

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

IEEE Power & Energy Society

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

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Switchgear Committee
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Approved 31 October 2011

IEEE-SA Standards Board

Abstract: Procedures and calculations necessary to apply the standard transient recovery voltage (TRV) ratings for ac high-voltage circuit breakers rated above 1000 V are covered in this application guide. The breaking capability limits of these circuit breakers are determined to a great degree by the TRV. The TRV ratings are compared with typical system TRV duties. Examples of TRV calculation are given with suggested options if the TRV duty exceeds the TRV ratings of the circuit breaker.

Keywords: high-voltage circuit breakers, IEEE C37.011, transient recovery voltage

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Introduction

This introduction is not part of IEEE Std C37.011-2011, IEEE Guide for the Application of 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 C37.04b™ and IEEE Std C37.06™.^a

The main changes implemented in this guide concern the following:

- Presentation of classes S1 and S2 for circuit breakers with rated maximum voltages less than 100 kV
- Revision of 4.2.1 to better explain the interpolation of TRVs for interrupting currents between 30% and 60% of rating
- Revision of 4.2.4 on line faults that is expanded and updated, using mainly the work done by CIGRE WG A3-19 (see CIGRE Technical Brochure 408 [B5]^b)
- Expansion of 4.4.2 on reactor limited faults

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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 [breaking](#) 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. Examples of TRV calculation are given [with suggested options if the TRV duty exceeds the TRV ratings of the circuit breaker](#).

1.2 Purpose

The purpose of this [standard](#) 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, IEEE Std C37.06™, IEEE Std C37.09™, and [ANSI C37.06.1](#). IEEE Std C37.010™ applies in other respects to these circuit breakers.

¹ Information on references can be found in Clause 2.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies. ~~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 C37.06.1, American National Standard Guide for High-Voltage Circuit Breakers Rated on Symmetrical Current Basis Designated Definite Purpose for Fast Transient Recovery Voltage Rise Times.²

IEEE Std C37.04™, IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers.^{3, 4}

IEEE Std C37.04b™, IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis Amendment 2: To Change the Description of Transient Recovery Voltage for Harmonization with IEC 62271-100.

IEEE Std C37.06™, IEEE Standard for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis Preferred Ratings and Related Required Capabilities for Voltages above 1000 V.

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

IEEE Std C37.010™, 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

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 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). Additionally, distributed and lumped circuit elements will produce different TRV wave shapes.

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.

² [ANSI publications are available from the Customer Service Department, American National Standards Institute, 25 W. 43rd Street, 4th Floor, New York, NY 10036, USA \(http://www.ansi.org/\).](http://www.ansi.org/)

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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 is determined on a single-phase basis during their early time periods. 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 IEEE Std C37.06.

While three-phase ungrounded faults produce the highest TRV peaks, the probability of their occurrence is very low (see the discussion in Wagner and Smith [B22]).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 below 100 kV, the TRV ratings assume that the systems can be operated ungrounded. 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. For circuit breakers applied on systems above 170 kV, the TRV ratings assume that the systems are all operated effectively grounded. See Annex C.

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

[For GIS with all three phases in one enclosure a grounded fault can evolve into a three-phase ungrounded fault prior to interruption. The user should choose the appropriate first-pole-to-clear factor, i.e., \$k_{pp} = 1.5\$ for three-phase ungrounded faults.](#)

In IEEE Std C37.04b and IEEE Std C37.06, the TRV capability of a circuit breaker is defined by a two parameter or a four-parameter envelope.

A circuit breaker TRV capability is sufficient if the two- or four-parameter envelope drawn with the rated parameters as specified in IEEE Std 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 the future system modifications.

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, a circuit breaker [with either a higher voltage rating or a circuit breaker with higher short-circuit current rating](#) should be used, [as described in 4.5](#), or the system should be modified in such a manner as to change its TRV characteristics. The addition of capacitors to a bus or line [or the addition of capacitors at one or both terminals of the circuit breaker are examples of methods](#) that can be used to [bring](#) the system TRV [below the TRV rating of the circuit breaker](#).

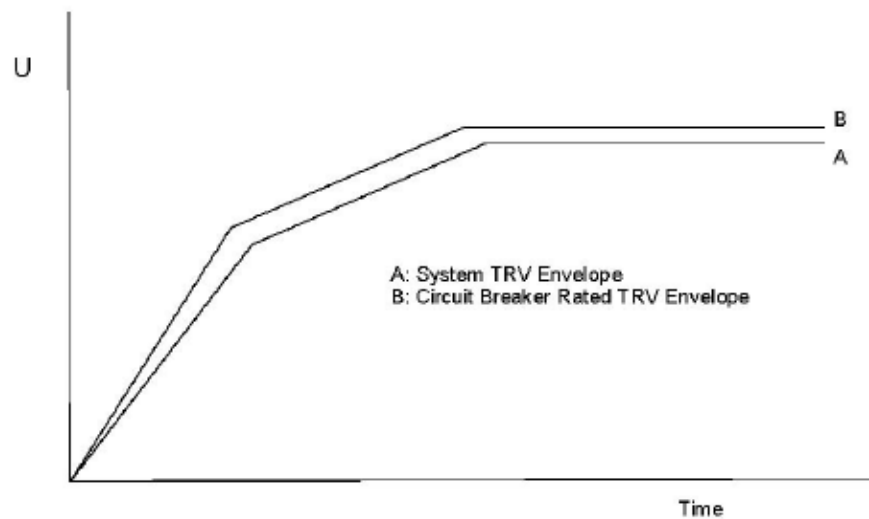


Figure 1—System TRV envelope and circuit-breaker rated TRV envelope

3.3.2 Classes of circuit breakers with rated voltages below 100 kV

Two classes of circuit breakers (S1 and S2) are defined in IEEE Std C37.04b; the specification is dependent on the type of application.

A circuit breaker class S1 is intended to be used in a cable system.

A circuit breaker class S2 is intended to be used in a line system or in a cable system with direct connection (without cable) to overhead lines.

Definitions of cable system and line system are reproduced here from IEEE Std C37.04b for readers' convenience; the following NOTE 2 is added for clarification.

A *cable system* is a system in which the TRV during interruption of terminal fault at 100% of short-circuit interrupting current does not exceed the two-parameter envelope derived from Column 5 of Table 2A in IEEE Std C37.04b.

This definition of cable systems is restricted to systems of rated voltages higher than 1 kV and less than 100 kV. Circuit breakers located in indoor substations with cable connections are generally in cable systems. A circuit breaker in an outdoor substation is considered to be in a cable system if the total length of cable (or equivalent length when capacitors are also present) connected on the supply side of the circuit breaker is at least 100 m (328 ft). However, if in an actual case with an equivalent length of cable shorter than 100 m (328 ft), a calculation can show that the actual TRV is covered by the envelope defined from Column 5 of Table 2A, then this system is considered a cable system. The capacitance of cable systems on the supply side of circuit breakers is provided by cables and/or capacitors and/or insulated bus.

