IEEE STANDARDS ASSOCIATION

IEEE Standard for Traction Power Rectifier Transformers for Substation Applications up to 1500 V DC Nominal Output

IEEE Vehicular Technology Society

Sponsored by the
Rail Transportation Standards Committee

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

IEEE Std 1653.1™-2016

IEEE Standard for Traction Power Rectifier Transformers for Substation Applications up to 1500 V DC Nominal Output

Sponsor

Rail Transportation Standards Committee
of the
IEEE Vehicular Technology Society

Approved 30 June 2016

IEEE-SA Standards Board

Abstract: Guidelines for establishing criteria for application, performance, interchangeability, tests, life cycle costs, and safety requirements of traction power rectifier transformers are established in this standard. Set forth are the electrical, mechanical and thermal design, manufacturing, and testing requirements for traction power rectifier transformers for dc electrification systems. Covered in this standard are liquid-immersed and dry-type transformers, including those with cast coil and epoxy resin encapsulated windings.

Keywords: basic lightning impulse insulation, BIL, commutating impedance, design optimization, electrical requirements, factory tests, ferroresonance, heavy rail, hot spot, IEEE 1653.1™, light rail, load cycle, overvoltage transient, partial discharge (PD) service conditions, tests, traction power duty cycle, traction power rectifier transformers, transit application

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

PDF: ISBN 978-1-5044-2268-0 STD21081
Print: ISBN 978-1-5044-2269-7 STDPD21081

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 Notices and Disclaimers Concerning IEEE Standards Documents." They can also be obtained on request from IEEE or viewed at http://standards.ieee.org/IPR/disclaimers.html.

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. IEEE Standards are documents developed through scientific, academic, and industry-based technical working groups. Volunteers in IEEE working groups 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 Standards do not guarantee or ensure safety, security, health, or environmental protection, or ensure against interference with or from other devices or networks. Implementers and users of IEEE Standards documents are responsible for determining and complying with all appropriate safety, security, environmental, health, and interference protection practices and all applicable laws and regulations.

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 U.S. 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 ten years. When a document is more than ten 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 Xplore at http://ieeexplore.ieee.org/ 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 standard was submitted to the IEEE-SA Standards Board for approval, the Traction Power Transformers Working Group had the following membership:

Vincenzo (Vince) Paparo, *Chair*
Ethan Kim, *Vice Chair*

Roger M. Avery
Steven Bezner
Yuanxiang Chen
Prakash Dave
Ray Davis
John Dellas
Ramesh Dingra
Mike Dinolfo
Earl Fish
Paul Forquer
Rajen Ganeriwal
Mark Griffiths
William Jagerburger
Mladen Jeftic
Sheldon Kennedy
Don Kline
Tristan Kneschke
Wolfgang Kropp
Bih Yuan-Ku
Louie Luo
Alok Mandel
Steve Norton
Constantinos Orphanides
Moustapha Ouattara
Chris Pagni
John Pascu
Dev Paul
Jeewan Puri
Charles Ross
Subhas Sarkar
Holali Sathya
Jay Sender
Narendra Shah
Richard Shiftlet
Jeffrey Sisson
Benjamin (Ralph) Stell
Rick Straubel
Ray Strittmatter
Gary Touryan
John Whitney
Richard Wolff
Tom Young

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

Roger M. Avery
William Aycock
Donald Ayers
Steven Bezner
William Bush
William Byrd
Robert Fisher
Paul Forquer
Doaa Galal
H. Glickenstein
Lowell Goudge
Randall Groves
John John
Andrew Jones
Walter Keevil
Sheldon Kennedy
Yuri Khersonsky
Ethan Kim
Jim Kulchisky
Saumen Kundu
Greg Luri
Michael Newman
Charles Ngethe
Vincenzo Paparo
Bansi Patel
Dev Paul
Michael Perez
Mark Pfeiffer
David R. Phelps
Moises Ramos
Charles Ross
Subhas Sarkar
Bartien Sayogo
Nikunj Shah
Suresh Shrimavle
Gil Shultz
Jeffrey Sisson
James Smith
Benjamin (Ralph) Stell
Rick Straubel
Gary Touryan
John Vergis
Robert Wilson
Jian Yu
Matthew Zeedyk

When the IEEE-SA Standards Board approved this standard on 30 June 2016, it had the following membership:

Introduction

This introduction is not part of IEEE Std 1653.1-2016, IEEE Standard for Traction Power Rectifier Transformers for Substation Applications up to 1500 V DC Nominal Output.

This is a new standard written specifically for transit industry applications, collecting requirements and references mainly from other existing IEEE transformer and testing standards, and other industry publications into one document. This standard is the result of an effort encompassing the interests of transit power authorities/owners, manufacturers, and others dedicated to producing voluntary consensus standards for traction power rectifier transformer technology.

Contents

IEEE Standard for Traction Power Rectifier Transformers for Substation Applications up to 1500 V DC Nominal Output

1. Overview

1.1 Scope

This standard covers design, manufacturing, and testing unique to the application of power rectifier transformers intended to operate in dc supplied transportation substation applications up to 1500 V dc nominal output.

1.2 Purpose

At the present time there are no suitable standards governing all requirements for traction power rectifier transformers. This standard will provide requirements specific to traction power transformers supplying power to dc supplied transportation equipment.

1.3 Mandatory requirements

In this document, the word *shall* is used to indicate a mandatory requirement. The word *should* is used to indicate a recommendation. The word *may* is used to indicate a permissible action. The word *can* is used for statements of possibility and capability.

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.

ASTM D2945-90(2003)e2, Standard Test Method for Gas content of Insulating Oils.[1]

IEC 60076-11, Dry-type transformers.[2]

[1]ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA (http://www.astm.org/).
[2]IEC publications are available from the International Electrotechnical Commission (http://www.iec.ch/). IEC publications are also available from the American National Standards Institute (http://www.ansi.org/).

IEEE Std 4™, IEEE Standard Technique for High Voltage testing.[3,4]

IEEE Std 519™, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.

IEEE Std 1653.2™, IEEE Standard for Uncontrolled Traction Power Rectifiers for Substation Applications Up to 1500 V DC Nominal Output.

IEEE Std C57.12.00™, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.12.01™, IEEE Standard General Requirements for Dry Type Distribution and Power Transformers Including Those with Solid Cast and/or Resin-Encapsulated Windings.

IEEE Std C57.12.80™, IEEE Standard Terminology for Power and Distribution Transformers.

IEEE Std C57.12.90™, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers and Guide for Short-Circuit Testing of Distribution and Power Transformers.

IEEE Std C57.12.91™, IEEE Test Code for Dry-Type Distribution and Power Transformers.

IEEE Std C57.18.10™, IEEE Standard Practices and Requirements for Semiconductor Power Rectifier Transformers.

IEEE Std C57.98™, IEEE Guide for Transformer Impulse Tests.

IEEE Std C57.104™, IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers.

IEEE Std C57.110™, IEEE Recommended Practice for Establishing Liquid-Filled and Dry-Type Power and Distribution Transformer Capability when Supplying Non-sinusoidal Load Currents.

IEEE Std C57.120™, IEEE Loss Evaluation Guide for Power Transformers and Reactors.

IEEE Std C57.124™, IEEE Recommended Practice for the Detection of Partial Discharges and the measurement of Apparent Charge in Dry-Type Transformers.

NEMA TR 1, Transformers, Regulators and Reactors.[5]

NFPA 70E, Standard for electrical Safety in the Workplace.[6]

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[7]

[3]The IEEE standards or products referred to in Clause 2 are trademarks owned by the Institute of Electrical and Electronics Engineers, Incorporated.
[4]IEEE publications are available from the Institute of Electrical and Electronics Engineers (http://standards.ieee.org/).
[5]NEMA publications are available from the National Electrical Manufacturers Association (http://www.nema.org/).
[6]NFPA publications are published by the National Fire Protection Association (http://www.nfpa.org/).
[7]The *IEEE Standards Dictionary Online* is available at: http://ieeexplore.ieee.org/xpls/dictionary.jsp.

cast-coil or cast-resin rectifier transformers: A transformer with windings that are vacuum cast or vacuum impregnated in epoxy resin and fillers, and cured under a vacuum for purpose of minimizing the probability of air voids contributing to partial discharges at higher voltages. Transformer windings of this type can be completely cast in epoxy or partially cast with only the primary windings being cast in epoxy.

dry-type rectifier transformer: A transformer cooled by the circulation of air. Dry-type transformers also include transformers with encapsulated windings or cast coils. Cooling of dry-type transformers is achieved by ambient air, which may or may not be forced by means of fans. Vacuum impregnated cast-resin or cast-coil, vacuum pressure impregnated and vacuum pressure encapsulated are among the types of dry-type transformers used as rectifier transformer for traction power application.

ferroresonance: A nonlinear resonance involving a capacitance in series with a saturable inductance. Maximum frequency for ferroresonace is 2 kHz to 3 kHz. Ferroresonance occurs when the inductance in the circuit is ferromagnetic. A transformer is an example of ferromagnetic inductance.

liquid-immersed rectifier transformer: A transformer cooled by the circulation of a liquid medium, either by natural convection of the liquid or by forced circulation. Liquid-Immersed transformers for traction power application are widely used pending environmental compliance and high voltage application.

partial discharge (PD): A partial discharge is a localized electric discharge that only partially bridges the insulation between conductors or between the insulation and surrounding air. A PD results from transient gaseous ionization in an insulation system when voltage stress exceeds a critical value. It is measured in picocoulombs, pC, where one pC is equal to 10^{-12} Coulombs.

PD extinction voltage: The highest voltage at which partial discharge (PD) no longer exceeds the specified intensity. PD extinction voltage is detected on instrumentation adjusted to a specified sensitivity as the applied voltage is gradually decreased from the PD inception level.

PD inception voltage: The lowest voltage at which partial discharge (PD) is detected on instrumentation adjusted to a specified sensitivity when the voltage applied to the test object is gradually increased from a lower value.

PD-free test voltage: A specified voltage, applied in accordance with a specified test procedure, at which the test object should not exhibit partial discharges above the acceptable background noise level.

recovery voltage: The maximum voltage that appears across the terminals of a pole of a switching device after the breaking of the current.

rolling stock: As used in this standard, transit vehicles, trains, and the associated on-board equipment receiving motive power from a traction power distribution system.

snubber device: A device containing a surge capacitor, resistor, and fuse that is used to reduce the magnitude and frequency of the transient recovery voltage and terminal voltage.

traction power analysis: A study to analyze the performance of the traction power supply system, which includes the ac supply system and dc traction power distribution systems, with operating vehicles as dynamic loads, and station auxiliary loads as static loads. The study results normally include distribution system voltages, currents, incoming power supply characteristics, available short-circuit current from the power supply at different nodes of the substation equipment, system X/R ratio, harmonic spectrum, voltage drop, voltage regulation, substation power demand requirements, substation spacing, and energy consumption.

traction power rectifier transformer: A rectifier transformer that supplies ac power to dc rectifiers, which supply traction power to dc rail equipment or rolling stock through uncontrolled or controlled rectifiers.

transient recovery voltage (TRV): The voltage that appears at the terminals of a pole of a switching device while interrupting current. Its characteristics, (amplitude, rate of rise) can lead to a successful current interruption or a failure (re-strike, reignition).

3.2 Acronyms and abbreviations

ASTM	American Society for Testing and Materials
BIL	basic lightning impulse insulation level
DGA	dissolved gas analysis
IEC	International Electrotechnical Commission
NEMA	National Electrical Manufacturers Association
NFPA	National Fire Protection Association
PD	partial discharge

4. Service conditions

4.1 Usual service conditions

Usual service conditions shall be as defined in IEEE Std C57.12.00 for liquid-immersed rectifier transformers and IEEE Std C57.12.01 for dry-type rectifier transformers, except where clearly not applicable to traction rectifier transformers or where otherwise specified herein.[8]

4.1.1 Fluctuating loads

Traction power rectifier transformers operate under rapidly changing and fluctuating loads, including short circuits, which are typical of traction power systems.

