qquad \text{(A-10)}$$

where

e_{i}	is the incident wave,
Z_{a} and Z_{b}	are the equivalent surge impedances on either side of the discontinuity.

Returning to the bus, the reflections are in turn reflected to begin the process again (see Colclaser, et al [B3] and Colclaser and Buettner [B5]). A typical TRV, including the first reflection, is shown in Figure A.4. Colclaser and Buettner [B5]shows that a reflected wave returning from an open ended line will contribute to the bus side TRV as follows:

$$E_{\mathrm{r}} = E_1 \left(\frac{2 Z_{\mathrm{eq}}\, t}{L_{\mathrm{eq}}}\right) e^{-\frac{Z_{\mathrm{eq}}\, t}{L_{\mathrm{eq}}}} \qquad \text{(A-11)}$$

where

$$Z_{\mathrm{eq}} = Z_{\mathrm{a}} = 1.14 \frac{Z_1}{n} \text{ and } L_{\mathrm{eq}} = \frac{3 L_0 L_1}{L_1 + 2 L_0}$$

The reflected voltage E_{r1}, given by Equation (A-11), has a maximum theoretical value of 0.736 E_1/N, which can be reduced to 0.7 E_1/N to account for damping as suggested in Colclaser and Buettner [B5]. The more lines connected, the lower the magnitude of the reflected wave.

In transmission systems such as shown in Figure A.1, the short-circuit current is fed through several lines. TRV is then the sum of several reflections, each one proportional to E_1/N, that may add or subtract, depending upon the type of termination at the end of the lines. It follows that in cases with the maximum short-circuit current, where several lines need to be connected, the amplitude factor is limited to a value of 1.4. A higher value of the amplitude factor is specified for less than rated short-circuit currents, as fewer lines are connected.

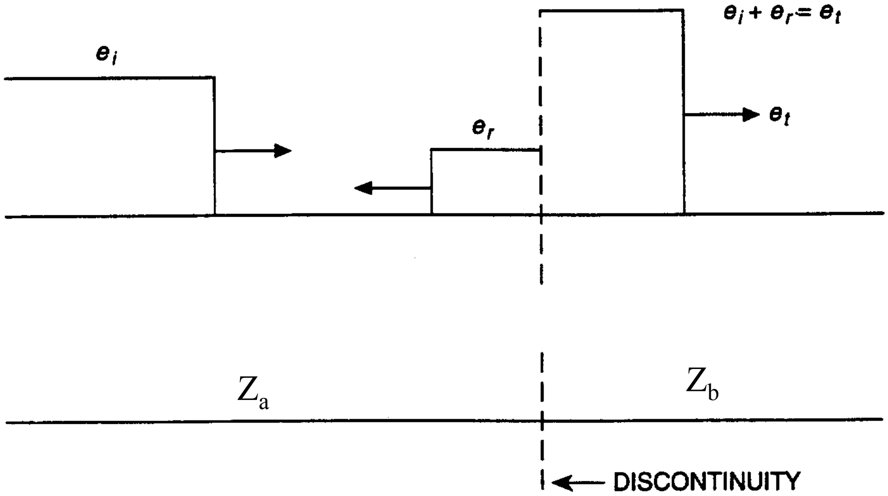


Figure A.3—Traveling waves at discontinuity

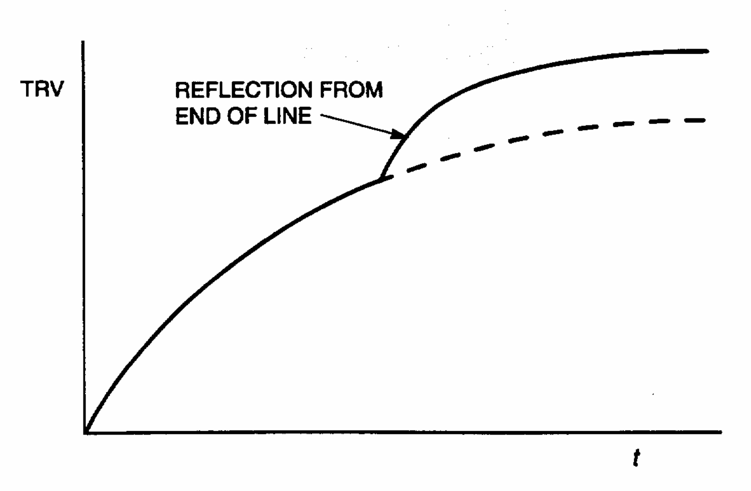


Figure A.4—Typical TRV including the first reflection

A.1.3 Short-line fault

A.1.3.1 General

Triangular-shaped recovery voltages are associated with line faults. Because cables and overhead lines have distributed constants, the line side voltage oscillates in the form of a travelling wave with positive and negative reflections at the open breaker and at the fault, respectively. The line side component of the recovery voltage has a sawtooth shape and a high rate of rise. Generally, the source recovery voltage rises much more slowly and only the line side triangular recovery voltage is important during the early portion of the TRV. As the fault is located closer to the circuit breaker, the initial rate of rise of the line side recovery voltage increases due to the higher fault current, while the crest magnitude of this line side triangular wave decreases due to the shorter time for the reflected wave to return.

The fault current for a line side fault is somewhat reduced from that obtained for a bus fault due to the additional reactance of the line. Let I_T be the fault current through the circuit breaker for a single-phase fault at the breaker terminal, and I_L be the reduced current for a line fault.

Figure A.5 illustrates the single-phase circuit where the short-circuit current is limited by the source reactance (X_S) in series with the line reactance ($X_L\ \lambda$):

$$I_L = \frac{V_{LG}}{X_L \lambda + X_S} \tag{A-12}$$

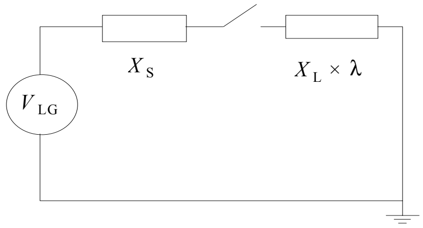


Figure A.5—Single-phase circuit with short-line fault

The source side reactance is given by

$$X_S = \frac{V_{LG}}{I_T} \tag{A-13}$$

The fault current is then

$$I_L = \frac{V_{LG}}{X_L \lambda + V_{LG} / I_T} \tag{A-14}$$

where

X_L is the reactance of the line to the fault point per unit length,
$L_{1\omega}$ is the positive sequence power frequency line inductance per unit length,
$L_{0\omega}$ is the zero sequence power frequency line inductance per unit length,
V_{LG} is the system line-ground voltage,
λ is the distance from the opening circuit breaker to the fault.

The peak factor (d) is the ratio of amplitudes of the first peak of the TRV ($U_L = V_{CDo} + V_{CDp}$) (as shown in Figure 13) to the peak voltage on the line side prior to interruption ($U_o = V_{CDo}$):

$$d = U_L / U_o \tag{A-15}$$

The rate-of-rise (R) of the line side TRV is equal to the effective line surge impedance (Z_{eff}) multiplied by the slope of current at current zero (di/dt) as follows:

$$R = \sqrt{2}\,\omega\, I_L Z_{eff} \tag{A-16}$$

where

$$\mathrm{di/dt} = \sqrt{2}\,\omega\, \mathrm{I_L} \tag{A-17}$$

The time to the first peak U_L is equal to two times the reflection time from the circuit breaker to the fault point (time necessary for the travelling wave to reach the fault and be reflected back to the circuit breaker):

$$t_L = \frac{2\lambda}{v} \tag{A-18}$$

where

λ is the distance from the opening circuit breaker to the fault,
v is the velocity of light.

It follows that the first peak of the line side TRV is given by:

$$U_L = Z_{eff}\, di/dt\ 2\,\lambda / v \tag{A-19}$$

$$U_o = X_L\, \lambda\, I_L \sqrt{2} \tag{A-20}$$

From Equation (A-15), Equation (A-16), and Equation (A-17):

$$d = 2\omega \frac{Z_{eff}}{X_L v} \tag{A-21}$$

where

$$X_L = \frac{(2L_{1\omega} + L_{0\omega})\omega}{3} \tag{A-22}$$

$$Z_{\text{eff}} = \frac{(2Z_1 + Z_0)}{3} \tag{A-23}$$

$$Z_1 = \sqrt{L_1 / C_1} \tag{A-24}$$

$$v = 1/\sqrt{L_1 C_1} \tag{A-25}$$

Z_1 = positive sequence surge impedance,

Z_0 = zero sequence surge impedance,

L_1 = high-frequency positive sequence line inductance per unit length,

C_1 = high-frequency positive sequence line capacitance per unit length.

The effective surge impedance Z_{eff} is influenced by bundle and tower configuration. Typical values for different voltage class lines are presented in A.2.5.

