



IEEE Guide for Establishing Power Transformer Capability while under Geomagnetic Disturbances

STANDARDS

IEEE Power and Energy Society

Developed by the
Transformer Committee

IEEE Std C57.163™-2023
(Revision of IEEE Std C57.163-2015)



IEEE Guide for Establishing Power Transformer Capability while under Geomagnetic Disturbances

Developed by the

Transformer Committee
of the
IEEE Power and Energy Society

Approved 21 September 2023

IEEE SA Standards Board

THIS IS A REDLINE DOCUMENT PRODUCED BY TECHSTREET, AN ASME COMPANY.

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

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

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

This Redline is produced solely by Techstreet. IEEE has not prepared this Redline and is not responsible for its accuracy.

Redline Processing Notes:

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

Abstract: The effects of geomagnetic disturbances (GMD) on power transformers when there is the presence of geomagnetically induced current (GIC) in a power transformer are described. Specification parameters and performance characteristics for power transformers to help minimize the risk and impact when GIC is present in the power system are established. The intent is to provide a background that can help evaluate the effect of GIC on a power transformer design and its GIC capability. This includes the evaluation techniques to determine the performance characteristics while under the influence of GIC.

Keywords: core saturation, design review, geomagnetic disturbances, geomagnetically induced current, geomagnetically induced current signature, GIC, GMD, IEEE C57.163™, magnetic, monitoring, power transformers, temperature gradient, testing, thermal

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

Copyright © 2024 by The Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 12 February 2024. Printed in the United States of America.

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

PDF: ISBN 979-8-8557-0324-5 STD26623
Print: ISBN 979-8-8557-0325-2 STDPD26623

IEEE prohibits discrimination, harassment, and bullying.

For more information, visit <https://www.ieee.org/about/corporate/governance/p9-26.html>.

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

Important Notices and Disclaimers Concerning IEEE Standards Documents

IEEE Standards documents are made available for use subject to important notices and legal disclaimers. These notices and disclaimers, or a reference to this page (<https://standards.ieee.org/ipr/disclaimers.html>), appear in all standards and may be found under the heading “Important Notices and Disclaimers Concerning IEEE Standards Documents.”

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

IEEE Standards documents are developed within IEEE Societies and subcommittees of IEEE Standards Association (IEEE SA) Board of Governors. IEEE develops its standards through an accredited consensus development process, which brings together volunteers representing varied viewpoints and interests to achieve the final product. IEEE standards are documents developed by volunteers with scientific, academic, and industry-based expertise in technical working groups. Volunteers are not necessarily members of IEEE or IEEE SA 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 makes no warranties or representations concerning its standards, and expressly disclaims all warranties, express or implied, concerning this standard, including but not limited to the warranties of merchantability, fitness for a particular purpose and non-infringement. IEEE Standards documents do not guarantee safety, security, health, or environmental protection, or guarantee against interference with or from other devices or networks. In addition, IEEE does not warrant or represent that the use of the material contained in its standards is free from patent infringement. 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 their 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: THE NEED TO PROCURE 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 balloting 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 is 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, nor 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 the presenter's views should be considered the personal views of that individual rather than the formal position of IEEE, IEEE SA, the Standards Committee, or the Working Group. Statements made by volunteers may not represent the formal position of their employer(s) or affiliation(s).

Comments on standards

Comments for revision of IEEE Standards documents are welcome from any interested party, regardless of membership affiliation with IEEE or IEEE SA. However, **IEEE does not provide interpretations, 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 subcommittees of the IEEE SA Board of Governors 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 evaluating comments or in revisions to an IEEE standard is welcome to join the relevant IEEE working group. You can indicate interest in a working group using the Interests tab in the Manage Profile and Interests area of the [IEEE SA myProject system](#).¹ An IEEE Account is needed to access the application.

Comments on standards should be submitted using the [Contact Us](#) form.²

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 constitute 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.

Data privacy

Users of IEEE Standards documents should evaluate the standards for considerations of data privacy and data ownership in the context of assessing and using the standards in compliance with applicable laws and regulations.

¹Available at: <https://development.standards.ieee.org/myproject-web/public/view.html#landing>.

²Available at: <https://standards.ieee.org/content/ieee-standards/en/about/contact/index.html>.

Copyrights

IEEE draft and approved standards are copyrighted by IEEE under US and international copyright laws. They are made available by IEEE and are adopted for a wide variety of both public and private uses. These include both use, by reference, in laws and regulations, and use in private self-regulation, standardization, and the promotion of engineering practices and methods. By making these documents available for use and adoption by public authorities and private users, neither IEEE nor its licensors waive any rights in copyright to the documents.

Photocopies

Subject to payment of the appropriate licensing fees, 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; <https://www.copyright.com/>. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Updating of IEEE Standards documents

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

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

In order to determine whether a given document is the current edition and whether it has been amended through the issuance of amendments, corrigenda, or errata, visit [IEEE Xplore](#) or [contact IEEE](#).³ For more information about the IEEE SA or IEEE's standards development process, visit the IEEE SA Website.

Errata

Errata, if any, for all IEEE standards can be accessed on the [IEEE SA Website](#).⁴ Search for standard number and year of approval to access the web page of the published standard. Errata links are located under the Additional Resources Details section. Errata are also available in [IEEE Xplore](#). Users are encouraged to periodically check for errata.

Patents

IEEE standards are developed in compliance with the [IEEE SA Patent Policy](#).⁵

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

³Available at: <https://ieeexplore.ieee.org/browse/standards/collection/ieee>.

⁴Available at: <https://standards.ieee.org/standard/index.html>.

⁵Available at: <https://standards.ieee.org/about/sasb/patcom/materials.html>.

filed a statement of assurance via an Accepted Letter of Assurance, then the statement is listed on the IEEE SA Website at <https://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.

IMPORTANT NOTICE

Technologies, application of technologies, and recommended procedures in various industries evolve over time. The IEEE standards development process allows participants to review developments in industries, technologies, and practices, and to determine what, if any, updates should be made to the IEEE standard. During this evolution, the technologies and recommendations in IEEE standards may be implemented in ways not foreseen during the standard's development. IEEE standards development activities consider research and information presented to the standards development group in developing any safety recommendations. Other information about safety practices, changes in technology or technology implementation, or impact by peripheral systems also may be pertinent to safety considerations during implementation of the standard. 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.