4.1.2 Short circuits

Traction power systems can experience a high number of short circuits while in operation, and transformers may be exposed to currents that are 10 to 20 times their rated current. During a short-circuit event, large pulsating mechanical forces will act on the windings and their supports during the passage of these currents. Short circuits will also cause high current densities in the windings and impose a rapid increase in winding temperature. As a result, the specification of short-circuit impedance is an important factor in the design of the transformer as the impedance will dictate the magnitude of the fault current and its effects during a short. For transformers with lower short-circuit impedances (less than 6%), the short-circuit current and associated mechanical forces would be higher still.

4.1.3 Voltage and current harmonics

Harmonic considerations shall be made for traction power rectifier transformers that supply non-sinusoidal power to operating loads. Transformers shall operate within the specified limits of voltage and current harmonics as specified by the owner or within the levels specified in IEEE Std C57.18.10 and IEEE Std C57.110 as a minimum. This is especially true for controlled rectifiers, which contribute a higher magnitude of harmonics compared to uncontrolled rectifiers. In either case, the transformer and rectifier should be designed to minimize harmonics.

Primary voltage unbalance caused by unbalanced loads on the transformer or a higher level of harmonics may cause increased flux density in one or two limbs of the core. An increased flux density may cause core satu-

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

ration, thus producing unacceptable levels of heat rise and higher losses. The increased flux density may also contribute to higher sound levels of the transformer.

4.1.4 Vibration

Since traction power substations are commonly located in close proximity to operating right-of-ways, transformers may be exposed to vibrations due to the passage of vehicles. This factor shall be considered in a traction power transformer design, and vibrations shall be minimized through the use of vibration isolation pads or dampers.

4.1.5 Audible sound level

The audible sound level of a traction power rectifier transformer, when tested at its rated voltage and no load in accordance with IEEE Std C57.12.90 for liquid filled transformers or IEEE Std C57.12.91 for dry-type transformers, shall not exceed the limits specified in NEMA TR1 for liquid-filled transformers or IEEE Std C57.12.01 for dry-type transformers.

4.2 Unusual service conditions

Conditions other than those described in 4.1 are considered unusual service conditions. When present, the conditions shall be brought to the attention of those responsible for the design and application of the transformer. Unusual service conditions include any one, or combination of, the following:

a) Ambient temperature above 40 ºC or below −30 ºC for dry-type transformers.

b) Ambient temperature above 40 ºC or below −20 ºC for liquid-immersed transformers.

c) Operation above its rated load cycle.

d) Altitude of 1000 m (3300 ft) or more above sea level.

e) Abnormal vibration, tilting, or seismic conditions.

f) Conductive brake dust, high pollution environment.

g) Unusual duty load cycle.

h) High X/R ratio at the source.

i) High re-striking voltage from transformer breaker.

j) Frequent repetitive energization and de-energization of the rectifier transformer.

k) Continuous phase voltage unbalance and or non-sinusoidal waveform.

l) Very dusty or high humidity environment.

m) Further examples of unusual operating conditions are given in IEEE Std C57.12.00 and IEEE Std C57.12.01.

5. Rating data

5.1 Continuous rating

Refer to 6.5 of IEEE Std C57.18.10-1998.

5.2 Duty cycles

5.2.1 General

Traction power rectifier transformers shall continuously supply 100% rated power in addition to a specified traction overload duty cycle occurring twice daily, at minimum. The overload duty rating and the time duration between the overload periods shall be supplied to the manufacturer by the owner.

The traction power system analyses shall be performed in accordance with IEEE Std C57.96 to determine the thermal capacity necessary to meet the required design life.

5.2.2 Standard duty cycles

The standard duty cycles for traction power rectifier transformers are specified in IEEE Std 1653.2 and described in 5.2.2.1, 5.2.2.2, and 5.2.2.3.

5.2.2.1 Light traction duty

Light traction duty consists of 100% rated load cycle of the rectifier current in amperes continuously followed by either of the following:

— 150% of rated load cycle of the rectifier current in amperes for 2 h

— 200% of rated load cycle of the rectifier current in amperes for 1 min following 100% rated load

5.2.2.2 Heavy traction duty

Heavy traction duty consists of 100% rated load cycle of the rectifier current in amperes continuously followed by either of the following:

— 150% of rated load cycle of the rectifier current in amperes for 2 h

— 300% of rated load cycle of the rectifier current in amperes for 1 min following 100% rated load

5.2.2.3 Extra-heavy traction duty

Extra-heavy traction duty consists of 100% rated load cycle of the rectifier current in amperes continuously followed by 150% of rated load cycle of the rectifier current in amperes for 2 h including 300% of rated load cycle of the rectifier current in amperes for five equally spaced periods, of 1 min each, followed by final 450% of rated load cycle of the rectifier current in amperes for 15 s. For clarity, see Figure 2 in IEEE Std 1653.2-2009.

5.2.3 Custom duty load cycle

A custom duty load cycle rating may be defined for load cycles not reasonably covered by the standard duty cycles identified in 5.2.2.1, 5.2.2.2, and 5.2.2.3. Custom duty load cycles should be based on traction power load analysis or load duty cycle study results as defined by the IEC or other international standards.

5.3 Winding temperature limits

5.3.1 Traction service load cycles

Winding hottest-spot temperature and average winding temperature shall not exceed the limits given in Table 10 of IEEE Std C57.18.10-1998 for liquid-immersed and dry-type transformers, taking into account the maximum ambient temperature specified.

Traction duty cycles, which typically occur twice a day during the morning and evening rush hours, shall be considered in a transformer design so that operating temperatures do not exceed the temperature limits. The time between these rush hours shall be specified by the owner and provided to the transformer manufacturer to assure that specified hottest-spot temperature limits are not exceeded for the specified operation. Exceeding the temperature limits may cause a loss of life in a transformer.

The hottest-spot temperature shall be determined by calculation or from temperature test data. The average temperature shall be measured by the resistance method in accordance with IEEE Std C57.12.90 for liquid-immersed transformers and IEEE Std C57.12.91 for dry-type transformers and cast coil transformers.

5.3.2 Custom or owner-defined load cycle

The data in Table 10 of IEEE Std C57.18.10-1998 applies to transformers rated to supply the recommended load cycles defined in IEEE Std C57.18.10. For transformers rated to supply a custom load cycle, similar temperature limits are recommended for specification and design.

5.4 Nameplates

In addition to the requirements contained in IEEE Std C57.18.10, traction power transformer nameplates shall show the following additional information:

- Percentage impedance of high to low voltage 1 (H-LV1)
- Percentage impedance of high to low voltage 2 (H-LV2)
- Impedances on a common kilovoltampere base, H-LV1 and H-LV2
- Rectifier transformer type: Dry—Cast Resin/Cast Coil Type, Dry—VPI Type, Dry—Epoxy Encapsulated, or Liquid-Immersed Type
- Primary and secondary voltages of each winding
- Commutating impedance in ohms (phase-to-neutral impedance of each secondary in ohms)
- Coupling factor

6. Design

6.1 Taps

If taps are required by the specification, they shall be provided in accordance with IEEE Std C57.12.00 for liquid-immersed rectifier transformers and with IEEE Std C57.12.01 for dry-type rectifier transformers.

6.2 Impedance

Proper impedance shall be specified by the rectifier manufacturer for the traction rectifier transformer to meet the regulation requirements of the specification, consistent with acceptable short-circuit requirements of the transformer-rectifier unit, and considering all other system impedances.

6.3 Winding connections

Traction transformer connections may be selected from Figure 1 of IEEE Std 1653.2-2009. In addition, circuit numbers 23 and 25, and 25 and 26, may be used in combination for 12-pulse operation.

6.3.1 Three-winding transformers

A three-winding rectifier transformer contains one primary and two secondary windings on the same core leg. The most common is an ANSI circuit 31 configuration in which the two secondaries are displaced from each other by 30 electrical degrees for the purpose of producing a 12-pulse output.

6.3.1.1 Winding configurations

The winding of a three-winding transformer may be configured in the following ways to yield specific characteristics required by the specification:

— Closely coupled

A closely coupled rectifier transformer is one in which the impedance between the two secondary windings at their rated kilovoltampere base is much less than the overall transformer impedance, or the impedance between the primary and each of the secondaries. Closely coupled transformers limit the magnitudes of short-circuit currents, thereby helping to protect the rectifier and systems. The voltage regulation of closely coupled transformers is fairly linear up to 200% to 300% load but becomes non-linear above those values. These windings have coupling factors ranging from 0.8 to 0.9.

— Partially coupled

Partially coupled transformers are built such that there is partial coupling between the two secondary windings, which and exhibit a coupling factor between 0.4 and 0.6. These types of windings are not generally used because they are normally prone to strong axial forces between primary and each of the secondaries.

— Loosely coupled

Loosely coupled transformers have similar characteristics as two independent transformers, much like an ANSI circuits 25 and 26. They exhibit nearly a linear voltage regulation from light transition load levels to a short circuit. Loosely coupled transformers will exhibit high magnitude short-circuit currents due to the overall transformer impedance being only slightly higher than the individual primary to each secondary impedance. Loosely coupled transformers normally have a coupling factor between 0.1 and 0.2.

6.3.2 Windings for auxiliary power

In general, it is recommended that any auxiliary power requirements be met by a separate auxiliary transformer and not by windings integrated within the traction power transformer. The disadvantages of utilizing traction power transformer windings for auxiliary power include the following:

— More complex traction power transformer design.

— A failure of the auxiliary power windings could cause a failure in the main traction transformer.

6.4 Secondary winding voltage, current, and impedance differences

6.4.1 Voltage difference

For three-winding rectifier transformers, the voltage difference between secondary commutating windings shall not exceed 0.28% of the transformer's secondary winding no-load voltage. This voltage difference shall include the permissible voltage distortion limits due to harmonics per IEEE Std 519.

In order to achieve a voltage difference that is less than 0.35% (0.28% plus manufacturing tolerance), compensating transformers may be used. These transformers shall be considered in the calculation of impedance, losses, and other test conditions.

6.4.2 Impedance tolerance and difference

The transformer shall be designed with proper short-circuit and commutating impedance and reactance to meet specified voltage regulation and minimum short-circuit impedance requirements of the transformer-rectifier unit. The standard short-circuit impedance tolerance for two- and three-winding transformers shall be as described in IEEE Std C57.12.00 for liquid-immersed transformers and in IEEE Std C57.12.01 for dry-type transformers.

The impedance of the traction transformer shall be specified by the rectifier manufacturer such as to meet the required voltage regulation.[9] For a three-winding rectifier transformer, the impedance difference between the primary and each of the secondary windings shall not exceed 5%.

6.5 Design optimization

6.5.1 Efficiency

The efficiency of the rectifier transformer for traction power duty shall be based upon the sine-wave winding loss measured, including stray and eddy current losses plus the measured no-load loss at 100% of the full-load rating of the transformer. The winding losses shall be based upon the rated temperature rise plus a 20 °C ambient at 100% rated load. Traction power rectifier transformers rated 500 kVA and below shall be designed with a minimum efficiency of 97.5% when operated at 100% load and 20 °C ambient temperature. Traction power rectifier transformers rated 501 kVA and above shall be designed for a minimum efficiency of 98.5% when operated at 100% load and 20 °C ambient temperature.

Efficiencies at other load points (150%, 125%, 75%, 50%, and 25%) may be specified by the owner.

Transformers with a primary voltage below 600 V (ac) are excluded from these requirements.

If loss-evaluation requirements are included in the specification, then IEEE Std C57.120 should be used as a guide for such loss evaluation.

6.6 Life expectancy and reliability

6.6.1 Life expectancy

The calculated life expectancy of a new transformer shall be a minimum of 30 years. The manufacturer shall provide the life expectancy of the transformer on the basis of load cycle provided by the purchaser, the design temperature rise, and insulation properties per referenced IEEE standards. Life expectancy shall be calculated for the daily (non-contingency) load curve provided by the purchaser.

6.6.2 Reliability

The primary requirement of a traction power transformer is to provide continuous, uninterrupted power for the highly fluctuating power requirements of the rolling stock, without any failure, throughout its life expectancy. This demands a high degree of reliability in performance for the transformer used in dc rapid transit systems. Typically, the replacement cost due to failure of a transformer during commercial operation in a public transit system is high. A list of factors that should enhance the reliability of a traction power transformer is provided as follows:

— Proper selection of the traction power transformer type matching the rectifier design for the intended application consistent with its duty cycle and environment

— Manufacturing design quality

[9] Refer to Annex C for guidance on estimating the inherent voltage regulation from commutating impedance.

