

IEEE Guide for the Application of Transient Recovery Voltage for AC High-Voltage Circuit Breakers with Rated Maximum Voltage above 1000 V

IEEE Power and Energy Society

Sponsored by the
Switchgear Committee



IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std C37.011™-2019
(Revision of IEEE Std C37.011-2011)

IEEE Guide for the Application of Transient Recovery Voltage for AC High-Voltage Circuit Breakers with Rated Maximum Voltage above 1000 V

Sponsor

Switchgear Committee
of the
IEEE Power and Energy Society

Approved 8 February 2019

IEEE-SA Standards Board

This is a Redline Document produced by Techstreet, a business of Clarivate Analytics

This document is intended to provide users with an indication of changes from one edition to the next. It includes a full-text version of the new document, plus an indication of changes from the previous version.

Redlines are designed to save time and improve efficiencies by using the latest software technology to find and highlight document changes. More professionals are using valuable new technologies like redlines, to help improve outcomes in a fastpaced global business world.

Because it may not be technically possible to capture all changes accurately, it is recommended that users consult previous editions as appropriate. In all cases, only the current base version of this publication is to be considered the official document.

Redline Processing Notes:

1. ~~Red Text~~ - Red strikethrough text denotes deletions.
2. Blue Text - Blue underlined text denotes modifications and additions.

Abstract: The 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 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 (TRV)

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Copyright © 2019 by The Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 30 May 2019. Printed in the United States of America.

IEEE is a registered trademark in the U.S. Patent & Trademark Office, owned by The Institute of Electrical and Electronics Engineers, Incorporated.

PDF: ISBN 978-1-5044-5556-5 STD23554
Print: ISBN 978-1-5044-5557-2 STDPD23554

IEEE prohibits discrimination, harassment, and bullying.

For more information, visit <http://www.ieee.org/web/aboutus/whatis/policies/p9-26.html>.

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

Important Notices and Disclaimers Concerning IEEE Standards Documents

IEEE documents are made available for use subject to important notices and legal disclaimers. These notices and disclaimers, or a reference to this page, appear in all standards and may be found under the heading “Important Notice” or “Important Notices and Disclaimers Concerning IEEE Standards Documents.”

Notice and Disclaimer of Liability Concerning the Use of IEEE Standards Documents

IEEE Standards documents (standards, recommended practices, and guides), both full-use and trial-use, are developed within IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (“IEEE-SA”) Standards Board. IEEE (“the Institute”) develops its standards through a consensus development process, approved by the American National Standards Institute (“ANSI”), which brings together volunteers representing varied viewpoints and interests to achieve the final product. Volunteers are not necessarily members of the Institute and participate without compensation from IEEE. While IEEE administers the process and establishes rules to promote fairness in the consensus development process, IEEE does not independently evaluate, test, or verify the accuracy of any of the information or the soundness of any judgments contained in its standards.

IEEE does not warrant or represent the accuracy or content of the material contained in its standards, and expressly disclaims all warranties (express, implied and statutory) not included in this or any other document relating to the standard, including, but not limited to, the warranties of: merchantability; fitness for a particular purpose; non-infringement; and quality, accuracy, effectiveness, currency, or completeness of material. In addition, IEEE disclaims any and all conditions relating to: results; and workmanlike effort. IEEE standards documents are supplied “AS IS” and “WITH ALL FAULTS.”

Use of an IEEE standard is wholly voluntary. The existence of an IEEE standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard.

In publishing and making its standards available, IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity nor is IEEE undertaking to perform any duty owed by any other person or entity to another. Any person utilizing any IEEE Standards document, should rely upon his or her own independent judgment in the exercise of reasonable care in any given circumstances or, as appropriate, seek the advice of a competent professional in determining the appropriateness of a given IEEE standard.

IN NO EVENT SHALL IEEE BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO: PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE PUBLICATION, USE OF, OR RELIANCE UPON ANY STANDARD, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE AND REGARDLESS OF WHETHER SUCH DAMAGE WAS FORESEEABLE.

Translations

The IEEE consensus development process involves the review of documents in English only. In the event that an IEEE standard is translated, only the English version published by IEEE should be considered the approved IEEE standard.

Official statements

A statement, written or oral, that is not processed in accordance with the IEEE-SA Standards Board Operations Manual shall not be considered or inferred to be the official position of IEEE or any of its committees and shall not be considered to be, or be relied upon as, a formal position of IEEE. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that his or her views should be considered the personal views of that individual rather than the formal position of IEEE.

Comments on standards

Comments for revision of IEEE Standards documents are welcome from any interested party, regardless of membership affiliation with IEEE. However, IEEE does not provide consulting information or advice pertaining to IEEE Standards documents. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Since IEEE standards represent a consensus of concerned interests, it is important that any responses to comments and questions also receive the concurrence of a balance of interests. For this reason, IEEE and the members of its societies and Standards Coordinating Committees are not able to provide an instant response to comments or questions except in those cases where the matter has previously been addressed. For the same reason, IEEE does not respond to interpretation requests. Any person who would like to participate in revisions to an IEEE standard is welcome to join the relevant IEEE working group.

Comments on standards should be submitted to the following address:

Secretary, IEEE-SA Standards Board
445 Hoes Lane
Piscataway, NJ 08854 USA

Laws and regulations

Users of IEEE Standards documents should consult all applicable laws and regulations. Compliance with the provisions of any IEEE Standards document does not imply compliance to any applicable regulatory requirements. Implementers of the standard are responsible for observing or referring to the applicable regulatory requirements. IEEE does not, by the publication of its standards, intend to urge action that is not in compliance with applicable laws, and these documents may not be construed as doing so.

Copyrights

IEEE draft and approved standards are copyrighted by IEEE under US and international copyright laws. They are made available by IEEE and are adopted for a wide variety of both public and private uses. These include both use, by reference, in laws and regulations, and use in private self-regulation, standardization, and the promotion of engineering practices and methods. By making these documents available for use and adoption by public authorities and private users, IEEE does not waive any rights in copyright to the documents.

Photocopies

Subject to payment of the appropriate fee, IEEE will grant users a limited, non-exclusive license to photocopy portions of any individual standard for company or organizational internal use or individual, non-commercial use only. To arrange for payment of licensing fees, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; +1 978 750 8400. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Updating of IEEE Standards documents

Users of IEEE Standards documents should be aware that these documents may be superseded at any time by the issuance of new editions or may be amended from time to time through the issuance of amendments, corrigenda, or errata. An official IEEE document at any point in time consists of the current edition of the document together with any amendments, corrigenda, or errata then in effect.

Every IEEE standard is subjected to review at least every 10 years. When a document is more than 10 years old and has not undergone a revision process, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE standard.

In order to determine whether a given document is the current edition and whether it has been amended through the issuance of amendments, corrigenda, or errata, visit the IEEE-SA Website at <http://ieeexplore.ieee.org/xpl/standards.jsp> or contact IEEE at the address listed previously. For more information about the IEEE-SA or IEEE's standards development process, visit the IEEE-SA Website at <http://standards.ieee.org>.

Errata

Errata, if any, for all IEEE standards can be accessed on the IEEE-SA Website at the following URL: <http://standards.ieee.org/findstds/errata/index.html>. Users are encouraged to check this URL for errata periodically.

Patents

Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken by the IEEE with respect to the existence or validity of any patent rights in connection therewith. If a patent holder or patent applicant has filed a statement of assurance via an Accepted Letter of Assurance, then the statement is listed on the IEEE-SA Website at <http://standards.ieee.org/about/sasb/patcom/patents.html>. Letters of Assurance may indicate whether the Submitter is willing or unwilling to grant licenses under patent rights without compensation or under reasonable rates, with reasonable terms and conditions that are demonstrably free of any unfair discrimination to applicants desiring to obtain such licenses.

Essential Patent Claims may exist for which a Letter of Assurance has not been received. The IEEE is not responsible for identifying Essential Patent Claims for which a license may be required, for conducting inquiries into the legal validity or scope of Patents Claims, or determining whether any licensing terms or conditions provided in connection with submission of a Letter of Assurance, if any, or in any licensing agreements are reasonable or non-discriminatory. Users of this standard are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility. Further information may be obtained from the IEEE Standards Association.

Participants

At the time this IEEE guide was completed, the Revision of C37.011 Working Group had the following membership:

Denis Dufournet, *Chair*
Jingxuan (Joanne) Hu, *Vice Chair*
Carl Schuetz, *Secretary*

Roy Alexander
Mauricio Aristizabal
Anne Bosma
Arben Bufi
Lucas Collette

Helmut Heiermeier
Victor Hermosillo
Roy Neil Hutchins
Amir Khosravi
Jim van de Ligt
Hua Y. Liu

Sushil Shinde
Mike Skidmore
R. Kirkland Smith
Jan Weisker
Xi Zhu

The following members of the individual balloting committee voted on this guide. Balloters may have voted for approval, disapproval, or abstention.