NOTE 1—The term *cable* used in this guide means shielded conductor.⁶

NOTE 2—The indication that a cable length of at least 100 m (328 ft) is necessary to have a cable system is based on a cable capacitance per unit length of 0.3 nF/m, i.e., the cable capacitance should be at least 30 nF. However, as stated in the definition, the relevant parameter is the envelope of the TRV during interruption of terminal fault at 100% of short-circuit interrupting current.

A *line system* is a system in which the TRV during interrupting of terminal fault at 100% of short-circuit interrupting current is covered by the two-parameter envelope derived from Column 4 of Table 2A in IEEE Std C37.04b and exceeds the two-parameter envelope derived from Column 5 of Table 2A.

This definition of *line systems* normally applies to systems of rated voltages equal to or higher than 15 kV and less than 100 kV. In line systems, no cable is connected on the supply side of the circuit breaker, with the possible exception of a total length of cable up to 100 m between the circuit breaker and the supply transformer(s). Systems with transmission lines directly connected to a busbar (without intervening cable connections) are typical examples of line systems.

The two-parameter envelopes of TRVs for line and cable systems are illustrated by Figure 2. TRV parameters are such that the rate of rise of recovery voltage (RRRV) for line systems is approximately two times higher than that for cable systems and the peak TRV is also higher (the amplitude factor of rated TRV is 1.54 for line systems and 1.4 for cable systems).

Only S2 circuit breakers have a defined short-line-fault (SLF) interrupting capability. Therefore circuit breakers with direct connection to overhead lines must be of class S2 independently of the type of system (line system or cable system).

NOTE 3—When a circuit breaker is cable-connected to an overhead line, it is considered to be directly connected to the overhead line if the capacitance of the connection is less than 5 nF. When the cable capacitance per unit length is 0.3 nF/m, it corresponds to a length of cable shorter than approximately 17 m (56 ft).

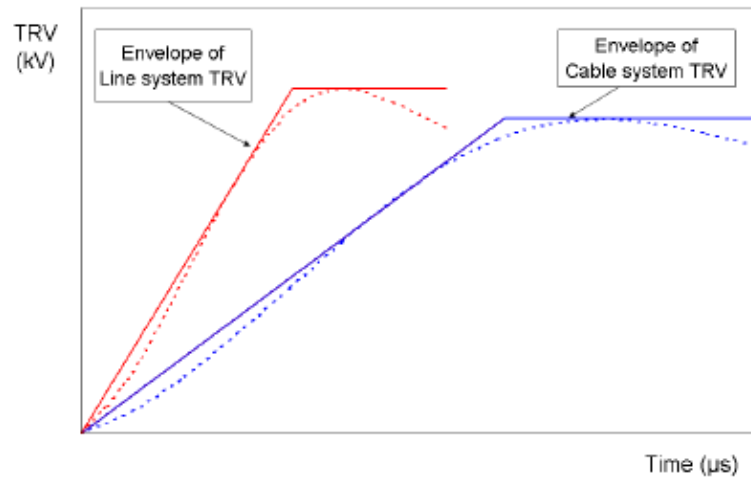
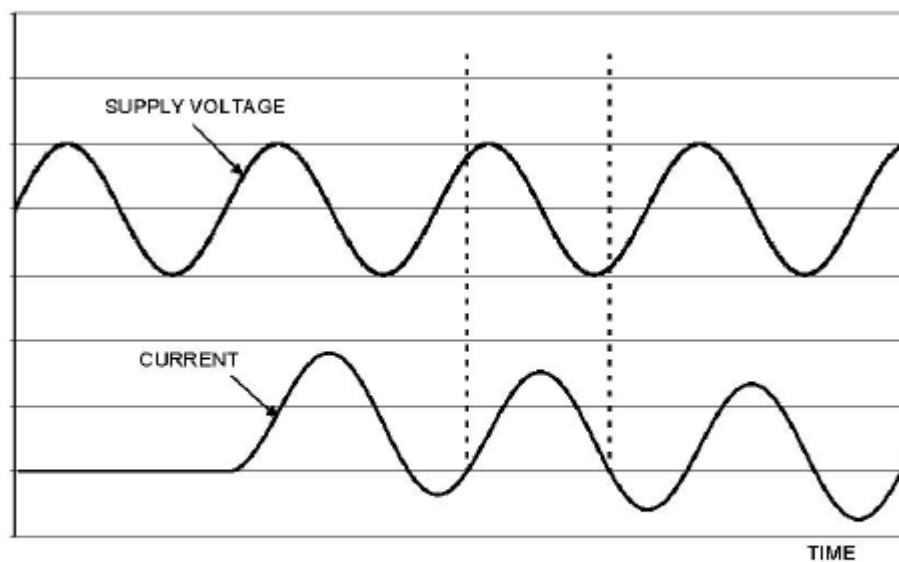


Figure 2—Comparison of line-system and cable-system rated TRVs

3.3.3 Effect of asymmetry on transient recovery voltage

The TRVs that occur when interrupting asymmetrical current values are generally less severe than 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 3). Circuit breakers have the capability of interrupting these asymmetrical currents providing the circuit breakers are applied within their rating.

NOTE—IEEE Std C37.081a™-1997 [B17], 8.3.2, gives the reduction factors of TRV peak and RRRV when interrupting asymmetrical currents.



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

Figure 3—Supply voltage and asymmetrical current

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 4, Figure 5, and Figure 6, respectively.

A typical exponential TRV is shown in Figure 4. 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.

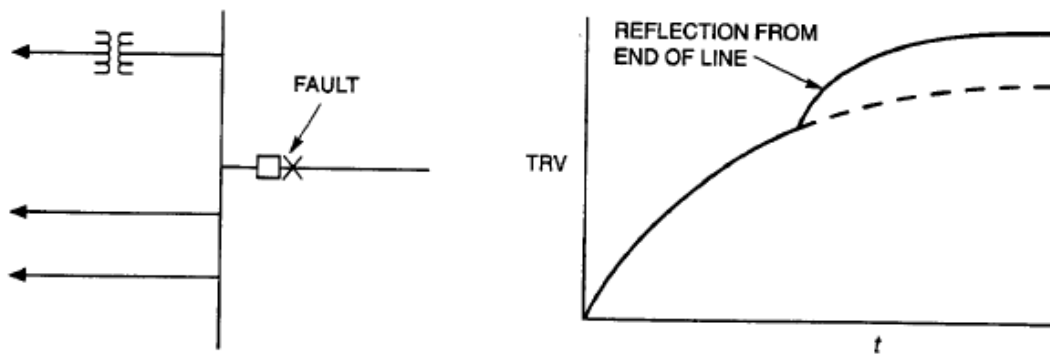


Figure 4—Exponential TRV characteristic

The oscillatory TRV shown in Figure 5 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.

Short-line faults (SLF) exhibit the characteristic shown in Figure 6. 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.