From Equation (A-24) and Equation (A-25):

$$Z_1 / v = L_1 \tag{A-26}$$

From Equation (A-21), Equation (A-23), Equation (A-24), and Equation (A-26):

$$d = 2\omega \frac{(2Z_1 + Z_0)L_1}{(3Z_1)(2L_{1\omega} + L_{0\omega})} \frac{3}{\omega}$$

or

$$d = 2\frac{(2 + Z_0/Z_1)L_1}{(2L_{1\omega} + L_{0\omega})} \tag{A-27}$$

If the high-frequency inductance L_1 is equal to the power-frequency inductance of the line $L_{1\omega}$, Equation (A-27) simplifies to:

$$d = 2\frac{(2 + Z_0/Z_1)}{(2 + L_{0\omega}/L_{1\omega})} \tag{A-28}$$

if $\frac{L_{0\omega}}{L_{1\omega}} \approx 3$ is assumed for high-voltage networks:

$$d = 0.4(2 + Z_0/Z_1) \tag{A-29}$$

In practice the high-frequency inductance L_1 is lower than the power-frequency value $L_{1\omega}$ and losses that are always present have been neglected in the calculation. For these reasons, the peak factor value obtained by Equation (A-29) is conservative.

As the ratio Z_0/Z_1 is always lower than 2 for HV networks (72.5 kV to 550 kV), the peak factor (d) is equal or lower than 1.6. Therefore, the standardized value of 1.6 is conservative.

Using Equation (A-23) and Equation (A-29) the peak factor is

$$d = 1.2\,Z_{\text{eff}} / Z_1 \tag{A-30}$$

Typical values of Z_{eff} and Z_1 are given in A.2.5.

The line side recovery voltage crest is then equal to

$$U_{\text{L}} = d\,U_0 = d\,X_{\text{L}}\,\lambda\,I_{\text{L}}\sqrt{2} \tag{A-31}$$

A.1.3.2 Influence of additional capacitors on SLF interruption

An additional capacitance connected between the circuit-breaker terminals (grading capacitor or capacitor used to assist the interruption) or phase-to-ground on the line side, has two effects:

a) It decreases the oscillation frequency and the RRRV of the line side TRV.

b) It increases the time delay of the line side TRV.

As both effects tend to facilitate the short-line-fault interruption, capacitors are sometimes used to increase the breaking capability of circuit-breakers.

Historically resistors were used on air-blast circuit-breakers to reduce the RRRV and facilitate the interruption. As SF_6 circuit-breakers are more sensitive to the initial part of the TRV (first micro-seconds) the use of additional capacitors has proved to be more efficient.

NOTE—CVTs due to their inherent capacitance have an influence on the TRV but they should be close enough to the circuit-breaker to influence current interruption.

For maximum effectiveness the capacitor should be close to the circuit-breaker line side terminal. If a capacitor is located too far from the circuit-breaker, the time delay of recovery voltage is decreased and the amplitude of the first voltage jump is increased, both effects resulting in a lower short-line fault interrupting capability.

Capacitors connected between terminals (grading capacitors for example) are more effective in reducing the TRV frequency than when connected phase-to-ground. A lower value of capacitor is needed to obtain a given reduction of the RRRV if it is connected between the terminals instead of phase-to-ground. However, when capacitors are mounted across the circuit-breaker terminals to meet a SLF breaking capability, caution is recommended as high capacitance could lead to ferro-resonance with any ferromagnetic inductance (i.e., magnetic instrument transformers and power transformers).

In a substation it can be advantageous to take into account the existing phase-to-ground capacitance between the circuit-breaker and the line in order to define the necessary additional value of the phase-to-ground capacitor that has to be delivered with the circuit-breaker. However, caution is recommended if the circuit-breaker is to be moved to a different location.

A.2 Equivalent circuit representation

In the calculation of inherent TRVs, it is first necessary to determine the effective inductances and capacitances at the frequencies of the TRV near the circuit breaker location. Next, the line and cable equivalents are determined by their surge impedance, length, and remote terminations and interconnections. The equivalent three-phase circuit representation of the transient system can be calculated using these parameters. From this representation, the circuit transient recovery voltages can be determined as indicated in A.3. The following examples in A.2.1 illustrate the various techniques for the reduction of system elements to equivalent transient circuits.

When three-phase faults in ungrounded systems are being examined, it is only necessary to include the positive-sequence components. When three-phase to ground faults in effectively grounded systems are considered, the zero sequence network must be included (see Figure A.2). Zero-sequence components must also be included when the single-phase grounded fault is analyzed

A.2.1 Examples of system inductance determination

The examples that follow are based on the system and characteristics shown in Figure A.1.

A.2.1.1 Transformer equivalent

The reactive ohmic values and normal frequency inductive values are calculated from equipment data as follows:

$$\text{Reactance} = \frac{(kV)^2}{MVA} \times X \tag{A-32}$$

where the impedance X is given in per unit.

For the autotransformer used in the example shown in Figure A.1,

$$\text{Reactance} = \frac{145^2}{200} \times 0.0926\ \Omega = 9.7\ \Omega$$

For the generator step-up transformer,

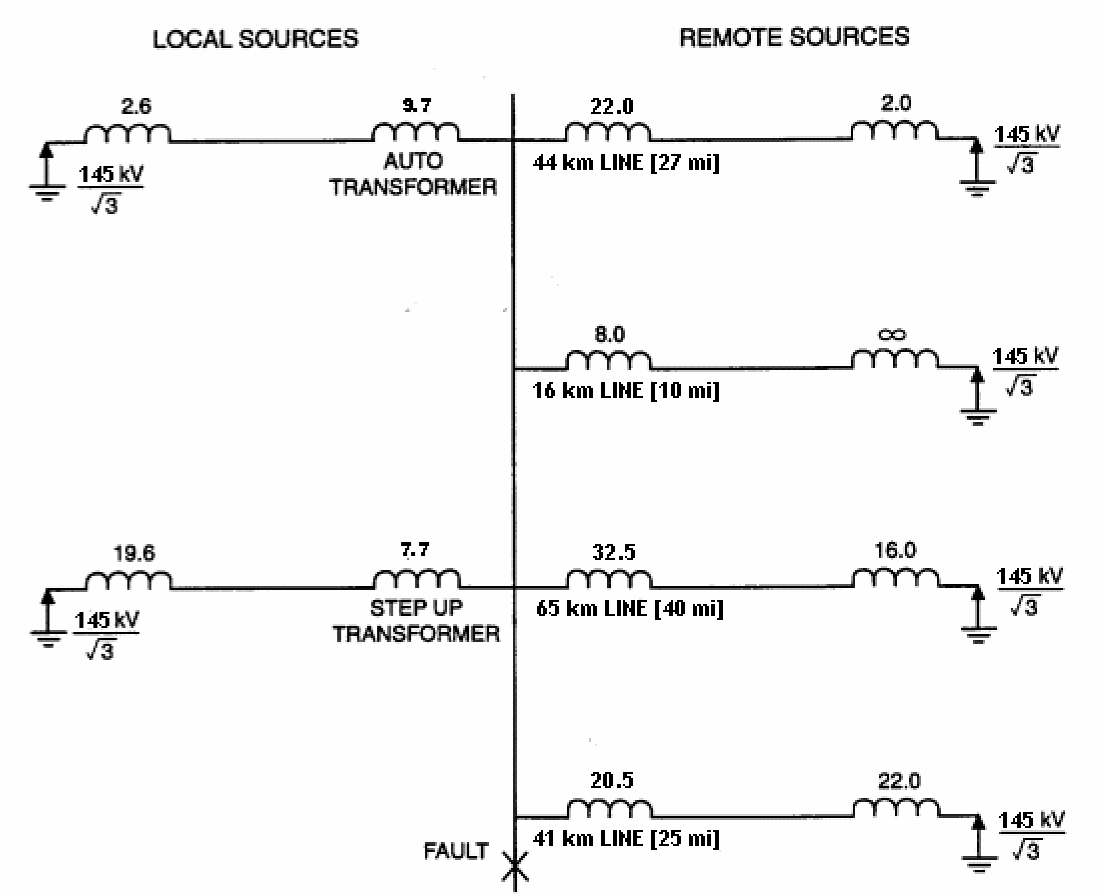
$$\text{Reactance} = \frac{145^2}{150} \times 0.055\ \Omega = 7.7\ \Omega$$

A.2.1.2 Line equivalents

The positive-sequence reactance of the 145 kV overhead line is assumed to be 0.50 Ω/km (0.80 Ω/mi).

A.2.1.3 Line termination equivalent

For the 145 kV system in Figure A.1, the line terminations are determined from equipment characteristic data or from a lumping of system parameters at a multi-element termination (see Figure A.6). The positive-sequence reactance of the generator is given as 19.6 Ω. The reactive equivalent of the 362 kV system is 2.6 Ω. The terminal reactive equivalents at the end of the 44 km (27 mi), 65 km (40 mi), and the 41 km (25 mi) lines are 2.0 Ω, 16.0 Ω, and 22.0 Ω, respectively. The 16 km (10 mi) line is load terminated at a unit substation, contributes no fault current, and is considered an open circuit.



NOTE—Ohms at 145 kV for figure A.1.

Figure A.6—System reactive ohms and effective voltages

A.2.2 Calculation of short-circuit currents

The short-circuit current associated with each local and remote source is calculated as indicated in IEEE Std C37.010.