Roy Alexander
Ficheux Arnaud
Roy Ayers
Thomas Barnes
W. J. (Bill) Bergman
Steven Bezner
Frank Blalock
William Bloethe
Anne Bosma
Jeffrey Brogdon
Demetrio Bucaneg Jr.
Arben Bufi
Paul Cardinal
Sean Carr
Stephen Cary
Michael Chirico
Chih Chow
Michael Christian
Lucas Collette
Michael Crawford
Gary Donner
Denis Dufournet
Edgar Dullni
Leslie Falkingham
Sergio Flores
Raymond Frazier III
Dale Fredrickson
Mietek Glinkowski
James Graham
Randall Groves
John Harley
Helmut Heiermeier
Victor Hermosillo
Werner Hoelzl

Jingxuan (Joanne) Hu
Todd Irwin
Richard Jackson
John John
Laszlo Kadar
John Kay
Peter Kelly
Yuri Khersonsky
James Kinney
Boris Kogan
Jim Kulchisky
Benjamin Lanz
John Leach
James van de Ligt
Hua Liu
James McBride
Neil McCord
Steven Meiners
David Mitchell
Charles Morse
Thomas Mulcahy
Jerry Murphy
Arthur Neubauer
Joe Nims
T. W. Olsen
Lorraine Padden
Mirko Palazzo
Shawn Patterson
Christopher Petrola
John Phouminh
Iulian Profrir
Reynaldo Ramos
Lakshman Raut

Rosy Raysaha
Samala Santosh Reddy
Anthony Ricciuti
Johannes Rickmann
Charles Rogers
Jesse Rorabaugh
Thomas Rozek
Roderick Sauls
Bartien Sayogo
Carl Schuetz
Nikunj Shah
Devki Sharma
Sushil Shinde
Hyeong Sim
Michael Skidmore
Jerry Smith
Gary Smullin
Donald Steigerwalt
Gary Stoedter
David Tepen
Marcelo Valdes
John Vergis
Mark Waldron
Haifei Wang
John Wang
John Webb
Jan Weisker
Matt Westerdale
Kenneth White
Terry Woodyard
Larry Yonce
Richard York
Wei Zhang
Xi Zhu

When the IEEE-SA Standards Board approved this guide on 8 February 2019, it had the following membership:

Gary Hoffman, *Chair*
Vacant Position, *Vice Chair*
Jean-Philippe Faure, *Past Chair*
Konstantinos Karachalios, *Secretary*

Masayuki Ariyoshi
Ted Burse
Stephen D. Dukes
J. Travis Griffith
Guido Hiertz
Christel Hunter
Thomas Koshy
Joseph L. Koepfinger*

Thomas Koshy
John D. Kulick
David J. Law
Joseph Levy
Howard Li
Xiaohui Liu
Kevin Lu
Daleep Mohla
Andrew Myles

Annette D. Reilly
Dorothy Stanley
Sha Wei
Phil Wennblom
Philip Winston
Howard Wolfman
Feng Wu
Jingyi Zhou

*Member Emeritus

Introduction

This introduction is not part of IEEE Std C37.011™-2019, IEEE Guide for the Application of Transient Recovery Voltage for AC High-Voltage Circuit Breakers with Rated Maximum Voltage above 1000 V.

This application guide has been revised to align the new TRV requirements introduced in IEEE Std C37.04™, IEEE Std C37.09™, and IEEE Std C37.06.1™.

The main changes implemented in this guide concern:

- Revision of [3.2](#) to develop the part on arc-circuit interaction
- Revision of [3.3](#) to incorporate information formerly in IEEE Std C37.04b™ but not incorporated in the latest revision of IEEE Std C37.04
- Revision of [3.3.4](#) to give more detailed explanations on TRV modification during interruption of asymmetrical currents
- Revision of [4.2.3](#) on short-line faults
- Revision of [4.4.1](#) to update with IEEE Std C37.06.1 and give guidance
- Addition of [4.5.2](#) to incorporate TRVs on series capacitor banks
- New [Clause 5](#) to cover testing issues
- New [Annex D](#) on guidance for TRV calculation by electromagnetic transients program
- New [Annex E](#) on abbreviations

Contents

1. Overview.....	14
1.1 Scope.....	14
1.2 Purpose.....	14
2. Normative references	14
3. Transient recovery voltage	15
3.1 General	15
3.2 Arc-circuit interaction.....	16
3.3 Method of rating and application.....	17
4. Application considerations	28
4.1 General	28
4.2 Circuit breaker capability	31
4.3 Exponential (overdamped) TRV	61
4.4 Oscillatory (underdamped) TRV	63
4.5 Application where circuit breaker capability may be exceeded	74
5. Testing issues.....	78
5.1 General	78
5.2 Application of TRV test data to a multi-break interrupter	79
Annex A (informative) Transient recovery voltage (TRV) calculation techniques	81
Annex B (informative) Typical capacitance values for various equipment	103
Annex C (informative) Selection of the first-pole-to-clear factors and factors for second and third poles to clear.....	110
Annex D (informative) Guidance for transient recovery voltage (TRV) calculation by electromagnetic transients program.....	115
Annex E (informative) Abbreviations	122
Annex F (informative) (Bibliography)	123

List of Figures

Figure 1—Oscillograms showing arc voltage and arc current during short-circuit current interruption (these examples illustrate short-line-fault interruption)	16
Figure 2—Four-parameter TRV envelope	19
Figure 3—Two-parameter TRV envelope	20
Figure 4—Comparison of line system and cable system rated TRVs	24
Figure 5—System TRV envelope and circuit breaker rated TRV envelope	26
Figure 6—Effect of current asymmetry on voltage at current zero (cz).....	27
Figure 7—Exponential TRV characteristic.....	28
Figure 8—Oscillatory TRV characteristic	29
Figure 9—Short-line-fault TRV characteristic	29
Figure 10—Example of inherent test TRV with two-parameter envelope which satisfies the conditions to be met during type test.....	30
Figure 11—Example of inherent test TRV with four-parameter envelope which satisfies the conditions to be met during type test	30
Figure 12—TRV capability envelope for a 550 kV circuit breaker at 100% of its rated fault current capability.....	32
Figure 13—Multipliers for circuit breakers rated below 100 kV	35
Figure 14—Multipliers for circuit breakers rated 100 kV and above.....	36
Figure 15—Example of TRV envelope for T50, interpolated between T30 and T60.....	40
Figure 16—TRV related capability envelope for a circuit breaker with rated voltage 550 kV interrupting a terminal fault at 75% of its rated short-circuit current	41
Figure 17—TRV envelopes for circuit breakers with rated voltages 100 kV and above (I_{sc} is the rated short-circuit current).....	42
Figure 18—TRV envelopes for circuit breakers with rated voltage below 100 kV (I_{sc} is the rated short-circuit current).....	42
Figure 19—TRV waveshape for short-line fault.....	43
Figure 20—Determination of TRV for SLF 90% 245 kV 40 kA 60 Hz	46
Figure 21—TRV related capability envelope for 550 kV circuit breaker at 75% of its rated fault current capability with SLF component	48
Figure 22—Contribution of the source-side voltage to TRV	48
Figure 23—RRRV schemes for last- and first-clearing pole.....	53
Figure 24—Equivalent circuit and TRV waveforms for single and three-phase SLF	54

Figure 25—Comparison of three-phase SLF TRV (blue lines) and single-phase SLF TRV (red lines) with 75% I_{sc} and the short-circuit power of the supply equal to I_{sc}	58
Figure 26—Comparison of three-phase SLF TRV (blue lines) and single-phase SLF TRV (red lines) with 75% I_{sc} and the short-circuit power of the supply equal to 80% I_{sc}	59
Figure 27—System configuration	62
Figure 28—Comparison of TRV capability for a circuit breaker with rated voltage 550 kV (at 75% of its rated interrupting-current capability) and system TRV	62
Figure 29—TRV capability curve for 40 kA and 63 kA circuit breakers when interrupting 40 kA at 550 kV .	63
Figure 30—Fault location	63
Figure 31—Comparison of standard TRV for terminal fault test duty T10 (10% of rated short-circuit current) for rated voltage 145 kV and system TRV with transformer-limited fault.....	64
Figure 32—Comparison of standard TRV for terminal fault T10 (10% rated short-circuit current) for rated voltage 145 kV and system TRV with transformer-limited fault when a capacitance is added between the circuit breaker and the transformer	65
Figure 33—Example of reactor-limited fault (equivalent single-phase representation)	69
Figure 34—Calculated TRV of reactor-limited fault without added capacitance, comparison with TRV capability for class S2 circuit breaker 38 kV 12.5 kA.....	70
Figure 35—Calculated TRV of reactor-limited fault with 195 nF added capacitance, compared with TRV capability for class S2 circuit breaker 38 kV 12.5 kA.....	71
Figure 36—Calculated TRV of reactor-limited fault with 12 nF added capacitance, compared with TRV capability for class S2 circuit breaker 38 kV 40 kA at 30% of rated short-circuit current.....	71
Figure 37—Typical series capacitor installation with non-linear resistor and single bypass gap configuration	76
Figure 38—Typical series capacitor installation with single bypass gap configuration.....	76
Figure 39—Typical series capacitor installation with dual bypass gap configuration	77
Figure 40—500 kV sub-system with series capacitors	77
Figure 41—TRV calculated for the line circuit breaker, case with series compensation.....	78
Figure 42—TRV calculated for the line circuit breaker, case without series compensation	78
Figure 43—Equivalent circuit of the two-break interrupter arrangement.....	79
Figure A.1—System diagram.....	81
Figure A.2—Circuit definition—interruption of a three-phase-to-ground fault	85
Figure A.3—Traveling waves at discontinuity	88
Figure A.4—Typical TRV including the first reflection.....	88
Figure A.5—Single-phase circuit with short-line fault.....	89
Figure A.6—System reactive ohms and effective voltages.....	94

Figure A.7—Circuit breaker TRV without reflected wave.....	98
Figure A.8—Circuit breaker TRV with reflected wave.....	98
Figure A.9—Short-line fault TRV	102
Figure B.1—Three-phase power transformer TRV frequencies across the first pole to clear for three-phase secondary faults—90th percentile curve	108
Figure B.2—Three-phase power transformer TRV frequencies across the first pole to clear for three-phase secondary faults—median curves.....	109
Figure C.1—Current in system with non-effectively neutral after interruption of the first phase	111
Figure C.2—TRV on each pole to clear during a three-phase-to-ground terminal fault in an ungrounded system.....	113
Figure C.3—TRV on each pole to clear during a three-phase-to-ground terminal fault in an effectively grounded system.....	113
Figure C.4—Pole-to-clear factors as function of arcing time	114
Figure D.1—Simplified model for transformer-fed/transformer-limited fault TRV calculation	115
Figure D.2—Simplified model for current-limiting reactor fault TRV calculation.....	116
Figure D.3—One-line diagram of a circuit model for a short-line fault analysis	116
Figure D.4—Comparison of the SLF TRV at 90% and 60% of rated short-circuit breaking current	117
Figure D.5—Comparison of the SLF TRV for cases with and without a wavetrap.....	118
Figure D.6—Model of a 345 kV station for breaker TRV study	119
Figure D.7—Generic model for circuit breaker TRV study.....	120
Figure D.8—Fault current contribution from lines and 115 kV system.....	121