Participants

At the time this guide was completed, the Standards—Transformer Capability Under Geomagnetic Disturbance Working Group had the following membership:

Daniel Blaydon, *Chair*
Ramsis Girgis, *Vice Chair*
Scott Digby, *Secretary*

Suresh Babanna	Zan Kiparizoski	Markus Schiessl
Jeffrey Benach	Dmitriy Klempner	Eric Schleismann
Mats Bernesjo	Balakrishnan Mani	Hemchandra Shertukde
William Boettger	Kumar Mani	Sanjib Som
Muhammad Ali Masood	Rogelio Martinez	Marc Taylor
Cheema	Martin Munoz Molina	Mark Tostrud
Hakim Dulac	Ali Naderian	Jason Varnell
Norman Field	Anastasia O'Malley	Kiran Vedante
Bruce Forsyth	Matthew Pinard	Rogelio Verdolin
Anthony Franchitti	Nitesh Patel	David Wallach
William Griesacker	Sanjay Patel	Alan Washburn
Gary Hoffman	Patrick Picher	Joe Watson
Saramma Hoffman	Ion Radu	William Whitehead
Kurt Kaineder	Afshin Rezaei-Zare	Trenton Williams
Stacey Kessler	Steven Schappell	Waldemar Ziomek

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

Stephen Antosz	Jalal Gohari	Ali Naderian Jahromi
Peter Balma	William Griesacker	Gearold O. H. Eidhin
Gilles Bargone	Gordon Halt	Sivaraman P.
Barry Beaster	John Harley	Bansi Patel
Jeffrey Benach	Roger Hayes	Dhiru Patel
Mats Bernesjo	Werner Hoelzl	Poorvi Patel
Enrique Betancourt	Gary Hoffman	Howard Penrose
Steven Bezner	Richard Jackson	Matthew Pinard
Wallace Binder	John John	Alvaro Portillo
Thomas Blackburn	Laszlo Kadar	Ion Radu
Daniel Blaydon	Kurt Kaineder	Pierre Riffon
William Bloethe	John Kay	Charles Rogers
W Boettger	Thomas Keels	Oleg Roizman
Paul Cardinal	Sheldon Kennedy	Rodrigo Ronchi
Arup Chakraborty	James Kinney	Daniel Sauer
Ritwik Chowdhury	Zan Kiparizoski	Roderick Sauls
John Crouse	Gary Kobet	Bartien Sayogo
Scott Digby	Krzysztof Kulasek	Markus Schiessl
Evgenii Ermakov	John Lackey	Stephen Schroeder
Jorge Fernandez Daher	Moonhee Lee	Hemchandra Shertukde
Joseph Foldi	Wang Lei	Hyeong Sim
Bruce Forsyth	Lawrenc Long	Jerry Smith
Anthony Franchitti	Greg Luri	Bradley Staley
Raymond Frazier III	Balakrishnan Mani	Wayne Stec
Carl Fredericks	Tapan Manna	Dragan Tabakovic
Robert Ganser	J.Dennis Marlow	Ed TeNyenhuus
Kamal Garg	Lee Matthews	Michael Thompson
Shubhanker Garg	Daleep Mohla	Mark Tostrud
Ramsis Girgis	Jerry Murphy	James Van De Ligt

Ajith Varghese
Jason Varnell
Jos Veens
Roger Verdolin
John Vergis
Jane Verner

David Wallace
David Wallach
Reigh Walling
Alan Washburn
Joe Watson
Bruce Webb
Drew Welton

Kenneth White
Trenton Williams
Nicholas Zagrodnik
Shibao Zhang
Peter Zhao
Waldemar Ziomek

When the IEEE SA Standards Board approved this guide on 21 September 2023, it had the following membership:

David J. Law, *Chair*
Ted Burse, *Vice Chair*
Gary Hoffman, *Past Chair*
Konstantinos Karachalios, *Secretary*

Sara R. Biyabani
Doug Edwards
Ramy Ahmed Fathy
Guido R. Hiertz
Yousef Kimiagar
Joseph L. Koepfinger*
Thomas Koshy
John D. Kulick

Joseph S. Levy
Howard Li
Gui Lin
Johnny Daozhuang Lin
Xiaohui Liu
Kevin W. Lu
Daleep C. Mohla
Andrew Myles

Paul Nikolich
Annette D. Reilly
Robby Robson
Lei Wang
F.Keith Waters
Karl Weber
Philip B. Winston
Don Wright

*Member Emeritus

Introduction

This introduction is not part of IEEE Std C57.163-2023, IEEE Guide for Establishing Power Transformer Capability while under Geomagnetic Disturbances.

This guide addresses the impact of geomagnetic disturbances on the operation and performance of power transformers. It provides the user with an understanding of the magnetic and thermal effects of geomagnetically induced current (GIC) on power transformers, their GIC thermal capability, and considerations for evaluating the susceptibility of transformers to these effects.

This guide was originally published in 2015, at a time of significant interest within the industry about the potential impacts of geomagnetic disturbances (GMD) to the reliability of the electric grid. This guide was developed to provide users with the technical information needed to assess the operational risk to power transformers and provide a methodology for performing related vulnerability assessments. Since that time, improvements in modeling and studies performed on transformer fleets have enhanced both the quality and quantity of available data related to GMD. Additionally, GMD event parameters have been adopted by the industry providing asset owners a common framework for assessing the impact to transformers during these events. One such example is the GIC reference signature provided in the NERC standard *TPL-007 Transmission System Planned Performance for Geomagnetic Disturbance Events*, which is widely used for transformer magnetic and thermal assessments. This has replaced the simplified GIC signature recommended in the original guide.

A working group was convened in 2020 to revise the guide. Editorial improvements and additions to the text were made throughout the document. The following is a summary of the main updates made into this revision:

- Reorganized sections of the guide and created a new clause dedicated to the magnetic response of transformers to GIC ([Clause 6](#)).
- Incorporated in [4.2](#) the reference GIC signature per the NERC TPL-007 Standard to replace the original Simplified GIC Signature. The revised guide uses this signature as the basis for revisions of GIC thermal Assessment sections of the guide.
- Moved this Simplified Signature from the main text and relocated it to [Annex A](#) for historical reference.
- Added a note in [4.3](#) regarding the polarities of I_H and I_N in [Equation \(1\)](#) and added brackets in that equation for clarity.
- Updated [Figure 8](#), [Figure 9](#), [Figure 11](#), [Figure 13](#), [Figure 14](#), and [Figure 15](#) with new calculations, and added [Figure 10](#) and [Figure 12](#) for three-phase core form transformers with the 3-Limb core type.
- Added text to [5.3](#) on the thermal impact of GIC caused by circulating currents in the tertiary windings and in designs of shell form transformers as a consequence of core saturation.
- Added more details in [Clause 6](#) on magnetic response of transformers to GIC.
- Added more details on thermal impact of GIC on tertiary windings and [Figure 16](#) in [7.1.1](#).
- Added more details to [7.1.5](#) on “Thermal effects of GIC on shell form transformer tanks,” and updated [Table 1](#) with new calculations.
- Text and figures in [7.3](#) have been revised to apply to the revised reference GIC Signature used in the guide per [4.2](#).
- [Subclause 7.5](#) on GIC thermal capability of transformers has been fully revised with new calculations and discussion on the basis for selecting hot-spot temperature limits under GMD scenarios.