— Satisfactory performance of factory and field tests
— Applying protective devices and measures against overtemperature
— Selecting a suitable basic lightning impulse insulation level (BIL)
— Applying protection against overvoltage transients and overcurrents
— Performing proper maintenance

7. Protection

7.1 Overtemperature protection

Transformer winding over temperature protection with two-stage temperature detection (three-stage if fan cooling is provided) for protecting against damage that may result due to over-temperature events is recommended. Protective devices with enhanced capability of recording the maximum temperature and the temperature during a triggered event are also recommended.

7.2 Voltage surge protection

Voltage surges are transient overvoltages with durations of up to a few microseconds. A transient overvoltage due to lightning, switching, or other causes can exceed the insulation rating of the electrical equipment causing degradation of insulation and damage to the equipment. The application of metal-oxide-type surge arresters, with a properly sized BIL level, maximum continuous operating voltage, and nominal operating voltage are recommended on the primary and secondary sides of the transformer.

7.3 Accessories

Designers shall specify accessories in accordance with the following IEEE standards:

a) Liquid-immersed transformers
   1) IEEE Std C57.12.00
   2) IEEE Std C57.12.90
   3) IEEE Std C57.18.10
b) Dry-type transformers
   1) IEEE Std C57.12.01
   2) IEEE Std C57.12.91
   3) IEEE Std C57.18.10

Common accessories for transformers include the following:

— Surge arresters
— Digital temperature recorders
— Temperature/humidity-controlled heaters
— Cooling fans
— Transformer enclosure door-interlocks

7.4 Grounding

Transformers shall be equipped, as a minimum, with two ground lugs, pads, or buses for connection to an earth ground on diagonally opposite sides of the enclosure/tank. The enclosure, transformer core, and any other exposed metal components that are conductive and non-energized shall be bonded to the grounding terminal per IEEE Std C57.12.00 or IEEE Std C57.12.01.

CAUTION

Grounding of the secondary dc side of the transformer shall be avoided to prevent dc stray currents.

8. Testing

8.1 General

The tests listed in Table 1 and Table 2, categorized as routine, design, or other, shall be performed on all traction power rectifier transformers at the factory or certified testing agency. The tests listed in Table 1 are for dry- and cast coil-type rectifier transformers, and Table 2 is for liquid-immersed rectifier transformers. Refer to IEEE Std C57.12.80 for additional detail on the individual tests. The required field tests shall be performed by a certified testing agency and/or owner.

8.2 Routine tests

Routine tests indicated in Table 1 and Table 2 shall be made on every traction power transformer to verify that the equipment meets the product design specification. Routine tests are summarized in Table 1 and Table 2 and listed as follows:

- Resistance measurements of all windings on the rated and extreme voltage tap connections.
- Polarity and phase relation tests on the rated voltage tap connection.
- Ratio tests on the rated voltage and all other voltage tap connections.
- No-load loss and excitation current tests.
- Load loss and impedance voltage tests at ambient temperature.
- Load loss and impedance voltage measurements usually vary with temperature and shall be corrected to a specified reference temperature.
- Commutating impedance shall be measured in accordance with IEEE Std C57.18.10. There is correlation between the per-unit commutating reactance of the rectifier transformer to percentage inherent voltage regulation of transformer-rectifier assembly of an ANSI rectifier circuit configuration.

8.3 Design tests

Design tests indicated in Table 1 and Table 2 shall be performed to determine the adequacy of the design of a particular type, style, or model of traction power transformer or its component parts. Design adequacy includes, but is not limited to, verification of satisfactory operation to meet specified ratings under normal service or special conditions and compliance with appropriate industry standards. Design tests are performed on representative transformers to establish the adequacy of all other transformers of similar type and design. Design tests that have been successfully performed and certified on an essentially duplicate unit should be submitted to the owner for consideration as satisfying the requirements of the present specification.

8.4 Other tests

Other tests indicated in Table 1 and Table 2 may be specified by the purchaser in addition to the routine tests.

Table 1—Dry or cast coil type rectifier transformer tests

Tests	Routine	Design	Other
Resistance measurements	X		
Ratio tests	X		
Polarity and phase relation	X		
No-load losses	X		
Excitation current	X		
Short-circuit impedance and commutating reactance	X		
Load loss	X		
Temperature rise tests		X	X
Overload tests:			
Light traction duty cycle		X	
Heavy traction duty cycle		X	
Extra-heavy traction duty cycle		X	
Custom traction duty cycle		X	
Dielectric tests:			
Applied voltage	X		
Induced voltage	X		
Impulse		X[a]	
Front of wave		X	X
Insulation power factor			X
Insulation resistance			X
Partial discharge	X[b]		X[b]
Audible sound level		X	X
Short-circuit capability			X
Mechanical: lifting and moving devices	X		
Mechanical: sealed transformers			
Pressure test		X	
Leak test	X		
Core ground test-low resistance	X		
Temperature recorder calibration/test	X		
Fan operation test	X		
Thermal shock test		X	X

[a]When an impulse test is required, it shall precede the applied and induced voltage test.
[b]Partial discharge tests may be performed on the windings of all types of dry-type transformers, but they are considered routine tests for transformers above 1.2 kV having solid cast and/or resin encapsulated windings as part of the insulation system.

Table 2—Liquid-immersed rectifier transformer tests

Tests	Routine	Design	Other
Resistance measurements	X		
Ratio tests	X		
Polarity and phase relation	X		
No-load losses	X		
Excitation current	X		
Short-circuit impedance and commutating reactance	X		
Load loss	X		
Temperature rise tests		X	X
Overload tests:			
Light traction duty cycle		X	
Heavy traction duty cycle		X	
Extra-heavy traction duty cycle		X	X
Custom traction duty cycle		X	
Dielectric tests:			
Applied voltage	X		
Induced voltage	X		
Impulse	X		
Front of wave			X
Insulation power factor	X		
Insulation resistance	X		
Partial discharge	X		
Audible sound level		X	X
Short-circuit capability		X	X
Mechanical: lifting and moving devices		X	
Tank pressure test		X	
Tank oil leak test	X		
Core ground test-low resistance	X		
Temperature recorder calibration/test	X		
Operation test of all devices	X		
Oil DGA test	X		X
Oil dielectric test	X		X
Corrosive sulfur test	X		

8.5 Factory testing and calculation

8.5.1 General

Unless otherwise specified, all tests required by IEEE Std C57.12.90 or IEEE Std C57.12.91, and IEEE Std C57.18.10 are required for all applicable dry or liquid-type traction power rectifier transformers. A factory test plan detailing type of tests, sequence of tests, and acceptance criteria shall be prepared by the manufacturer based on specifications provided by the owner prior to testing. The factory tests shall be performed by the manufacturer or an approved testing agency at the manufacturing facility or a recognized and approved testing facility. If the transformer fails during testing or within the warranty period, a new or reconditioned transformer shall be re-tested as if "new" as determined by the manufacturer and the owner. All necessary test equipment utilized for transformer testing shall be in current calibration within the test equipment manufacturer's recommended calibration cycle.

8.5.2 Losses

The total losses of a transformer shall be calculated to be the sum of the no-load and load losses. The load losses shall be based on the reference temperature equal to the rated winding temperature rise plus 20 °C. If required or otherwise specified, the total losses and no-load losses measured by testing a traction power transformer shall not exceed the total losses by more than 6% or the no-load losses by more than 10% of the required losses by contract.

8.5.3 Temperature rise test

The temperature rise test is a test to determine the temperature rise above the ambient temperature of the transformer windings measured at the terminals. For the conditions under which temperature limits apply, refer to IEEE Std C57.12.01 for dry-type transformers and IEEE Std C57.12.00 for liquid-immersed transformers.

The average temperature rise of a winding shall be the average winding temperature minus the ambient temperature. The average temperature of the winding shall be determined by the resistance method. In exceptional cases where the resistance method cannot be performed, other methods may be used with the approval of the owner. For instance, if the temperature rise of the transformer is done in conjunction with the rectifier, it would not be possible to obtain satisfactory resistance readings in a timely manner as the rectifier bussing would need to be disconnected. In this case, a temperature recorder with multiple thermocouples embedded in the top third and in close contact with the secondary winding would be acceptable to obtain temperature values. The thermocouples would, in this case, measure the hottest-spot temperature of the windings. The average temperature rise shall be corrected to the specified ambient temperature, which is usually 30 °C for dry transformers and 30 °C for liquid-immersed transformers. For a new rectifier transformer, the temperature rise and specified overload tests may be performed on a combined transformer and rectifier unit.

8.5.3.1 Temperature rise test and correction factors

In cases where the ambient temperature for temperature rise is not specified but the ambient temperature during test is other than 30 °C, the result of average temperature rise shall be corrected per the procedures described in IEEE Std C57.12.90 and IEEE Std C57.12.91 for liquid and dry-type transformers respectively.

If the current used in the temperature rise test differs from the rated current, and location of the test exceeds 1000 m above sea level, a correction of the winding temperature rise is required in each case. All test procedures and correction procedures shall be applied per IEEE Std C57.12.90 and IEEE Std C57.12.91 for liquid and dry types, respectively.

The following test pre-requisites shall be applied for the temperature rise test:

a) Prior to temperature rise tests, transformers shall be completely assembled with temperature indicators/recorders or other accessories within the enclosure. Liquid-immersed transformer tanks shall be filled to the proper liquid level.

b) The temperature rise tests shall be made in a draft-free location. All temperature rise tests shall be performed under normal conditions and normal mode of cooling.

c) When transformers are equipped with fans, two temperature rise tests shall be made. One test shall be at self-cooled rating and the other shall be at the maximum fan-cooled rating.

d) Temperature sensors may be thermocouples, resistance temperature detectors, thermistors, thermometers, or other suitable devices. Use of thermocouples is the preferred method of measuring surface temperature.

e) The average temperature of a winding on the primary or secondary side shall be determined by the equations provided in IEEE Std C57.12.91 for dry-type and cast coil transformers.

8.5.4 Dielectric tests

Dielectric tests shall be performed to demonstrate that the traction power rectifier transformer has been designed and constructed to withstand the impressed voltages experienced at the specified insulation level. Unless otherwise specified, the dielectric test voltages, measurement and application, and procedure shall follow the methods set forth in IEEE Std 4. Prior to performing dielectric tests including impulse tests, transformers shall be fully assembled with its enclosures and any terminal compartments. The dielectric tests to be performed on the transformers and bushings shall follow IEEE Std C57.12.90, IEEE Std C57.12.91, and IEEE Std C57.18.10. For guidance on the test voltages for different dielectric tests, interrelationships of nominal system voltages, and BIL levels, the specific tables in IEEE Std C57.12.00 and IEEE Std C57.12.01 for liquid-immersed and dry transformers, respectively, shall be followed.

8.5.4.1 Applied voltage tests

The applied voltage tests shall be performed on all windings by applying low frequency ac voltages from an external source, between the winding under test and all other windings connected to ground, or between one winding to ground while other windings are also connected to ground. A normal power frequency test voltage, such as 60 Hz, shall be used for duration of one minute. During these tests, the transformer enclosure, tank, core, and grounded terminal of the testing transformer shall be connected to same reference ground.

8.5.4.2 Induced voltage tests

The induced voltage test shall be applied for 7200 cycles but the duration shall not exceed 60 s. Table 3 provides guidelines for frequency and test duration. The test frequency is selected according to the applied voltage so that no core saturation occurs. The induced test voltage is impressed across the terminals of a suitable transformer winding at a value of two times the rated voltage of the winding.