List of Tables

Table 1—Related required transient recovery voltage capabilities of circuit breakers at various interrupting levels for terminal faults	33
Table 2—Typical d and Z values for three-phase faults with rated $I_{sc} = 40$ kA, $f = 60$ Hz, source TRV parameters: $k_{af} = 1.40$, RRRV = 2 kV/ μ s, L90, L75, and L60 are short-line faults at 90%, 75%, and 60% of rated interrupting current	57
Table A.1—Single-phase station capacitance.....	95
Table A.2—Typical surge impedances	96
Table A.3—Relation between T_2 and t_3 as function of TRV amplitude factor.....	100
Table B.1—Effective generator capacitance (per phase).....	105
Table B.2—Outdoor bushing capacitance	105
Table B.3—Effective capacitance of inductive instrument transformer	105
Table B.4—Capacitive voltage transformer capacitance.....	106
Table B.5—Bus capacitance—air-insulated bus	106
Table B.6—Gas-insulated substation capacitance.....	106
Table B.7—Effective capacitance of circuit breakers, circuit switchers, and disconnect switches	107
Table B.8—Effective capacitance of miscellaneous equipment.....	107
Table B.9—Effective capacitance of transformers for three-phase ungrounded faults, first pole to clear.....	107
Table C.1—Multipliers for pole-to-clear factors (kp) for each pole when clearing three-phase-to-ground faults.....	112

IEEE Guide for the Application of Transient Recovery Voltage for AC High-Voltage Circuit Breakers with Rated Maximum Voltage above 1000

V

~~IMPORTANT NOTICE: This standard is not intended to ensure safety, security, health, or environmental protection. Implementers of the standard are responsible for determining appropriate safety, security, environmental, and health practices or regulatory requirements.~~

~~This IEEE document is made available for use subject to important notices and legal disclaimers. These notices and disclaimers appear in all publications containing this document and may be found under the heading "Important Notice" or "Important Notices and Disclaimers Concerning IEEE Documents." They can also be obtained on request from IEEE or viewed at <http://standards.ieee.org/IPR/disclaimers.html>.~~

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 with rated maximum voltage 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 ~~guide 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 C37.09™, ~~and~~ IEEE Std C37.09™, ~~and ANSI C37.06.1™~~. IEEE Std C37.010™ applies in other respects to these circuit breakers.

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.

IEC 62271-100, ~~First edition 2001-05,~~ High-voltage switchgear and controlgear—Part 100: ~~High-voltage~~ Alternating-current circuit-breakers.¹ ~~See Table 12, 6.102.10.2.5, p. 193.~~⁹

IEC 62271-101, High-voltage switchgear and controlgear—Part 101: Synthetic testing.

IEEE Std C37.04™, IEEE Standard for Ratings and Requirements ~~Rating Structure~~ for AC High-Voltage Circuit Breakers with Rated Maximum Voltages above 1000 V.^{2,3 3,4}

^{1,9} IEC publications are available from the ~~Central Office of the~~ International Electrotechnical Commission (<http://www.iec.ch>) and ~~the 3, rue de Varembo, P.O. Box 131, CH 1211, Geneva 20, Switzerland (http://www.iec.ch/).~~ IEC publications are also available in ~~the United States from the Sales Department,~~ American National Standards Institute, ~~25 West 43rd Street, 4th Floor, New York, NY 10036, USA~~ (<http://www.ansi.org/>).

¹ ~~Information on references can be found in Clause 2.~~

^{2 4} The IEEE standards or products referred to in Clause 2 are trademarks owned by The Institute of Electrical and Electronics Engineers, Incorporated.

³ IEEE publications are available from The Institute of Electrical and Electronics Engineers, ~~445 Hoes Lane, Piscataway, NJ 08854, USA~~ (<http://standards.ieee.org/>).

~~IEEE Std C37.04bTM, 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 ~~ANSI~~ C37.06.1TM, IEEE Recommended Practice for Preferred Ratings American National Standard~~ for High-Voltage (> 1000 volts) AC Circuit Breakers ~~Rated on Symmetrical Current Basis~~ Designated Definite Purpose for Fast Transient Recovery Voltage Rise Times.²

IEEE Std C37.09TM, IEEE Standard Test Procedure for AC High-Voltage Circuit Breakers with Rated ~~on a Symmetrical Current Basis~~ Maximum Voltage above 1000 V.

IEEE Std C37.010TM, IEEE Application Guide for AC High-Voltage Circuit Breakers > 1000 Vac 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 recovery voltage (TRV) exists, 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 depends ~~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.

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/>).~~

In principle, the response of the load side and source side of the circuit breaker can be analyzed separately, and the results can be 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 interrupt the fault current and is also 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 clear ~~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 (RRRVs) 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 ~~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).

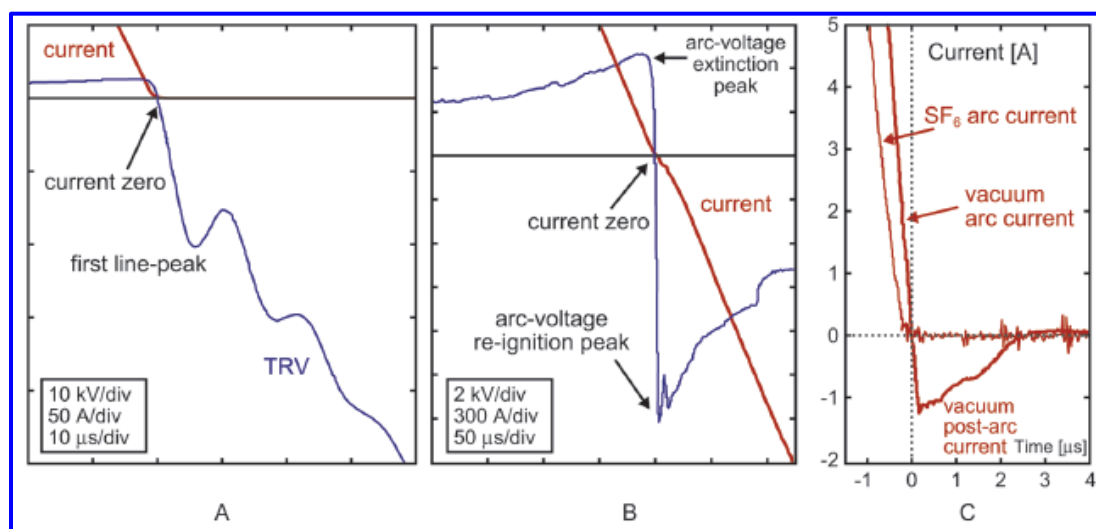
3.2 Arc-circuit interaction

3.2.1 General

During a short-circuit current interruption, arc resistance rises very rapidly during tens of microseconds before current zero. The resulting arc voltage increase tends to charge the circuit capacitances. As a consequence, the slope of current through the arc is reduced as can be seen in part A of Figure 1, which shows a successful interruption of a short-line-fault current. In case of a gas-blast circuit breaker, the short period of a few microseconds with a low current before current zero is important for current interruption as it gives time for the blast to reduce arc temperature and allows then a fast reduction of arc conductivity before the increase of TRV. This short period of a few microseconds around current zero is called the *thermal phase of interruption*.

Part B of Figure 1 shows the evolution of arc current and arc voltage in case of an unsuccessful (thermal) interruption by a gas-blast circuit breaker.

Part C of Figure 1 shows that gas-blast circuit breakers can effectively reduce the slope of current just before current zero and that the increase of arc resistance is so fast that there is no measurable post-arc current after current zero. In case of a vacuum circuit breaker, the current slope is not modified as arc voltage is low. Arc conductivity after current zero in a vacuum circuit breaker leads to post-arc currents that can be 1 A or higher; it can damp a TRV of low amplitude.



(New)

Figure 1—Oscillograms showing arc voltage and arc current during short-circuit current interruption (these examples illustrate short-line-fault interruption)

The interactions between arc and circuit shown on Figure 1 are the same during laboratory tests and in service as long as the requirements given in IEEE Std C37.09™ are fulfilled (supply voltage, TRV, short-circuit current).

3.2.2 Inherent TRV

~~3.2 Effect of circuit breaker on transient recovery voltage~~

~~As The~~ the circuit TRV can be modified by the arc of the circuit breaker, ~~Therefore,~~ the transient recovery voltage ~~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.

3.2.3 Influence of an additional capacitor or opening resistance

The TRV slope can be reduced by a capacitor either in parallel to the arc or phase to ground. Additional capacitors can be used to improve the short-line-fault (SLF) performance of circuit breakers. Opening resistors may be used to improve the SLF performance of circuit breakers by reducing the TRV slope; they are often used with air-blast circuit breakers.

3.3 Method of rating and application

3.3.1 TRV basics

3.3.1.1 General

At rated voltages, up to 100 kV, all circuit breakers in this range of rated voltages are required to interrupt three-phase ungrounded terminal faults.

In the range of rated voltages from 100 kV to 170 kV, the grounding is sometimes accomplished through an impedance, which makes these systems non-effectively grounded. In addition, three-phase ungrounded faults are still common, although less common compared to rated voltages less than 100 kV. Therefore, the user can specify the circuit breakers for use in these impedance grounded systems to be required to interrupt three-phase ungrounded terminal faults as well.

