



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 transformer 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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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 C37.04¹ 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.

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

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

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

IEEE Std C37.081aTM-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). Additionally, 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

⁵The 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.

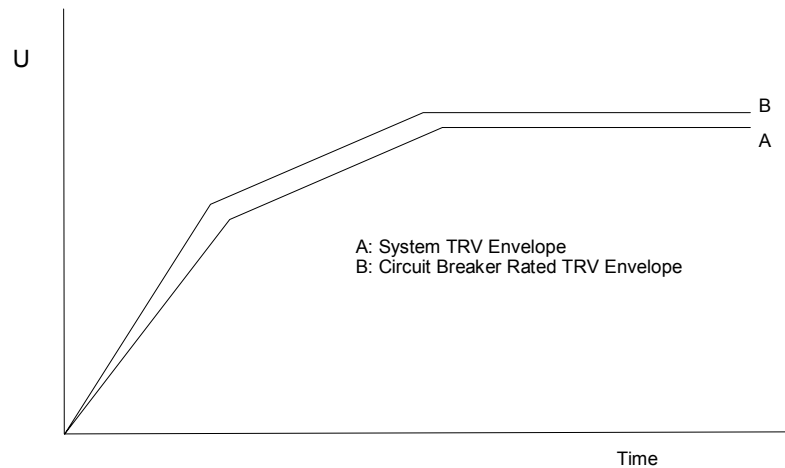
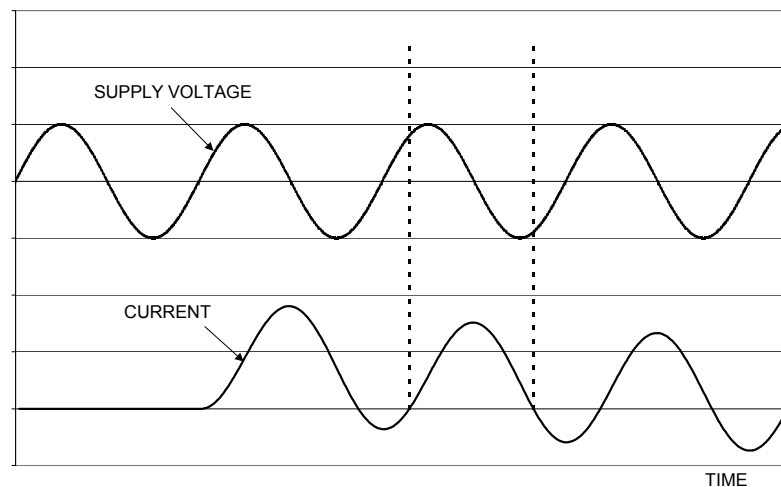


Figure 1—System TRV envelope and circuit breaker rated TRV envelope

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

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.

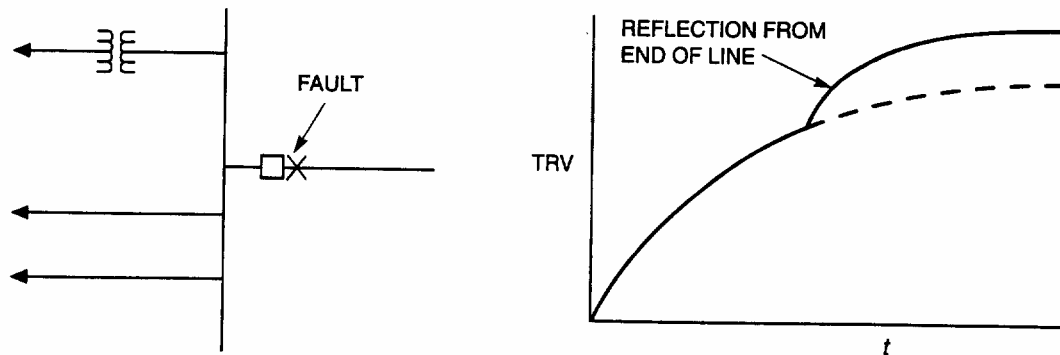


Figure 3—Exponential TRV characteristic

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.