A.2.2.1 Total short-circuit current calculation

Using the reactances calculated in A.2.1, the total short-circuit current is equal to the line-to-neutral system voltage divided by the system reactance at the fault location. As an example, the current for a fault at the 145 kV bus, illustrated in Figure A.1, is calculated as follows:

$$\text{Total short-circuit current} = \frac{145}{\sqrt{3}\times 4.9}\ \text{kA} = 17.1\ \text{kA}$$

A.2.2.2 Individual source short-circuit current calculation

The total short-circuit current is supplied by the contributions from the individual sources. For a fault at the 145kV bus, the short-circuit current contribution of the autotransformer is as follows:

$$\frac{145}{\sqrt{3}\times(2.6+9.7)}\ \text{kA} = 6.8\ \text{kA}$$

The fault current contribution from each branch is given in Figure A.1.

A.2.3 Equivalent local source inductance

The equivalent local source inductance is defined in A.1.1 and illustrated in Figure A.2.

The equivalent local source inductance L_{eq} is the parallel combination of the equivalent inductances that are active in producing the TRV.

For three-phase to ground faults in ungrounded systems (L_0 infinite), $L_{eq} = 1.5\ L_1$. The positive sequence source inductance L_1 is the parallel combination of the positive sequence inductances that are active in producing the TRV.

For three-phase to ground faults in effectively grounded systems, assuming the same ratio between positive sequence and zero sequences inductances, the positive sequence source inductance L_1 is also the parallel combination of the positive sequence inductances that are active in producing the TRV.

In the frequency ranges of concern, equipment capacitances and line surge impedances often have the effect of shorting the transformer terminal opposite the circuit interrupting device and, thus, eliminating the effect of system inductance. That is, the high side frequency is generally slower than the transformer component and is not significant during the period of interest (see *Circuit Interruption* [B2]). That response is assumed in this example. Using the transformer reactances calculated in A.2.1.1.

$$\text{Inductance (autotransformer)} = \text{Reactance}/(2\pi f) = \frac{9.7}{377}\ \text{H} = 0.026\ \text{H}$$

$$\text{Inductance (generator transformer)} = \frac{7.7}{377}\ \text{H} = 0.020\ \text{H}$$

$$L_1 = \frac{0.026\times 0.020}{0.026+0.020}\ \text{H} = 0.011\ \text{H}$$

NOTE—The example applies for a 60 Hz system.

A.2.4 Equivalent capacitance

The equivalent capacitance is defined in A.1.1. The total substation capacitance is labeled as C_{eq} in Figure A.2. It is determined by summing the equipment equivalent capacitance. Typical values are given in Annex B.

For three-phase-to-ground faults on effectively grounded systems, the equivalent capacitance is the sum of 2/3 of the positive sequence capacitances and 1/3 of the zero sequence capacitances of all equipments.

For three-phase ungrounded faults on effectively grounded systems, $C_{eq} = 2C_1/3$ and the positive sequence capacitance is the sum of the positive sequence capacitances of all equipments.

A.2.4.1 Station capacitance equivalent

The single-phase station capacitance, excluding power transformers, consists of the following assumed equipment (see Table A.1). The fault side capacitance is neglected because it is small. Operating breaker capacitance is not included because the intent is to produce the inherent TRV generated external to the operating breaker.

Table A.1— Single-phase station capacitance

4 Dead-tank oil circuit breakers (closed) · 600 pF each	=2400 pF
2 Live-tank air circuit breakers (closed) · 100 pF each	=200 pF
2 Live-tank air circuit breakers (open) · 50 pF each	=100 pF
4 Current transformers · 300 pF each	=1200 pF
59 m (193 ft) bus and switches · 9.8 pF/m (3.0 pF/ft)	=580 pF
12 Disconnect switches (closed) · 90 pF each	=1080 pF
2 Potential transformers · 400 pF each	=800 pF
1 Current limiting reactor · 200 pF	=200 pF
Total	6560 pF

A.2.4.2 Transformer capacitance equivalent

Transformer capacitances often make up a significant part of the total at a given bus; however, they are often difficult to determine especially in the planning stage. A more detailed discussion is given in Annex B. For the transformer in this example, the following single-phase, line-to-ground capacitances are assumed:

Autotransformer capacitance = 3200 pF

Generator transformer capacitance = 2440 pF

A.2.5 Line and cable equivalent

The line and cable surge impedances for line transient consideration appear as resistances and may be calculated using techniques developed by Carson and others. They may be approximated as summarized in Table A.2.

Table A.2— Typical surge impedances

	System (kV)	**Z_0 (Ohms)**	**Z_1[a] (Ohms)**	**Z_{eff}[b] (Ohms)**
Overhead lines	145 245 362 550 800	560 525 430[c] 430[c] 400[c]	350 375 280[c] 280[c] 265[c]	420 425 330[c] 330[c] 310[c]
Cables	72.5 145 245 362		Cable surge impedance depends on the cable type and configuration. Typically Z_1 and Z_{eff} range from 50 to 75 Ω with $Z_1 \cong Z_{eff}$	
SF_6 buswork	All voltages		55	55

[a] Used for three-phase grounded terminal faults.

[b] Used for short-line faults where $Z_{eff} = (2 Z_1 + Z_0)/3$ and Z_0 is determined at switching surge frequencies.

[c] Bundled conductors assumed for 362 kV class lines and above.

These values do not take into account conductor clashing. Calculations performed on 420 kV lines have shown that the effective surge impedance is between 434 Ω and 450 Ω when bundle contraction during fault is considered.

In the case of a three-phase to ground fault in the system shown in Figure A.1, the equivalent surge impedance for all four lines at the 145 kV bus is Z_{eq} = 1.14 × 350/4 = 100 Ω. This representation of the lines is correct until the first wave reflection from the nearest remote terminal is received.

A.3 Example of transient recovery voltage calculation

Using the system shown in Figure A.1 and the equivalent circuits determined in Figure A.2, the TRVs are calculated for a bus fault and for a short-line fault.

A.3.1 Three-phase to ground terminal fault

In this paragraph the TRV is calculated on the first phase of the last breaker to clear a three-phase to ground fault as labeled in Figure A.1.

The equivalent inductance is 1.3 × 11 mH = 14.3 mH (see A.1.1 and A.2.3). Assuming C_0 = C_1, the total equivalent capacitance is 12 200 pF (see A.1.1, A.2.4.1, and A.2.4.2).

The equivalent surge impedance for the four lines is 1.14 × 350/4 = 100 Ω (see A.1.1). The circuit will be oscillatory if the conditions given in A.1.1.2 are satisfied as follows:

$$Z_{\mathrm{eq}} > 0.5\sqrt{L_{\mathrm{eq}} / C_{\mathrm{eq}}}$$

or

$$100 > 0.5\sqrt{(0.0143)/(12.2\ 10^{-9})}$$
$$100 > 541$$

Because the condition is not met, the circuit is not oscillatory and the exponential solution form (either the hyperbolic or the simplified form given in A.1.1.1) is applicable.
The shunt capacitance essentially results in a delay at the start of the exponential TRV. The amount of the delay is equal to $Z \times C$, which in this case amounts to the following:

$$Z \times C \quad = 100(12.2 \times 10^{-9})\ \mu\mathrm{s}$$
$$= 1.22\ \mu\mathrm{s}$$

This delay is small and can be neglected. Note that for other conditions, such as when only one line is connected, the delay will be more significant due to the increased Z.

For the example, the delay is small, the capacitance can be neglected, and the simplified exponential form, shown in Equation (A-33) can be used:

$$V_{\mathrm{cb}} = E_1\,(1 - e^{-t/\tau}) \tag{A-33}$$

where

$$E_1 = \sqrt{2}\, I\, \omega\, L_{\mathrm{eq}}$$
$$= \sqrt{2}\,(17.1)\,(377)\,(1.3 \times 0.011)\ \mathrm{kV}$$
$$= 130.4\ \mathrm{kV}$$
$$\tau = L_{\mathrm{eq}} / Z_{\mathrm{eq}} = 0.0143/100$$
$$= 143\ \mu\mathrm{s}$$

$$V_{cb} = 130.4(1-e^{-t/0.000143})\ \text{kV}$$

The rate of rise of the TRV is

$$\begin{aligned} R &= \sqrt{2}\, I\, \omega\, Z_{eq}\, 10^{-6} \quad \text{kV/µs} \\ &= \sqrt{2}\,(17.1)\,(377)\,(100)\,(10^{-6})\ \text{kV/µs} \\ &= 0.91\ \text{kV/µs} \end{aligned}$$

NOTE—The example applies for a 60 Hz system.

Figure A.7 illustrates the resultant TRV, taking into account also the influence of capacitance C_{eq} [see Equation (A-4)].

This TRV then acts as a traveling wave, and will be transmitted down each line connected to the station. As this wave reaches the remote termination of the line, it will be reflected. The reflected wave will return to the faulted station and will be superimposed on the circuit breaker TRV.