For rated voltages above 170 kV, most systems have the neutral grounded. In addition, system experience has shown that three-phase ungrounded faults are very rare (Baltensperger et al. [B2]⁴), accounting for less than 1.3% of all faults. So, although three-phase ungrounded faults produce the highest TRV peaks, the probability of their occurrence is very small. Based on these statistics, the CIGRE working group [B2] recommended that three-phase grounded faults be considered as the basis of rating for circuit breakers rated 100 kV and above and applied in effectively grounded systems; this recommendation is so implemented in IEC 62271-100. IEEE Std C37.04TM also considers the three-phase grounded fault as the most typical basis of rating for circuit breakers rated 100 kV and above. However, IEEE Std C37.04 also provides the user the option to specify three-phase ungrounded faults as the basis of rating to cover all application conditions where the user considers that the higher TRV capability is required. Because earlier editions of IEEE standards were based on the three-phase ungrounded fault for all voltages, this option also provides the user with a choice where replacement of older breakers is contemplated. Clause 171 of the National Electrical Code® (NEC®) [B26] states the following concerning circuit breaker applications:

“Devices that are intended to interrupt fault current shall be capable of safely interrupting the maximum short-circuit current they are intended to interrupt, and for the circumstances under which they are designed to operate.”

a) Clause 171 is interpreted by some users to mean that three-phase ungrounded faults must be used as the basis for circuit breaker applications, even though the rate of occurrence is very low.

⁴ ⁵ The numbers in brackets correspond to those of the bibliography in Annex F D.

- b) However, testing with an ungrounded system will result in shorter maximum arcing times and lower TRV values for the second and third phase to clear. Therefore, it is not clear that using the three-phase ungrounded condition as the basis for applications will increase the overall margins of performance for the circuit breaker.
- c) The user will have to judge which basis of the application is most suitable for a given situation.

The choice between the three-phase grounded and three-phase ungrounded condition is accomplished by choosing the value of the first-pole-to-clear factor k_{pp} in calculating the TRV peak. For ungrounded systems, which are often found at lower rated voltages, the value of k_{pp} is 1.5. For effectively grounded systems, which are the norm at higher rated voltages, the value of k_{pp} is 1.3. The tables of preferred ratings in IEEE Std C37.04 include the option of both the first-pole-to-clear factors at 100 kV and above.

The waveform of the transient recovery voltage as a function of time varies according to the arrangement of the actual circuit. The TRV waveform starts at zero volts and zero time at the point in time when the current comes down to zero and is interrupted. The TRV then increases at some rate reaching a peak value after which the TRV reduces and is damped out. Actual TRV waveforms observed in a power system can be as simple as a single-frequency oscillation produced by a lumped parameter R-L-C circuit, or it can be more complicated, with various oscillatory components and traveling wave reflections.

For the purposes of standards for high-voltage circuit breakers, these TRV waveforms are described in simplified terms with some straight lines called *reference lines*. The first reference line is horizontal and tangent to the TRV waveform at only one point and does not intersect or contact the waveform at any other points. This line then provides the upper bound to the TRV magnitude. Another reference line starts at the origin with zero volts at zero time and increases with some positive slope; it is tangent to the TRV waveform at only one point. In this way, the sloped line is also an upper boundary that the TRV waveform never crosses. These lines then in combination form an upper boundary that the actual TRV waveform never exceeds. A voltage and a time pair define the point of intersection of the horizontal line and the sloped line. The voltage and time values are called *parameters*. The voltage and time pair also define the upper end of the sloped straight reference line segment. The intersection of the straight lines always occurs at a point in time sooner than the point at which the actual TRV reaches its peak. For two straight lines, one sloped and one horizontal, two parameters, a voltage and a time, are enough to define the intersection of the two lines and to specify the TRV envelope. Some TRV waveshapes start with an exponential rise and then a 1-cosine rise to the peak as defined in older IEEE standards. For these waveshapes, there are three straight lines that form the envelope in which two of them are tangent to the maximum rate of rise on the two different rising slopes, and the third is tangent to the peak. For three straight lines, two sloped and one horizontal, four parameters, two voltages and two times, are required to define the two intersection points.

Although two straight lines work well for a simple, single-frequency waveform, a third line segment is useful for more complicated TRV waveforms where returning traveling waves describe parts of the TRV envelope. The simpler case is more typical of systems with rated voltages below 100 kV, whereas the more complicated case is more typical of systems with rated voltages 100 kV and above. In recognition of this, two types of TRV waveforms at rated short-circuit current are used based on the voltage class of the equipment.

- A four-parameter TRV is used for rated voltages of 100 kV and above.
- A two-parameter TRV is used for rated voltages less than 100 kV.

The two-parameter TRV is also used at all rated voltages for the TRVs for fault currents that are 30% or less of the rated short-circuit current. Methods of drawing TRV envelopes by constructing the tangent lines are given in Annex B and Annex C of IEEE Std C37.04. The numerical values of the parameters for preferred ratings are listed in rating tables of IEEE Std C37.04.

The TRV reference lines form a voltage-time boundary that is essential for both testing and applying circuit breakers. The relationship of the test TRV envelope to the rated TRV envelope, for the purpose of testing the circuit breaker, is described in IEEE Std C37.09.

The relationship of the TRV envelope in a specific application to the rated TRV envelope, for the purpose of applying the circuit breaker, is described in this guide.

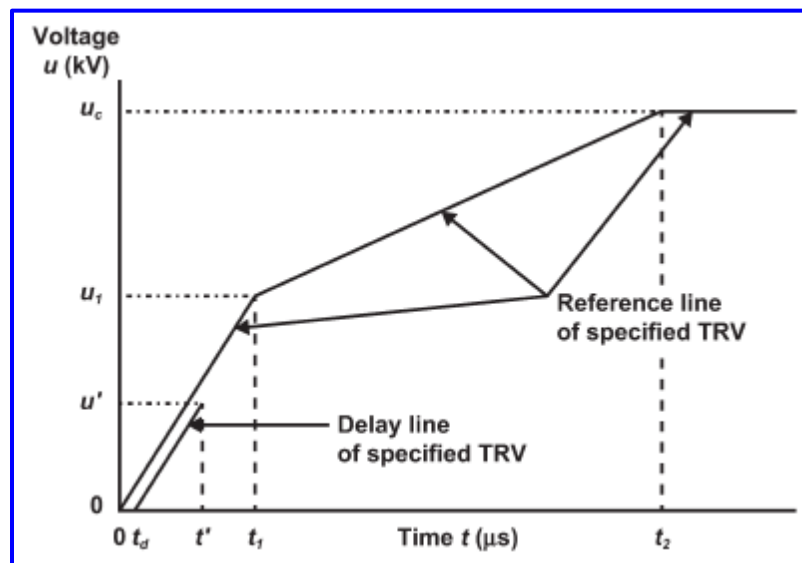
The objective of tests is to stress the breaker with a TRV whose envelope formed by the reference lines meets or exceeds the standard envelope. The objective of the application is to ensure that the TRV envelope produced by the actual system is at or below the standard envelope. In this way, a successful application is made when the interrupting stress imposed by the system does not exceed the capability of the circuit breaker as demonstrated by test.

Generally, it will not be necessary to consider alternative transient recovery voltages as the standard values specified cover the majority of practical cases. More severe conditions may occur in some cases, for example in systems with series capacitor banks that are not bypassed or discharged in due time (see 4.5.2).

Every part of the TRV wave influences the interrupting capability of a circuit breaker. For some types of circuit breakers, the initial rate of rise is most important, whereas for others, the peak value is most important. Therefore, the entire TRV envelope must be considered for testing and application.

3.3.1.2 Four-parameter TRV for rated voltages of 100 kV and above

In some cases, particularly in systems above 100 kV, the transient recovery voltage contains first a period of high rate of rise, followed by a later period of lower rate of rise. The initial portion is typically an exponentially increasing function asymptotic to some voltage value. The exponential waveform is produced by the parallel combination of the local source inductance and the resistance of the transmission line surge impedance. The later portion is formed by the return of the initial portion as a traveling wave from the connected transmission lines. As illustrated on Figure 2, a four-parameter TRV envelope consisting of three line segments as described below adequately represents this waveform.

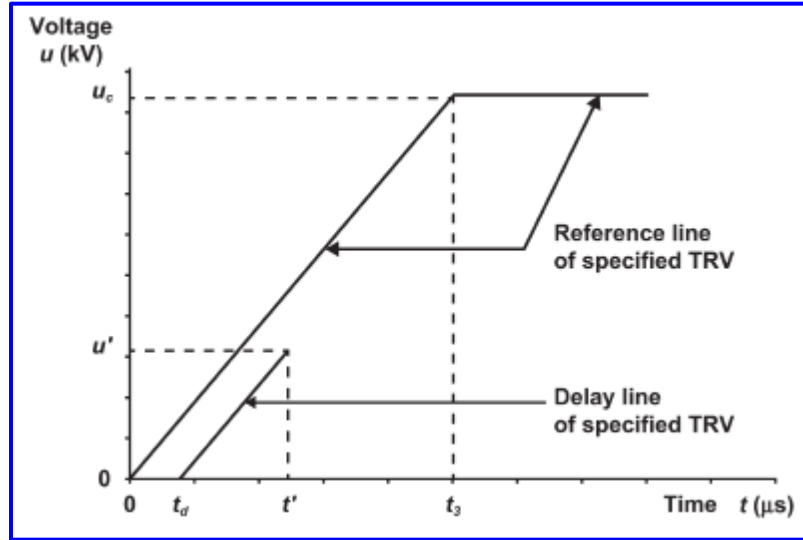


(New)

Figure 2—Four-parameter TRV envelope

3.3.1.3 Two-parameter TRV for rated voltages less than 100 kV

For rated voltages less than 100 kV, the transient recovery voltage approximates to a damped single-frequency oscillation. A two-parameter TRV envelope as shown in Figure 3 adequately represents this waveform.



(New)

Figure 3—Two-parameter TRV envelope

Earlier versions of IEEE Std C37.04 used a 1-cosine wave as the standard TRV envelope with the 1-cosine wave reaching a peak of E_2 at time T_2 . In this simple case, t_3 , the time to reach u_c in microseconds is equal to 0.88 multiplied by T_2 .

3.3.1.4 A delay line defines the initial lower boundary to the TRV

The influence of local capacitance on the source side of the circuit breaker slows the rate of rise of the voltage during the first few microseconds of the TRV. This is taken into account by introducing a time delay t_d in the initial build-up of the TRV wave. The delay line shown in Figure 2 and Figure 3 accounts for this initial delay in the TRV and establishes a lower boundary for the initial delayed build-up of the TRV wave. A delay line is then an additional part of the TRV requirement, which defines an initial lower boundary to the TRV.