- Added 10.3, “Monitoring of GIC thermal impact on power transformers.”
- Rearranged the Bibliography alphabetically and added recent publications.
- Revised references in the text of the guide to indicate where material in the guide is extracted from these references.

Contents

1. Overview	15
1.1 Scope	15
1.2 Word usage	15
2. Normative references	16
3. Definitions, acronyms, and abbreviations	16
4. Background	17
4.1 Geomagnetic disturbances.....	17
4.2 Typical signature/profile of GIC	18
4.3 Effective GIC in autotransformers.....	20
5. Effects of GIC on power transformers	20
5.1 Basics of the effects of dc current on power transformers.....	20
5.2 Magnetic effects of GIC	24
5.3 Thermal effects of GIC	25
5.4 Other effects of GIC in transformers	25
6. Magnetic response of transformers to GIC	25
6.1 Magnetizing current pulse associated with core saturation.....	26
6.2 Inductive reactive power (vars) drawn by the transformer.....	27
6.3 Current harmonics associated with GIC	29
7. Thermal response of transformers to GIC.....	30
7.1 Thermal effects of dc current	30
7.2 The effect of the short duration of GIC pulses on transformer temperatures.....	34
7.3 Procedure for calculation of thermal response of windings and structural parts to a GIC profile.....	35
7.4 Examples of thermal performance of transformers due to a typical GIC profile	36
7.5 GIC thermal capability	39
8. Evaluation of degree of susceptibility of transformers to thermal effects of GIC	41
8.1 Design-based susceptibility	42
8.2 GIC level-based susceptibility.....	43
8.3 Total GIC susceptibility	43
9. Specifications	44
9.1 GIC signature	44
9.2 Recommended hot-spot temperature limits	44
9.3 Recommended design review requirements	44
9.4 Testing	45
10. Transformer GIC monitoring	46
10.1 Monitoring.....	46
10.2 Predicting part-cycle core saturation	48
10.3 Monitoring of GIC thermal impact on power transformers	49
Annex A (informative) Simplified GIC signature	50
Annex B (informative) Bibliography	51

List of Figures

Figure 1—GIC flow in a power network	17
Figure 2—Reference GIC profile with a 100 A highest peak	19
Figure 3—A 60-min period that includes highest series of GIC pulses in Figure 2	19
Figure 4—A 10-min period that includes the highest GIC peaks in Figure 2	20
Figure 5—GIC flow through grounded neutral connections of power transformers.....	21
Figure 6—Example of flux density shift in a transformer core caused by dc current.....	22
Figure 7—Part-cycle saturation of transformer cores under effect of dc current	23
Figure 8—Magnetizing current pulse for three different levels of GIC	24
Figure 9—Calculated magnetizing current of a 250 MVA, single-phase core form transformer.....	26
Figure 10—Calculated magnetizing current of a 448 MVA, three-phase core form transformer with the 3-limb core type.....	27
Figure 11—Calculated reactive power drawn by a 250 MVA, single-phase autotransformer	28
Figure 12—Calculated reactive power drawn by a 448 MVA, three-phase core form transformer with the three-limb core type.....	28
Figure 13—Calculated 2nd to 5th order current harmonics.....	29
Figure 14—Calculated 6th to 9th order current harmonics.....	29
Figure 15—Calculated temperature gradient of the winding hot-spot of a fully loaded 250 MVA single-phase autotransformer due to the flow of dc current	30
Figure 16—Calculated circulating current developing in the tertiary winding of a 500 kV, 250 MVA single-phase core form transformer when subjected to a moderate level of GIC	31
Figure 17—Measured steady-state temperature rises of tie-plates upon application of dc current	32
Figure 18—Measured steady-state temperature rises of yoke clamp upon application of dc current	33
Figure 19—Steady-state temperature rise of the T-beam with different dc currents.....	33
Figure 20—Measured temperature rises of tie-plates at different time durations [B34]	35
Figure 21—Measured temperature rise of yoke clamps at different time durations [B34]	35
Figure 22—Calculated winding hot-spot temperature caused by the GIC signature of Figure 2	37
Figure 23—Calculated tie-plate hot-spot temperature caused by the GIC signature of Figure 2	37
Figure 24—Calculated tank hot-spot temperature corresponding to the GIC signature of Figure 2	38
Figure 25—Calculated hot-spot temperature of tertiary winding caused by the GIC signature of Figure 2 ...	38
Figure 26—Extract from full calculated hot-spot temperature signature.....	39
Figure 27—Example of Calculated thermal GIC capability of a core form transformer design; using the tie-plate hot-spot temperature limit criteria	41

Figure 28—Example of Calculated thermal GIC capability of a shell form transformer design; using
the tank hot-spot temperature limit criteria..... 41

Figure 29—GIC and harmonic monitoring points..... 48

Figure A.1—Simplified GIC signature..... 50

List of Tables

Table 1—Calculated steady-state temperature rise of a shell form transformer tank for different levels
of GIC..... 34

Table 2—Recommended hot-spot temperature limits under GMD scenarios 40

Table 3—Transformer total susceptibility to the effect of GIC..... 43

IEEE Guide for Establishing Power Transformer Capability while under Geomagnetic Disturbances

~~IMPORTANT NOTICE: IEEE Standards documents are not intended to ensure safety, security, health, or environmental protection, or ensure against interference with or from other devices or networks. Implementers 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.~~

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

1. Overview

1.1 Scope

This guide describes the effects of geomagnetic disturbances (GMD) on power transformers when there is the presence of geomagnetically induced current (GIC) in a power transformer. It establishes specification parameters and performance characteristics for power transformers to help minimize the risk and impact when GIC is present in the power system. The intent is to provide a background that can help evaluate the effect of GIC on a power transformer design and its GIC capability. This includes the evaluation techniques to determine the performance characteristics while under the influence of GIC.

It does not include the effect of GIC on other power system devices beyond power transformers and accessories. It does not discuss mitigation techniques and mitigation devices such as neutral-blocking devices on equipment beyond power transformers and accessories.