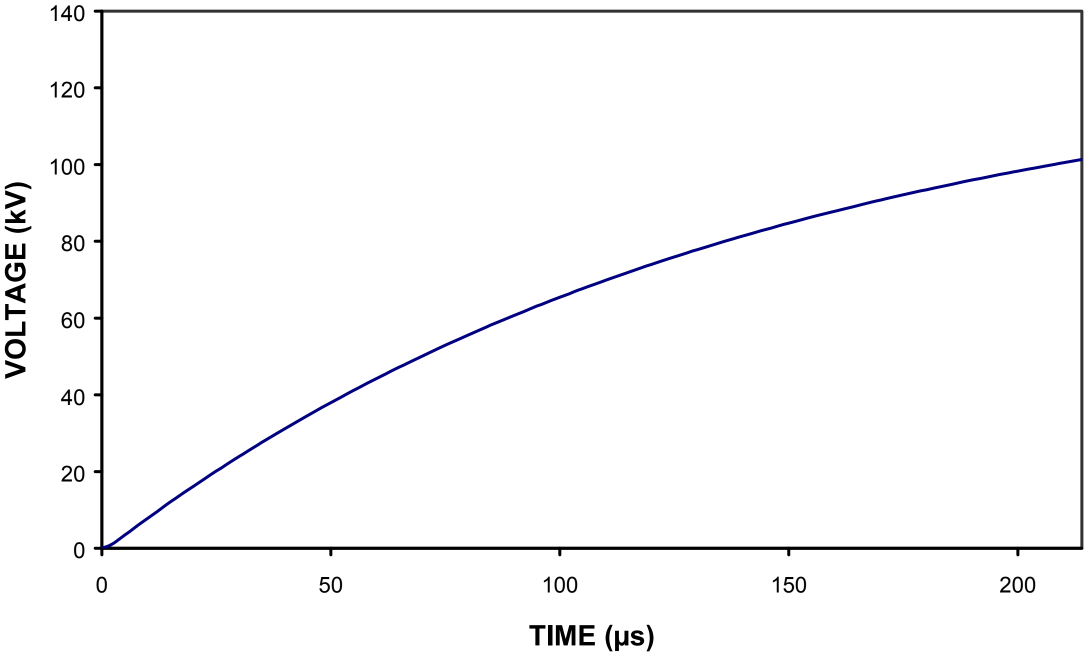


Figure A.7—Breaker TRV without reflected wave

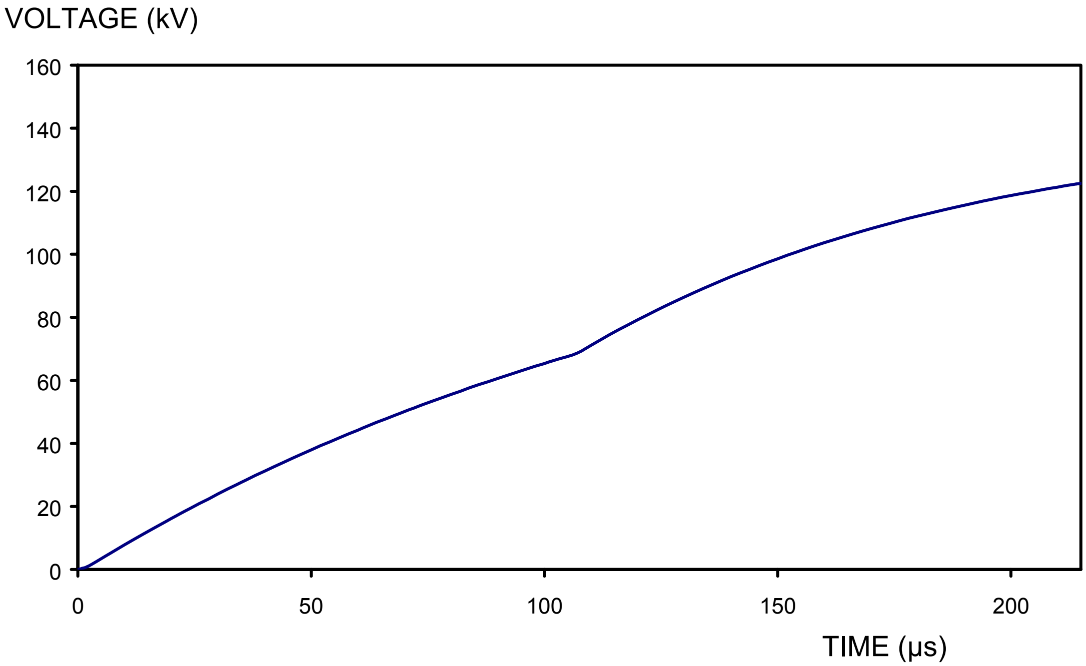


Figure A.8—Breaker TRV with reflected wave

The first reflection will come back from the shortest line, which is 16 km (10 mi) long. Since this line is transformer terminated, it can be considered an open circuit (i.e., $Zb = \infty$, as illustrated in Figure A.3). The reflected wave front will then be identical with and superimposed on the incoming wave. In actuality, the transformer will initially appear as an open circuit to surges and then change to a short circuit. This transposition is exponential, having a time constant of L of the transformer divided by the surge impedance of the line. Because the line is 16 km (10 mi) long, it will take 107 µs for the wave to be reflected back to the bus [see Equation (A-8)]. The front of the wave will be positive and added to the original outgoing wave. The voltage at the remote transformer will be double that of the incident wave. That portion of the returning wave that will be transmitted through the bus and out on the other three lines (neglecting the effects of bus inductance and capacitance) is as follows:

$$e_t = e_i \; 2\,Z_b / (Z_a + Z_b) = e_i \; (2\,Z/3)/ (Z + Z/3) = 0.50\, e_i \qquad \text{(See A.1.2).}$$

The wave reflecting back on the line is

$$e_r = e_i \; (Z_b - Z_a) / (Z_a + Z_b) = e_i \; (Z/3 - Z)/ (Z + Z/3) = -\,0.50\, e_i$$

The second reflection will enter the bus at 214 µs and will reduce the breaker TRV. The TRV waveform for the first 214 µs, up to the TRV peak and including the first reflection, is illustrated in Figure A.8. The TRV is calculated using Equation (A-5) and Equation (A-11). Alternatively it can be determined by calculating transients in the circuit represented on Figure A.6.

When the remote source inductance is considered, the transmitted voltage waves at the bus will be a more complex function of time (see Colclaser and Buettner [B5]). For an incident wave of $e_i = E_1\,(1 - e^{-Z\mathrm{eq}\,t\,/\,L\mathrm{eq}})$ the first transmitted wave is of the following form [see Equation (A-11)]:

$$e_r = \; (2\,Z_{eq}\,E_1\,t\,/\,L_{eq}).\; e^{-Z\mathrm{eq}\,t\,/\,L\mathrm{eq}} \tag{A-34}$$

where

L_{eq} is the source inductance,

Z_{eq} is $\frac{3}{n} \frac{Z_0 Z_1}{Z_1 + 2Z_0}$,

n is the number of transmission lines connected to the bus.

The inclusion of the remote transformer inductance will tend to reduce the TRV and may be sufficient to make marginal breaker applications suitable.

The first reflections from the 44 km (27 mi), 65 km (40 mi) and 41 km (25 mi) lines will return at 293 µs, 432 µs, and 273 µs, respectively. These reflections may add or subtract from the total TRV, depending upon the type of termination at the remote ends of the lines.

A.3.2 Three-phase terminal fault—Autotransformer breaker last to clear

In the system shown on Figure A.1, it is assumed that circuit breaker 3 is the last to open and that breaker 4 is open prior to the fault, with breakers 1 and 2 already having cleared. The capacitance of the transformer plus that of the bus, disconnect switch, etc. is assumed to be 3228 pF.

The initial part of the breaker TRV, with the highest rate or rise of recovery voltage due to the low value of the capacitance and the high corresponding TRV frequency, can be calculated as follows for a three-phase to ground fault:

$$\text{Time to peak} = \pi\sqrt{LC} = \pi\sqrt{(9.7/377)(3228\ .10^{-12})}\ \mu\text{s}$$

$$= 28.6\ \mu\text{s}$$

The corresponding t_3 value (as defined in Figure 6) is 28.6 × 0.858 µs = 24.5 µs.

The ratio between t_3 and the time to peak T_2 is given in Table A.3. In this case, an amplitude factor of 1.7 is assumed.

NOTE 1—If damping is taken into account, the value of the time to peak is higher than calculated above. Therefore, the calculation of time t_3 and of the rate of rise of recovery voltage is conservative.
NOTE 2—The example applies for a 60 Hz system.

Table A.3 – Relation between T_2 and t_3 as function of TRV amplitude factor

AMPLITUDE FACTOR	t_3/T_2	T_2/t_3
1.20	0.771	1.297
1.30	0.801	1.248
1.40	0.822	1.217
1.50	0.837	1.195
1.60	0.849	1.178
1.70	0.858	1.165
1.80	0.866	1.155
1.90	0.873	1.146
2.0	0.878	1.138

The first peak of breaker TRV is

$$V_{\mathrm{cb}} = k_{\mathrm{af}} \sqrt{2}\, X_{\mathrm{a}}\, I \tag{A-35}$$

where

X_{a}	is the autotransformer reactance
I	is short-circuit current
k_{af}	is the amplitude factor

$$V_{\mathrm{cb}} = 1.7 \sqrt{2} \times 9.7 \times 7.1 = 165.5 \text{ kV}$$

The maximum rate of rise of TRV (V_{cb} / t_3) is

$$RRRV = \frac{V_{\mathrm{cb}}}{t_3} = \frac{165.5}{24.5} \text{ kV/µs} = 6.75 \text{ kV/µs.}$$

A.3.3 Single-phase short-line fault

A single line-to-ground fault is evaluated at 3.2 km from the substation illustrated in Figure A.1 on the 16 km (10 mi) long line (see A.1.3). The key parameters assumed for this evaluation are given as follows:

a) The single line-to-ground bus fault is 17.1 kA, which is the same as the three-phase bus fault.

b) The positive and zero sequence line impedances are

$X_1 = 0.5$ Ω/km (0.8 Ω/mi) and $X_0 = 1.2$ Ω/km (2.0 Ω/mi).

