

IEEE Application Guide for Transient Recovery Voltage for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis

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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 interrupting devices are determined largely 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 C37.011-1994, IEEE Application Guide for Transient Recovery Voltage for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.)

The manner of presentation of TRV applications has been changed in this revision of IEEE Std C37.011-1979 from an emphasis on system application examples to a dual emphasis on 1) a generalized description of the effect of circuit parameters on TRV shape, rate of rise, and magnitude, and 2) a relating of the TRV requirements as presented in the standards IEEE Std C37.04-1979, ANSI C37.06-1987, and IEEE Std C37.09-1979 to these various circuit conditions. The methods for determining a circuit breaker's TRV withstand capability from circuit breaker standard ratings are also illustrated.

Examples of techniques for calculating TRVs for different circuit conditions are presented in the annexes. The annexes also include an updated and expanded listing of typical capacitance values of substation components, graphs of transformer limited fault frequencies, and an updated bibliography.

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IEEE Application Guide for Transient Recovery Voltage for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis

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 and on a symmetrical current basis. The capability limits of these circuit interrupting devices are determined largely 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 standard is to provide an application guide on the TRV ratings given in IEEE Std C37.04-1979¹ 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 C37.04-1979, ANSI C37.06-1987, and IEEE Std C37.09-1979. IEEE Std C37.010-1979, IEEE Std C37.010b-1985, and IEEE Std C37.010e-1985 apply in other respects to these circuit breakers.

2. References

This guide shall be used in conjunction with the following publications.

ANSI C37.06-1987, AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis—Preferred Ratings and Related Required Capabilities.²

¹Information on references can be found in clause 2.

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

ANSI C37.06a-1989, AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis—Preferred Ratings and Related Required Capabilities.

IEEE Std C37.04-1979, IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis (ANSI).³

IEEE Std C37.09-1979, IEEE Standard Test Procedure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis (ANSI).

IEEE Std C37.010-1979 (Reaff 1988), IEEE Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis (ANSI).

IEEE Std C37.010b-1985 (Reaff 1988), Supplement to IEEE Std C37.010-1979 (ANSI).

IEEE Std C37.010e-1985 (Reaff 1988), Supplement to IEEE Std C37.010-1979 (ANSI).

3. Transient recovery voltage (TRV)

3.1 General

During the interruption process the arc voltage, which occurs across the terminals of a pole of a circuit breaker prior to current zero, approaches the normal-frequency pole-unit recovery voltage occurring after current zero, in a manner called the transient recovery voltage (TRV). If the circuit breaker is able to withstand the TRV, and also the normal-frequency pole-unit recovery voltage, circuit interruption will be successful.

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 ungrounded symmetrical fault at its terminal when the system voltage is maximum. 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 of the TRV. The amplitude of the recovery voltages for these line faults is determined on a single-phase basis during their early portions.

3.2 Effect of circuit breaker on transient recovery voltage

The circuit TRV can be modified or changed by the circuit breaker's design or by the circuit breaker's action. Therefore, the transient recovery voltage 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 when 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.

³IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

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 ungrounded terminal 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 5.11 of IEEE Std C37.04-1979 and given in detail in ANSI C37.06-1979.

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 circuit breaker's rated or related capability. Either a different circuit breaker should be used, or the system should be modified in such a manner as to change its transient recovery voltage characteristics. The addition of capacitors to a bus or line is one method that can be used to improve the system's recovery voltage characteristics.

3.3.2 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. Circuit breakers have the capability of interrupting these asymmetrical currents providing the circuit breakers are applied within their rating.

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 figures 1, 2, and 3, respectively.

A typical exponential TRV is shown in figure 1. 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 ungrounded fault is cleared at the breaker terminals.