1.2 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{6,7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

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.

IEEE Std C57.12.00™, IEEE Standard for General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers. ^{8,9} 1, 2

⁶ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.

⁷ The use of *will* is deprecated and cannot be used when stating mandatory requirements, *will* is only used in statements of fact.

^{8, 2} IEEE publications are available from the Institute of Electrical and Electronics Engineers, Inc., (<https://standards.ieee.org/>). 445
Hoes Lane, Piscataway, NJ 08854, USA (<http://standards.ieee.org/>).

⁹ The IEEE standards or products referred to in this clause are trademarks of the Institute of Electrical and Electronics Engineers, Inc.

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

IEEE Std C57.91™, IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators.

IEEE Std C57.110-2018™, IEEE Recommended Practice for Establishing Liquid-Filled and Dry-Type Power and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents.

~~IEC 60076-7, Power Transformers—Part 7: Loading Guide for Oil-Immersed Power Transformers.³~~

3. Definitions, acronyms, and abbreviations

For the purposes of this document, the following terms and definitions apply. For other terms, the standard transformer terminology available in IEEE Std C57.12.80™ shall apply.¹⁰ The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.^{11 4}

geoelectric field: The electric field within the earth. A geomagnetic disturbance of sufficient intensity and duration changes the earth's magnetic field, thereby inducing atypical electric fields in the earth. The horizontal field near the surface of the earth, typically measured in V/km and characterized by the earth surface potentials, induces the flow of geomagnetically induced currents in power systems.

¹⁰ [Information on references can be found in Clause 2.](#)

³ ~~IEC publications are available from the International Electrotechnical Commission (<http://www.iec.ch/>). IEC publications are also available in the United States from the American National Standards Institute (<http://www ansi.org/>).~~

^{11 4} ~~IEEE Standards Dictionary Online subscription~~ is available at: <http://dictionary.ieee.org>. ~~An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.~~
~~http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.~~

geomagnetic disturbance (GMD): A disturbance of the magnetic field of the earth caused by the ejection of plasma from the sun, due to coronal mass ejections (CME) and high-speed solar wind streams, and its interaction with the earth's magnetic field. The changing magnetic field induces voltages in the loops formed by transmission lines, grounded-wye transformers, and the paths through earth between the transformer neutrals. The changing magnetic field induces the changes in the geoelectric field and the earth and surface potentials, resulting in the flow of geomagnetically induced current (GIC).

quasi-dc potentials: The potentials existing in geoelectric field, characterized by relatively slowly time-varying values of same polarity. Quasi-dc potentials are also commonly referred to as earth surface potentials.

T-beam: A T-shaped beam used in shell form transformers. T-beams are typically made of non-magnetic steel and are located at the bottom (~~and~~ may also be at the top of the core), supporting the core passing through the coils and the winding assembly.

temperature gradient: In transformers, temperature gradients are most frequently used to indicate the difference between the temperature of the core, winding, or other transformer components and adjacent oil temperature in kelvin (K) in response to a change in loading.

tie-plates: Structural members typically utilized in core form transformers to tie the top and bottom core ~~yokes and~~ clamping structures together, which maintain clamping force on the windings. They are also known as flitch plates or tie-bars.

yoke clamps: Structural members utilized in core form transformers to clamp the top and bottom core yokes.

4. Background

4.1 Geomagnetic disturbances

Geomagnetic disturbance (GMD) is a naturally occurring phenomenon of a disturbance in the earth's magnetic field that starts with activity in the sun. Various events can occur on the surface of the sun, which can produce strong and complex magnetic fields. Sunspots, which are relatively cool areas shielded by complex magnetic fields, can give rise to solar flares and coronal mass ejections (CME). The CME can be visualized as an enormous ball of plasma that travels outward into space. When a CME is directed toward the earth, it interacts with the earth's magnetic field. One effect is to direct charged particles toward the earth's magnetic poles where, upon impacting the upper atmosphere, cause the phenomenon commonly known as the northern lights (aurora borealis), and southern lights (aurora australis). When a CME interacts with the magnetosphere, the movement of the geomagnetic field relative to the conductive ionosphere increases the magnitude of currents flowing 100 km to 150 km above the earth's surface in the *electrojets*, which are currents in the order of millions of amperes. These electrojet currents induce quasi-dc potential in series with the transmission lines, which in turn drives the flow of geomagnetically induced current (GIC) wherever there is a path for them to flow. It is the GIC that flows in the transmission lines which affects the power grid, i.e., the transmission systems and the power transformers. This flow is depicted in Figure 1.

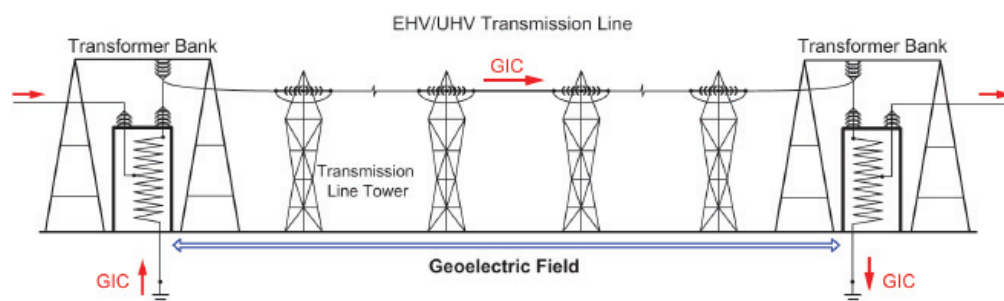


Figure 1—GIC flow in a power network

GIC is quasi-dc current because of its generally low frequency, typically 0.01 Hz to 0.5 Hz. At these frequencies, the high-voltage (HV) network is essentially resistive; thus, inductance, capacitance, and the effects of magnetic coupling can be ignored in the calculation of steady-state GIC levels.

A GMD event can last one to two days, and continually generates low to moderate levels of GIC relative to the maximum GIC during the event. The periods of high intensity GIC are generally of the most concern for power system impacts and operation.

This guide provides some engineering information to help gain a better understanding of the extent of the potential problems, and to understand that GIC risk is not uniform across the system. It is highly dependent on the actual characteristics of the GMD event and each part of the power system.