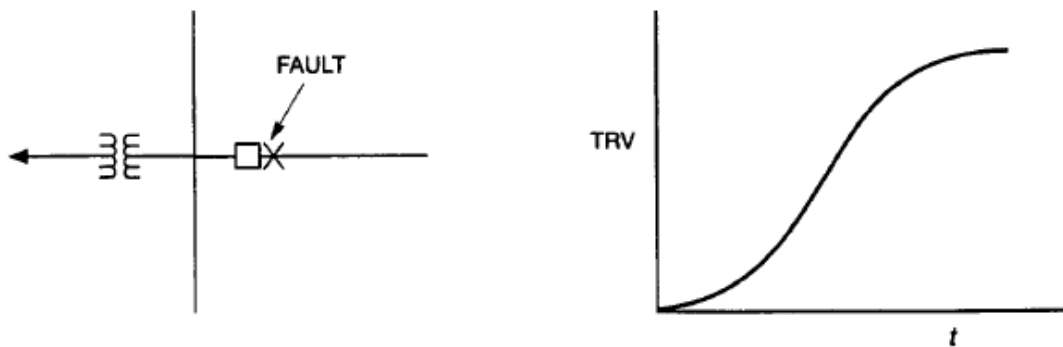


Figure 5—Oscillatory TRV characteristic

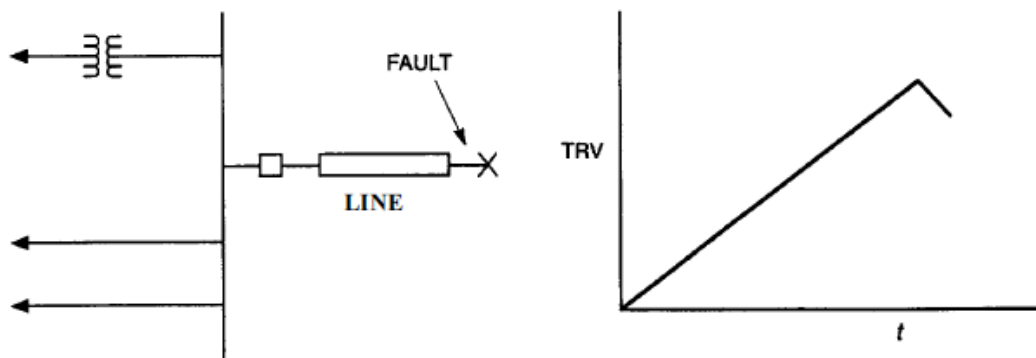


Figure 6—Short-line fault TRV characteristic

The two-parameter and four-parameter envelopes, illustrated in Figure 7 and Figure 8, have been introduced in ~~the draft revision of~~ IEEE Std C37.04b to facilitate the comparison between a TRV obtained during testing and a specified TRV (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.

The two parameters are described as follows:

u_c = reference voltage (TRV peak value), in kilovolts

t_3 = time to reach u_c , in microseconds

The four parameters are described as follows:

u_1 = first reference voltage, in kilovolts

t_1 = time to reach u_1 , in microseconds

u_c = second reference voltage (TRV peak value), in kilovolts

t_2 = time to reach u_c , in microseconds

The delay line is defined by a voltage parameter u' , a time parameter t' , and a time delay t_d as follows:

u' = reference voltage, in kilovolts

t' = time to reach u' , in microseconds

t_d = time delay, in microseconds

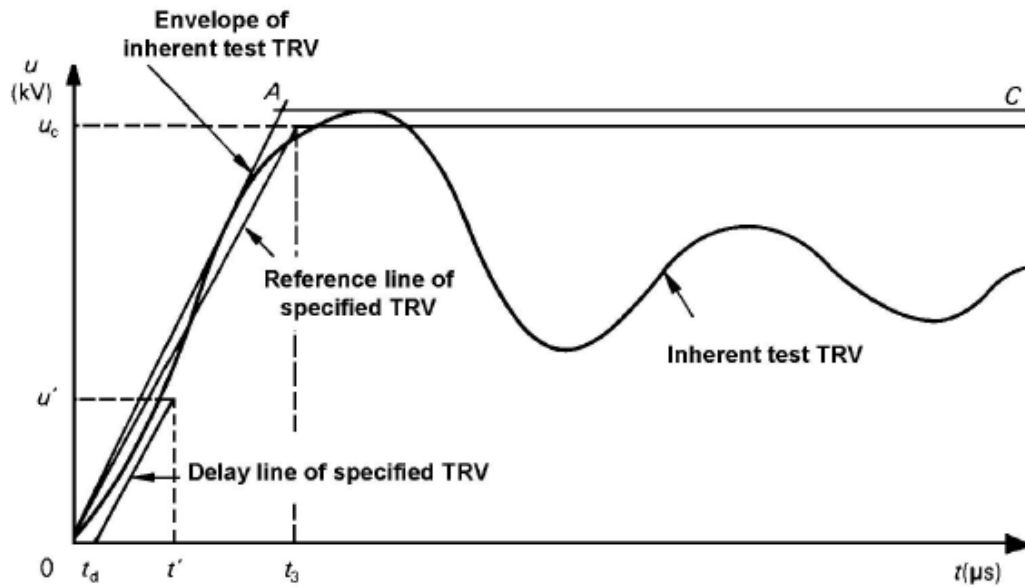


Figure 7—Example of inherent test TRV with two-parameter envelope that satisfies the conditions to be met during type test

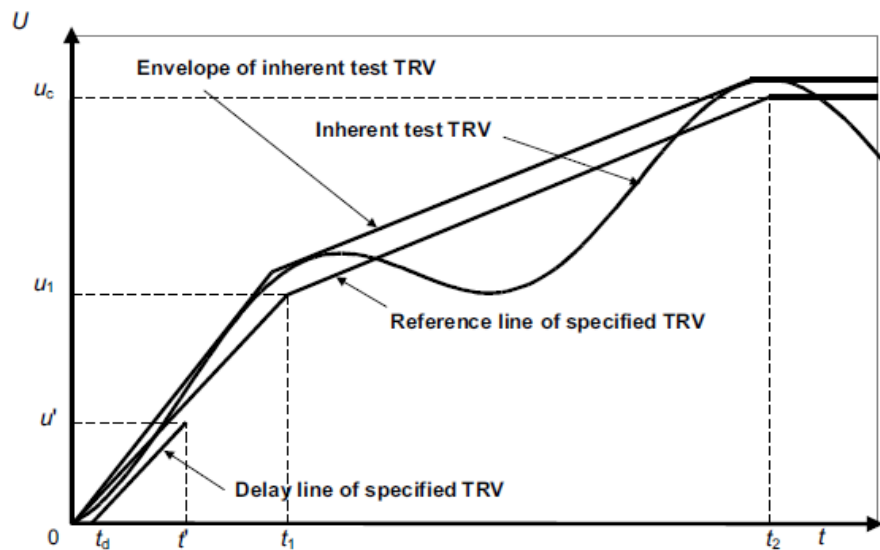


Figure 8—Example of inherent test TRV with four-parameter envelope that satisfies the conditions to be met during type test

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 re-ignition 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). SLF 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 guide 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 a High-Voltage Circuit Breaker Subcommittee task force determining natural frequencies of transformers.