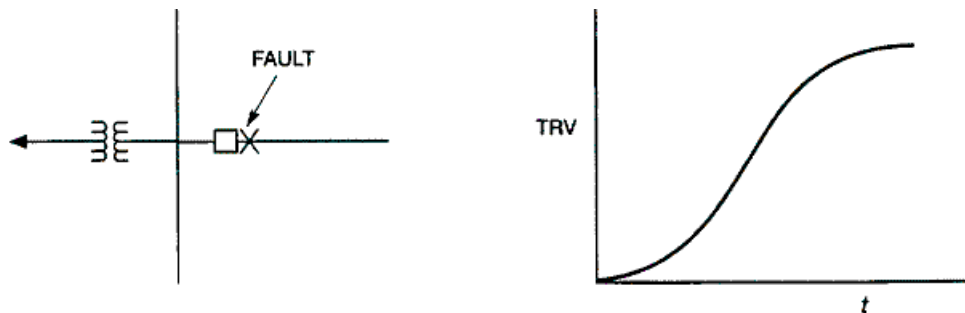


Figure 4—Oscillatory TRV characteristic

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.

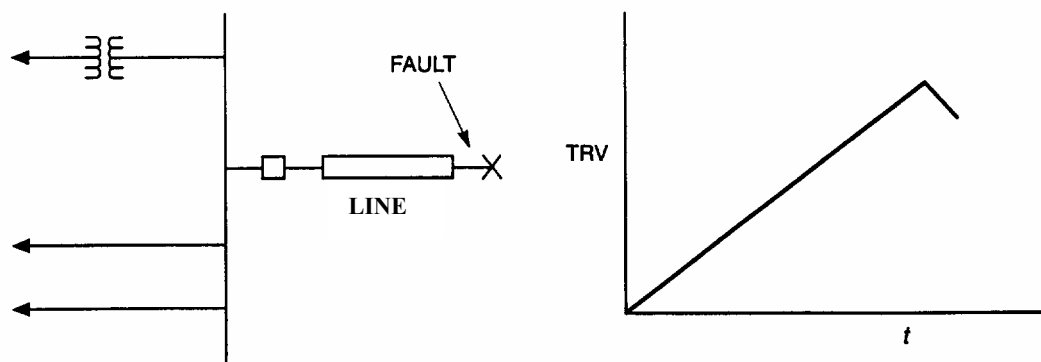


Figure 5—Short-line fault TRV characteristic

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.

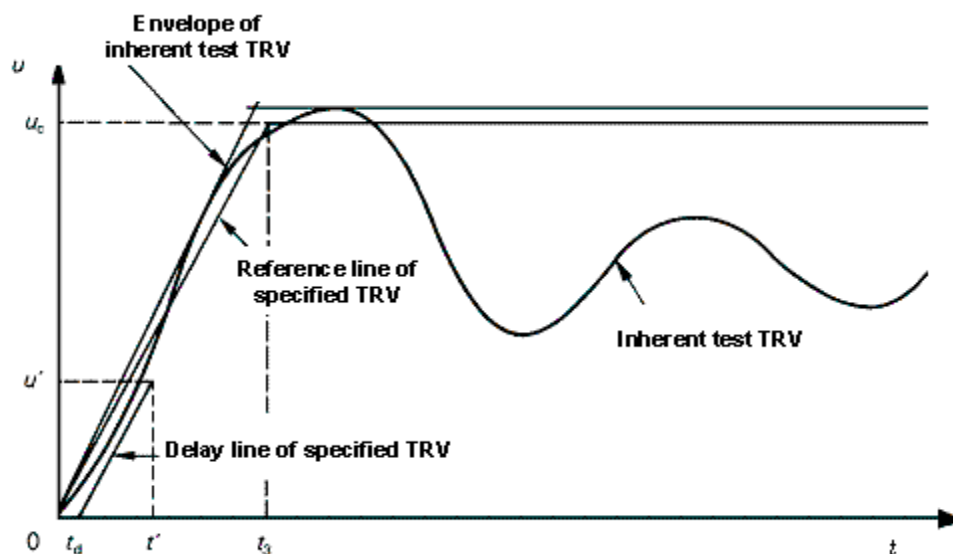


Figure 6—Example of inherent test TRV with two-parameter envelope that satisfies the conditions to be met during type test