The values of the time delay are based on the typical system TRVs. For transmission systems at 100 kV and above, the reference time delay is 2 μ s at the rated short-circuit current. In an actual test, the TRV must be either tangent to or above the delay line to be a valid test stress on the circuit breaker according to its rating. The 2 μ s reference value is a conservatively small value and was chosen in 1997 for the IEEE standards to match the same value used in IEC standards at that time. In earlier editions of IEEE Std C37.06™ in 1987 and before, the time delay values ranged from 2.9 μ s at 121 kV up to 7.9 μ s at 800 kV. Thus, the value of 2 μ s is viewed to be smaller than typical for high-voltage (HV) systems, and an actual TRV produced by a system would have a longer time delay than 2 μ s. Therefore, an actual application with a time delay longer than 2 μ s is conservative in that the test TRV would be required to be 2 μ s or less.

For a 1-cosine TRV wave described by the two-parameter reference lines and the parameters u_c and t_3 , a time delay of $0.15 \times t_3$ makes the delay line tangent to the 1-cosine wave from below.

3.3.1.5 Initial transient recovery voltage (ITRV)

The beginning of the TRV may be of importance for some types of circuit breakers. This part of the TRV, called *initial transient recovery voltage (ITRV)*, is caused by the initial oscillation of small amplitude due to reflections from the first major discontinuity along the busbar. The ITRV is mainly determined by the busbar and line bay configuration of the substation. The ITRV is a physical phenomenon, which is very similar to the short-line fault. Compared with the short-line fault, the first voltage peak is rather low, but the time to the first peak is extremely short, that is, within the first microsecond after current zero. Therefore, the thermal mode of interruption may be influenced.

If the circuit breaker has a short-line-fault rating, then the ITRV requirement is considered covered if the short-line-fault tests are carried out using a line with a time delay less than 100 ns. For details, see the circuit breaker short-line-fault test procedure in IEEE Std C37.09.

The ITRV is proportional to the busbar surge impedance and to the current:

- ITRV is only applicable to circuit breakers rated 100 kV and above because the bus lengths at lower voltages are too short to produce noticeable ITRVs.

- Bus surge impedance is considered to be 260 Ω in contrast to the higher value of 450 Ω used for lines. Therefore, at currents below 31.5 kA, ITRV is not considered significant in comparison to the short-line-fault (SLF) TRV.
- For circuit breakers installed in gas-insulated substations, the initial TRV can be neglected because of low bus surge impedance and small distances to the first major discontinuity.

3.3.2 Rated transient recovery voltage parameters

3.3.2.1 Factors that influence the TRV parameters

The TRV rating for a three-phase circuit breaker is defined by an envelope of required withstand capability. The parameters, which define the envelope, are based on the characteristic features of the actual system transient recovery voltages. TRV parameters are influenced by three factors as follows:

— U_r = the rated voltage

— k_{pp} = the first-pole-to-clear factor

— k_{af} = the amplitude factor

3.3.2.2 Circuit breakers with rated voltages 100 kV and above

For circuit breakers rated 100 kV and above, a four-parameter reference line envelope as shown in Figure 2 represents the rated TRV. Equations for the TRV parameters in terms of the three basic factors U_r , k_{pp} , and k_{af} follow.

The magnitude of the first reference voltage parameter, u_1 , is:

$$u_1 = 0.75 \times k_{pp} \times U_r \times \sqrt{\frac{2}{3}} \quad (1)$$

(New)

The value of 0.75 represents a compromise value that also is consistent with reported values from system studies reported in the literature, as in Baltensperger et al. [B2] and Catenacci et al. [B6].

The rate of rise of the TRV, $RRRV = \frac{u_1}{t_1}$, at the rated short-circuit current for circuit breakers rated 100 kV and above has been established as 2 kV/μs as given in IEEE Std C37.04. Time, t_1 , is derived from u_1 and rate-of-rise-of-recovery voltage (RRRV).

The magnitude of the TRV peak u_c at the rated voltage of U_r is given by Equation (2):

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

(New)

The amplitude factor k_{af} is equal to:

$k_{af} = 1.4$ for terminal faults and short-line faults

$k_{af} = 1.25$ for out-of-phase

These values are based on system studies reported in the literature, as in Baltensperger et al. [B2] and Catenacci et al. [B6]. The value of 1.4 was formerly 1.44 in the IEEE standards of 1979 as the peak voltage parameter u_c for terminal fault was defined as 1.76 times the rated maximum voltage,

where 1.76 is equal to $1.44 \times 1.5 \times \sqrt{\frac{2}{3}}$

The first-pole-to-clear factor k_{pp} is equal to:

$k_{pp} = 1.3$ or 1.5 for terminal fault conditions

$k_{pp} = 1.0$ for short-line-fault conditions

$k_{pp} = 2.0$ for out-of-phase conditions in grounded systems

$k_{pp} = 2.5$ for out-of-phase conditions in ungrounded systems

The rated times t_2 to reach the peak voltage parameter u_c for terminal and short-line-fault switching conditions are related to t_1 as follows:

$$t_2 = 4 \times t_1 = t_2(\text{T100}) \quad (3)$$

(New)

For out-of-phase (OP) switching conditions:

$$t_2(\text{OP}) = 2 \times t_2(\text{T100}) \quad (4)$$

(New)

The rated time to the peak u_c of the four-parameter envelope varies with circuit breaker rated voltage and is given in IEEE Std C37.04.

The preferred rated values for t_2 are the same as those specified in IEC 62271-100 and are similar to the values for T_2 in ANSI C37.06-2000. IEC used a relationship between t_2 and t_1 of $t_2 = 3 t_1$ as representative of values from system studies reported in the literature (as in Baltensperger et al. [B2] and Catenacci et al. [B6]) for $u_1 = 1.0 \times k_{\text{sp}} \times U_r \times \left(\frac{2}{3}\right)^{\frac{1}{2}}$. To retain the same values of t_2 , this relationship is

now adjusted to $t_2 = 4 \times t_1$ for the new value of u_1 given by $u_1 = 0.75 \times k_{\text{sp}} \times U_r \times \left(\frac{2}{3}\right)^{\frac{1}{2}}$. See also Smith et al. [B28] that describes TRV harmonization between IEC and IEEE standards.

The time delay value of 2 μs specified for the test duties covered by four-parameter TRVs is a value agreed to by both the IEEE and IEC around 1990 and is typical of the delay introduced to the initial exponential part of the TRV by the stray capacitance of the bus. A longer value may be used on the source-side circuit when testing with a short-line-fault network because the SLF network has a much shorter time delay.

3.3.2.3 Circuit breakers with rated voltages below 100 kV

3.3.2.3.1 Classes of circuit breakers with rated voltages below 100 kV

Two classes of circuit breakers (S1 and S2) are defined in IEEE Std C37.04, [depending on the type of application](#). These two classes of circuit breakers, class S1 for cable systems and class S2 for line systems, are described in Clause 3 of IEEE Std C37.04 and are also included in IEC 62271-100 [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 [transient recovery voltage \(TRV\)](#) during interruption of terminal fault at 100% of short-circuit interrupting current does not exceed the two-parameter envelope derived from [values given in](#) ~~Column 5 of Table 8 of 2A in~~ IEEE Std C37.04 [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 ([91.4 yards](#) ~~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 ~~derived defined~~ from [values given in](#) ~~Column 5 of~~ Table [8 in IEEE Std C37.04](#) ~~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.^{5 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. In other words, 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 the interruption ~~interrupting~~ of a terminal fault at 100% of short-circuit interrupting current is covered by the two-parameter envelope derived from values given in ~~Column 4 of~~ Table 12 of 2A in IEEE Std C37.04~~b~~ and exceeds the two-parameter-~~envelope-derived~~ values given in ~~from Column 5 of~~ Table 8 in IEEE Std C37.04 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 systems and cable systems are illustrated by Figure 4 ~~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).

^{5 6} Notes to ~~in~~ text, tables, and figures ~~of a standard are given~~ for information only and do not contain requirements needed to implement the ~~this~~ standard.

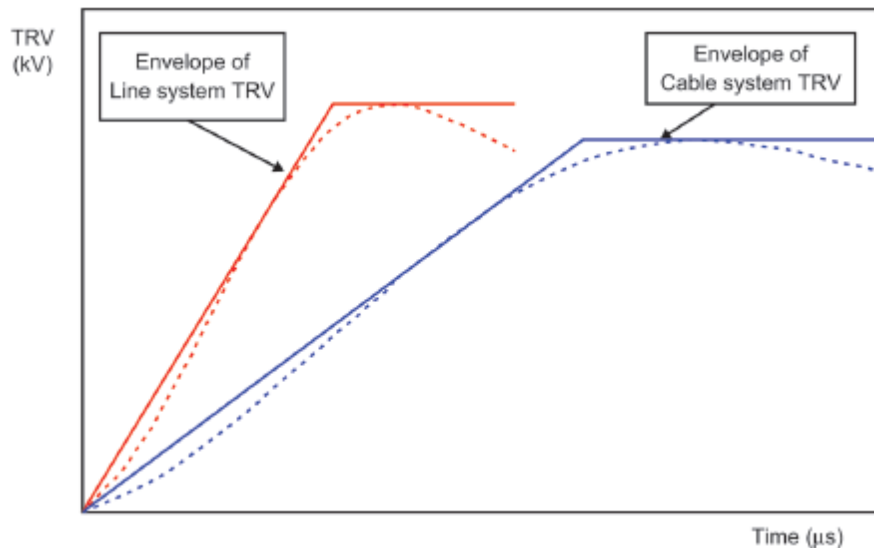


Figure 4—Comparison of line system and cable system rated TRVs

Only [class](#) 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~~).

3.3.2.4 TRV for circuit breakers with rated voltages below 100 kV

For circuit breakers rated below 100 kV, a two-parameter reference line envelope as shown in Figure 3 represents the rated TRV. Equations for the TRV parameters in terms of the three basic factors U_r , k_{pp} , and k_{af} follow below.