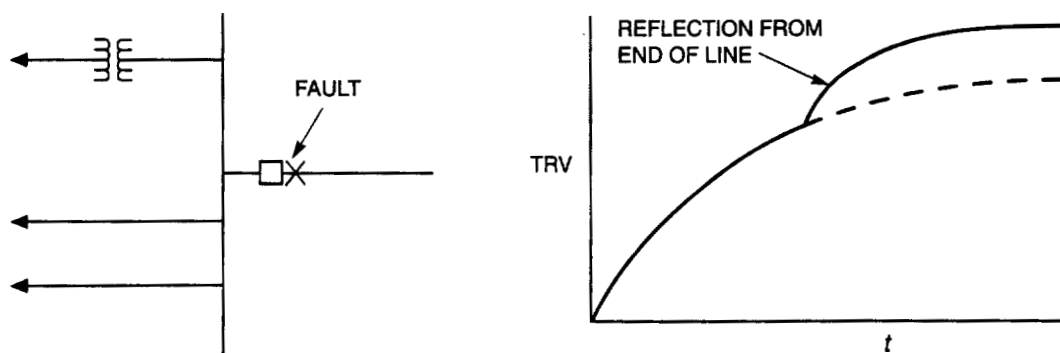


Figure 1—Exponential TRV characteristic

The oscillatory TRV shown in figure 2 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 3. 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.

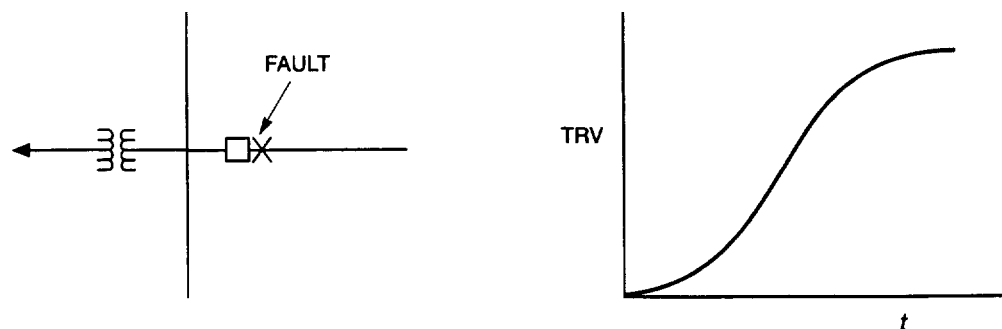


Figure 2—Oscillatory TRV characteristic

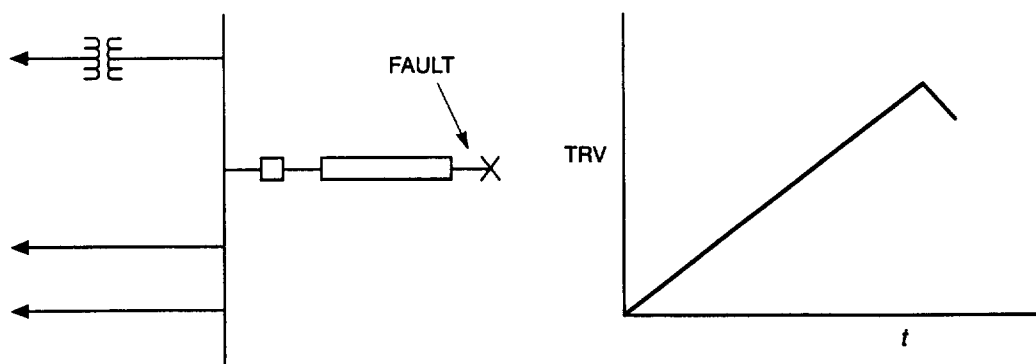


Figure 3—Short-line fault TRV characteristic

The three-phase ungrounded fault is usually the most severe terminal fault type and is used as the basis of rating. 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 clause illustrate the use of the standard for some typical system applications. System TRVs may be complex and are often calculated using digital or analog computers. Consequently, the details of the calculations for the examples in this section are not included. An example of a detailed TRV calculation is given in annex A. In addition, typical equipment capacitance values are given in annex B.

4.2 Circuit breaker capability

Rated and related circuit breaker transient recovery voltage capabilities are defined by parameters given in ANSI C37.06-1987. For breakers rated 121 kV and above, the parameters describe an exponential-cosine TRV envelope for three-phase ungrounded terminal faults where the symmetrical short circuit currents are above 30% of the breaker's capability. At 30% and below, the TRV is described by a 1-cosine envelope. For breakers rated 72.5 kV and below, the envelope is described by a 1-cosine envelope over the entire current range. Short line fault capability, which is a related capability, is described and defined in IEEE Std C37.04-1979.

4.2.1 Three-phase ungrounded terminal fault

As an example, figure 4 shows the three-phase ungrounded fault related transient recovery voltage capability for a 550 kV circuit breaker at 75% of its symmetrical current rating.