4.2 Circuit breaker capability

Rated and related circuit breaker TRV capabilities are defined by parameters given in IEEE Std 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 [circuit breakers 100 kV and above](#), 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 8).

For terminal fault currents between 10% and 30% for [circuit breakers 100 kV and above](#), and for all terminal fault currents for [circuit breakers below 100 kV](#), the standard assume a TRV envelope described by two parameters (u_c , t_3), as illustrated in Figure 7.

For circuit breakers rated below 100 kV, the TRV envelope is described by two parameters over the entire current range.

4.2.1 Three-phase terminal fault

As an example, Figure 9 shows the three-phase-to-ground fault related TRV capability for a 550 kV circuit breaker at 100% of its symmetrical [short-circuit](#) current rating (first-pole-to-clear factor $k_{pp} = 1.3$). [The TRV envelope is defined by four parameters \(\$u_1\$, \$t_1\$, \$u_c\$, \$t_2\$ \) given in IEEE Std C37.06](#). It shows also the TRV capability for the optional case with $k_{pp} = 1.5$.

[The parameters that define the circuit-breaker TRV capabilities vary with the breaker voltage rating and short-circuit current interrupting level. The circuit-breaker TRV capabilities at 10%, 30%, 60%, and 100% of rated short-circuit interrupting current, corresponding to terminal fault test duties T10, T30, T60, and T100, are given in IEEE Std C37.06.](#)

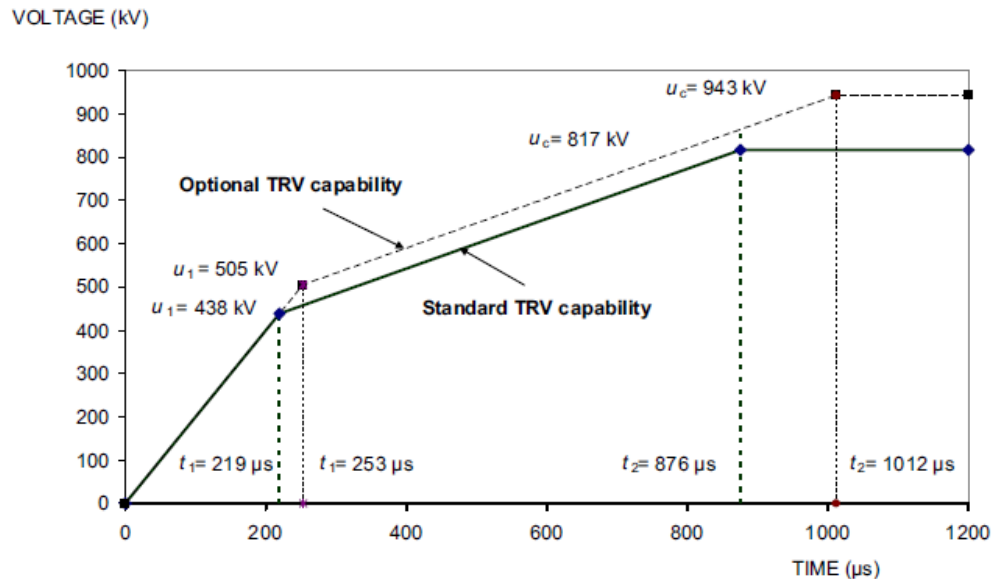


Figure 9—TRV capability envelope for a 550 kV circuit breaker at 100% of its rated fault current capability

Usually TRV studies should be carried out to determine if a system TRV is covered by the circuit-breaker TRV capability demonstrated by type tests, either when new circuit breakers are to be installed or following a system change. It is not uncommon that the maximum short-circuit current falls in between 30% and 60% of the circuit-breaker rated short-circuit current. To allow comparison of system TRV and circuit-breaker TRV capability and to avoid additional testing, a method of interpolation of TRV capabilities demonstrated by type tests was introduced in the previous editions of this guide. Following the introduction of the two- parameter and four- parameter description of TRVs, this method of interpolation in the current range T30- T60 (terminal faults with respectively 30% and 60% of the circuit-breaker rated short-circuit current) was not clearly stated in the 2005 version of this guide. Therefore, the method of interpolation is further developed in the following to define the breaker TRV capability for short-circuit currents in the range between T30 and T60.

The circuit-breaker TRV capability envelope at any short-circuit interrupting current below rated can be derived using the parameter values interpolated from rated parameters defined for 100% rated short-circuit current using the multipliers as given in Table 1.

The method of interpolation is not applicable to circuit breakers that have critical currents, i.e., if the minimum arcing times in any of the test duties T10, T30, or T60 is 5 ms or more longer than the minimum arcing times in the adjacent test duties.

Figure 10 and Figure 11 give a graphical representation of the multipliers as function of the percentage of interrupting capability (ratio of the symmetrical current component of the current being considered to the related required symmetrical interrupting capability).

**Table 1—Related required TRV capabilities of circuit breakers
at various interrupting levels for terminal faults**

Percent of interrupting capability (see NOTE 1)	Multipliers for rated parameters								
	Below 100 kV				100 kV and above				
	Cable system		Line system						
	Ku_c	Kt_3	Ku_c	Kt_3	Ku_1	Kt_1	Ku_c	Kt_2	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	2.11/2.05 (see NOTES 2 and 3)	0.84/0.82 (see NOTES 2 and 3)	1.13/1.1 (see NOTES 2 and 3)	0.21 (see NOTES 2 and 3)	
10	1.21	0.22	1.17	0.4	—	—	1.17/1.26 (see NOTE 2)	—	0.16/0.17 (see NOTE 2)

NOTE 1— 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. For other percentage of interrupting capability, interpolation can be done as shown in Figure 10 and Figure 11.

NOTE 2— Two values are given for each. The value on the left corresponds to multiplier for applications with $k_{pp} = 1.5$ and value on the right is for applications with $k_{pp} = 1.3$.