Factors that influence magnitude and signature ~~the degree of GIC risk to power transformers~~ include the following:

- Geomagnetic latitude
- Local earth resistivity
- Coastal effect
- The network topology
- ~~— The design and technical specification of the power transformer~~

Factors that influence impact of GMD on power transformers and power systems include the following:

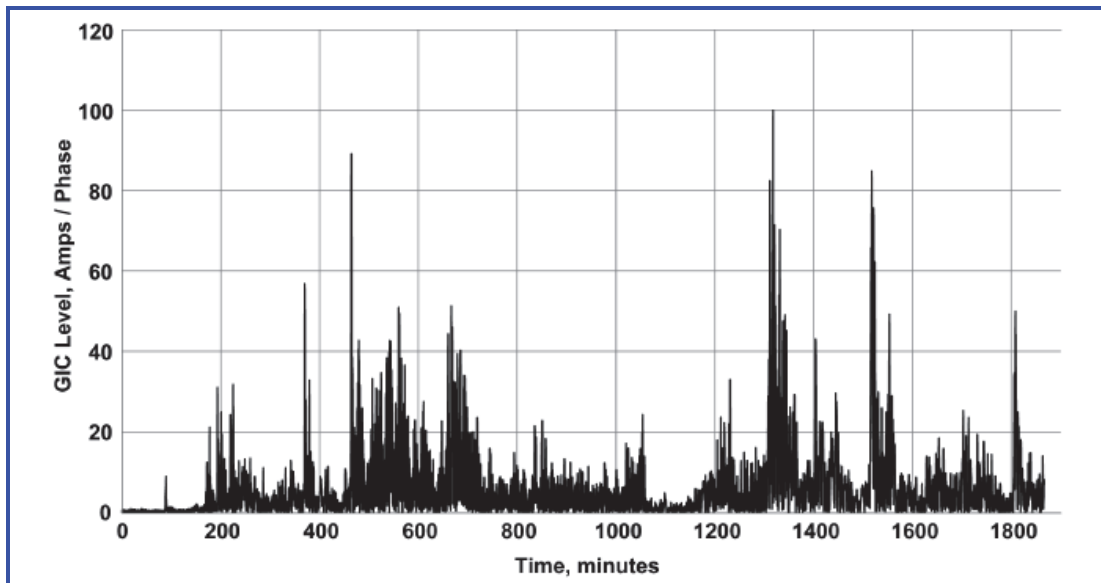
- Storm duration and intensity
- Power system components
- Type, ratings, and design of power transformers on the system
- Loading of the transformer

These factors play critical roles in determining the risk exposures, both in terms of the frequency and the severity on the impact to the power grids, per the IEEE Power & Energy Society Technical Council Task Force on Geomagnetic Disturbances [B20].¹² (IEEE PES [B16])⁵

4.2 Typical signature/profile of GIC

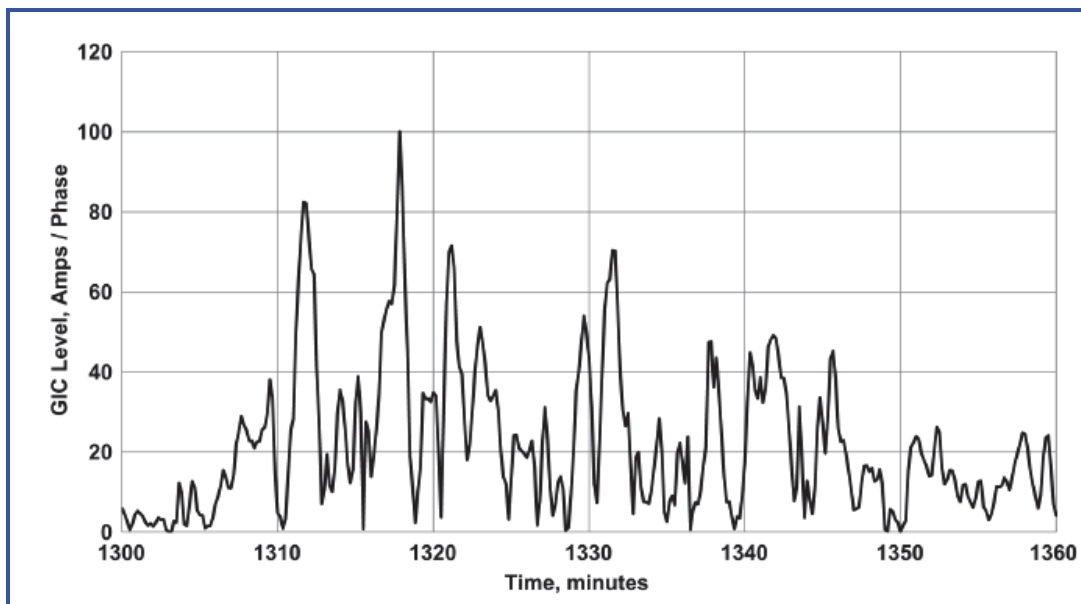
For the GIC thermal evaluation of power transformers, the GIC signature shown in Figure 2 is recommended. This signature is based on the reference geoelectric profile proposed in the NERC thermal assessment document and referred to as the GMD benchmark event (NERC Project 2013–03) [B26]. This GMD event is the basis for the power system GMD vulnerability assessment as required by the NERC standard TPL-007 [B42]. The associated power entities use this benchmark event to calculate the GIC flow in the corresponding power systems and transformers. Magnitudes of the GIC flow depend on the system parameters and topology. The NERC application guide [B27] provides the guidelines for the computation of the GIC in power systems and transformers. Figure 2 shows the magnitude of the GMD benchmark extracted GIC with the peak of 100 A/phase, which can be adjusted based on the GIC magnitudes obtained from the system studies. Figure 10 shows an example of GIC signature; measured in 2012 at a large generating station located in the northeastern part of the United States of America. As it is demonstrated in this figure, the GIC signature is a geomagnetic disturbance associated with GIC is quasi-de characterized by a large number of short duration narrow consecutive pulses of low to medium levels over a period of hours separated by a few high peak pulses of less than a minute to a few-minute minutes duration. For a better illustration, the part of the signature in Figure 10 that includes the highest peak (from the 1300 min mark to the 1360 min mark) peaks and the following pulses is presented in Figure 3 11 and Figure 12 with an expanded time scale. Similarly, scales. Figure 4 11 presents the 10 a-4 min period that specifically includes the two highest GIC peaks pulses on left side of Figure 3. graph in Figure 3 and 10, while Figure 4 demonstrate 12 presents the short duration of 12-min period following the high highest GIC peak pulses. In Figure 4, the 11 shows that the highest peak pulse has a magnitude of 45 A and pulse width of 45 sec at the base. The second highest pulse contains two peaks of 35 A, and remains for a total duration of the two highest pulses is in the 2 min to 3 min range 80 sec. Figure 12 shows a base GIC level of approximately 15 A during that 12-min period.