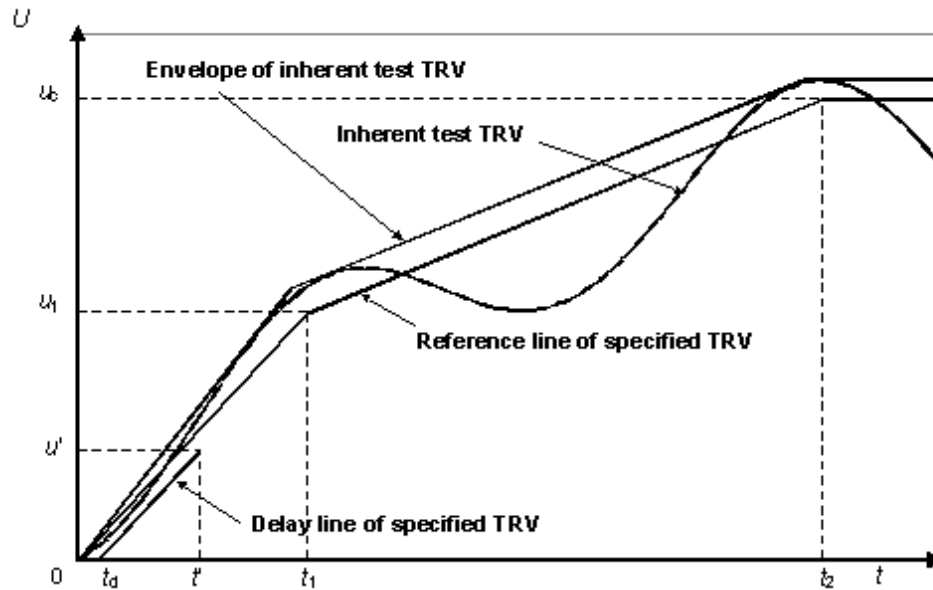


Figure 7—Example of inherent test TRV with four-parameter envelope that satisfies the conditions to be met during type test

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 $k_{pp} = 1.5$.