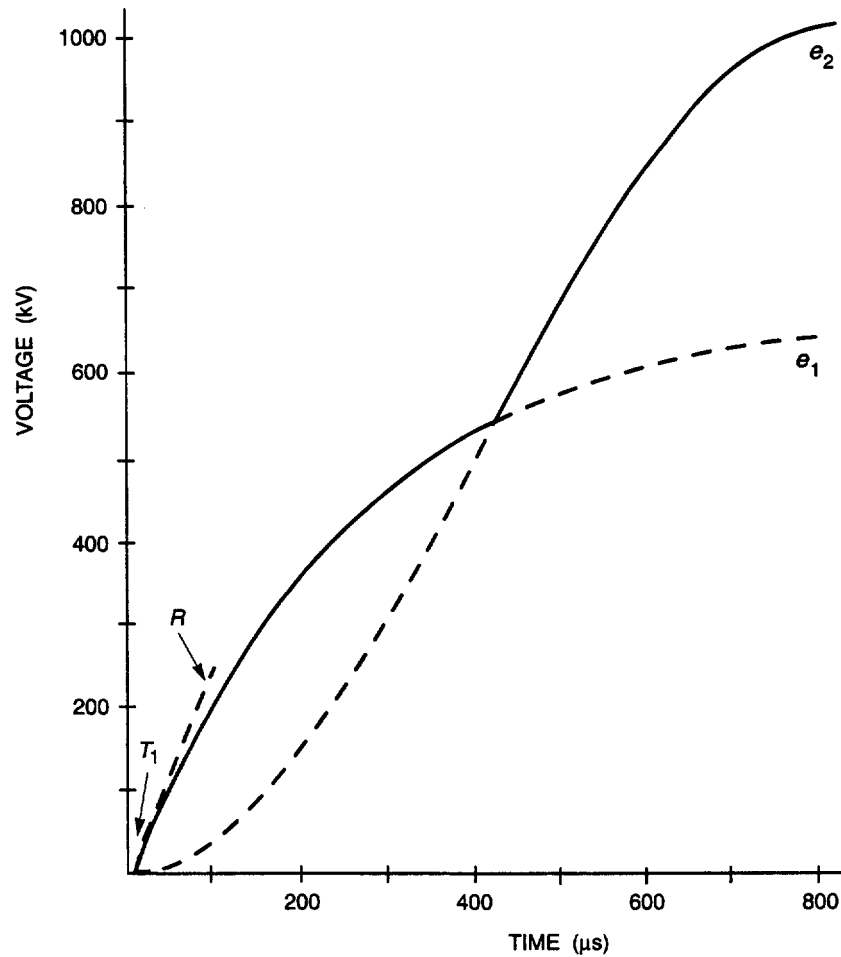


Figure 4—TRV related capability envelope for 550 kV circuit breaker at 75% of its rated fault current capability

The exponential-cosine envelope is defined by the larger of e_1 and e_2 in the following:

$$e_1 = E_1(1 - e^{-t/T_1}) \text{ kV} \quad (1)$$

with a delay of $T_1 \mu\text{s}$

where

$$T = E_1/R$$

$$e_2 = \frac{E_2}{2}(1 - \cos(\pi t/T_2)) \text{ kV} \quad (2)$$

The constants in these equations (1) and (2) for this example are given in table 3 of ANSI C37.06-1987.