^{12,5}The numbers in brackets correspond to those of the bibliography in Annex B A.



[\(New\)](#)

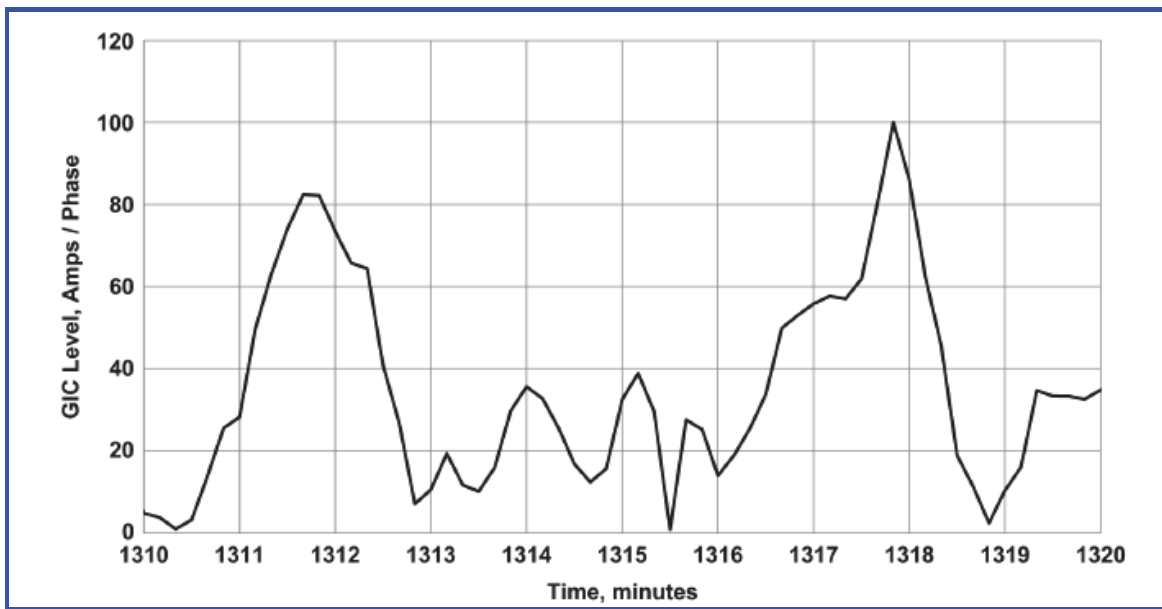
Figure 2—Reference GIC profile with a 100 A highest peak



[\(New\)](#)

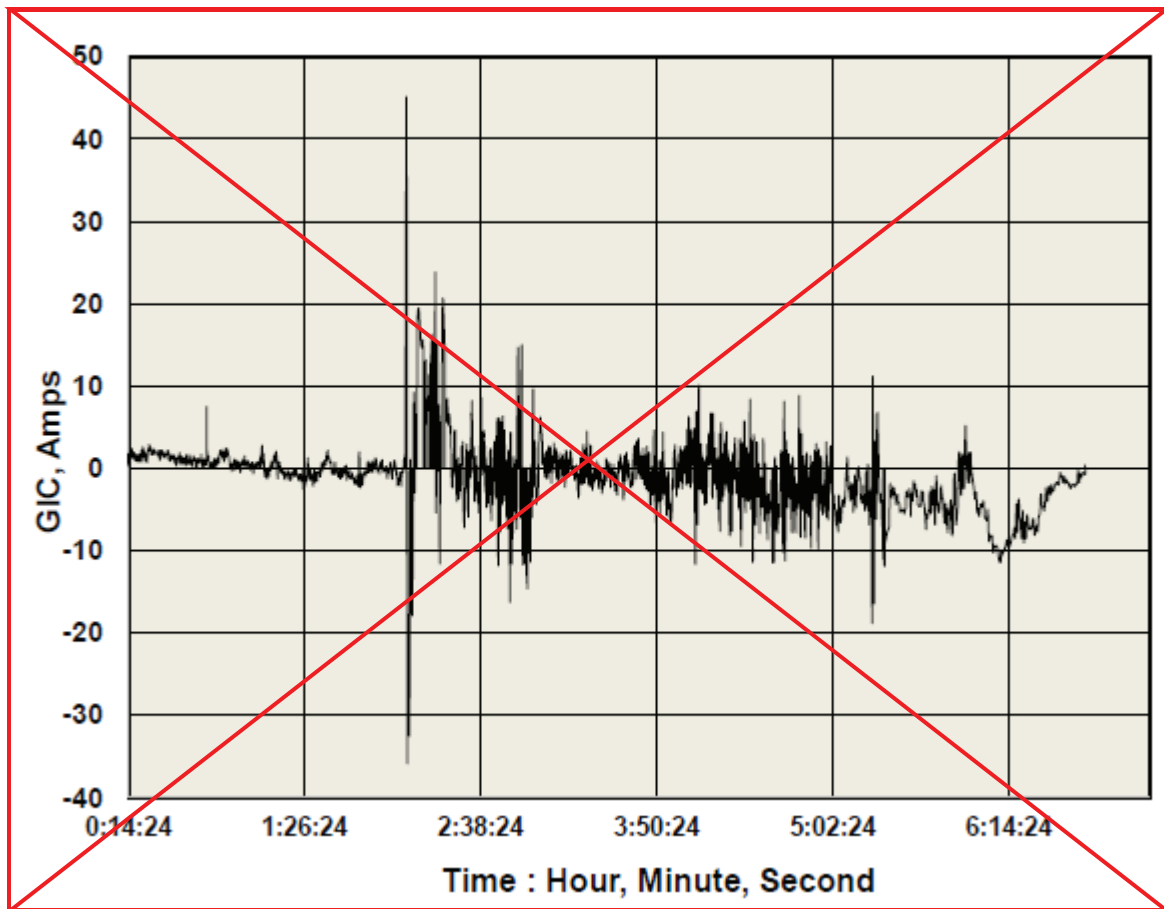
Figure 3—A 60-min period that includes highest series of GIC pulses in