The voltage parameter u_c , for interrupting rated short-circuit current, is given also by Equation (2):

$$u_c = k_{af} \times k_{pp} \times U_r \times \sqrt{\frac{2}{3}}$$

(New)

For circuit breakers in overhead line-connected systems (or line systems):

k_{af} = amplitude factor = 1.54 for terminal fault and supply circuit of short-line fault

For circuit breakers in cable-connected systems (or cable systems):

k_{af} = amplitude factor = 1.4 for terminal fault

For circuit breakers in overhead line-connected systems and cable-connected systems:

k_{af} = amplitude factor = 1.25 for out-of-phase

The time parameter t_3 is specified based on system parameters. The RRRV is then determined from u_c and t_3 using the relationship in Equation (5):

$$\text{RRRV} = \frac{u_c}{t_3} \quad (5)$$

(New)

At rated voltages below 100 kV, the rated time parameter t_3 to the TRV peak u_c of the two-parameter envelope varies with circuit breaker rated voltage as given in IEEE Std C37.04. For line systems, time, t_3 , for terminal fault and short-line fault is equal to $4.65 \times (u_c)^{0.7}$ with t_3 in microseconds and u_c in kilovolts. The equation is derived from the values given in Table 12 of IEEE Std C37.04 for rated voltages 15.5 kV, 25.8 kV, 48.3 kV, and 72.5 kV. The same equation is used for other rated voltages. For cable systems, the values of t_3 are those found in IEC 62271-100.

The amplitude factor is affected by the amount of damping in the system to TRV transients:

- a) The amplitude factor of 1.54 is the value that has been used in ANSI/IEEE standards for many years for outdoor circuit breakers with rated voltages up to and including 72.5 kV. This is at least partly based on the fact that many applications in North America at these voltage levels are in outdoor, overhead line-connected systems for which this value of the amplitude factor is appropriate.
- b) The amplitude factor of 1.4 is the value that has been used in IEC standards for many years for circuit breakers with rated voltages up to and including 52 kV. This is at least partly based on the fact that many applications at these voltage levels are in cable-connected systems for which this value of the amplitude factor is appropriate.

The RRRV is affected by the amount of capacitance in the system:

- Overhead line-connected systems have a smaller amount of inherent capacitance, and hence, the RRRVs of these systems are faster.
- Cable-connected systems have a larger amount of inherent capacitance, and hence, the RRRVs of these systems are slower.

Time delay t_d for terminal faults (test duty T100) is a function of the system, cable, or line, and the switching condition, terminal fault, short-line fault, or out-of-phase switching.

$t_d = 0.15 t_3$ for terminal fault and out-of-phase in the case of cable systems

$t_d = 0.05 t_3$ for terminal fault and short-line fault in the case of line systems

For line systems, the time delay is a shorter value $t_d = 0.05 t_3$ instead of the longer value of $t_d = 0.15 t_3$. The shorter value of t_d is consistent with the TRVs observed in overhead lines that are produced by the interaction of traveling waves, whereas the longer value of t_d is consistent with production of the TRV in cable systems where the added capacitance of the cables and more compact systems produce TRVs that are observed to be more like the 1-cosine waveshape of lumped parameter circuits.

Experience in service has been very good with regard to the circuit breakers designed and tested to the TRVs of both IEEE and IEC standards. Based on this good service experience and the known typical effects that line-connected systems and cable-connected systems have on the TRV, both are therefore used as the basis of rating in the respective system conditions.

3.3.3 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 ([Baltensperger et al. \[B2\]](#) ~~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.

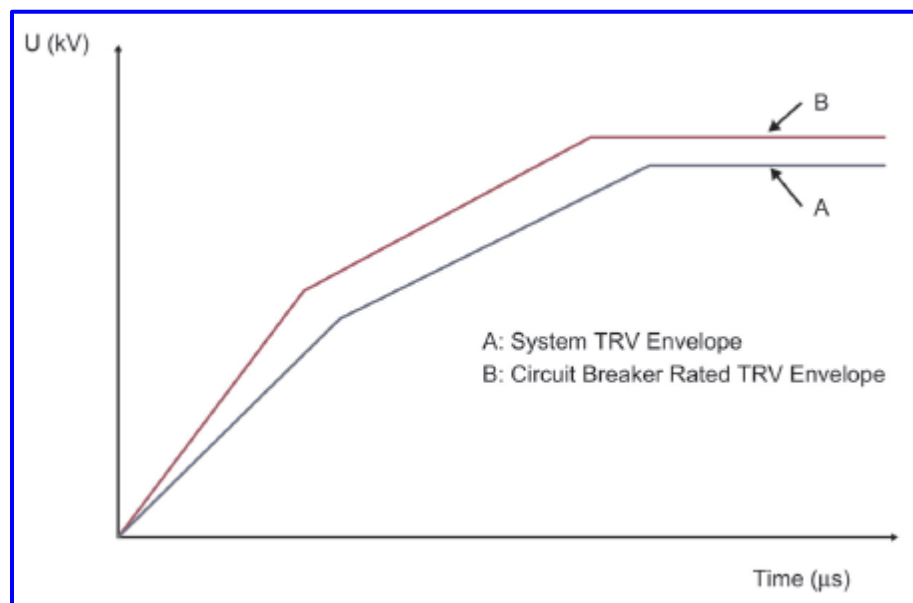
For circuit breakers applied on systems below 100 kV, the TRV ratings assume that the systems can be operated ungrounded. For systems 100 kV through 170 kV, the systems can be operated either ungrounded or effectively grounded so two TRV ratings are available for these systems. For circuit breakers applied on systems above 170 kV, the TRV ratings assume that the systems are all operated effectively grounded. See Annex C.

For [gas-insulated switchgear \(GIS\)](#) 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.

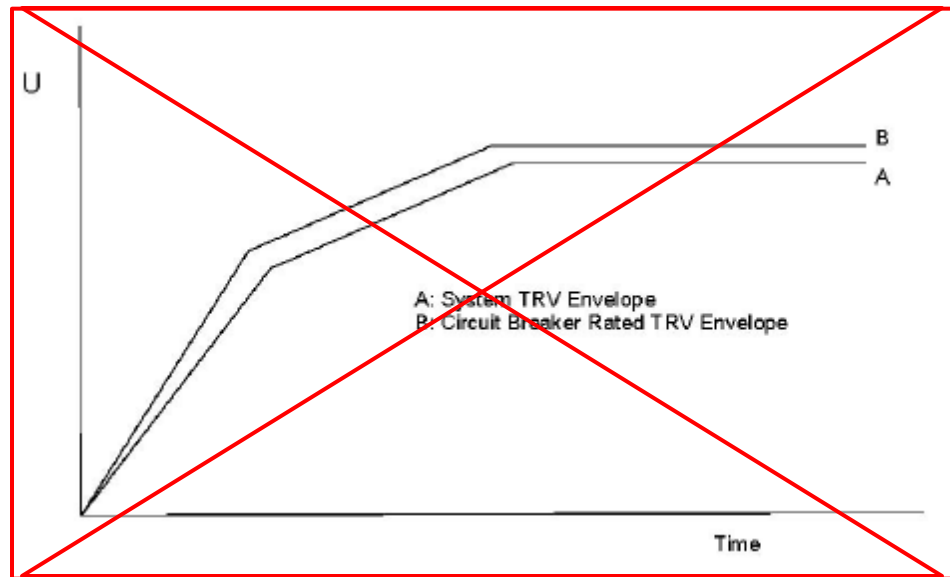
~~In IEEE Std C37.04b and IEEE Std C37.06, the TRV capability of a circuit breaker is defined by a two-parameter or a four-parameter envelope.~~

A circuit breaker TRV capability is sufficient if the two- or four-parameter envelope drawn with the rated parameters as specified in IEEE Std C37.04 06 is higher than the two- or four-parameter envelope of the system TRV at the point of application (see Figure 5 4). 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.



(New)

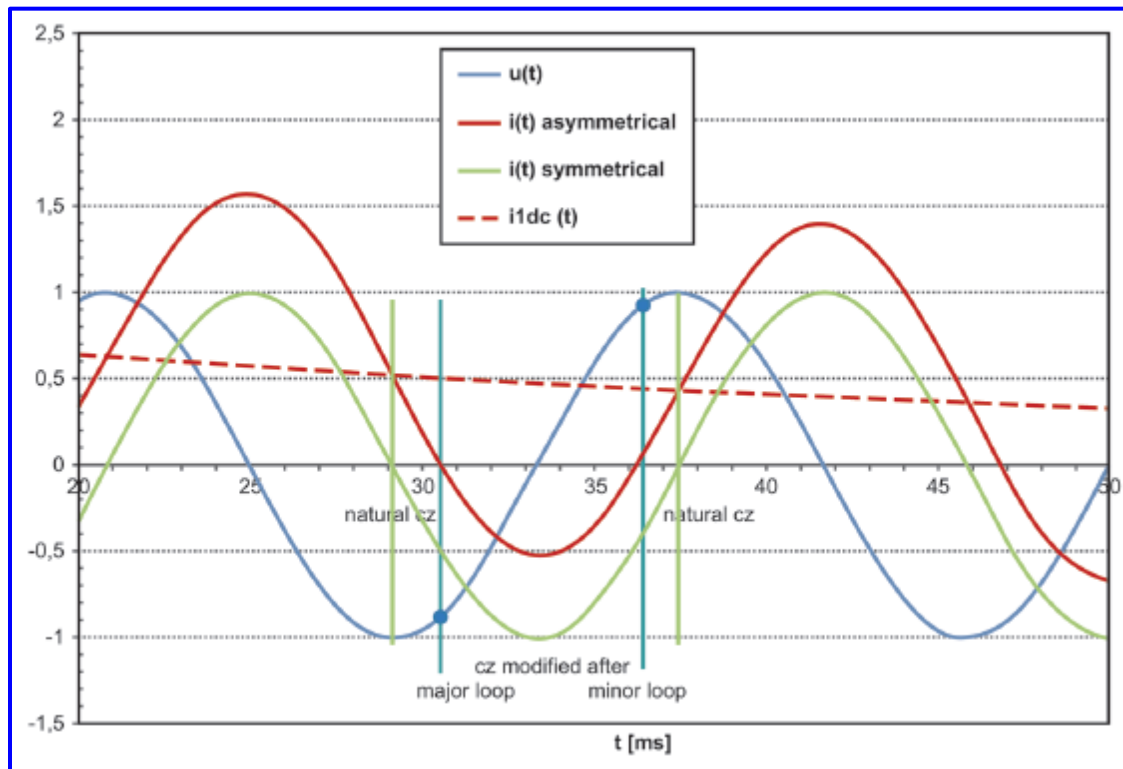


(Deleted)

Figure 5—System TRV envelope and circuit breaker rated TRV envelope

3.3.4 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 6 3). Circuit breakers have the capability of interrupting these asymmetrical currents provided that ~~providing~~ the circuit breakers are applied within their rating.