Table 3—Induced voltage test frequency and duration of test

Test frequency	Duration of test (seconds)
120	60
180	40
240	30
360	20
400	18
900	8

8.5.4.3 Impulse tests

8.5.4.3.1 General

Impulse tests shall be performed on all dry and liquid-type traction power rectifier transformers when specified. Prior to impulse tests, the transformer shall be fully assembled, including its enclosures, buses, and any other terminal compartments. The impulse test techniques, interpretation of charts, oscillograms, or other digital failure detection criteria shall follow IEEE Std C57.98. The impulse tests shall be performed on each coil in the following sequence or order:

a) One reduced full wave (calibration shot)

b) Two chopped waves

c) One full wave

The tests shall serve the purpose of verifying that the manufacturing design clearances between phase terminals, buses, bus compartment, insulators, energized parts, and the grounded enclosure are suitable for the BIL ratings of the transformer. Impulse tests also demonstrate that the insulation and air clearances within the transformer and its enclosure will withstand impulses that lie below the volt-time curve of the specified BIL level. When a lightning disturbance travels some distance along the line, or an overvoltage transient develops within the vicinity of the transformer, its waveshape may approach that of the full wave; that is, a wave that is generally referred as 1.2 × 50 µs. This wave rises from zero to crest value in 1.2 µs and then decays to half of the crest value at 50 µs.

The time interval between the application of the last chopped wave and the final full wave shall be minimized to avoid recovery of the insulation system. IEEE Std C57.12.90 and IEEE Std C57.12.91 shall be used as reference for the detailed description for impulse testing.

8.5.4.3.2 Test voltage-wave polarity

For liquid-immersed traction power transformers, the test waves are normally of negative polarity. For dry-type transformers, the test waves are of positive polarity.

8.5.4.3.3 Electronic isolation

Prior to impulse tests, electronic accessories attached to the transformer, namely, digital temperature recorder and metal-oxide varistor -type surge arresters, shall be isolated.

8.5.4.3.4 Acceptable tolerance

The acceptable tolerance for impulse tests is as follows:

a) The reduced full wave impulse test (calibration) shall have a crest voltage value equal to 50% to 70% of rated BIL (full wave value).

b) The full-wave test crest voltage shall be within a tolerance of ±3% of the specified BIL level (recorded per oscillogram/chart or digital transient recording equipment). See IEEE Std C57.12.91 for determination of the crest level when oscillations exist at the crest.

c) During the full wave test, the tolerance on time to crest shall be within a tolerance of ±30% of 1.2 µs or the range 0.84 µs to 1.56 µs, and time to half crest value shall be within a tolerance of ±20% of 50 µs or the range 40 µs to 60 µs.

d) For chopped wave tests, the minimum time to flashover, in microseconds, shall be per the tables in IEEE Std C57.12.00 or IEEE Std C57.12.01 for dry and liquid types, respectively, and in accordance with specified BIL levels referred to in those tables.

8.5.4.3.5 Impulse test reports

Test reports shall include impulses applied to a traction power transformer with a documented ID and sequence, serial number of the tested transformer, test date, crest value, and the measured time of the impulses recorded. The waveshapes, which are recorded by an oscilloscope or by a suitable digital transient recorder, shall include voltage oscillograms for all impulses and ground-current oscillograms for all full-wave and reduced full-wave impulses. The ground-current record is not required for chopped wave tests.

8.5.4.4 Partial discharge (PD) test

PD in the insulation system of a traction power transformer occurs when a void or foreign material such as moisture is present in the insulation system. It can also occur at a location where damage or cracking in the insulation of the dry- or cast-resin-type transformer has occurred. This type of discharge can cause further degradation of the insulation in its vicinity and lead to eventual failure of the transformer.

All dry-type traction power transformers, particularly cast coil transformers, shall be tested for PD. The PD tests for all dry-type transformers, including cast coil, are considered routine tests for all transformer capacities. Reference is made to IEEE Std C57.124 when testing dry-type transformers. See IEEE Std C57.12.01 and IEC 60076-11 for testing requirements, pre-stress voltage levels, and PD limits for open dry-type, resin encapsulated, and cast coil transformers. The limits shall be 50 pC for open wound and resin encapsulated transformers and 10 pC for cast coil transformers.

Liquid-immersed transformers shall be tested if specified by owner or for transformers 501 kVA or larger. The PD test for liquid-immersed transformer shall be per the requirements of IEEE Std C57.12.00 and IEEE Std C57.12.90 with limits set therein. The PD tests shall be performed on a fully assembled transformer.

The following list provides the general procedure for testing PD in a transformer:

a) Transformers shall be tested for PD by employing the picocoulomb measurement method. When the test equipment is completely installed, test for PD within the test stand itself after removing the test element from the circuit.
b) If the test stand measures less than or equal to 5 pC of PD at and below the maximum test voltage, the test stand shall be considered PD-free.
c) The oscilloscope/digital display and measuring device shall be calibrated by means of a standard reference calibrator of known PD prior to PD tests on the transformer.
d) Use an alternate voltage source having a frequency that allows the test to be performed up to 150% of the nominal high-voltage primary of the transformer under test on the highest tap without the possibility of saturating the core of the transformer under test.
e) Background noise level within the controlled test area during PD measurement should be zero or less than 10 pC, but less than 5 pC if testing a cast coil.
f) Prior to tests, check for solid grounding connection of all conducting objects in the high-voltage field, otherwise high noise level may affect the test result.
g) All objects that have sharp points or corners on the transformer should be smoothed or shielded prior to a successful PD test. All electrical testing connections shall be clean and secure.

8.5.4.5 Insulation-power-factor tests

Insulation power factor is the ratio of the power dissipated in the insulation in watts to the product of the effective voltage and current in volt-amperes when tested under a sinusoidal voltage and prescribed conditions.

The methods described in IEEE Std C57.12.90 are applicable to liquid-immersed traction rectifier transformers, and the methods of IEEE Std C57.12.91 are applicable to dry-type traction rectifier transformers.

8.5.5 Short-circuit tests

A short-circuit test is a design test and, when specified, shall be performed on a traction power transformer. Short-circuit tests of traction power rectifier transformers may be performed as short-circuit tests of the entire transformer and rectifier line-up. The short-circuits tests on the transformer shall be conducted as described in IEEE Std C57.12.90 for liquid-immersed transformers and IEEE Std C57.12.91 for dry-type transformers.

a) The symmetrical short-circuit current shall be calculated based on the combined values of the transformer impedance and a value of the system impedance and system megavoltampere (MVA) available at the transformer, specified by the owner and or based on a system traction power analysis.

b) When specified, or when the system impedance is known to be negligible, the symmetrical short-circuit current shall be calculated using the transformer impedance only.

c) In any case, the short-circuit current magnitude and duration shall not exceed 25 times rated current and 2 s, respectively.

d) The transformer impedances shall be measured before the test and immediately after the test. The transformer has passed the test successfully if the impedance values before and after the test do not deviate by more than ±2% for circular coils and ±5% for rectangular coils, there is no visible mechanical damage, and the transformer passes routine dielectric testing after the short-circuit tests.

8.5.6 Thermal shock test (optional—design/conformance)

Thermal shock tests shall be performed on a dry-type traction power transformer particularly cast coil and epoxy resin encapsulated type transformers when specified. It is a design environmental test specific to traction duty applications. The thermal shock test verifies that when transformer coils are exposed to extreme weather cycles (namely, −25 °C to 35 °C) they are suitable for traction duty load cycling (rapid heating and cooling of the windings with traction duty cycle) without degradation or cracking of the epoxy or any other solid insulation system of the transformer coils, which could result in moisture ingress and PD. The thermal shock tests shall be performed per IEC 60076:11 and the following guidelines or per the owner's contract specification. The test shall be carried out on a complete transformer without an enclosure. The transformer shall be tested within the temperature-controlled chamber. If the transformer is for an application where it would be exposed to a minimum ambient temperature of −25 °C during its operation, storage, or transport, the thermal shock tests are carried out at −25 °C. Otherwise, the thermal shock tests are carried out at −5 °C when the transformer is exposed to an ambient temperature not below −5 °C during operation but could be exposed to a temperature as low as −25 °C during transport or storage. The following are the guideline steps for the thermal shock tests:

a) The air temperature inside the chamber shall be gradually decreased to −25 °C ± 3 °C in about 8 h and kept until a steady state condition is reached in the cold chamber.

b) The temperature shall then be gradually raised up to −5 °C ± 3 °C in about 4 h and kept at this temperature until a steady state is reached inside the cold chamber.

c) A thermal shock is then provided by applying a current equal to twice the rated current of the transformer winding under test, while the other windings are short circuited. The current shall be maintained until the winding under test reaches the average temperature corresponding to the specified average temperature rise for the transformer plus 40 °C (maximum ambient temperature).

d) The temperature in each of the windings is monitored by calibrated temperature sensors installed near top and bottom of the transformer winding.

e) After the thermal shock test, the transformer shall be restored to a temperature of 25 °C ± 10 °C.

f) After the temperature is stabilized, the transformer shall be subjected to visual inspection, routine dielectric tests, and PD tests to check for cracking or failure of the insulation system of the transformer.

8.5.7 Insulating fluid tests

The fluid in liquid-immersed transformers has several requirements that shall be tested and certified before use in the transformer. Mineral oil is the most common liquid used.

The oil samples drawn from a liquid-immersed traction power transformer shall be tested in a certified laboratory for several requirements including dissolved gas analysis (DGA), dielectric breakdown voltages, and the presence of corrosive sulfur after completion of all factory tests. Incipient faults in the transformer, either thermal or electrical, may cause degradation of the oil and cellulose insulation resulting in the formation of dissolved gases. These faults can be detected and monitored through a DGA. Corrosive sulfur in the insulating oil is undesirable as it may lead to premature winding failures. The referenced ASTM and IEEE standards shall be followed for test guidelines and acceptance criteria. The transformer oil that is being used shall be tested and certified to be polychlorinated biphenyl (PCB)-free.

8.5.8 Transformer core effective grounding and insulation resistance test

The effective grounding of the transformer core is tested by measuring resistance using a low-resistance ohm meter (milliohm meter). One end of the meter's test probe is connected to the grounding strap or grounding cable of the transformer core and the other end to the transformer ground terminal. The acceptable value shall be less than 100 mΩ, however, because of size and structural variations, the actual determination as to whether the core is effectively grounded shall be made by the responsible engineer. The core insulation is tested by a megohm meter with test voltages not exceeding 500 V. The insulation resistance is checked between the core and the transformer phases.

8.5.9 Temperature recorder calibration and overtemperature tests

The specified set points for high temperatures shall be verified and set on a digital temperature recorder/controller for the transformer. Specified values for the transformer's high temperature alarm point and breaker trip point are set after calibrating the digital meter. Tests and calibration of the temperature recorder/controller are done by simulating the specified temperature set points at the factory.

When the transformer fan cooling is specified, the temperature recorder/controller shall be tested and calibrated for a fan-cooling temperature set point.

8.5.10 Fire/toxic gas emission (optional—design/conformance) test

When specified, these tests shall be performed to check the emission of corrosive and harmful gases that may be present in the combustible material of the dry-type transformer for an application in a confined space. The tests detect the presence of any component such as formaldehyde, sulfur dioxide, and other halogenic compound (HCL, HCN, HF, HBr, etc.). The tests shall be per IEC procedure or a procedure agreed upon between the supplier and owner.

8.6 Factory test sequence

After successful performance of all routine tests, the transformer shall be subjected to a sequence of tests starting with temperature rise tests and specified overload tests followed by impulse tests per indicated ANSI/IEEE sequence. Applied tests, induced tests, or PD tests shall be performed following the impulse tests if impulse tests are required. For liquid-immersed traction power transformers, insulating fluid tests shall be performed after all other specified factory tests are done on the transformer.

8.7 Factory test report

The factory test report containing transformer ID/serial number, test-procedure, actual inspection results, test data, supporting charts/oscillograms with acceptable criteria, and test dates with signature of the qualified testing authority/agency shall be provided and maintained for future maintenance record. When specified, the report shall include transformer efficiencies, which shall be calculated at specified loads and measured temperature rise.

8.8 Field inspection and field tests

8.8.1 General

Requirements of field inspections and tests, which shall be performed by owner before and after installation, during commissioning and maintenance of a new traction power transformer, repaired transformer, or reconditioned transformer, are given in 8.8.2, 8.8.3, and 8.8.4.