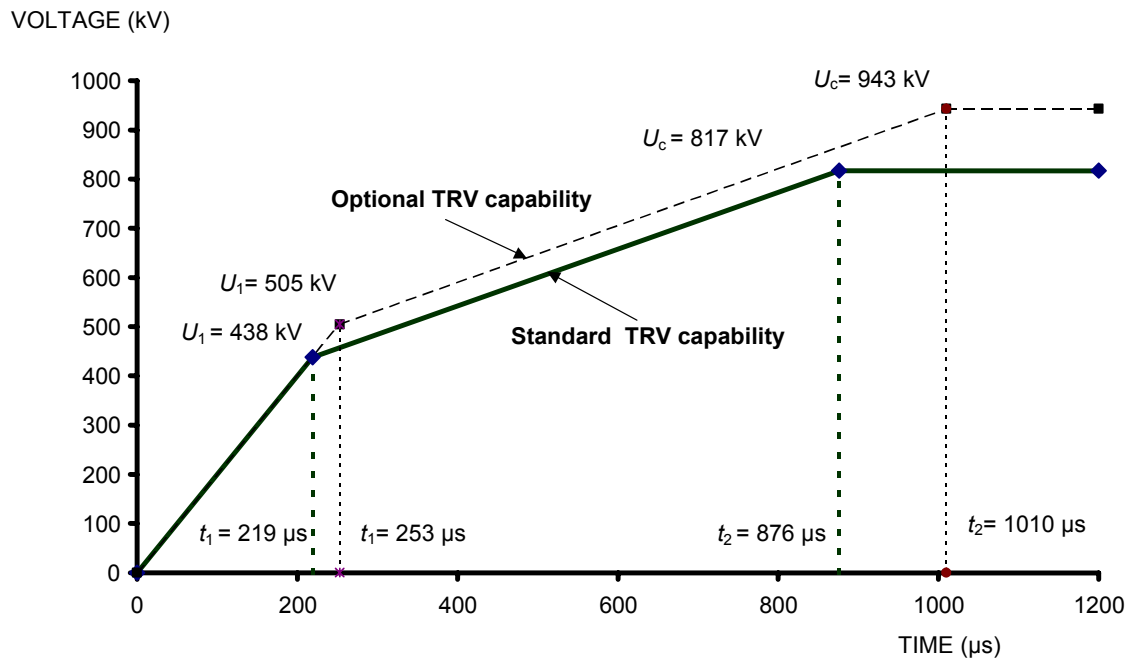


Figure 8—TRV capability envelope for a 550 kV circuit breaker at 100% of its rated fault current capability

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

Percent of interrupting capability ^a (Note 1)	Multipliers for rated parameters							
	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 capability is:

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

where

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

$$k_{pp} = 1.5,$$

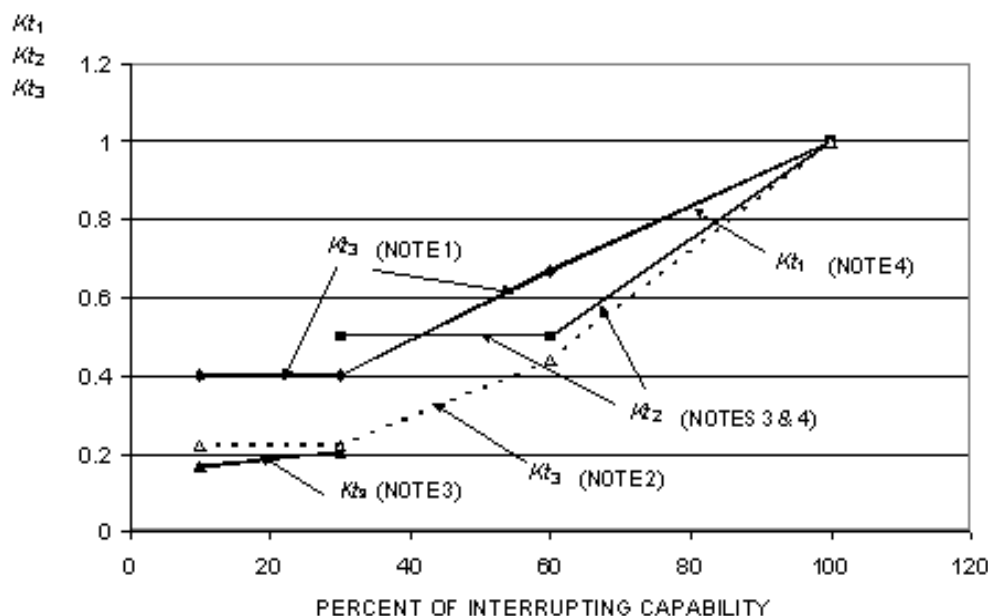
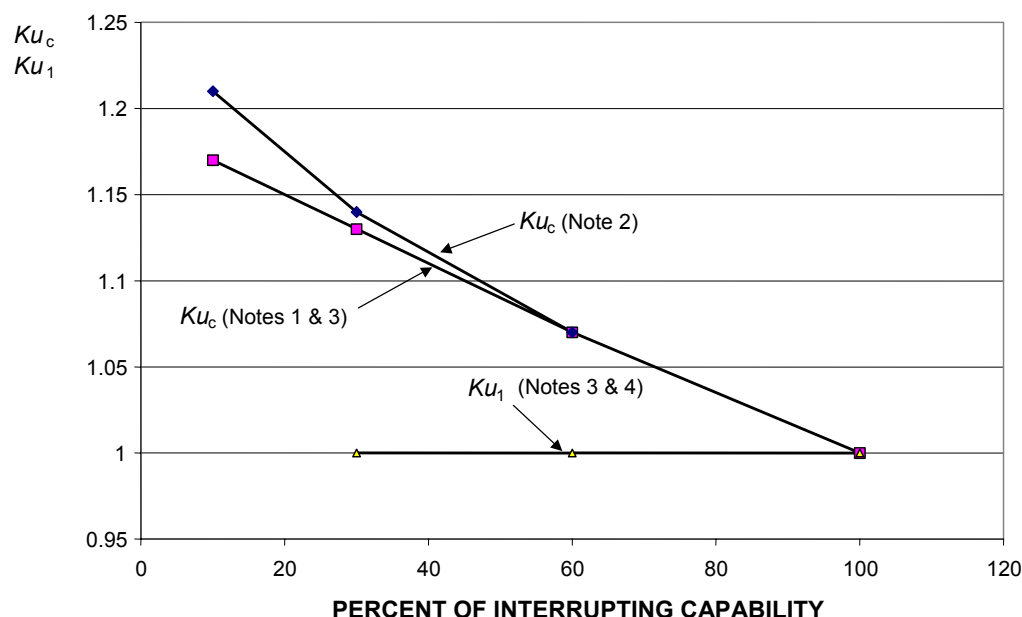
$$k_{af} = 1.54, \text{ (from Table 2A of IEEE PC37.04b [B16])}$$