Using Equation (A-14) and Equation (A-15), the single line-to-ground fault current at 3.2 km (2 mi) from the substation is determined as follows:

$$X_{\mathrm{L}}\lambda = \frac{[(2)(0.5)+1.2]}{3} 3.2 \ \Omega = 2.4 \ \Omega$$

$$I_{\mathrm{L}} = \frac{145}{\sqrt{3}\,(2.4+4.9)} \text{ kA} = 11.5 \text{ kA}$$

Using a value of 420 Ω for the effective line side surge impedance (see Table A.2), the line side component is a sawtooth wave with a slope of

$$R_{\mathrm{lineside}} = \sqrt{2} \times 377 \times 11.5 \times 420\ 10^{-6} \text{ µs} = 2.57 \text{ kV/µs}$$

NOTE—The example applies for a 60 Hz system.

Using Equation (A-31), the line side recovery voltage crest is

$$U_{\mathrm{L}} = 1.6 \times 2.4 \times 11.5 \times \sqrt{2} \text{ kV} = 62.4 \text{ kV}$$

Time to crest is

$$T_{\mathrm{L}} = \frac{U_{\mathrm{L}}}{R_{\mathrm{lineside}}} = \frac{62.4}{2.57}\ \mu\mathrm{s} = 24.3\ \mu\mathrm{s}$$

The source side component, assuming capacitance can be neglected, is as follows:

$$V_{\text{source side}} = E_1\,(1 - e^{-t/\tau})$$

where

$$E_1 = (145\frac{\sqrt{2}}{\sqrt{3}} - X_L\,\lambda I_L\,\sqrt{2})\ \mathrm{kV} = 118.4 - 2.4 \times 11.5 \times \sqrt{2}\ \ \mathrm{kV} = 79.4\ \mathrm{kV}$$

$$\tau = \frac{L}{Z}$$

with

$L\ = L_1 = 0.011$ H

as the single-phase bus fault current is assumed to be equal to the three-phase bus fault current, the positive and zero sequence of the supply side inductances, respectively L_1 and L_0, are necessarily equal. In this case, $L = (2\,L_1 + L_0)/3 = L_1$

$$Z = \frac{Z_{\mathrm{eff}}}{3}$$ as three lines are connected on the supply side

$$= \frac{420}{3}\ \Omega \quad = 140\ \Omega$$

It follows that

$$\tau = \frac{0.011}{140}\,\mu s \quad = 78.6\ \mu\mathrm{s}$$

Therefore, $V = 79.4\,(1 - e^{-t/78.6})\ \mathrm{kV}$

The source side, line side, and total TRV are shown in Figure A.9.

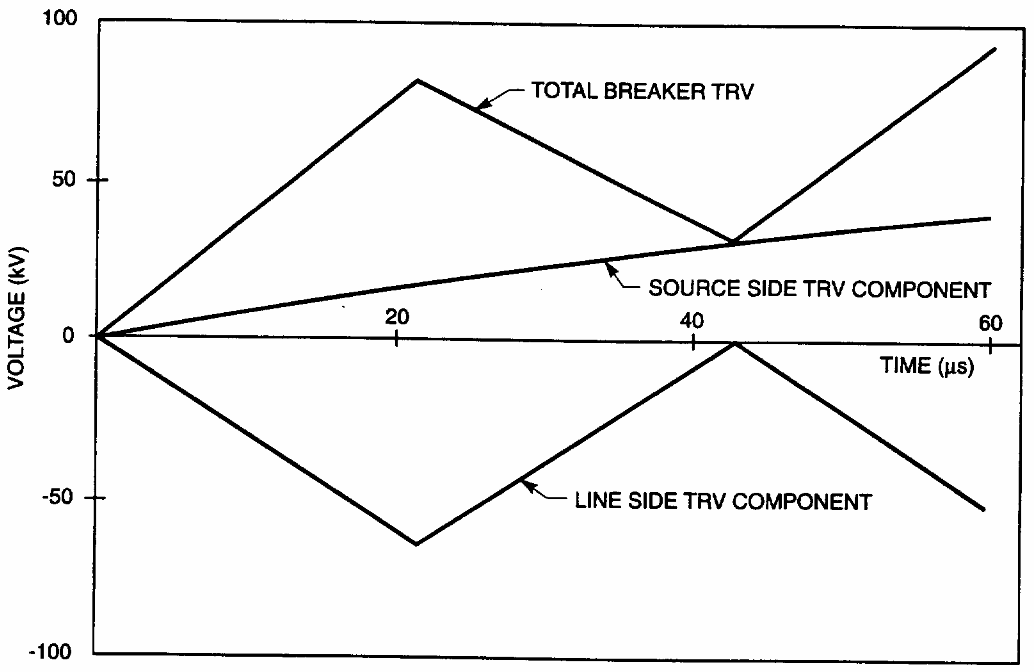


Figure A.9—Short-line fault TRV

If the TRV duty is excessive, capacitance to ground can be added on the line side of the breaker to reduce the rate-of- rise of the TRV. For heavy fault currents, conductor clashing may occur when bundled conductors are used. In this case, the effective line surge impedance will increase, resulting in a higher TRV. A detailed discussion of added capacitance and bundle clashing can be found in Colclaser, et al [B4] and Hedman and Lambert [B9].

Annex B

(informative)

Typical capacitance values for various equipment

In the calculation of TRVs, circuit constants should be supplied for each of the elements on the system. In general, only inductances and capacitances are needed; resistance can be neglected. Accurate information on the inductance of apparatus is given by the manufacturer, but little or no information is given on the positive sequence and zero sequence capacitances of apparatus. Table B.1 through Table B.9 of this annex provide a guide for estimating the capacitance of various apparatus. The values in the tables represent the positive sequence capacitance of the apparatus. For solidly grounded apparatus the zero sequence capacitance is equal to the positive sequence capacitance, $C_0 = C_1$.

The equivalent capacitance of several items in parallel can be simply summed to yield a total equivalent capacitance that can then be combined with the equivalent inductance for TRV calculations.

For three-phase to ground faults on effectively grounded systems, the equivalent capacitance of several items in parallel is the sum of 2/3 of the positive sequence capacitance (C_1) and 1/3 of the zero sequence capacitance (C_0) of all equipments (see Figure A.2).

For three-phase ungrounded faults on effectively grounded systems, $C_{eq} = 2/3\ C_1$ and the positive sequence capacitance is the sum of the positive sequence capacitance of all equipments.

The effective value of capacitance is the lumped value at the terminals that is equivalent to the distributed capacitance of the apparatus in the frequency range of the recovery voltage. In many cases, there may not be an opportunity to measure the effective capacitance of the equipment to be used. In these cases, Table B.1 through Table B.9 may be used for estimated values (these tables give ranges of possible values).

In those cases where more accurate capacitance values are needed, values should be determined by measurement or calculation. It is possible to calculate effective capacitance from simple apparatus geometry, e.g., GIS bus. It is also possible to calculate effective capacitance from low-frequency measurements of capacitances combined with apparatus geometry, e.g., reactors and transformers, but these calculations are complex and beyond the scope of this annex, and caution should be used in applying the results.

The effective capacitance can be evaluated by measuring the natural frequency of the apparatus under specified fault conditions. The natural frequency can be determined by low-voltage current injection to excite the system by variable- frequency resonant measuring circuitry and by measurement of the TRV during interruption of short-circuits at full or reduced voltage. The effective capacitance can then be evaluated using the inductance of the apparatus and the measured natural frequency.

In those cases of oscillatory transients where the total capacitance is large, e.g., more than 10 times the equivalent capacitance of the current limiting apparatus, the effect of the wide range of capacitances in the tables is small and the resulting frequency is accurately predicted. In those cases where only a few pieces of apparatus are connected, the large range of capacitance results in a wide range of estimated TRV frequencies.

The interruption of fault currents limited by transformers without additional capacitance between the transformer and the circuit breaker results in very high TRV frequencies that impose severe duty on the circuit breaker. These frequencies have been extensively measured by several investigators (Harner and Rodriquez [B8], Heinmiller, et al [B10], and Petitpierre and Watschingen [B12]).

Figure B.1 and Figure B.2 show the 50th and 90th percentile frequencies vs. fault current for maximum system voltages from 15 kV to 550 kV. The graphs are based on transformer-limited faults supplied by an infinite source.

Figure B.1 and Figure B.2 should be used with the breaker voltage rating and not the actual operating voltage. It is recommended to use these graphs to estimate TRV frequencies of transformer limited faults and to calculate the effective capacitances from those frequencies when required. However, users are cautioned that transformer capacitance values can vary over a wide range dependent on the rating and the winding electrical connections and physical connections. This is particularly the case for circuit breakers applied at medium voltages on the secondaries of stepdown transformers.