8.8.2 Pre-energization check/inspection

The items to check prior to the initial energization of a transformer include the following:

a) Visual inspection shall be performed on the unit upon arrival to determine if any signs of damage or rough handling occurred during shipment and handling. If an impact recorder was included in the shipment, it shall be checked to see if rough travel has occurred. Dry-type and cast-resin coils shall be checked for dents or damage on the epoxy resin castings to verify that no damage has occurred, which would make the coils vulnerable to unacceptable or increased PD. After locating to final location, installation tests shall be performed to verify usability.

b) Check for safety labels, namely, that voltage shock hazard and arc-flash hazard warning labels per NFPA 70E are visibly installed on the front side of the transformer enclosures.

c) Verify that transformer tank, enclosure, surge arresters, core grounding connections, and ground buses are properly bonded to the system ground.

d) Verify that all transformer protective devices, sensors, alarms, door interlocks, temperature indicators, cable terminations, and cooling fans, if any, are in order and fully operational.

8.8.3 Field tests

8.8.3.1 General

All necessary test equipment shall be calibrated and within the manufacturer's calibration cycle prior to performing field tests.

8.8.3.2 Insulation resistance test

The insulation resistance tests are usually performed to check the state of dryness and whether the transformer winding insulation system is of acceptable value, or its readiness to be subjected to further applied voltage tests. Though the insulation tests are of value for previous and future comparative purposes, it is sometimes misleading to make any definite conclusion regarding some flaws in the insulation until further tests are performed. For instance, the tests may reveal hidden bushing damages. The test data shall be recorded with temperature and humidity at the time of measurement. The insulation resistance test is performed per IEEE Std C57.12.90 and IEEE Std C57.12.91 for liquid and dry transformers.

8.8.3.3 Applied voltage test

Both dc and ac sources of voltages are acceptable. Test methods are described in IEEE Std 4, IEEE Std C57.12.90, and IEEE Std C57.12.91. Field installation tests using ac test equipment shall be limited to 75% of factory test voltages or manufacturer's recommended voltages. If dc test equipment is used, the test voltage shall not exceed rms test voltages for factory tests. The maintenance tests are performed at 65% of factory test voltages.

8.8.3.4 Turns ratio test

The ratio tests are performed per IEEE Std C57.12.91 and IEEE Std C57.12.90 for dry and liquid transformers, respectively.

8.8.3.5 Insulation power factor/dissipation factor test

The insulation power factor/dissipation factor (tan delta) test is performed on liquid-immersed transformers. It is a dimensionless ratio—a measure of the dielectric loss expressed in percent, which indicates the condition of insulation. A high loss may indicate deterioration or contamination of the insulation by moisture, chemical substances, or physical damages.

Insulator bushings for the transformers are also tested for insulation power factor as with the transformer. High power factor readings are indicative of bad bushings. Previous test data may be used to evaluate the test results. If it is determined that an insulator bushing or bushings are bad, they may be repaired or replaced in the field.

8.8.3.6 Insulating oil test

Liquid-immersed transformer oil is tested for water content, DGA, dielectric strength, and corrosive sulfur. These tests shall be performed if the transformer oil is new, stored for long periods of time, suspected of contamination, or required as a routine maintenance test for condition monitoring during operation. The collected oil samples from the transformer are tested in a recognized laboratory. ASTM D2945-90(2003)e2 and IEEE Std C57.104 shall be followed for test guidelines and acceptable criteria.

8.8.3.7 Overtemperature annunciation/fan cooling/trip test

Verify the proper operation of all devices.

8.8.3.8 Core effective grounding and insulation resistance test

Follow the procedure given in 8.5.8.

8.8.3.9 Tank/enclosure/surge arresters grounding/bonding check

Verify that all parts of the tank/enclosure are properly bonded to earth ground. Also verify that all surge arrestors are directly bonded to earth ground.

8.8.3.10 Phase sequence/voltage level and unbalance check (post-energization)

Check that the phase sequence, frequency, and voltage level are the same as indicated on the nameplate of the unit. If possible, the secondary voltage(s) should be checked to verify that any voltage unbalance is within tolerance limits.

8.8.3.11 Infrared inspection (post-energization)

After the transformer is energized, infrared inspection is performed by a thermal imaging camera on the transformer, its bus connections, terminal board, and high-voltage and low-voltage side cable terminations to check for excessive heat loss or thermal anomalies. Poor connections and cable termination, excessive stray flux, or other potential problems that would cause eventual failure of the transformer may be revealed by an infrared thermal scanning camera. The record of thermal images after first installation and commissioning of the transformer shall be used for subsequent analysis and corrective action.

8.8.3.12 Ping test (optional)

If the ping test is performed, the surge test does not need to be performed. This test is performed to check the waveform at the transformer terminal during a transformer circuit-breaker (vacuum interrupter type) switching operation without actually energizing the transformer from incoming high-voltage supply. This test also confirms whether the system is a candidate for a snubber device, which is used to limit the overvoltage transient on the transformer.

See Annex B for details on the ping test.

8.8.3.13 Surge test (optional)

The following list provides information on how a surge test is performed:

a) The transformer and rectifier are energized from the high-voltage supply source at rated voltage with no load.

b) The transformer and rectifier are then de-energized by switching off the transformer primary circuit breaker.

c) Voltage waveforms and amplitudes are recorded by digital oscilloscope/meters before and during switching operation at the transformer terminal as well as the rectifier output.

d) Tests are repeated several times to check maximum voltage transient due to transformer breaker switching.

8.8.4 Field test reports

Field inspection and tests for rectifier transformers are summarized in Table 4. A test report shall contain the transformer ID, serial number, test procedure, actual inspection results, test data, supporting charts and oscillograms with acceptance criteria, and test dates with signature fields of the qualified testing authority/agency.

Table 4—Field inspection and tests for rectifier transformers

Inspection/tests	Dry-type transformer	Liquid-type transformer
Visual inspection for impact, damage, dent	X	X
Tank oil leak check		X
Tank/enclosure corrosion check	X	X
Safety warning labels	X	X
Grounding connection check/test	X	X
Check for accessories/surge arresters/ protective devices/cooling fans	X	X
Insulation resistance test	X	X
Applied voltage test	X	X
Turns ratio test	X	X
Insulation power factor/dissipation factor tests		X
Insulating oil tests		X
Grounding/bonding resistance tests	X	X
Overtemperature annunciation/trip/ fan cooling set points	X	X
Post-energization tests:		
Phase sequence, voltage level and voltage unbalance tests	X	X
Infrared inspection	X	X
Ping test (optional)	X	X
Surge test (optional)	X	X

Annex A

(informative)

Design considerations for transformer specification development

A.1 Application guidelines

A.1.1 General

The factors given in this annex should be considered before developing a design specification for the manufacturing and application of a traction power transformer for a public, rapid transit system; the transformer needs to be cost-effective on the basis of life-cycle cost and an optimum level of reliability in a public transit application.

A.1.2 Life cycle costs

The transformer life cycle cost or total ownership cost should be determined based on loss evaluation guidance in IEEE Std C57.120. Alternatively, the following procedure may be used for loss evaluation and to determine the life cycle cost of a traction power transformer:

a) Because the transformers are required to meet the fluctuating traction power demand, the designer of the transformer specification should provide the information to manufacturers regarding planned operation duration in hours-per-year no-load operation and expected operation at power demand at several transformer loadings, namely, at 50%, 100%, and specified overload cycle of rated power. This data also may be used during the traction power system simulations and load-flow studies.

b) If loss evaluation is required by the owner's specification, costs for no-load and load losses shall be given to the manufacturer for use in the design. The transformer manufacturer shall not be responsible for interpreting the cost standards of the owner.

c) The manufacturer should be required to provide in their bids the transformer no-load losses and load losses at the same power demands as indicated in item a), i.e., 50%, 100%, and required traction power overload duty cycle of the transit system.

d) Based on the losses and their duration, the total annual energy loss (efficiency) of the transformer can be determined. Using the equation in the specification, the manufacturer/owner can calculate the present worth of the transformer losses over the transformers expected life. Estimated no-load and load losses of the transformer and cost of losses will be required to be presented in the manufacturer's bid for claimed transformer's efficiency. When the transformer is tested, the contract specification should require the owner to verify the quoted no-load and load losses at loadings indicated earlier through specified tests.

e) The life expectancy of the transformer over which the life cycle cost should be calculated is recommended to be 30 years. The expected life of the transformer with number of years shall be shown in the mathematical model of the present-worth loss calculation.

f) Minimum operational failures, low life-cycle cost, and reliability are key factors for a highly regulated and generally cash-strapped public transit agency. Therefore, cost of testing and maintenance, any replacement or repair cost, and cost of outages due to failure of a transformer during its life expectancy shall be added to the present worth of losses and purchase price of a transformer to calculate total ownership cost of the transformer.

A.2 System overvoltages and transformer failures

A.2.1 General

Transformers in traction power duty may be exposed to voltages over normal operating voltages. These overvoltages may be classified as follows:

a) Temporary overvoltages

b) Transient overvoltages

c) A combination of both temporary and transient overvoltages

The duration of temporary overvoltages within the existing service power frequency may be a few seconds or longer. A transient overvoltage usually lasts for a period ranging from less than a micro second to a few milliseconds. These transient overvoltages may be oscillatory or non-oscillatory type. A transformer may be exposed to just transient overvoltages or a combination of temporary and transient overvoltages.

Prior to specifying a traction power transformer for a typical transit application, a computer based system power analysis, especially an electromagnetic simulation with the Electro-Magnetic Transients Program (EMTP), should be performed. The simulation should be based on system data to determine whether the transformer would be subjected to overvoltage transients because of an undesirable X/R ratio with available high voltage incoming supply characteristics, harmonics spectrum, dv/dt, or susceptibility to ferromagnetic resonance effects due to weaknesses in specific system configurations. If the study determines that a snubber device should be incorporated, the transformer should be specified by the system engineer to have a provision for required space in the transformer assembly prior to manufacturing. After installation of the transformer, a ping test in the field should confirm the effectiveness of the properly sized snubbers in a system; especially a system equipped with a breaker having a vacuum interrupter or SF6 interrupter on the transformer primary, which may contribute undesirable transient recovery voltage (TRV) causing overvoltage transients on the transformer during circuit breaker interruptions.

A.2.2 Overvoltages caused by lightning

These are transient overvoltages mostly due to lightning strike directly on the equipment or to the ground near electric power lines connected to the transformer. The distance between the transformer and the striking zone influences the front time of the surge that strikes the transformer—the shorter the distance of the striking zone from the transformer, the shorter the front time of the transient overvoltage.

A.2.3 Overvoltages caused by ground faults

A ground fault on any phase may result in phase-to-ground overvoltages, which would affect the other two phases. An ungrounded ac power system, typical for a traction power transformer application where the secondary side is usually ungrounded, is quite vulnerable to such overvoltages resulting from phase-to-ground faults. Overvoltages due to ground faults in an ungrounded system could be amplified due to resonant effects; resonance may occur when the reactance due to inductive elements in the system approximates the summed values of distributed capacitive reactance of the transformer windings, bus runs, insulators, bushings, etc. An effectively grounded system generally provides sufficient damping for these transient overvoltages.

A.2.4 Overvoltages due to ferroresonance

Ferroresonance may develop in a system with magnetizing inductance of the transformers (during no-load condition, switching of the rectifier transformer from full load to no load, or low-load condition) and large capacitance of the lines, cables, or distributed capacitance of the ungrounded system. Any malfunction on the part of a circuit-breaker operation, blown fuse on one or two phases, or damaged phase due to ground fault also may cause overvoltages due to ferroresonance.

A.2.5 Overvoltages due to re-striking or higher transient recovery voltages (TRV)

If the system is inductive or capacitive, then a TRV of higher magnitude and frequency may cause a vacuum breaker to re-ignite during the interruption of current as the breaker is opened. The problem compounds in a typical traction power system with ungrounded transformer winding configurations and periods of lightly loaded conditions, breaker speed, and current chopping time during opening operation.

TRV value may have higher potential for breakers to re-strike. If the voltage increases at a rapid rate, the vacuum breaker for the transformer in a system with higher TRV may also flash over or re-strike. This re-strike or re-ignition may produce oscillatory-type overvoltages on the transformer windings. The frequency, waveform, and duration of the oscillatory voltages control the severity of challenges to transformer windings causing a degree of failures. Systems with large capacitive reactance between the breaker and the transformer are usually not affected by the breaker re-ignition.

A.2.6 Preventive measures from transient overvoltage failures

A.2.6.1 Application of surge arresters

Installing metal-oxide varistor-type surge arresters on transformer terminals provide a first line of defense against such line-to-ground transient overvoltages on transformer winding structures, but they do not provide full protection.