$$Ku_c = 1.17.$$

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

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:

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



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.

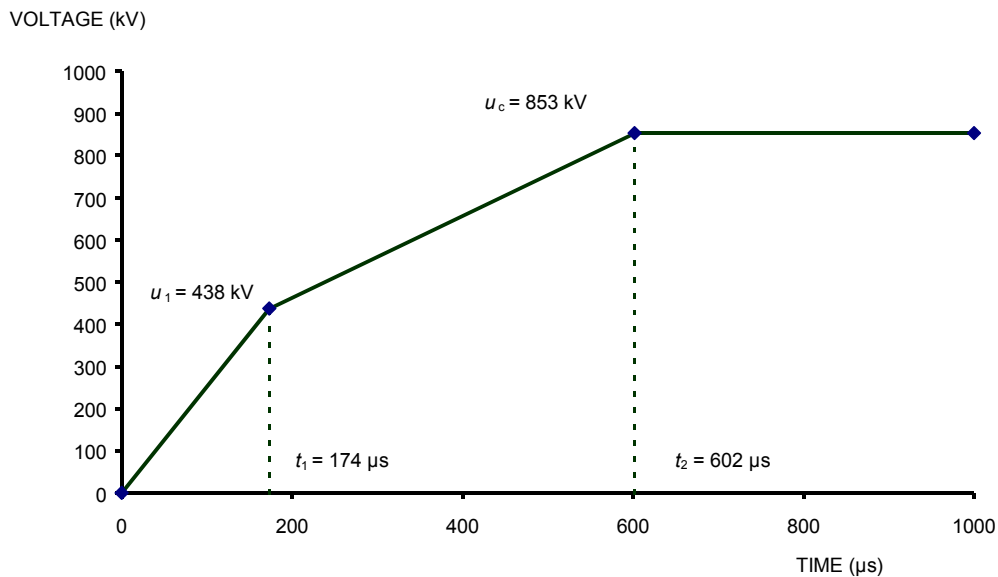


Figure 10—TRV related capability envelope for 550 kV circuit breaker at 75% of its rated interrupting capability

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.