The curves on Figure B.1 and Figure B.2 are based on the transformer winding voltage, they are valid for the high side and the low side. The voltage on the Figures correspond to the side where the switching device is applied. The current is the three-phase fault current through the switching device. The TRV frequency is read from the calculated fault current and the appropriate voltage curve.

NOTE—Curves on Figure B.1 and Figure B.2 cover all types of transformers winding configurations, including autotransformers (Harner and Rodriguez [B8]).

As an example, for the transformer limited fault condition shown in Figure 21, the following gives the calculation of the effective capacitance of the transformer.

Considering a breaker rated voltage of 145kV and a fault current of 4 kA, a TRV frequency of 10.4 kHz is derived from Figure B.2.

Assuming a source of infinite short-circuit current, the inductance of transformer is given by

$$L = \frac{145}{\sqrt{3} \times 4 \times 377} \text{ H} = 0.055 \text{ H}$$

The transformer capacitance is then

$$C = \frac{1}{(2\pi f)^2 L} = \frac{1}{(2\pi \times 10\,400)^2\, 0.055} \text{ nF} = 4.3 \text{ nF}$$

NOTE—The example applies for a 60 Hz system.

The definite purpose TRV parameters for Fast Transient Recovery Voltage Rise Times are given in Tables 1B, 2B and 3B of ANSI C37.06.1. TRV frequencies are consistent with the values given in Figure B.1.

Table B.1— Effective generator capacitance (per phase)

	Generator size (MVA)	Capacitance (nF)
Steam-turbine driven	15–70	30–85
	70–300	50–110
	300 and up	65–250
Hydro driven	10–25	50–85
	25–100	150–300
NOTE—There is no direct correlation between MVA size and capacitance limits. For instance, a 50 MVA generator may have a capacitance-to-ground anywhere from 30–85 nF depending upon machine design.		

Table B.2— Outdoor bushing capacitance

Maximum system voltage (kV)	**Capacitance (pF)**			
	Air-to-oil, air-to- SF_6 laminated foil, oil and paper insulated	**Air-to-SF_6, SF_6 insulated**	**SF_6-to-oil, SF_6 and oil insulated**	**Air-to-air, air-to- oil, air-to-SF_6, solid insulated**
15–72.5	150–650	25–150	-	30–200
72.5–800	100–1200	25–150	100–500	100–500
NOTE—Larger values of capacitance are typically associated with higher voltages but there is a wide range at each voltage level. Not all types of bushings are made at every voltage level.				

Table B.3— Effective capacitance of inductive instrument transformer

Maximum system voltage (kV)	**Outdoor potential transformers capacitance (pF)**	**Outdoor current transformer Capacitance (pF)**	**SF_6 insulated potential transformer for GIS capacitance (pF)**
15–72.5	125–500	75–260	200–400 (Epoxy insulated)
72.5–800	150–450	150–450	70–150 (Laminated foil, SF_6 insulated)

Table B.4— Capacitive voltage transformer capacitance

Voltage class (kV)	**Capacitance (pF)**
145	8000–16 000
170	4300-15 000
242	8000–11 000
362	7000–11 000
550	4000–7000
800	2000–4000

Table B.5— Bus capacitance—Air insulated bus

Ampere rating	**Isolated phase bus capacitance (pF/m) (pF/ft) up to 38 kV maximum system voltage**	**Segregated phase bus capacitance (pF/m) (pF/ft) 15 kV maximum system voltage**	**Outdoor substation bus capacitance (pF/m) (pF/ft)**
1200–3500	26-52 (8–16)	33-66 (10–20)	8.2-18.0 (2.5–5.5)
4000–6500	39-62 (12–19)	33-66 (10–20)	8.2-18.0 (2.5–5.5)
7000–12000	14-24 (46-79)	—	—

Table B.6— Gas-insulated substation capacitance

Rated maximum voltage (kV)[a]	Isolated phase bus (pF/m) (pF/ft)	Three-in-one bus (pF/m) (pF/ft)[b]
242 and below	49-66 (15–20)	66-82 (20–25)
362 and above	39-56 (12–17)	49-72 (15–22)

[a] Surge impedance is typically 50-70 Ω.
[b] In the case of disconnecting and grounding switches, elbows, tees, etc., their capacitances do not vary significantly from the values per foot. A conservative value for circuit breakers will result if the length which they occupy is used to calculate the capacitance.

Table B.7— Effective capacitance of circuit breakers, circuit switchers, and disconnect switches

Apparatus description	Capacitance (pF)			
	Maximum system voltage 15–72.5 kV		Maximum system voltage 72.5–800 kV	
	Open[a]	Closed	Open[a]	Closed
Outdoor, dead-tank, air, oil, vacuum, or SF_6 circuit breakers with oil and paper bushings	150–650	300–1300	250–550	500–1300
with SF_6 bushings	25–150	50–300	25–150	50–300
with solid resin bushings	50–200	100–400	100–500	200–1000
Outdoor, live-tank, air, oil, vacuum, or SF_6 circuit breakers	20–50	40–100[b]	25–150	50–250[b]
GIS circuit breakers	Note 2	Note 2	Note 2	Note 2
GIS disconnect switches	Note 2	Note 2	Note 2	Note 2
Outdoor SF_6 circuit switchers	20–40	40–100[b]	25–100	50–200[b]
Outdoor SF_6 circuit switchers with integral disconnect blade	25–80	60–120	30–200	80–250
Outdoor disconnect switches	20–60	30–100	30–130	60–200
NOTE 1—The higher values of capacitance are associated with the higher voltages. NOTE 2—For GIS systems, the capacitance of disconnecting switches and circuit breakers does not vary greatly from the values per foot for the bus.				

[a] Voltage-grading capacitances or resistances may be present across the open gap of circuit breakers. Consult the manufacturer for specific values.
[b] Capacitance is based on one interrupter per pole. The closed capacitance is in proportion to the number of interrupters per pole.

Table B.8— Effective capacitance of miscellaneous equipment

Description	Capacitance (pF)
Outdoor support insulators	8–12[a] maximum
Outdoor lightning arresters	80–120
Outdoor current-limiting reactors	150–250

[a] The effective capacitance of support insulators is overshadowed by the connected apparatus' effective capacitance and it can be neglected.

Table B.9— Effective capacitance of transformers for three-phase ungrounded faults, first pole-to-open

Transformer size (MVA)	**Capacitance (pF)**	
	Maximum system voltage 15 to 121 kV	**Maximum system voltage 121 to 550 kV**
1 to 10	900 to 10 000	—
10 to 100	2000 to 12 000	2000 to 6500
100 to 1000	—	3500 to 16 000