A.2.7 Application of snubber device

Addition of a properly sized resistor-capacitor (R-C) snubber device on the terminals of a transformer is a cost-effective solution. Snubber circuits usually contain a capacitor, resistor, and protective fuse. The addition of this capacitor increases the capacitance of the load and the transformer and reduces the high frequency of the TRV. It keeps the oscillatory voltage out of the range of transformer's natural frequency for resonance. The resistor has the damping effect on the oscillatory voltage on the transformer. The resistor value should be chosen such that it balances damping effect and losses during normal operation.

A.2.7.1 Operational procedures

Transit operational procedures should minimize switching events on the rectifier transformers' vacuum breakers, which cause opening of the transformer breakers in unloaded conditions. Also, procedures should avoid frequent running of the rectifier transformers on no-load or lightly loaded conditions where system conditions are conducive to the occurrence of transient overvoltages.

A.3 Other application criteria

Other factors that shall be considered by the designer for a specific application of the traction power transformer include the following:

a) Matching of transformer/rectifier characteristics with the correct ANSI circuit configuration as well as proper choice of short-circuit impedance and voltage regulation.

b) Environment-specific application, choice of transformer type, and enclosure selection.

c) Required BIL level for the transformer voltage class and traction power duty cycle.

d) Operational reliability.

e) Incoming utility power source and traction power system characteristics studies with available fault current, X/R ratio, and harmonics spectrum for the particular application.

f) Quality assurance and reliability verification through specified testing program.

g) Requirements for traction power transformer characteristics to be suitable for parallel operation.

h) The cooling and ventilation system of the installed transformer on the traction power duty cycle shall be sufficient to maintain ambient air temperature below the specified maximum limit.

i) Limitation of noise emission outside the installed area.

j) Probable risk and consequences of fire originating in the transformer or outside with preventive measures to contain or inhibit the fire.

Annex B

(informative)

Ping test

B.1 Purpose

B.1.1 General

Ping ests are performed to induce breaker re-ignition transients under realistic system conditions. It is well recognized that breaker contact re-ignition occurs during the very initial stages of contact separation. As the contacts of the circuit breaker separate, they draw an arc and a high frequency current flows in the system. The arc between the breaker contacts can go out only as the current cycles through zero magnitude. This voltage buildup breaks down the breaker contact gap since the breaker contact is still in motion and is in the process of separating. This re-ignition process continues and repeats itself until the contacts are sufficiently apart and the gap cannot be reignited by the recovery voltage.

The rate of rise of the recovery voltage transients is a function of the inductance and capacitance of the system. Depending upon the natural resonance frequencies of the transformer windings, these re-ignition transients can be magnified hundreds of times resulting in a failure of the transformer windings. The simultaneous occurrence of re-ignition transients on both ends of delta-connected windings typically result in excessive voltage buildup at the midpoint of the winding, resulting in flashovers at these locations. Lightning arresters are generally not effective in protecting the transformer against these types of disturbances.

This destructive transformer/breaker interaction is a function of system parameters on the downstream side of the circuit breaker. It is also recognized that due to the statistical nature of the breaker re-ignition, the mathematical modeling of a typical system is complicated and expensive. It therefore can predict this destructive interaction only with marginal reliability.

As an alternative to the mathematical modeling, direct current interruption tests (ping test) offer an effective alternative for evaluating the presence of breaker re-ignition transients and demonstrating the effectiveness of the corrective means (snubbers) provided for eliminating these transients.

B.1.2 Breaker re-ignition

The causes of breaker re-ignition transients can be understood by considering a simple system consisting of a transformer connected to a generator through a cable and a circuit breaker as shown in Figure B.1.

Opening the vacuum circuit breaker (VCB) to interrupt the current flowing in the system traps energy in its inductive and capacitive components. This results in a recovery voltage transient Trv1 across the breaker contacts as shown in Figure B.1. The rate of rise of this transient is dependent upon inductive and capacitive elements of the system. In the initial stages of the contact separation, the Trv1 transient breaks down the contact gap and a current I1 flows across the gaps. The arc across the gaps disappears when this current reaches its natural zero. At this point, a second transient Trv2 appears and again breaks down the breaker contact gap since they are still in the process of separating. This cycle continues until the breaker contacts separate far enough to a point where the recovery voltage transients cease to arc between the contacts.

Interrupting relatively larger magnitudes of currents produce larger magnitudes of current cycles that take longer to reach their current zeros or current chopping levels. In the meantime, the breaker contacts can separate far enough so that the recovery voltage transient cannot break them down, and thus, the re-ignition process cannot continue. Therefore, interrupting light load is more likely to produce breaker re-ignitions as compared to interrupting relatively larger loads.

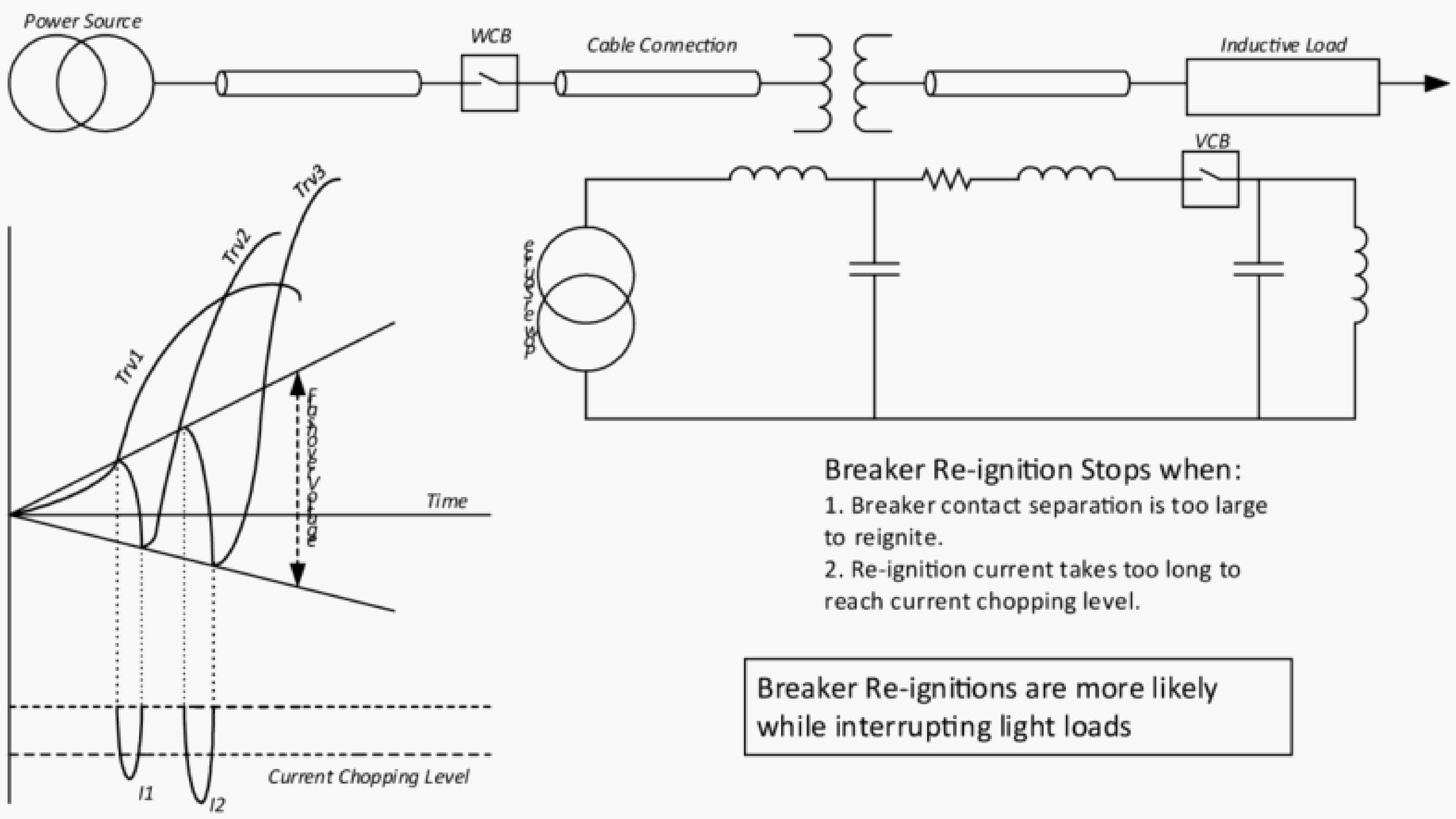

Figure B.1—Typical circuit with vacuum circuit breaker (VCB) connected to inductive load

The repetitive re-ignition of the breaker contacts can induce part winding resonance in transformers resulting in voltage stresses that are far beyond the voltage withstand capability of the winding insulation.

B.1.3 Current chopping

During the breaker re-ignition, the current is sometimes instantaneously reduced to zero as it reaches a threshold value known as the current chopping level. This current chopping level is generally dependent upon the material of the breaker contacts. This sudden current chopping results in high-frequency transient Trv3 and sudden collapse of voltages as shown in Figure B.2.

The sudden collapse of voltages can cause stress accumulations within the windings, resulting in insulation failures.

B.1.4 Ping test procedure

Ping tests are performed by setting up a dc flow with batteries through one of the phases of the transformer and its high-voltage winding side system, including the breaker and the cable connections, and then interrupting it with the circuit breaker. The secondary side of the unit is connected to its load components to simulate realistic system conditions as much as possible. The dc flow through the system traps energy in the inductive and capacitive elements. Interrupting the current flow with the circuit breaker generates realistic breaker re-ignition transients similar to the ones shown in Figure B.1 and Figure B.2. The dc voltage applied to the ping circuit is incrementally raised after each breaker interruption until a point is reached where re-ignition starts to decrease.

These transients may be observed by monitoring line-to-ground and tap-to-ground, and line-to-tap voltages as shown in the typical circuit diagram in Figure B.3.

B.2 Mitigation of breaker transients

The causes and effects of breaker-induced transients are well recognized in technical literature. The effectiveness of snubber circuits in protecting the transformers from these transients is also well understood.

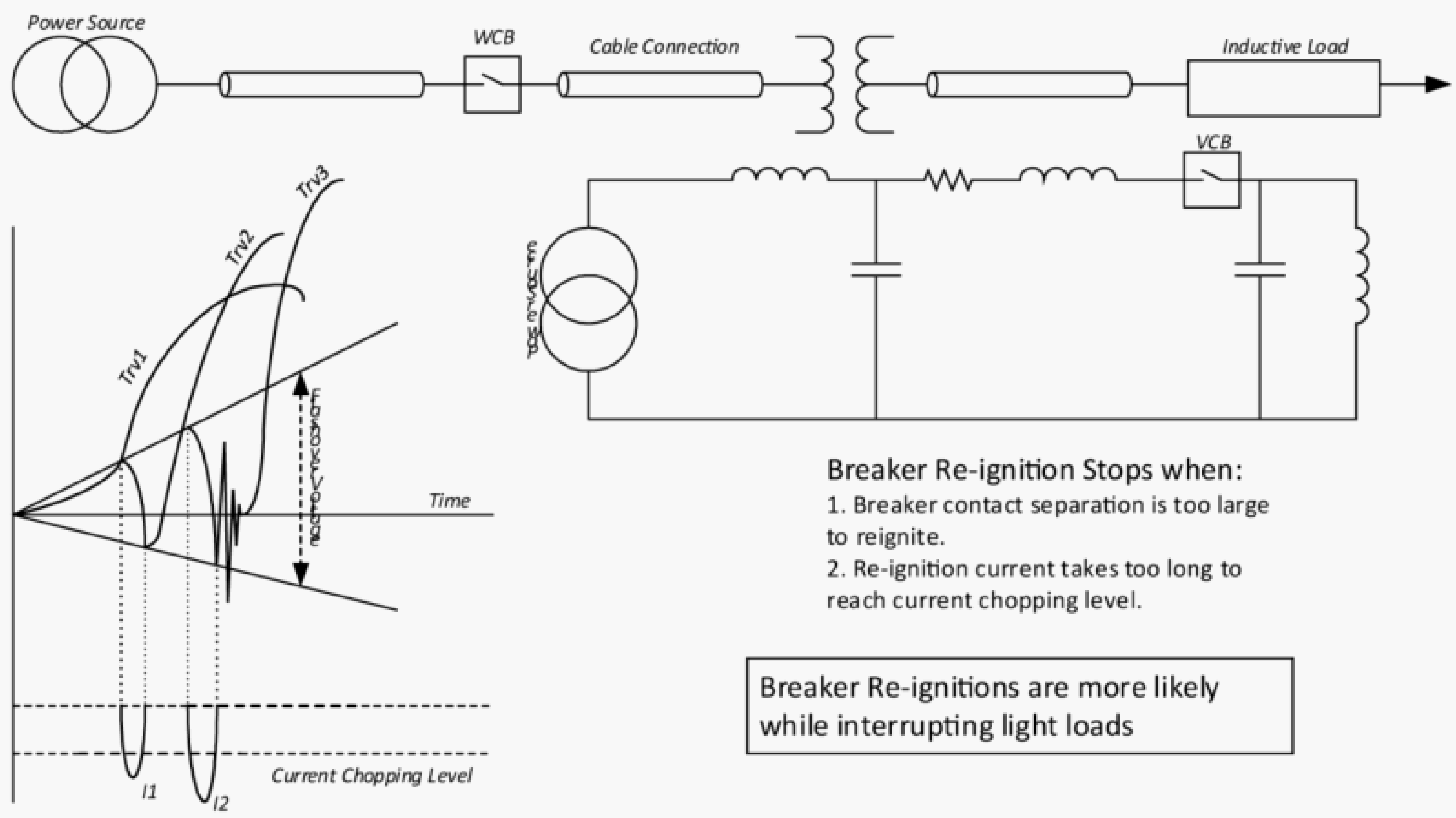

Figure B.2—High-frequency voltage transients due to current chopping by vacuum circuit breaker