NOTE 3— Multipliers Ku_1 , Kt_1 , and Kt_2 are added to T30 for the interpolation of the TRV capability between interrupting currents T30 and T60. Multipliers Ku_c and Kt_3 have been revised to add value for $k_{pp} = 1.3$ with K_{af} of 1.54. For applications with $k_{pp} = 1.3$:

$$Ku_c = \frac{1.54}{K_{af}} = 1.1 \quad Ku_1 = \frac{K_{af} \times Ku_c}{0.75} = \frac{1.4 \times 1.1}{0.75} = 2.05 \quad Kt_1 = \frac{K_{af} \times Ku_c \times 2}{5 \times 0.75} = 0.82$$

$$Kt_2 = \frac{Kt_1}{4} = 0.21 \quad Kt_3 = Kt_2 = 0.21$$

For applications with $k_{pp} = 1.5$:

$$Ku_c = \frac{1.58}{K_{af}} = 1.13 \quad Ku_1 = \frac{K_{af} \times Ku_c}{0.75} = \frac{1.4 \times 1.13}{0.75} = 2.11$$

$$Kt_1 = \frac{K_{af} \times Ku_c \times 2}{5 \times 0.75} = 0.84 \quad Kt_3 = Kt_2 = \frac{Kt_1}{4} = 0.21$$

Where K_{af} is the amplitude factor at T100 (1.4).

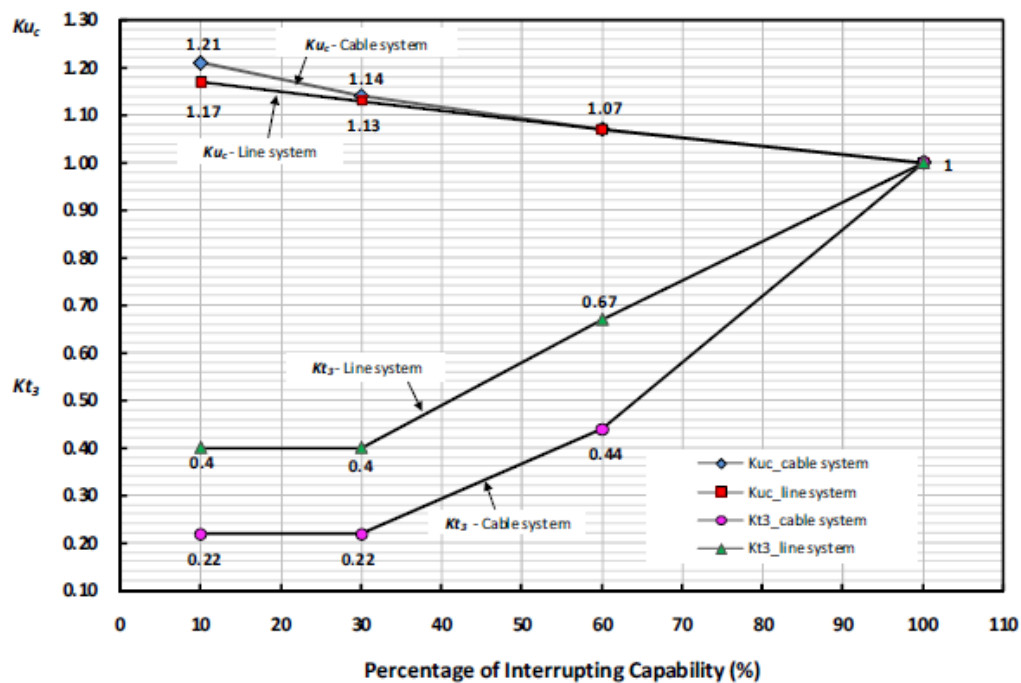


Figure 10—Multipliers for circuit breakers rated below 100 kV

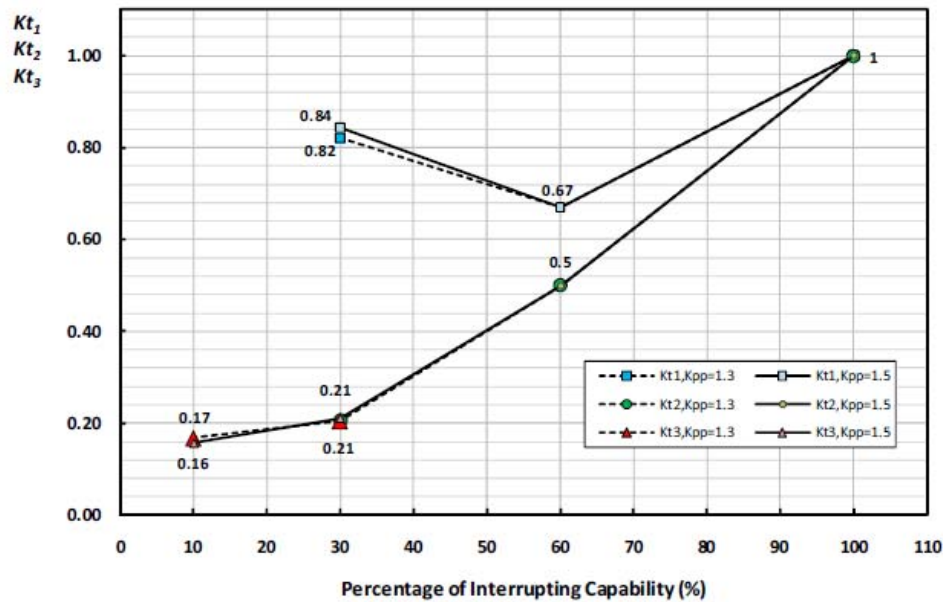
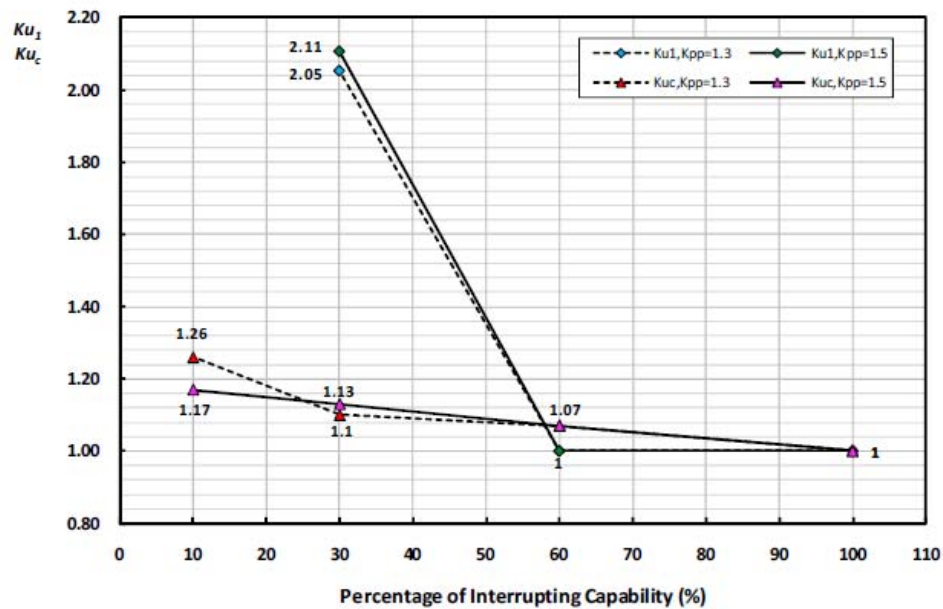


Figure 11—Multipliers for circuit breakers rated 100 kV and above

The following examples are given to illustrate how to interpolate the related TRV capability at a percentage of rated interrupting capability using Table 1, Figure 10, and Figure 11.