(New)

Figure 6— Effect of current asymmetry on voltage at current zero (cz)

Due to the asymmetry of the current, the zero crossing of the short-circuit current is modified compared to the symmetrical current. On one hand, the di/dt is reduced as its maximum values are reached at current zero under symmetrical conditions. On the other hand, the instant of occurrence of the current zeros no longer corresponds to the voltage peak. After a minor loop the current zero is advanced (compared to the symmetrical current), and after a major loop it is retarded (see Figure 6).

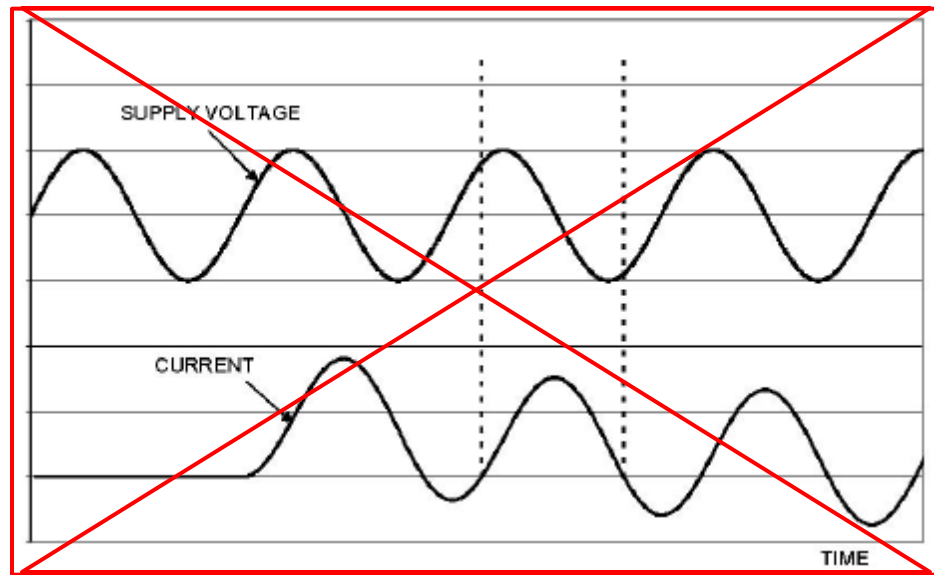
During direct testing, short-circuit current and recovery voltage are fed by the same source. The modification of di/dt occurs automatically when the current is asymmetrical. It is recognized that after correct adjustment of TRV-shaping circuits for symmetrical current conditions no further adaptation is necessary when the current is asymmetrical.

During synthetic testing, short-circuit current and recovery voltage are fed by different sources. When the current injection method is used, the di/dt at current zero is determined by the injected current fed by the voltage source. To avoid overstressing of the circuit breaker under test, it is necessary to adjust the voltage (and di/dt if applicable) separately. The method to calculate the modified di/dt and TRV was initially given in IEEE Std C37.081aTM-1997 [B22]. It is now superseded by the calculated values in IEC 62271-101 [B18]. The adjustment of TRV and di/dt is done by changing the charging voltage of the voltage source, by modification of the main inductance, and/or by modification of the TRV-shaping elements.

IEEE Std C37.081a-1997 [B22] calculated a correction factor F_1 using the di/dt modified by the dc component at current zero in relation to the symmetrical value. For a time-to-peak TRV not exceeding 500 μs , it was assumed that the du/dt and u_c are reduced by the same factor F_1 . For a time-to-peak TRV longer than 500 μs , a second correction factor F_E was introduced. This factor took into account that for a long time-to-peak the instantaneous value of the power frequency recovery has an impact on the TRV peak. In this case, the time to peak, and therefore the frequency of TRV oscillations, is the same for symmetrical and asymmetrical currents.

Annex I of IEC 62271-101 [B18] makes the same assumption as IEEE Std C37.081a-1997 [B22] for calculating the modified di/dt . The value u_c , for two-parameter TRV envelopes, and of u_1 , for four-parameter envelopes, are calculated based on the di/dt reduction and on the instantaneous value of the power frequency recovery voltage. For four-parameter TRV envelopes, the value u_c is calculated based on the instantaneous value of the power frequency recovery voltage and the modified value of u_1 . As the times t_1 , t_2 , or t_3 remain unchanged, the TRV rate of rise is lower during asymmetrical current interruption.

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



(Deleted)

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

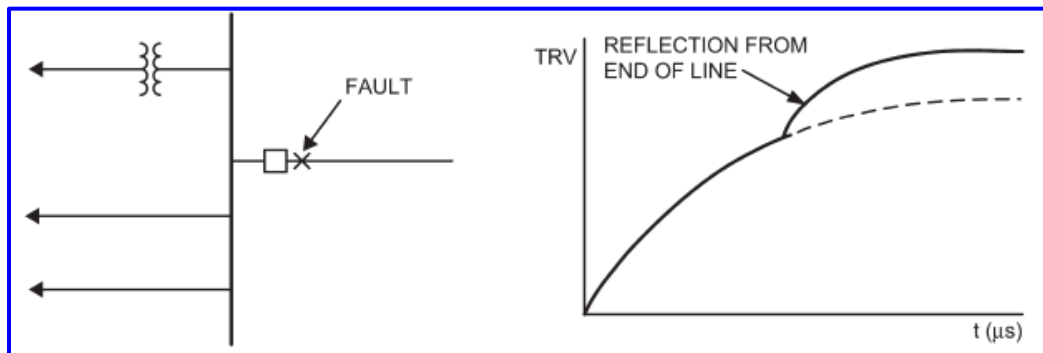
Figure 3—Supply voltage and asymmetrical current

4. Application considerations

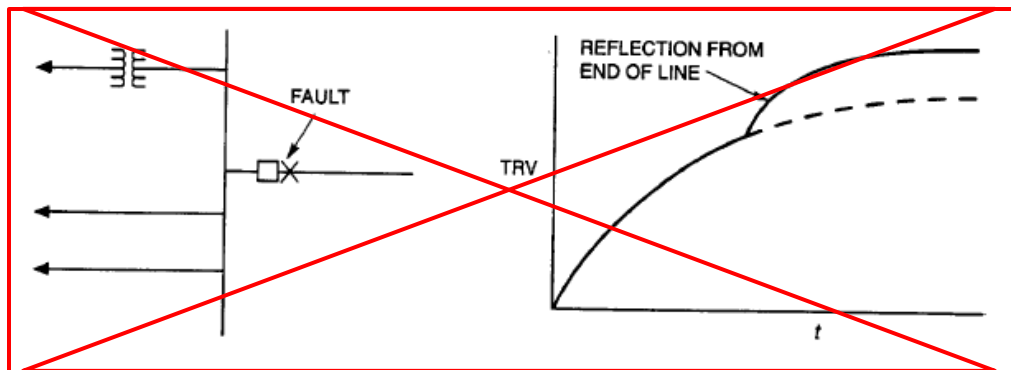
4.1 General

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 7 4, Figure 8 5, and Figure 9 6, respectively.

A typical exponential TRV is shown in Figure 7 4. This exponential TRV typically occurs when at least one transformer and one line are on the un-faulted side of the circuit breaker when a three-phase fault is cleared at the breaker terminals.



(New)



(Deleted)

Figure 7—Exponential TRV characteristic

The oscillatory TRV shown in Figure 8 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 9 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.