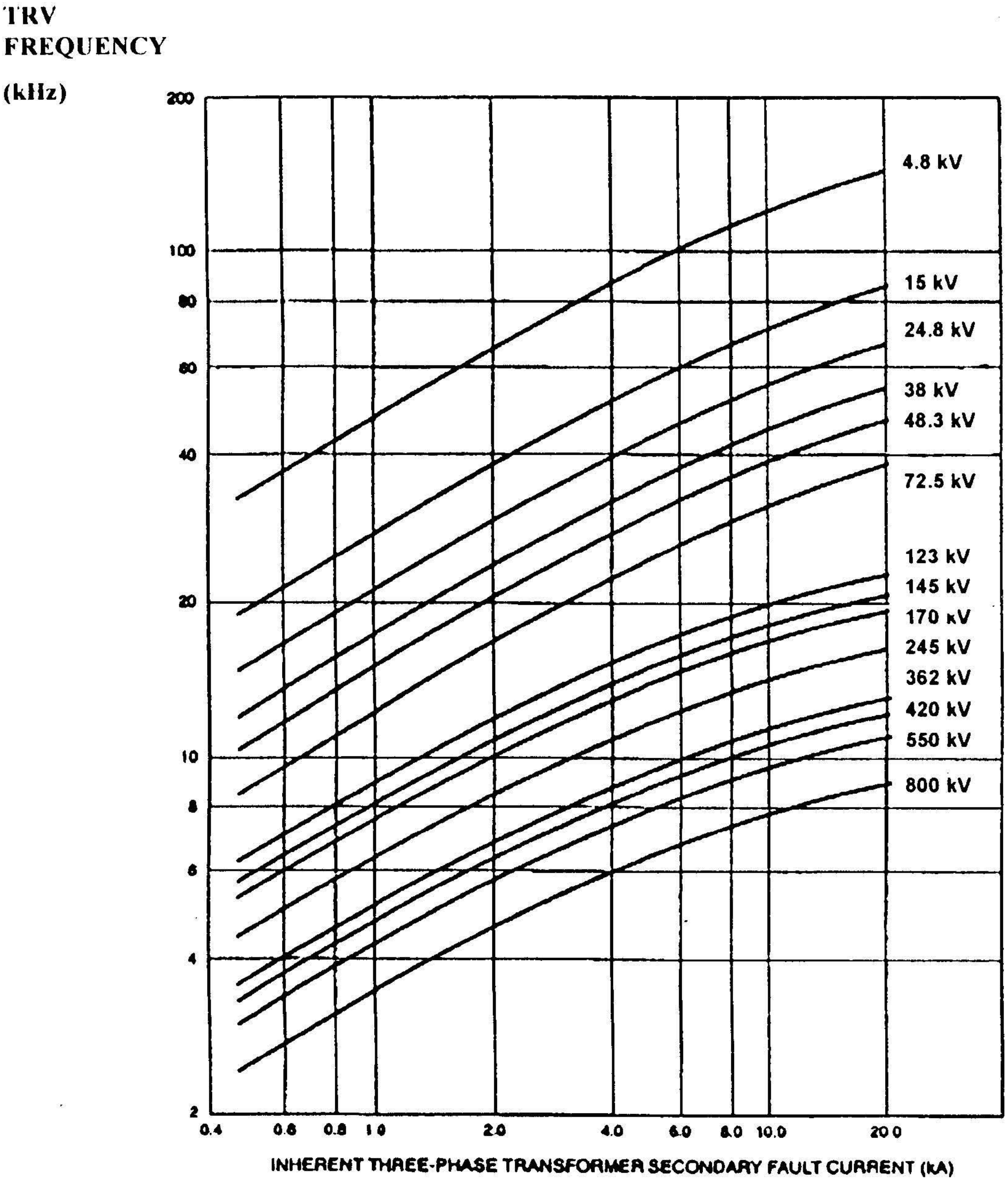


Figure B.1—Three-phase power transformer TRV frequencies across the first pole to clear for three-phase secondary faults—90th percentile curve

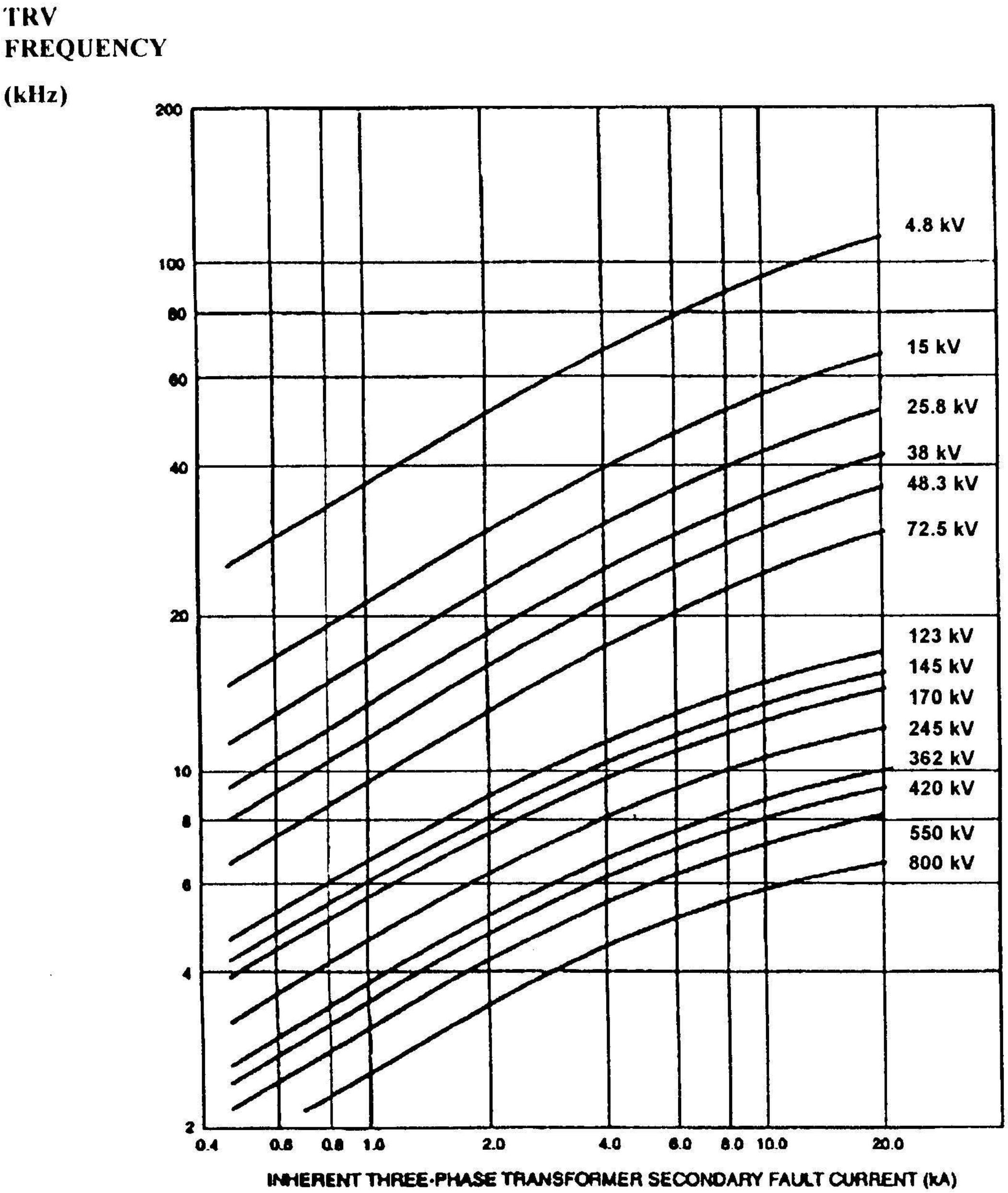


Figure B.2—Three-phase power transformer TRV frequencies across the first pole to clear for three-phase secondary faults—Median curves

Annex C

(informative)

Selection of the first pole-to-clear factors and factors for second and third pole-to-clear

C.1 Selection of the first pole-to-clear factor

The first pole-to-clear factor (k_{pp}) is a function of the grounding arrangements of the system. It is the ratio of the power frequency voltage across the interrupting pole before current interruption in the other poles, to the power frequency voltage occurring across the pole or poles after interruption in all three poles.

For systems with ungrounded neutral, k_{pp} is or tends towards 1.5. Such systems can be met with rated voltages less than 245 kV, however at transmission voltages, i.e., greater than 72.5kV, it is increasingly rare and effective grounding is the norm.

For effectively grounded neutral systems, the realistic and practical value is dependent upon the sequence impedances of the actual earth paths from the location of the fault to the various system neutral points (ratio X_0/X_1). For these systems the ratio X_0/X_1 is taken to be ≤3.0.

Three-phase to ground faults are the basis for rating because it is recognized that three-phase ungrounded faults have a very low probability of occurrence.

For lower voltages, less than 100 kV, the case of three-phase ungrounded faults, should they occur, is automatically covered since a first pole-to-clear factor of 1.5 is specified to cover three-phase faults in non effectively grounded systems.

For special applications in transmission systems with effectively grounded neutral where the probability of three-phase ungrounded faults cannot be disregarded, a first-pole-to-clear factor of 1.5 may be required. Hence, for rating purposes, two values of the first-pole-to-clear factor are defined for the three-phase short-circuit condition. The choice between these two values is dependent on the system grounding arrangement:

a) Systems with ungrounded neutral: a standardized value for k_{pp} of 1.5 is used;

b) Effectively grounded systems: for standardization purposes the value for k_{pp} used is 1.3.

A third condition does exist, this is where the fault is single-phase in an effectively grounded system and the last-pole-to-clear is considered. For this k_{pp} is 1.0.

Generally it will not be necessary to consider alternative transient recovery voltages as the standard values specified cover the majority of practical cases.

C.2 Factors for each pole-to-clear

C.2.1 Equation for the first-to-clear factor

$$k_{pp} = \frac{3X_0}{X_1 + 2X_0} \tag{C-1}$$

where X_0 is the zero sequence, and X_1 the positive sequence reactance of the system.

If $X_0 >> X_1$, as in ungrounded systems then:

$\boldsymbol{k}_{\mathbf{pp}} = \mathbf{1.5}$

If $X_0 = 3.0\ X_1$, as in effectively grounded neutral systems then:

$\boldsymbol{k}_{\mathbf{pp}} = \mathbf{1.3}$

C.2.2 Equations for the other clearing poles

a) Systems with ungrounded neutrals

As illustrated in Figure C.1, after interruption of the first phase (A), the same fault current is carried in phases B and C (but with opposite sign). This current is interrupted by the last two poles in series under the phase-to-phase voltage ($E_B - E_C$) equal to $\sqrt{3}$ times the phase-to-ground voltage. Each pole shares ½ of the phase-to-phase voltage, so that for each pole,

$$k_{\text{pp}} = \frac{\sqrt{3}}{2} = 0.87$$

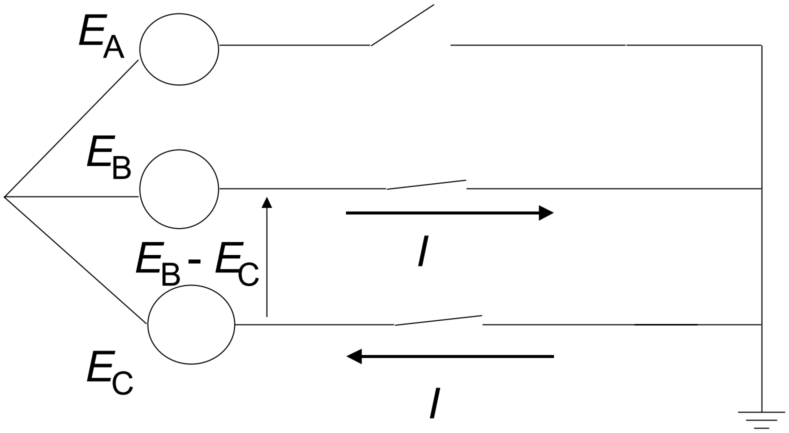


Figure C.1—Ungrounded system after interruption of the first phase

b) Systems with effectively grounded neutrals

In systems with effectively grounded neutrals, the second pole clears a three-phase to ground fault with a factor of

$$k_{\text{pp}} = \frac{\sqrt{3}\sqrt{X_0^2 + X_0 X_1 + X_1^2}}{X_0 + 2X_1} \qquad \text{(C-2)}$$

This formula can be expressed as a function of the ratio X_0/X_1:

$$k_{\text{pp}} = \frac{\sqrt{3}\sqrt{\alpha^2 + \alpha + 1}}{2 + \alpha} \qquad \text{(C-3)}$$

where $\alpha = X_0/X_1$

If $\alpha = 3.0$, the second pole-to-clear factor is 1.25.