NOTE—Small differences in the evaluation of TRV parameters can occur due the rounding of values, they are not significant as the method of interpolation gives only an approximation of the circuit-breaker TRV withstand capability.

Example 1: TRV capability of a 72.5 kV circuit breaker for interrupting terminal fault currents between 10% and 30% of rated short-circuit current (I_{sc})

If we consider the case of a line system 72.5 kV circuit breaker, the TRV peak withstand capability when interrupting a terminal fault at 10% of rated short-circuit current is shown in Equation (1):

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

where

$$U_r = 72.5 \text{ kV}$$

$$k_{pp} = 1.5$$

$$k_{af} = 1.54 \text{ (from Table 6 of IEEE Std C37.06)}$$

$$Ku_c = 1.17$$

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

In a similar way, the TRV peak withstand capability when interrupting a terminal fault at 10% of rated short-circuit current for a 72.5 kV circuit breaker in a cable system is:

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

where

$$k_{af} = 1.4$$

Example 2: TRV capability of a 123 kV circuit breaker interrupting terminal fault currents between 30% and 60% of rated short-circuit current (I_{sc})

In standards, it is considered that 30% of I_{sc} is the maximum short-circuit current for which a two parameter TRV is applicable for circuit breakers rated 100 kV and above. The related TRV capability for short-circuit currents between 30% of I_{sc} and 60% of I_{sc} is necessarily a four-parameter TRV. It should have a rate of rise (u_1/t_1) and a first reference voltage (u_1) that have intermediate values between those of T30 and T60.

The multipliers in Table 1 corresponding to 30% interrupting capability have been revised so that the TRV parameters (u_1, t_1, u_c, t_2) for any terminal fault current between 30% and 60% can be obtained in the following manner:

u_1 and t_1 are interpolated between u_1 and t_1 of T60 and u_c and t_3 of T30

u_c and t_2 are interpolated between u_c and t_2 of T60 and u_c and t_3 of T30

Two methods are demonstrated to calculate the interpolation of circuit-breaker TRV parameters for a 123 kV breaker interrupting a terminal fault at 50% rated short-circuit current with $k_{pp} = 1.3$.

Method 1: Calculate directly from TRV parameters of T30 and T60

From IEEE Std C37.06, Table 12, TRV parameters for terminal fault at 60% of rated short-circuit current and rated maximum voltage (U_r) = 123 kV:

$$u_{1_60\%} = \underline{\hspace{10em}} 98 \text{ kV} \quad t_{1_60\%} = \underline{\hspace{10em}} 33 \text{ } \mu\text{s} \quad u_{c_60\%} = \underline{\hspace{10em}} 196 \text{ kV} \quad t_{2_60\%} = \underline{\hspace{10em}} 99 \text{ } \mu\text{s}$$

TRV parameters for terminal fault at 30% of rated short-circuit current:

$$u_{c_30\%} = \underline{\hspace{10em}} 201 \text{ kV}$$

$$t_{3_30\%} = \underline{\hspace{10em}} 40 \text{ } \mu\text{s}$$

The TRV parameters for terminal fault at 50% of rated short-circuit current can then be interpolated as follows:

$$u_{1_50\%} = \frac{u_{1_60\%} - u_{c_30\%}}{60\% - 30\%} \times (50\% - 30\%) + u_{c_30\%} = \frac{98 - 201}{60\% - 30\%} \times (50\% - 30\%) + 201 = 132 \text{ kV}$$

$$t_{1_50\%} = \frac{t_{1_60\%} - t_{3_30\%}}{60\% - 30\%} \times (50\% - 30\%) + t_{3_30\%} = \frac{33 - 40}{60\% - 30\%} \times (50\% - 30\%) + 40 = 35.3 \text{ } \mu\text{s}$$

$$u_{c_50\%} = \frac{u_{c_60\%} - u_{c_30\%}}{60\% - 30\%} \times (50\% - 30\%) + u_{c_30\%} = \frac{196 - 201}{60\% - 30\%} \times (50\% - 30\%) + 201 = 198 \text{ kV}$$

$$t_{2_50\%} = \frac{t_{2_60\%} - t_{3_30\%}}{60\% - 30\%} \times (50\% - 30\%) + t_{3_30\%} = \frac{99 - 40}{60\% - 30\%} \times (50\% - 30\%) + 40 = 79.3 \text{ } \mu\text{s}$$

Method 2: Calculate from multipliers given in Figure 11 and TRV parameters for terminal fault at 100% rated short-circuit current and rated maximum voltage.

From IEEE Std C37.06, Table 12, TRV parameters for terminal fault at 100% rated short-circuit current and rated maximum voltage (U_r) = 123 kV:

$$\begin{aligned} u_{1_100\%} &= 98 \text{ kV} \\ t_{1_100\%} &= 49 \text{ } \mu\text{s} \\ u_{c_100\%} &= 183 \text{ kV} \\ t_{2_100\%} &= 196 \text{ } \mu\text{s} \end{aligned}$$

From Table 1 and Figure 11, the multipliers for terminal fault at 30% and 60% rated short-circuit current are as follows:

$$Ku_{1_30\%} = 2.05$$

$$Kt_{1_30\%} = 0.82$$

$$Ku_{c_30\%} = 1.1$$

$$Kt_{2_30\%} = 0.21$$

$$Ku_{1_60\%} = 1.0$$

$$Kt_{1_60\%} = 0.67$$

$$Ku_{c_60\%} = 1.07$$

$$Kt_{2_60\%} = 0.5$$

As shown in Figure 11, the multipliers for terminal fault at 50% rated short-circuit current can be interpolated from multipliers for 30% and 60% interrupting capability as illustrated below:

$$Ku_{1_50\%} = \frac{Ku_{1_60\%} - Ku_{1_30\%}}{60\% - 30\%} \times (50\% - 30\%) + Ku_{1_30\%} = \frac{1 - 2.05}{60\% - 30\%} \times (50\% - 30\%) + 2.05 = 1.35$$

$$Kt_{1_50\%} = \frac{Kt_{1_60\%} - Kt_{1_30\%}}{60\% - 30\%} \times (50\% - 30\%) + Kt_{1_30\%} = \frac{0.67 - 0.82}{60\% - 30\%} \times (50\% - 30\%) + 0.82 = 0.72$$

$$Ku_{c_50\%} = \frac{Ku_{c_60\%} - Ku_{c_30\%}}{60\% - 30\%} \times (50\% - 30\%) + Ku_{c_30\%} = \frac{1.07 - 1.1}{60\% - 30\%} \times (50\% - 30\%) + 1.1 = 1.08$$

$$Kt_{2_50\%} = \frac{Kt_{2_60\%} - Kt_{2_30\%}}{60\% - 30\%} \times (50\% - 30\%) + Kt_{2_30\%} = \frac{0.5 - 0.21}{60\% - 30\%} \times (50\% - 30\%) + 0.21 = 0.40$$