VOLTAGE

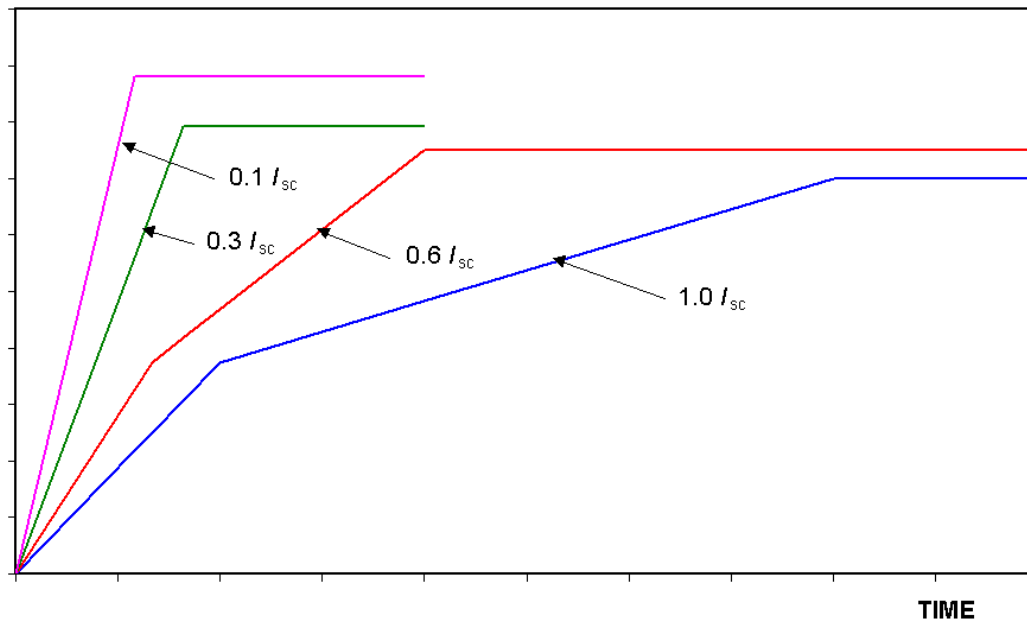


Figure 11—TRV envelopes, systems above 72.5 kV (I is the rated short-circuit current)

VOLTAGE

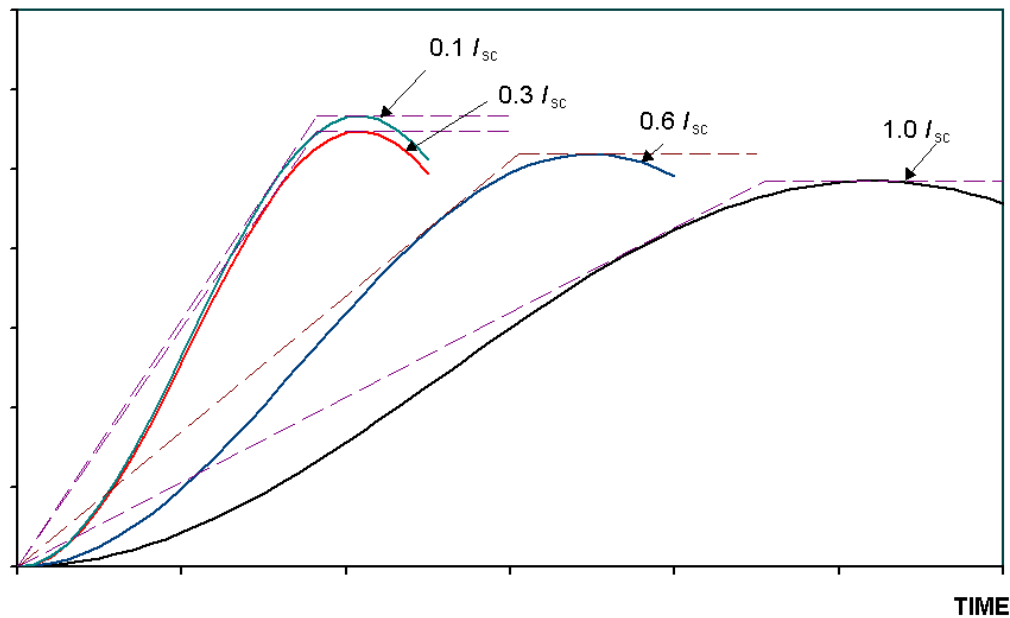


Figure 12—TRV envelopes, systems 72.5 kV and below (I is the rated short-circuit current)