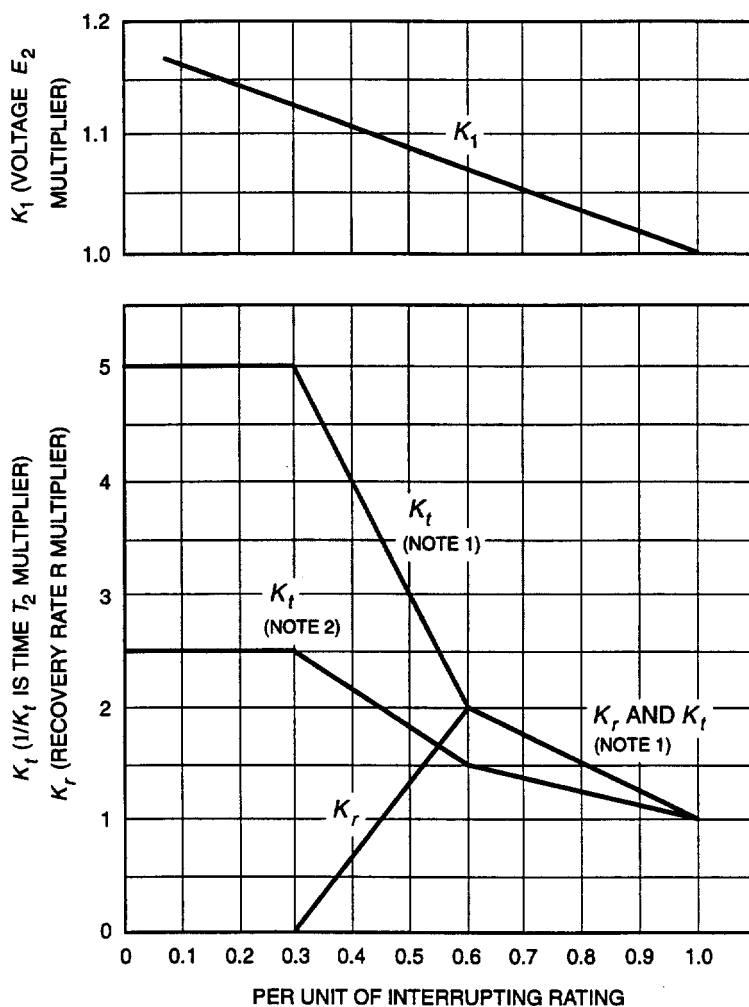
The multipliers to adjust for a fault current less than rated are given in table 6 of ANSI C37.06-1987. These multipliers are also given here in table 1.

NOTE — Rating values from ANSI C37.06-1979 are used in this guide for examples. While revisions to ANSI C37.06-1979 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 rating*	Multipliers for rated parameters				
	72.5 kV and below		121 kV and above		
	E_2	T_2	R	E_2	T_2
100	1.00	1	1	1.00	1
60	1.07	0.67	2	1.07	0.5
30	1.13	0.4	0	1.13	0.2
7	1.17	0.4	0	1.17	0.2
NOTE — Interpolation between the above given points is linear, as shown in figure 5.					

*Ratio of the symmetrical current component of the current being considered to the related required symmetrical interrupting capability (defined in 5.10.2.1 of IEEE Std C37.04-1979) is stated in percent.



NOTES:

- 1 — K_t = 121 kV and above.
- 2 — K_t = 72.5 kV and below.
- 3 — See table 1.

Figure 5—TRV rate and voltage multipliers for fractions of rated current

The values for this example are summarized in the following:

From table 3 in ANSI C37.06-1987, for rated current and rated maximum voltage ($E_{\max}$) = 550 kV:

$$E_1 = 1.5(\sqrt{2}/\sqrt{3})E_{\max} = 674 \text{ kV}$$

$$E_2 = 1.76E_{\max} = 968 \text{ kV}$$

$$R = 1.6 \text{ kV}/\mu\text{s}$$

$$T_2 = 1325\mu\text{s}$$

$$T_1 = 5.4\mu\text{s, time delay before exponential wave starts}$$

From table 6 in ANSI C37.06-1987, for 75% current:

$$K_r = 1.625$$

$$K_1 = 1.044$$

$$K_t = 1.625$$

where

K_r is the rate R multiplying factor
 K_1 is the voltage E_2 multiplying factor
 K_t is the time T_2 multiplying factor

TRV capability for 75% current:

$$\begin{aligned}
 E_1 &= 674 \text{ kV} \\
 E_2 &= 968 \cdot 1.044 = 1011 \text{ kV} \\
 R &= 1.6 \cdot 1.625 = 2.60 \text{ kV}/\mu\text{s} \\
 T_2 &= 1325.0/1.625 = 815.4 \mu\text{s} \\
 T_1 &= 5.4 \mu\text{s} \\
 T &= E_1/R = 673.6/2.60 = 259.1 \mu\text{s}
 \end{aligned}$$

Based upon the evaluation of many actual system configurations, standards assume for 121 kV systems and above, that clearing terminal fault currents between 30% and 100% of rating will result in a TRV characteristic, which has an exponential-cosine waveform (see figure 1). For terminal fault currents between 7% and 30% for 121 kV systems and above, and for all terminal fault currents for 72.5 kV systems and below, the standards assume a 1-cosine waveform that is characteristic of a transformer limited fault illustrated in figure 2. The shapes of the TRV capability curves are adjusted by the factors given in figure 5 as is illustrated in figure 4. The general characteristics of the TRV envelopes defined by IEEE Std C37.04-1979 are illustrated in figures 6 and 7 as a function of the fault current magnitude.