Thus, TRV capability for terminal fault at 50% rated short-circuit current can be obtained as follows:

$$u_{1_50\%} = Ku_{1_50\%} \times u_{1_100\%} = 1.35 \times 98 \text{ kV} = 132 \text{ kV}$$

$$t_{1_50\%} = Kt_{1_50\%} \times t_{1_100\%} = 0.72 \times 49 \mu\text{s} = 35.3 \mu\text{s}$$

$$u_{c_50\%} = Ku_{c_50\%} \times u_{c_100\%} = 1.08 \times 183 \text{ kV} = 198 \text{ kV}$$

$$t_{2_50\%} = Kt_{2_50\%} \times t_{2_100\%} = 0.40 \times 196 \mu\text{s} = 78.4 \mu\text{s}$$

The interpolation of the circuit-breaker TRV capability envelope for a 123 kV breaker interrupting a terminal fault at 50% rated short-circuit current and TRV parameters is also shown in Figure 12.

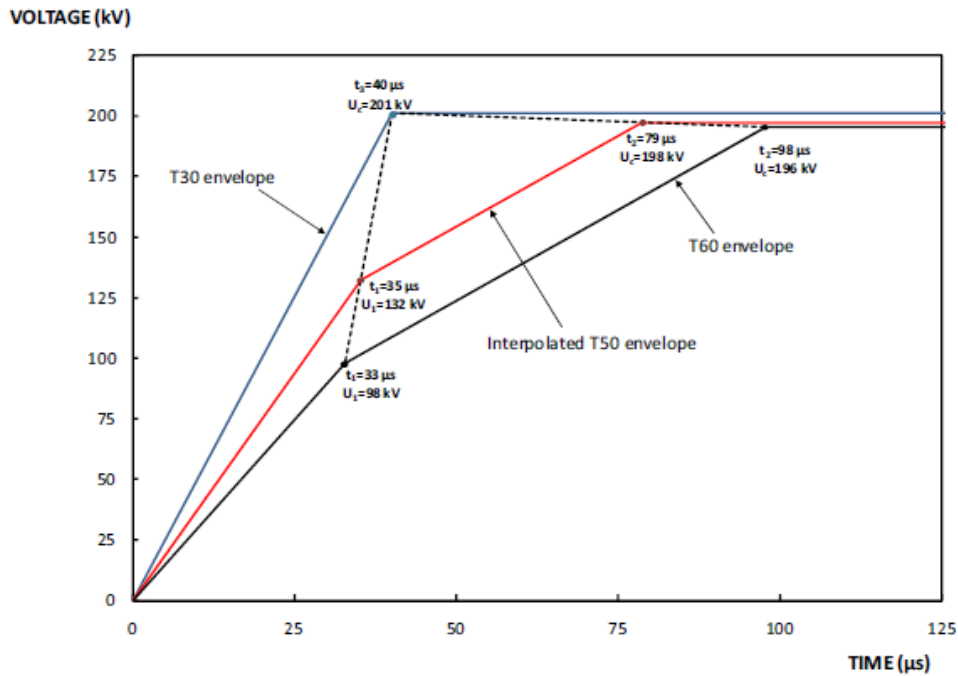


Figure 12—Example of TRV envelope for T50, interpolated between T30 and T60

Example 3: TRV capability of a 550 kV circuit breaker for interrupting terminal fault currents between 60% and 100% rated short-circuit current (I_{sc})

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

From IEEE Std C37.06, Table 12, TRV parameters for rated short-circuit current and rated maximum voltage (U_r) = 550 kV:

$$u_1 = 438 \text{ kV}$$

$$t_1 = 219 \text{ } \mu\text{s}$$

$$u_c = 817 \text{ kV}$$

$$t_2 = 876 \text{ } \mu\text{s}$$

From Table 1 and Figure 11, the following multipliers are obtained by interpolation for 75% of rated short-circuit current:

$$Ku_1 = 1.0$$

$$Kt_1 = 0.79$$

$$Ku_c = 1.044$$

$$Kt_2 = 0.687$$

TRV capability for 75% of rated short-circuit current:

$$u_1 = 438 \text{ kV}$$

$$t_1 = 173 \text{ } \mu\text{s}$$

$$u_c = 853 \text{ kV}$$

$$t_2 = 602 \text{ } \mu\text{s}$$

The shape of the TRV capability curve adjusted by the factors as given in Figure 11 is illustrated in Figure 13.

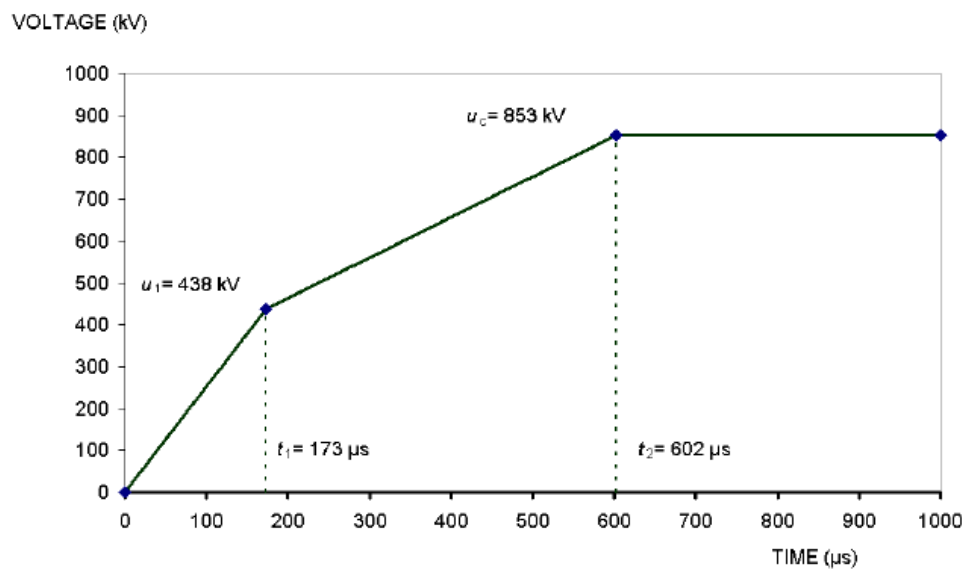


Figure 13—TRV related capability envelope for 550 kV circuit breaker interrupting a terminal fault at 75% of its rated short-circuit current

The general characteristics of the TRV envelopes defined by IEEE Std C37.06 are illustrated in Figure 14 and Figure 15 as a function of the interrupting current. Figure 14 shows the circuit-breaker TRV capability envelopes of breakers rated 100 kV and above. As the interrupting current increases, the TRV capability envelope defined by two parameters makes a transition to the four parameter envelope. Figure 15 represents the breaker TRV capabilities defined by using the two parameter method for system voltages below 100 kV.