For the third pole-to-clear: $k_{\text{pp}} = 1$

Table C.1 gives k_{pp} for each clearing pole as a function of X_0/X_1 as appropriate.

Table C.1—Pole-to-clear factors (k_{pp}) for each pole when clearing three-phase to ground faults

Neutral	X_0/X_1	Pole-to-clear factor k_{pp}		
	Ratio	**First**	**Second**	**Third**
Ungrounded	Infinite	1.5	0.87	0.87
Effectively grounded	3.0	1.3	1.25	1.0
See Note	1.0	1.0	1.0	1.0

NOTE—Values of the pole-to-clear factor are given for $X_0/X_1 = 1.0$ to indicate the trend in the special case of networks with a ratio X_0/X_1 of less than 3.0.

It is important to note that as the amplitude factor is the same for each pole, the multiplying factors of Table C.1 are applicable to the power frequency voltages and to the TRV on each pole.

In the special case of three-phase ungrounded faults, the pole-to-clear factors are as defined in C.2.2 a) for three-phase faults in ungrounded systems.

C.2.3 TRV on each pole-to-clear

Figure C.2 shows the TRV on each pole-to-clear during interruption of a three-phase to ground terminal fault in an ungrounded system. The same TRV would be applied in the case of three-phase ungrounded faults.

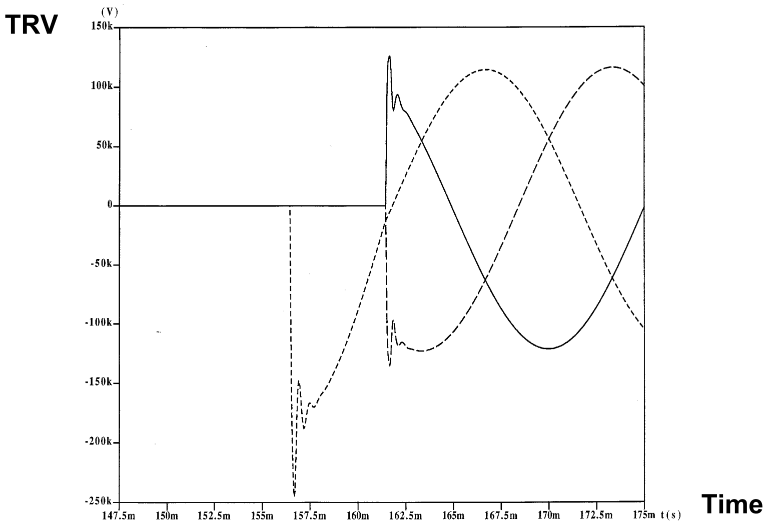


Figure C.2—TRV on each pole-to-clear during a three-phase to ground terminal fault in an ungrounded system

Figure C.3 shows currents and TRV on each pole-to-clear during interruption of a three-phase to ground terminal fault in an effectively grounded system.

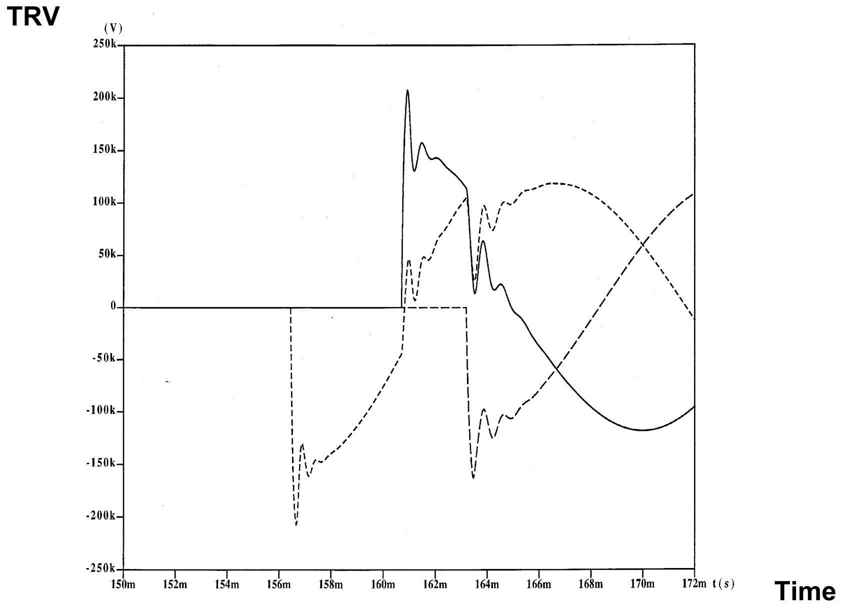


Figure C.3—TRV on each pole-to-clear during a three-phase to ground terminal fault in an effectively grounded system

Figure C.4 gives the pole-to-clear factor as function of the circuit breaker arcing time, in the case of a three-phase to ground fault in effectively grounded system, a three-phase fault in ungrounded system and a three-phase ungrounded fault in an effectively grounded system. The origin of x-axis is the minimum arcing time of the circuit breaker. Values are taken from IEC 62271-100 [B15].

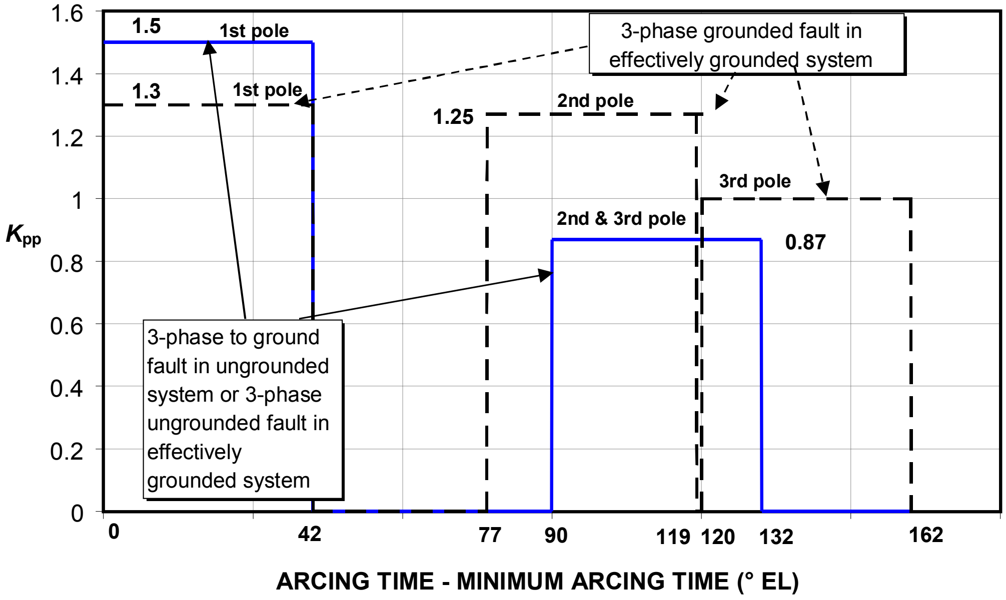


Figure C.4—Pole-to-clear factor as function of the circuit breaker's arcing time

Annex D

(informative)

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[B13] *Transient Recovery Voltages on Power Systems (as Related to Circuit Breaker Performance)*. New York: Association of Edison Illuminating Companies, 1963.[8]

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[7] See footnote 6.

[8] The symbols used in this reference do not correspond to the references of IEEE Std C37.100-1992.

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[B15] IEC 62271-100, First edition 2001-05, "High-voltage switchgear and controlgear – Part 100: High-voltage alternating-current circuit breakers", Table 12 in 6.102.10.2.5 on page 193.

[B16] IEEE PC37.04b, DRAFT Supplement to IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers.[9]

[B17] IEEE PC37.06, DRAFT Standard Test Procedure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis-Preferred Ratings and Related Required Capabilities.[10]

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[9] This IEEE Draft was not approved by the IEEE-SA Standards Board at the time this publication went to press. For information about obtaining a draft, contact the IEEE.

[10] See footnote 9.