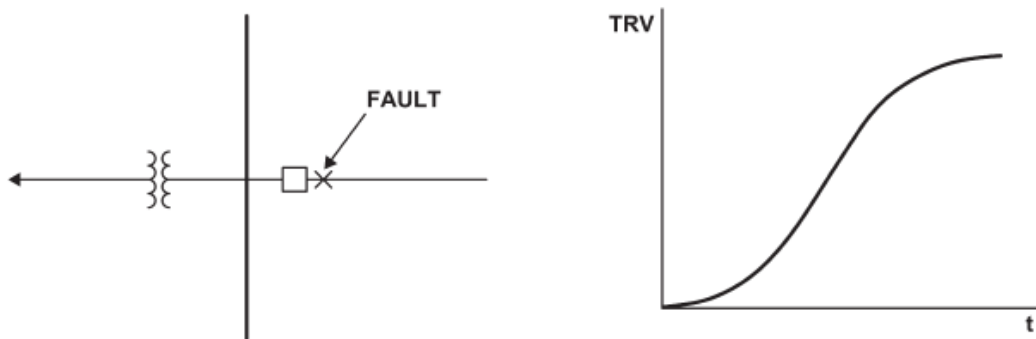
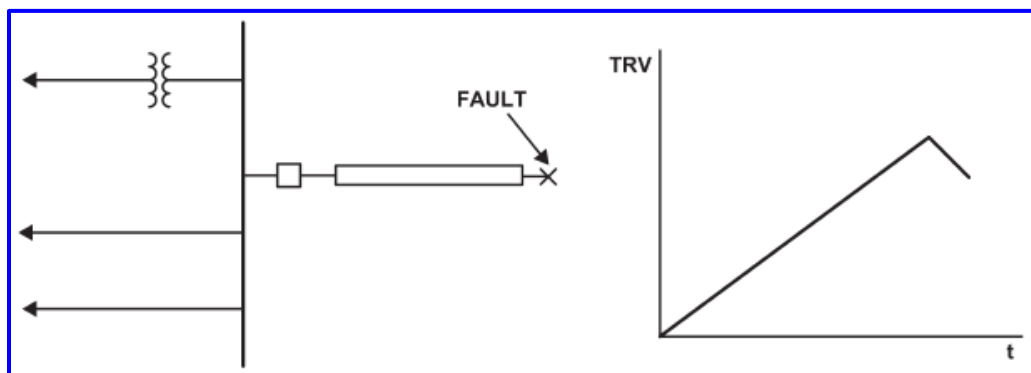
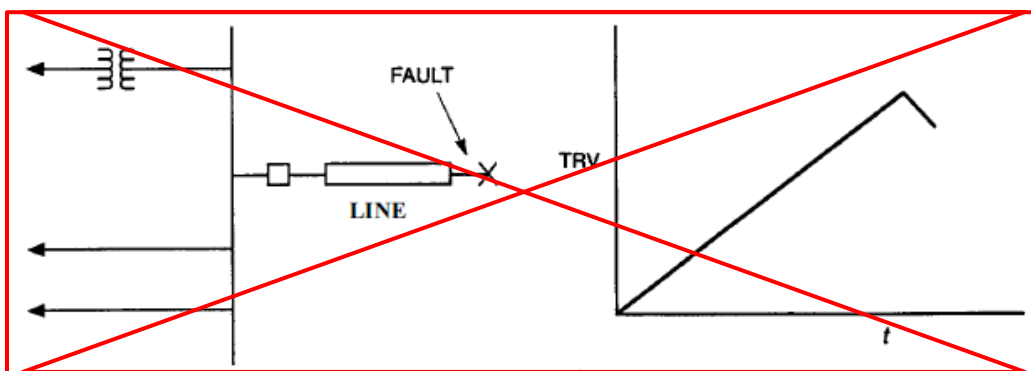


Figure 8—Oscillatory TRV characteristic



(New)



(Deleted)

Figure 9—Short-line-fault TRV characteristic

The two-~~parameters~~ ~~parameter~~ and four-parameter envelopes, illustrated in Figure ~~10~~ ~~7~~ and Figure ~~11~~, ~~are included~~ ~~8~~, ~~have been introduced~~ in IEEE Std C37.04~~b~~ 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 ~~listed below~~ ~~follows~~:

— u' = reference voltage, in kilovolts

— t' = time to reach u' , in microseconds

— t_d = time delay, in microseconds

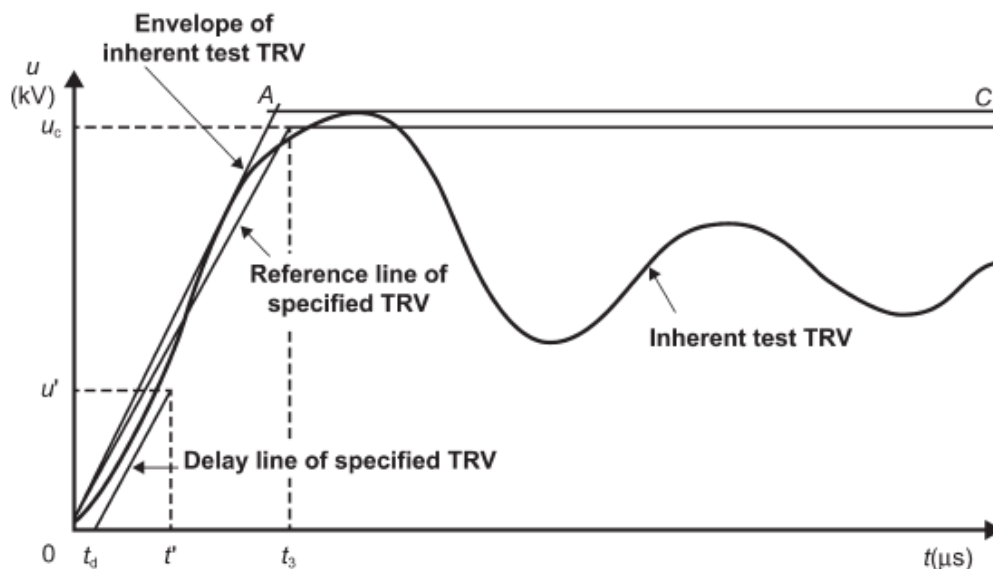


Figure 10—Example of inherent test TRV with two-parameter envelope
which ~~that~~ satisfies the conditions to be met during type test

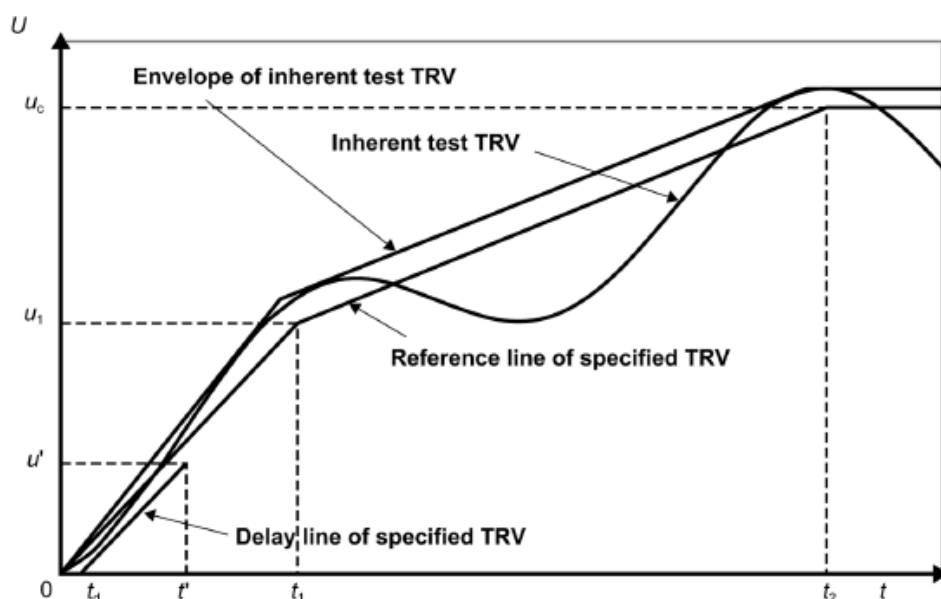


Figure 11—Example of inherent test TRV with four-parameter envelope
which ~~that~~ satisfies the conditions to be met during type test

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). [Short-line-fault TRVs](#) ~~SLF generally~~ have higher rates-of-rise of recovery voltage than ~~that of de~~ terminal fault [test duties T100 and T60 due to the high frequency of the line-side oscillation](#) ~~TRVs~~, but have lower crest voltage magnitudes.

Examples given in this [clause](#) ~~subclause~~ illustrate the use of the [standard](#) ~~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.

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

[4.2.1 Introduction](#)

Rated and related circuit breaker [transient recovery voltage](#)~~TRV~~ capabilities are defined by parameters given in IEEE Std C37.04 [6](#).

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 [11 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 [assumes](#) ~~assume~~ a TRV envelope described by two parameters (u_c , t_3), as illustrated in Figure [10 7](#).

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

4.2.2 Three-phase terminal fault

As an example, Figure [12 9](#) shows the three-phase-to-ground fault related [transient recovery voltage TRV](#)-capability for a ~~550 kV~~-circuit breaker [with rated voltage 550 kV](#) 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.[04 06](#). It shows also the TRV capability for the optional case with $k_{pp} = 1.5$.

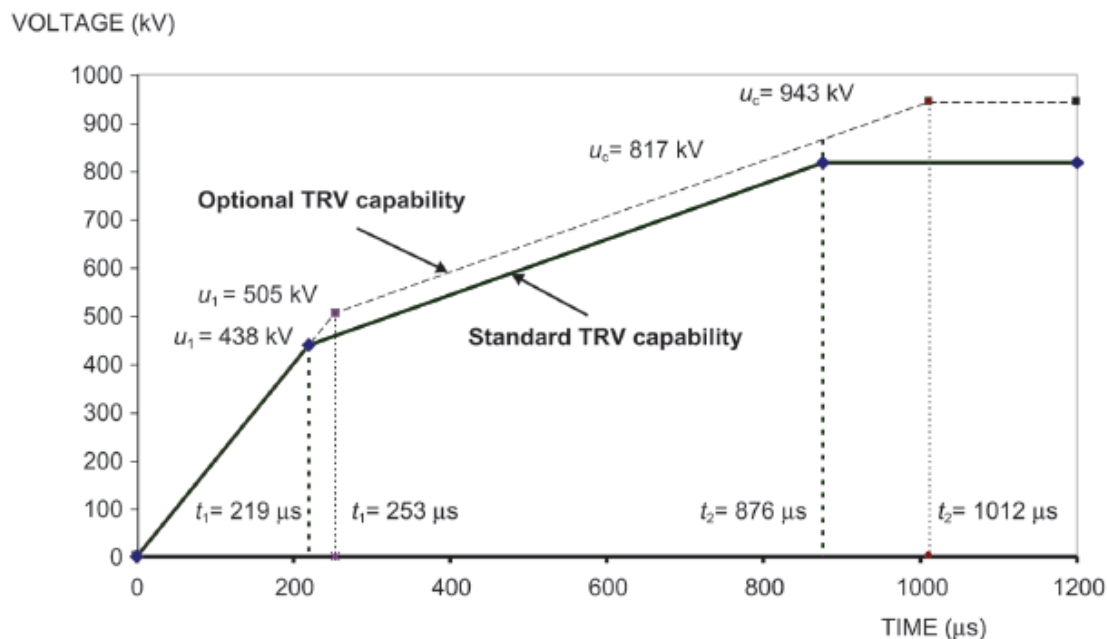


Figure 12—TRV capability envelope for a 550 kV circuit breaker at 100% of its rated fault current capability