Figure 2



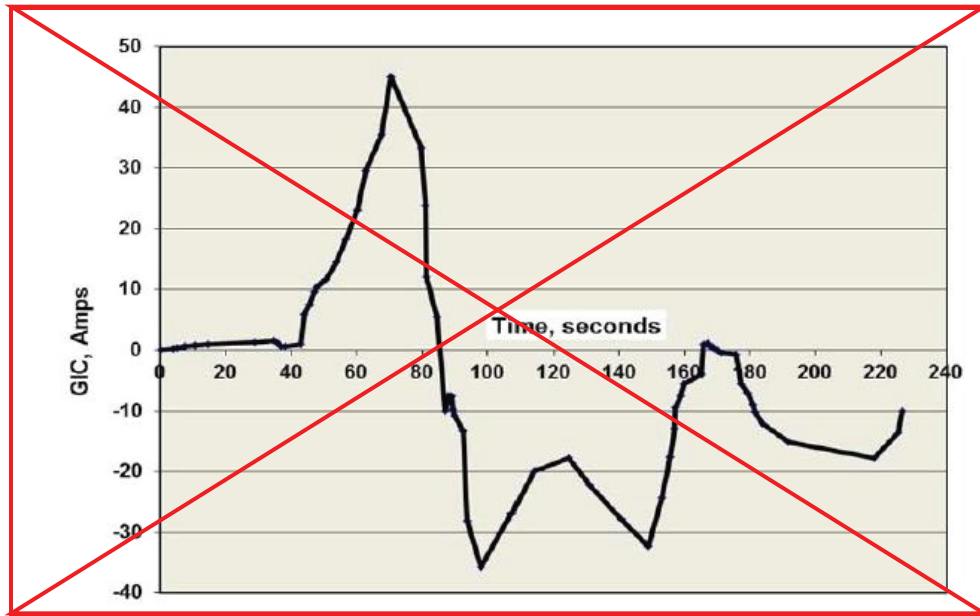
[\(New\)](#)

Figure 4— A 10-min period that includes the highest GIC peaks in Figure



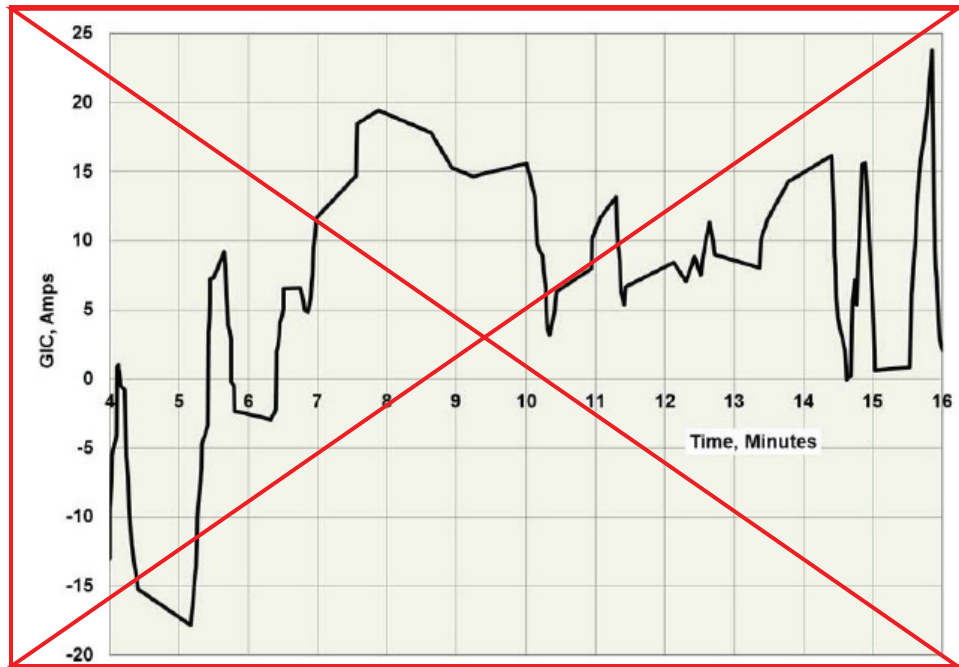
(Deleted)

Figure 10 — Measured GIC profile at neutral of a generator step-up transformer



(Deleted)

~~Figure 11—A 4-min period that includes the two highest pulses on left side of graph above~~



(Deleted)

Figure 12 ~~A 12-min period following the highest GIC peaks period~~

4.3 Effective GIC in autotransformers

7.1 GIC magnetic capability

Upon customer's request, the following calculated data can be provided for a particular transformer design versus level of GIC per phase:-

- Peak of magnetization current
- Fundamental reactive power
- Peak amplitude of magnetizing current harmonics up to the eleventh harmonic

NOTE—Power systems analysts need such data to perform various power system studies to determine the effect of these on the system and its components, as well as to study mitigation of these effects if deemed necessary.

In two-winding transformers, the value of GIC flowing in the HV winding produces the Ampere-turns ~~It is noted~~ that cause core saturation. However, for autotransformers, the value of the GIC current to be used in the calculations should be the effective current ($I_{effective}$) that accounts for the different levels of GIC current that the HV and low-voltage (LV) sides of the transformer experience during a GMD storm. Using $I_{effective}$ produces the same GIC ampere-turns of I_H passing through the series winding and $I_N/3$ passing through the common winding of the autotransformer.

The value of $I_{effective}$ is determined using Equation (1). [B1]: ~~(NERC [B23])~~.

$$I_{effective} = \left[I_H + \left(\left(\frac{I_N}{3} \right) - I_H \right) \times \left(\frac{V_X}{V_H} \right) \right] \quad (1)$$

(New)

$$I_{effective} = I_H + \left(\frac{I_N}{3} - I_H \right) \times \left(\frac{V_X}{V_H} \right) \quad (1)$$

(Deleted)

where

I_H is = GIC in the series high voltage winding per phase

I_N is = GIC in the neutral of a three-phase system or three-phase transformer

V_H is = rms rated voltage at the HV terminals

V_X is = rms rated voltage at the LV terminals-

Note that I_H and I_N have positive values when their directions are from the HV terminal into the transformer for I_H , and into the ground for I_N , respectively. Otherwise, values of I_H and I_N need to be used with their corresponding polarities.

5. Effects of GIC on power transformers

5.1 Basics of the effects of dc current on power transformers

The flow of GIC through power transformers is the root cause of nearly all GMD-related issues (~~IEEE TDC B18~~). It causes part-cycle core saturation in power transformers, which can result in issues such as increased reactive power absorption, current harmonic generation, system voltage instability, increased transformer noise, and transformer heating. Therefore, an accurate assessment of the GIC that is expected to occur during a given GMD is paramount. This GIC flow through the transformer is described pictorially in Figure 5 2.