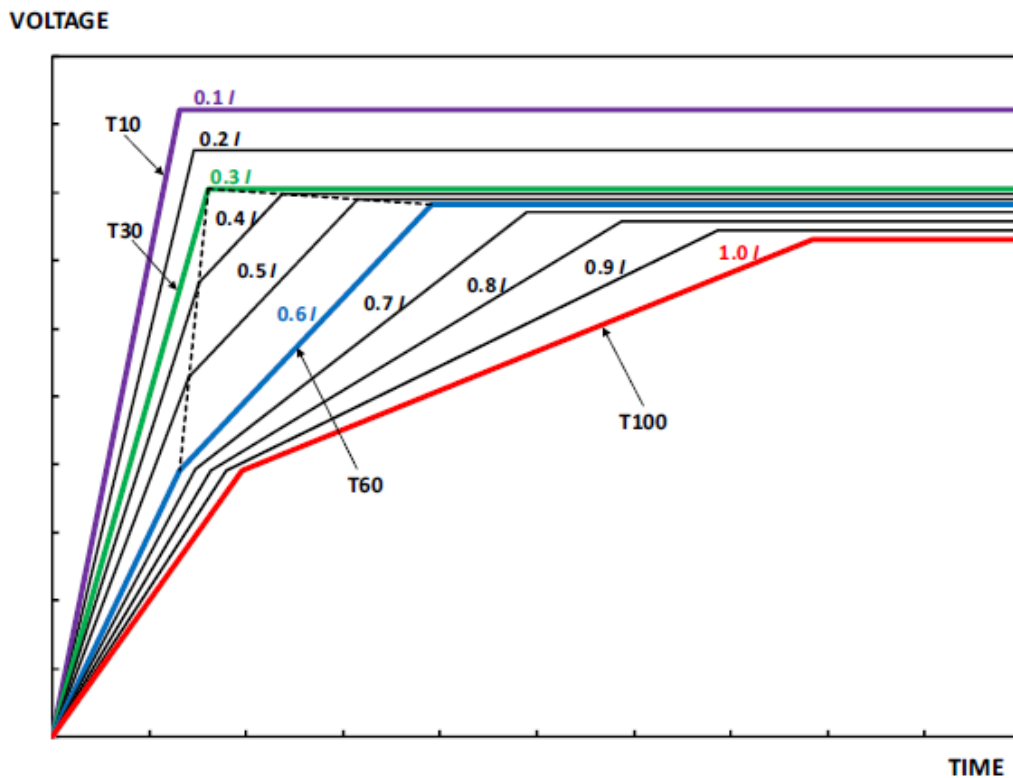


Figure 14—TRV envelopes for circuit breaker rated at 100 kV and above
(I_{sc} is the rated short-circuit current)

VOLTAGE

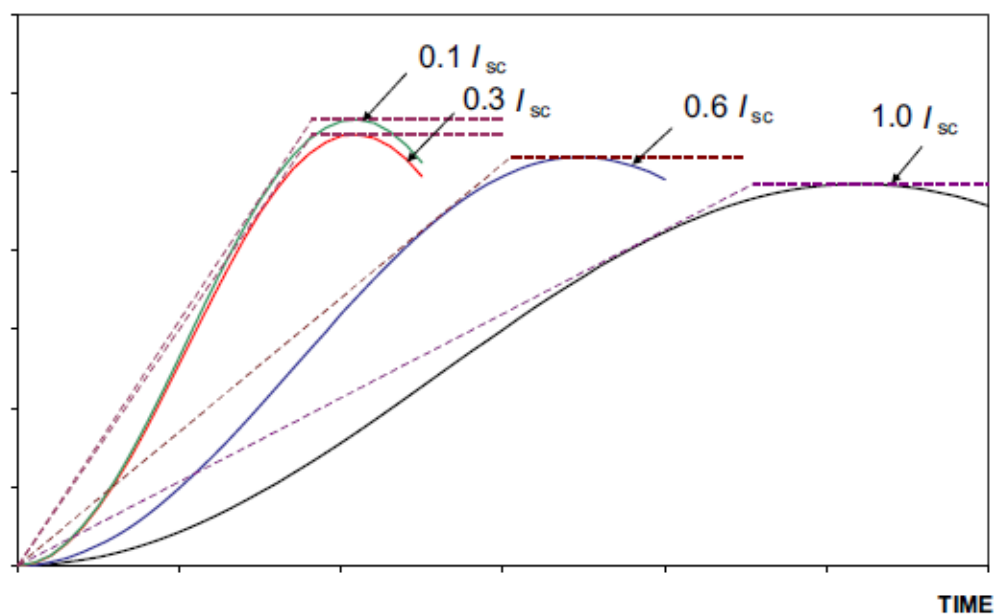


Figure 15—TRV envelopes for circuit breaker below 100 kV
(I_{sc} is the rated short-circuit current)

4.2.2 Short-line fault

SLF capability, which is a related capability, is described and defined in IEEE Std C37.04 [and IEEE Std C37.06](#). The line side component of the TRV is characterized by a triangular wave shape 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 16.

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 C37.06. 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 [shown in Equation \(2\)](#):

$$d = 2\omega \frac{Z_{\text{eff}}}{X_L c} \quad (2)$$

where

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

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

- c is the velocity of light, equal to 300 000 km per second
- X_L is the reactance of the line to the fault point per kilometer
- $L_{1\omega}$ is the positive sequence power-frequency line inductance per kilometer
- $L_{0\omega}$ is the zero sequence power-frequency line inductance per kilometer
- Z_{eff} is the effective surge impedance of the line (Ω)
- Z_1 is the positive sequence surge impedance (Ω)
- Z_0 is the zero sequence surge impedance (Ω)
- ω is $2\pi \times$ 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, SLF correspond to cases where the interrupting pole is the last pole to clear a fault. Standard values [of line characteristics are](#) defined in IEEE Std C37.04 as follows:

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

$$d = 1.6$$

The SLF TRV capability (up to the first peak of TRV) is defined as [shown in Equation \(3\) to Equation \(7\)](#):

$$u_T = u_L + u_S \quad (3)$$

$$u_L = d(1 - M)\sqrt{2/3} U_r \quad (4)$$

$$u_S = 2 M (t_L - t_d) \quad (5)$$

$$\frac{du_L}{dt} = \sqrt{2}\omega M I Z_{\text{eff}} \times 10^{-6} \quad (6)$$

$$t_L = \frac{u_L}{\frac{du_L}{dt}} \quad (7)$$

where

u_T	is the first peak value of TRV (kV)
u_L	is the line-side contribution to TRV (kV)
u_S	is the source side contribution to TRV (kV)
$\frac{du_L}{dt}$	is the rate of rise of recovery voltage (kV/ μ s)
t_L	is the time to peak (μ s)
d	is 1.6
I_{sc}	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 (μ s)
U_r	is the rated maximum voltage (kV)
Z_{eff}	is 450 (Ω)