In order to be effective, snubbers should be applied as close to the transformers as possible. The resistors and the capacitors as shown in Figure B.4 have to be sized properly depending upon the characteristic impedance of the cable connection between the breaker and the transformer.

It is believed by some breaker experts that indiscriminate use of snubbers can in rare cases result in creating destructive transformer/breaker interaction instead of preventing it. It is therefore prudent to check the effectiveness of the snubbers through performing ping tests with and without snubber circuits connected.

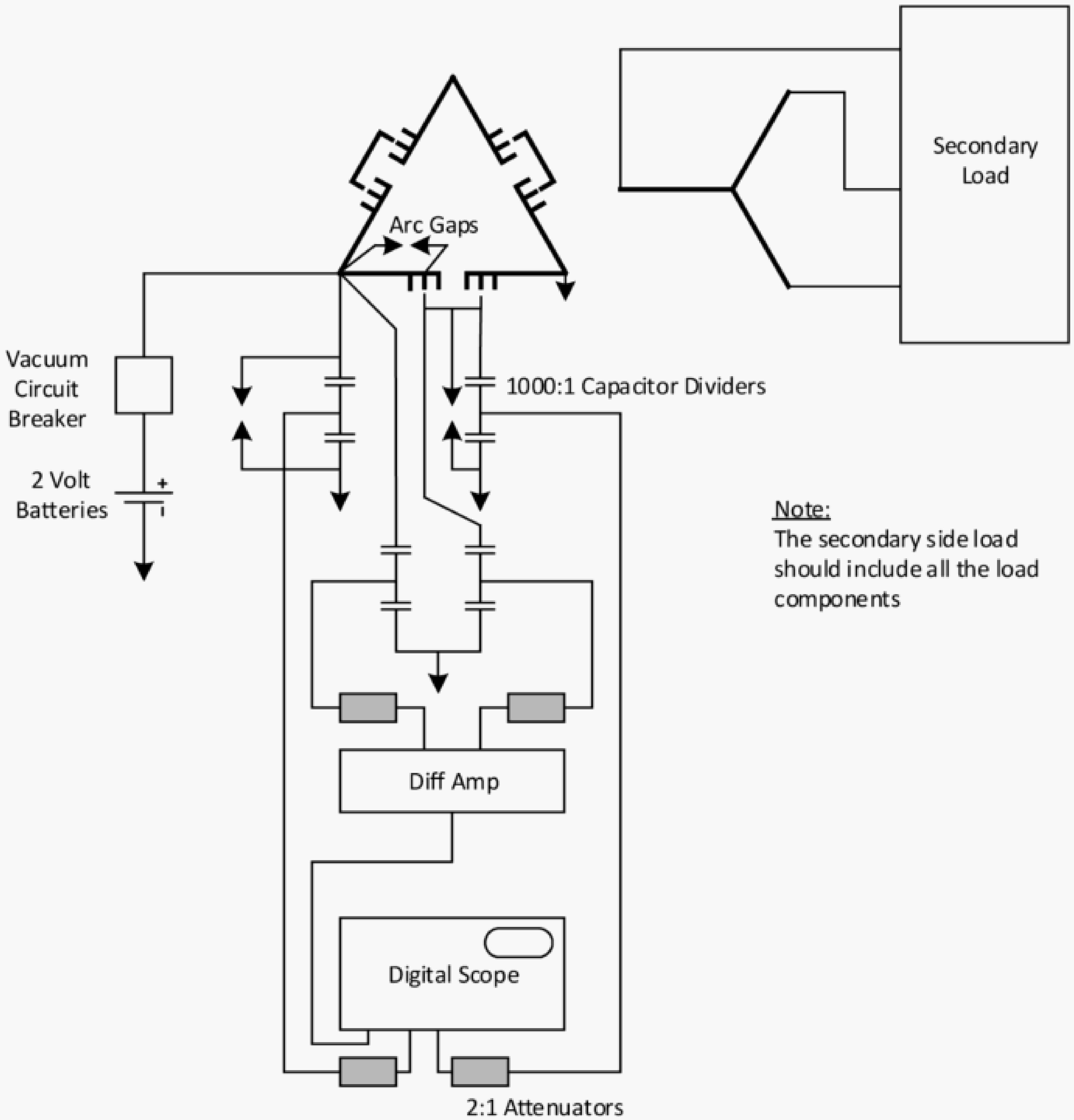

Figure B.3—Typical ping test circuit

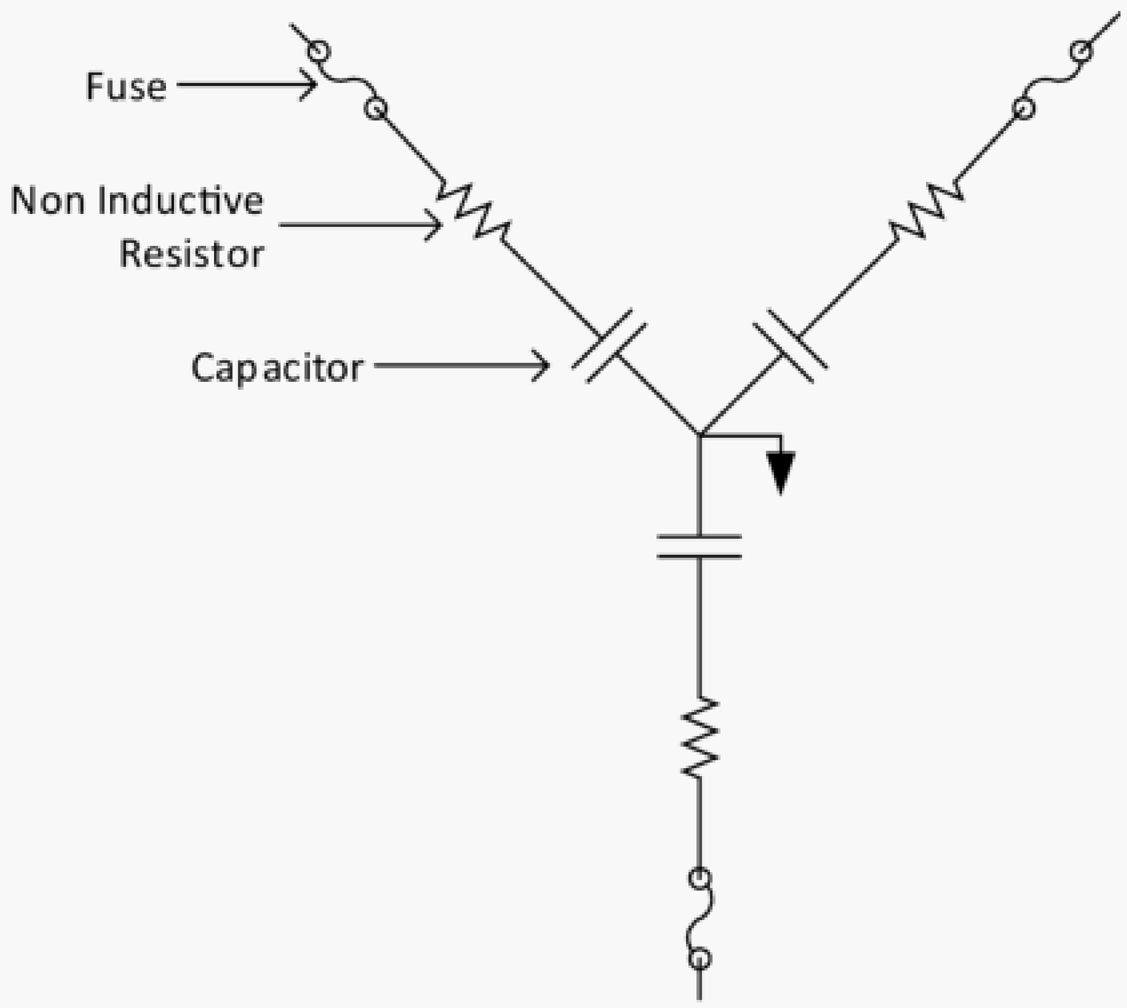

Figure B.4—Typical snubber circuit

Annex C

(informative)

Correlation between per-unit commutating reactance of rectifier transformer and inherent voltage regulation of transformer-rectifier assembly

C.1 Introduction

Subclauses C.3 through C.8 provide empirical equations to correlate per-unit commutating reactance of rectifier transformers to percentage inherent voltage regulation of transformer-rectifier assemblies with ANSI rectifier circuit numbers 25, 26, and 31.

C.2 Symbols

The following list of symbols applies to this annex:

E_d is the rated dc voltage of the rectifier at 100% load

E_{do} is the theoretical dc voltage (average dc voltage at light transition load assuming no overlap)

E_F is the total forward voltage drop per circuit element

E_s is the transformer secondary winding line-neutral, open-circuit no-load voltage (rms)

E_x is the direct voltage drop caused by transformer commutating reactance

$\mathcal{E}_{tr}$ is the efficiency of transformer-rectifier assembly in percent

P_r is the transformer load losses in watts (including resistance and eddy current losses)

I_d is the rated dc current of the rectifier

$Loss\% = 100\% - \mathcal{E}_{tr}$

Xc_{pu} is the per-unit commutating reactance

C.3 Reactive voltage drop calculation

The reactive voltage drop calculation is shown in Equation (C.1) as follows:

$$E_x = 1.17 \times Xc_{pu} \times E_s \tag{C.1}$$

C.4 Resistive voltage drop calculation

The resistive voltage drop calculation is shown in Equation (C.2) as follows:

$$E_r = P_r / I_d = (E_d \times I_d \times Loss\%) / I_d = [(2.34 \times E_s - E_x) \times Loss\% - E_F] / (100\% + Loss\%) \tag{C.2}$$

C.5 Open circuit voltage and rated voltage of rectifier unit

The calculation of the open-circuit voltage and rated voltage of rectifier unit is shown by Equation (C.3) Equation (C.4) as follows:

$$E_{do} = 2.34 \times E_s \text{(circuit number 25, 26, and 31)} \tag{C.3}$$

$$E_d = E_{do} - E_x - E_r - E_F \tag{C.4}$$

C.6 Inherent voltage regulation calculation

The inherent voltage regulation calculation is shown in Equation (C.5) as follows:

$$V_R\% = (E_x + E_r)/(E_d) = (E_x + E_r)/(E_{do} - E_x - E_r) \tag{C.5}$$

C.7 Correlation between rectifier transformer and transformer and rectifier assembly

The calculation of the correlation between Xc_{pu} of the rectifier transformer and $V_R\%$ of transformer and rectifier assembly is shown in Equation (C.6) as follows:

$$V_R\% = \mathrm{A} \times Xc_{pu} + \mathrm{B} \tag{C.6}$$

Where Xc_{pu} is the per unit commutating reactance of the rectifier transformer, and A and B are two constants that can be calculated by Equation (C.7) and Equation (C.8) as follows:

$$\mathrm{A} = -0.546 \times E_{tr} + 1.0835 \tag{C.7}$$

$$\mathrm{B} = -1.0239 \times E_{tr} + 1.0203 \tag{C.8}$$

C.8 Example

A rectifier-transformer assembly has $E_{tr} = 98.5\%$ and $Xc_{pu} = 8\%$.