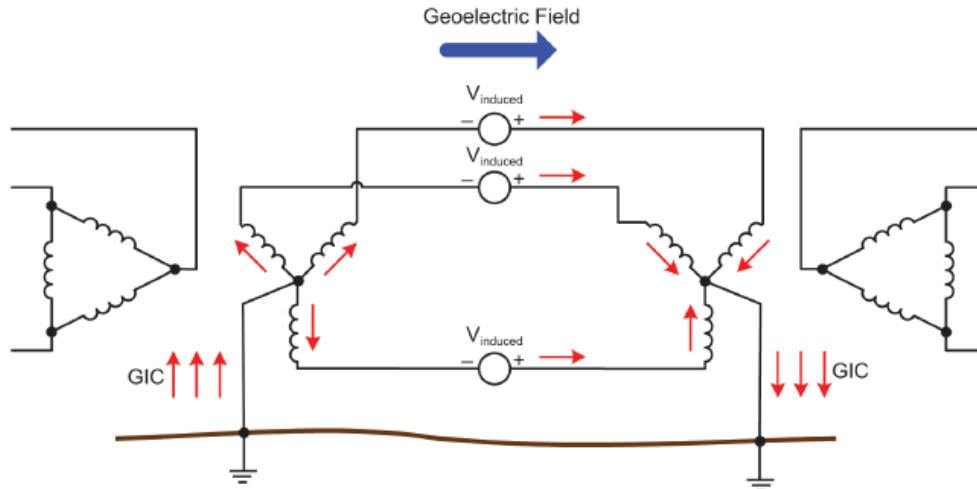
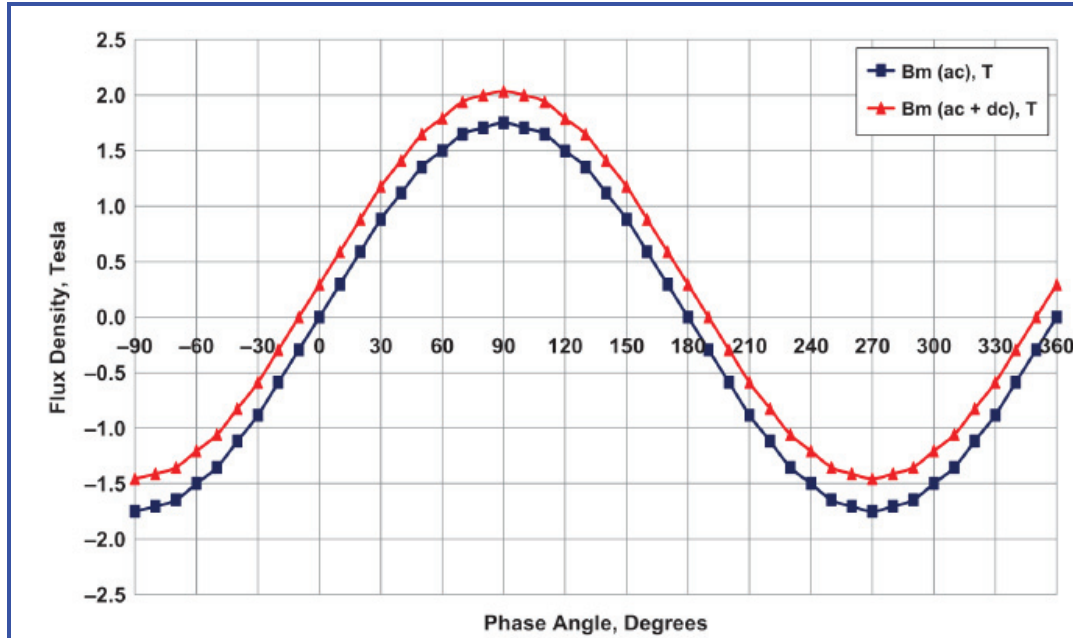


Figure 5—GIC flow through grounded neutral connections of power transformers

As per Figure 5.2, when the induced voltage, V_{induced} , appears in the transmission line, transformer, and ground loop, almost all of this voltage appears initially across the unsaturated magnetizing inductances of the transformers in the loop because these inductances are far greater than those of the transmission line. Because the induced voltage is very low frequency (quasi-dc), it causes an increase in the dc flux density offset, allowing only a small amount of dc current to flow until the ac plus dc peaks and the transformer core flux density reaches the transformer core saturation level. The dc voltage drops across the circuit resistance and causes a decrease in the quasi-dc voltage applied to the transformer and therefore the rate of increase of the dc flux density offset slows down. The dc flux density offset stops increasing when the dc component of the magnetizing current equals the dc induced voltage divided by the circuit resistance. This dc current is the steady-state GIC_{dc} which gives rise to the eventual dc flux density shift in the transformer core.

The magnitude of this flux density shift depends on the magnitude of the dc current, number of turns in the windings carrying the dc current, and reluctance of the path of this dc flux. The result is that the dc flux adds to the amplitude of the ac flux in one half-cycle and subtracts from the amplitude of the ac flux in the other half-cycle as illustrated in Figure 6.3. When the dc flux is large enough, the peak flux densities in the magnetic core reach the pre-saturation range in one half of the cycle resulting in core saturation for a small part of a cycle. This is referred to as part-cycle saturation. Figure 7.4 shows the (B-I) magnetic flux density-current characteristics which represents the B-H curve of core material since magnetic field strength, (H) is proportional to current. The B-H characteristics of the transformer core materials is inherently very non-linear. For higher magnitudes of dc current, the core provides a much higher reluctance to the dc ampere-turns; and therefore, results in a smaller incremental increase in the flux density shift and a higher peak magnetizing current pulse.-

Three-phase, three-limb cores with core form construction provide a high reluctance path to dc flux. This is because this core type offers an order of magnitude higher magnetic reluctance to the dc ampere-turns in the core-tank magnetic circuit. The dc flux has to pass through the ~~very~~ high reluctance path from the top yoke of the core to the tank cover and ~~, through the~~ tank walls, and return to the bottom yoke through the high reluctance path from the tank bottom. Therefore, transformers with this core type require a certain value of GIC before their ~~is less susceptible to part-cycle~~ core is saturated. This value ~~saturation. However, it~~ is different for different transformer designs, and is referred to as I_{cs} . Hence, these transformers are susceptible to part-cycle core saturation at GIC levels $> I_{cs}$. Conversely, ~~high magnitudes of magnetizing current.~~ single-phase transformers, shell form transformers, and three-phase five-leg core form transformers with the five-limb core type present lower reluctance to the dc flux within the core. Therefore, they are ~~more~~ susceptible to part-cycle core saturation at low ~~lower~~ levels of GIC current ~~de~~. Also, while the flux density of the core is an important factor in determining the final value of the peak of the sum of the ac and dc flux density in three-phase core form transformers with the a three-limb core type, this is not the case for transformers with other core types.



(New)