4.2.2 Short-line fault

Short-line fault (SLF) capability is defined in 5.11.4.2 of IEEE Std C37.04-1979. Exhibiting a triangular waveshape with a relatively high rate-of-rise but a low peak magnitude compared to the three-phase ungrounded terminal fault, a typical SLF waveform is illustrated in figure 8.

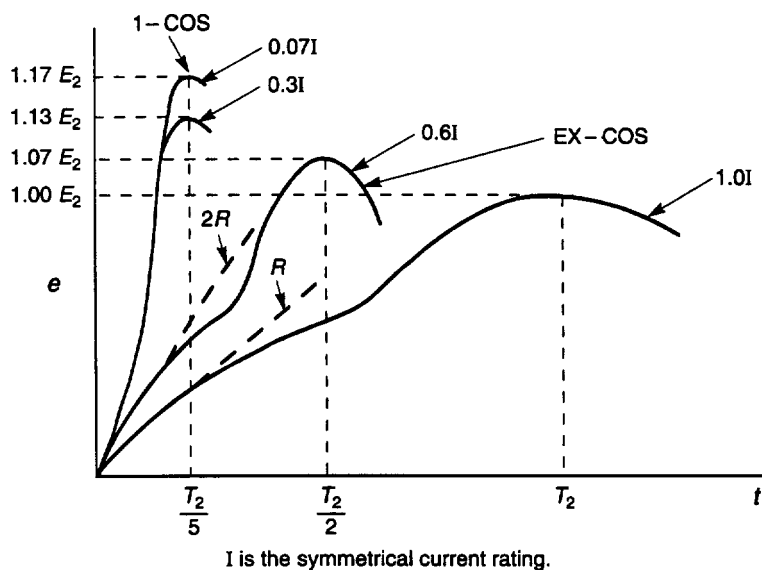


Figure 6—TRV envelopes, 121 kV and above

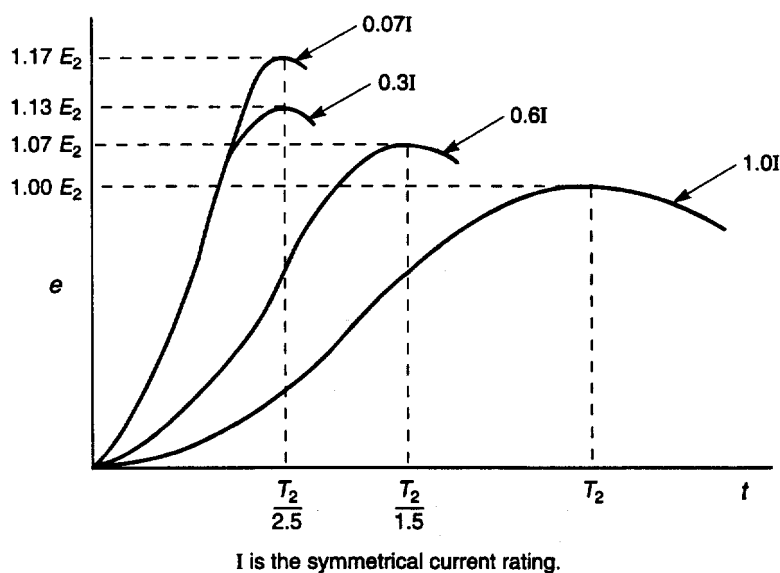


Figure 7—TRV envelopes, 72.5 kV and below

In general, it is not necessary to calculate the SLF TRV as long as the three-phase ungrounded bus or terminal fault TRVs are within rating and transmission line parameters are within the values specified in IEEE Std C37.04-1979. The transmission line parameters are given in terms of the effective surge impedance, Z , of the faulted line and the amplitude constant, d , defined as

$$d = \frac{6\omega Z\tau}{2X_{L1} + X_{L0}} \quad (3)$$

where