The $V_R\%$ is calculated as follows:

a) Assuming $E_F = 1.5$ V

b) Constant A = −0.546 × 98.5% + 1.0835 = 0.546

c) Constant B = −1.0239 × 98.5% + 1.0203 = 0.0118

d) $V_R\% = 0.546 \times 8\% + 0.0118 = 5.55\%$

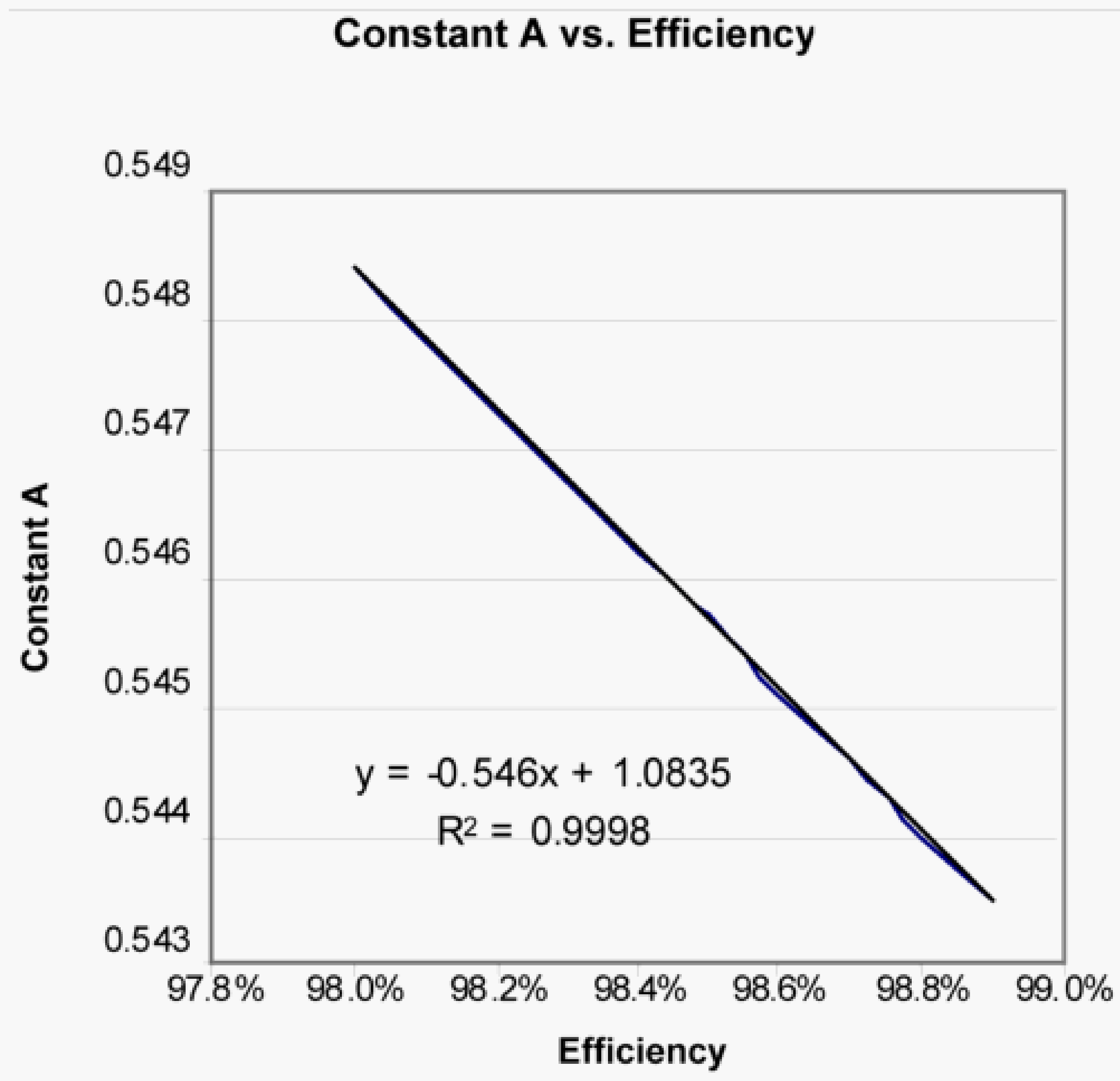

Figure C.1—Constant A versus efficiency

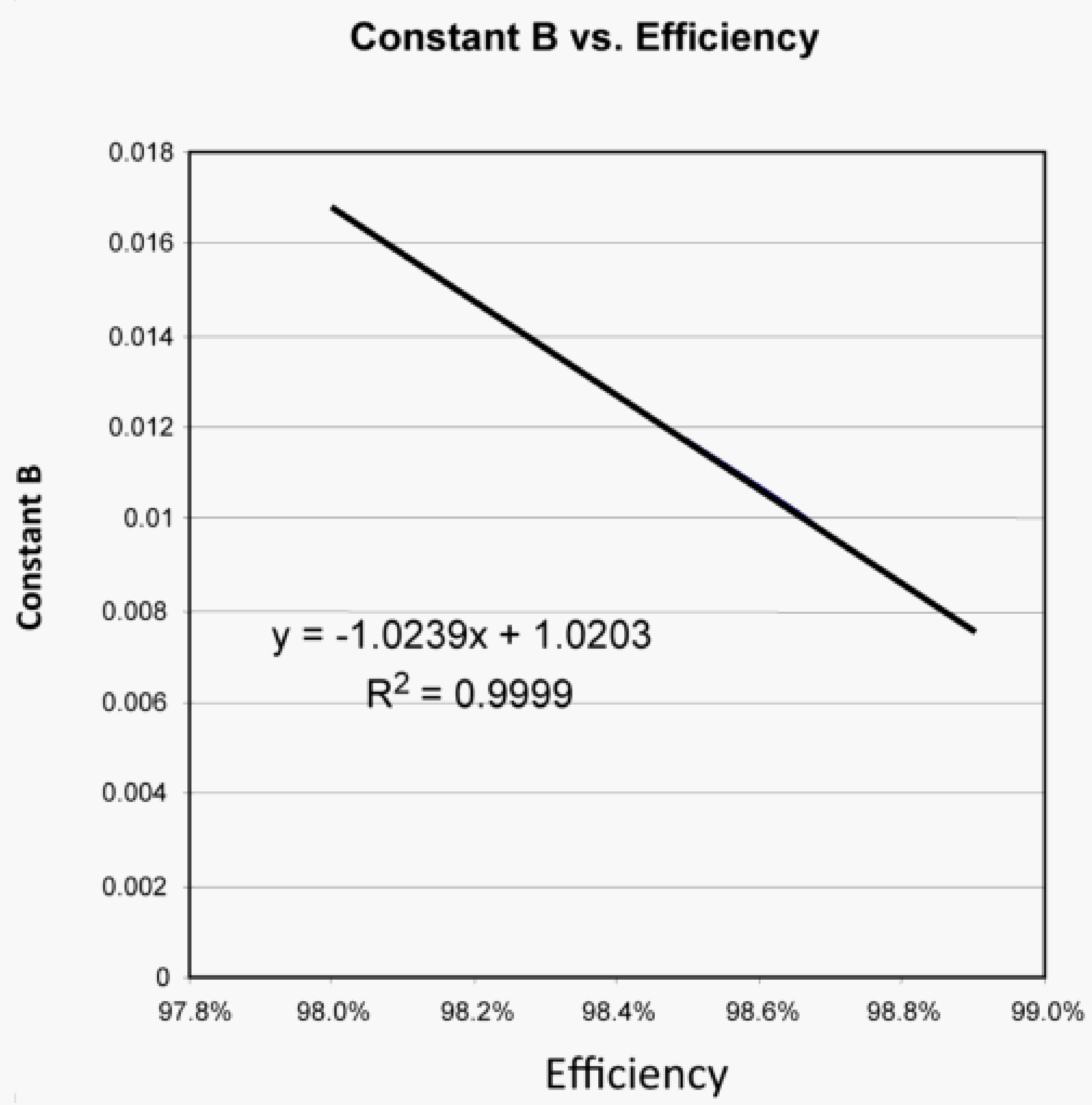

Figure C.2—Constant B versus efficiency

C.9 Conclusion

The inherent voltage regulation of a given transformer-rectifier assembly can be easily estimated based on the per-unit commutating reactance of the rectifier transformer, estimated efficiency of the transformer-rectifier assembly, and estimated total diode total forward voltage drop.

Annex D

(informative)

Bibliography

Bibliographical references are resources that provide additional or helpful material but do not need to be understood or used to implement this standard. Reference to these resources is made for informational use only.

[B1] Accredited Standards Committee C2-2007, National Electrical Safety Code® (NESC®).[10,11]

[B2] ASTM D1275, Standard Test Method for Corrosive Sulfur in Electrical Insulating Oils.

[B3] ASTM D3487, Standard Specification for Mineral Insulating Oil Used in Electrical Apparatus.

[B4] ASTM D6871, Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus.

[B5] Borsi, H. and O. Cachay, "Partial discharge behavior of epoxy resin-impregnated transformer coils," IEEE Transactions on Electrical Insulation, vol. 27, no. 6, pp. 1118–1126, Dec. 1992, http://dx.doi.org/10.1109/14.204862.

[B6] Borsi, H., "The relation between thermal and electrical stress and the PD behavior of epoxy-resin transformers," IEEE Transactions on Electrical Insulation, vol. 28, no. 6, pp. 1007–1015, Dec. 1993, http://dx.doi.org/10.1109/14.249374.

[B7] IEC 61099, Insulating liquids – Specification for unused synthetic organic esters for electrical purposes.[12]

[B8] IEC 61203, Synthetic organic esters for electrical purposes – Guide for maintenance of transformer esters in equipment.

[B9] IEEE Std C57.12.56™-1986 (Reaff 1998), IEEE Standard Test Procedure for Thermal Evaluation of Insulation Systems for Ventilated Dry-Type Power and Distribution Transformers.[13,14]

[B10] IEEE Std C57.96™-1989, IEEE Guide for Loading Dry-Type Distribution and Power Transformers.

[B11] IEEE Std C57.106™-2002, IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment.

[B12] IEEE Std C57.109™-1993 (Reaff 2008), IEEE Guide for Liquid-Immersed Transformer Through-Fault-Current Duration.

[B13] NEMA 250, Enclosures for Electrical Equipment (1,000 V Maximum).[15]

[B14] Takeuchi, R., K. Fukushi, and H. Kubo, "Reliability of resins for molded transformers," IEEE Transactions on Electrical Insulation, vol. 26, no. 6, pp. 1183–1188, Dec. 1991, http://dx.doi.org/10.1109/14.108157.

[10]National Electrical Safety Code and NESC are both registered trademarks and service marks of the Institute of Electrical and Electronics Engineers, Inc.
[11]The NESC is available from the Institute of Electrical and Electronics Engineers (http://standards.ieee.org/).
[12]IEC publications are available from the International Electrotechnical Commission (http://www.iec.ch/) and the American National Standards Institute (http://www.ansi.org/).
[13]The IEEE standards or products referred to in this annex are trademarks owned by the Institute of Electrical and Electronics Engineers, Incorporated.
[14]IEEE publications are available from the Institute of Electrical and Electronics Engineers (http://standards.ieee.org/).
[15]NEMA publications are available from the National Electrical Manufacturers Association (http://www.nema.org/).

Consensus

WE BUILD IT.

IEEE
standards.ieee.org
Phone: +1 732 981 0060 Fax: +1 732 562 1571