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Incorporating corrigendum April 2023

BSI Standards Publication

Measuring relays and protection equipment

Part 187-1: Functional requirements for differential protection — Restrained and unrestrained differential protection of motors, generators and transformers

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National foreword

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The start and finish of text introduced or altered by corrigendum is indicated in the text by tags. Text altered by ISO/IEC corrigendum [month/year on corrigendum] is indicated in the text by ⟦AC1⟩ ⟨AC1⟧.

The UK participation in its preparation was entrusted to Technical Committee PEL/95, Measuring relays and protection systems.

A list of organizations represented on this committee can be obtained on request to its committee manager.

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EN IEC 60255-187-1

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English Version

Measuring relays and protection equipment - Part 187-1: Functional requirements for differential protection - Restrained and unrestrained differential protection of motors, generators and transformers (IEC 60255-187-1:2021)

Relais de mesure et dispositifs de protection - Partie 187-1: Exigences fonctionnelles pour la protection différentielle - Protection différentielle avec et sans caractéristique de retenue des moteurs, générateurs et transformateurs (IEC 60255-187-1:2021)

Messrelais und Schutzeinrichtungen - Teil 187-1: Funktionsanforderungen für den stabilisierten und nicht stabilisierten Differentialschutz von Motoren, Generatoren und Transformatoren (IEC 60255-187-1:2021)

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The text of document 95/465/FDIS, future edition 1 of IEC 60255-187-1, prepared by IEC/TC 95 “Measuring relays and protection equipment” was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN IEC 60255-187-1:2021.

The following dates are fixed:

- latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement (dop) 2022-06-01
- latest date by which the national standards conflicting with the document have to be withdrawn (dow) 2024-09-01

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In the official version, for Bibliography, the following notes have to be added for the standards indicated:

IEC 61850 (series)	NOTE Harmonized as EN 61850 (series)
IEC 61850-7-4:2010	NOTE Harmonized as EN 61850-7-4:2010 (not modified)
IEC 61850-9-2	NOTE Harmonized as EN 61850-9-2

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Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE 1 Where an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cenelec.eu.

Publication	Year	Title	EN/HD	Year
IEC 60255-1	-	Measuring relays and protection equipment - Part 1: Common requirements	EN 60255-1	-
IEC 61850-8-1	-	Communication networks and systems for power utility automation - Part 8–1: Specific communication service mapping (SCSM) - Mappings to MMS (ISO 9506-1 and ISO 9506-2) and to ISO/IEC 8802-3	EN 61850-8-1	-
IEC 61869-2	-	Instrument transformers - Part 2: Additional requirements for current transformers	EN 61869-2	-
IEC 61869-9	-	Instrument transformers - Part 9: Digital interface for instrument transformers	EN IEC 61869-9	-

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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MEASURING RELAYS AND PROTECTION EQUIPMENT –

Part 187-1: Functional requirements for differential protection – Restrained and unrestrained differential protection of motors, generators and transformers

FOREWORD

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IEC 60255-187-1 has been prepared by IEC technical committee 95: Measuring relays and protection equipment. It is an International Standard.

This document, together with IEC 60255-187-2 and IEC 60255-187-3, cancels and replaces IEC 60255-13. This document constitutes a technical revision.

This document includes the following significant technical changes with respect to IEC 60255-13:

a) IEC 60255-13 has been significantly revised to follow the common structure of the functional standards for protection relays (IEC 60255-1xx series). IEC 60255-187-1 has been developed to address the restrained and unrestrained differential protection of motors, generators and transformers. The revisions include detailed description of the functions including the performance specification, testing and documentation requirements.

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The text of this International Standard is based on the following documents:

FDIS	Report on voting
95/465/FDIS	95/471/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

This International Standard contains attached files in COMTRADE file format. Configuration file: IEC 60255-187-1_External_Internal_YY0_50 Hz_4 kHz.CFG and data file: IEC 60255-187-1_External_Internal_YY0_50 Hz_4 kHz.DAT. These files are intended to be used as a complement and do not form an integral part of the document.

A list of all parts in the IEC 60255 series, published under the general title *Measuring relays and protection equipment*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The "colour inside" logo on the cover page of this document indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

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MEASURING RELAYS AND PROTECTION EQUIPMENT –

Part 187-1: Functional requirements for differential protection – Restrained and unrestrained differential protection of motors, generators and transformers

1 Scope

This part of IEC 60255 specifies the minimum requirements for functional and performance evaluation of (longitudinal) differential protection designed for the detection of faults in ac motors, generators and transformers. This document also defines how to document and publish performance test results.

This document covers the differential protection function whose operating characteristic can be defined on a bias-differential plane. It includes specification of the protection function, measurement characteristics, compensation of energizing quantities, additional restraint or blocking methods (for overexcitation and magnetizing inrush), starting and time delay characteristics. This document also covers unrestrained differential protection functions traditionally combined with the restrained (biased) differential element to form a single differential relay.

This document defines the influencing factors that affect the accuracy under steady state conditions and performance characteristics during dynamic conditions. The test methodologies for verifying performance characteristics and accuracy are also included in this document.

This document also includes current transformer requirements for the protection functions.

The differential protection functions covered by this document are as follows:

	IEEE/ANSI C37.2 function numbers	IEC 61850-7-4 logical nodes
Transformer differential	87T	PDIF
Motor differential	87M	PDIF
Generator differential	87G	PDIF
Restricted earth fault (ground differential)	87N	PDIF
Inrush restraint or inrush blocking		PHAR
Overexcitation restraint or overexcitation blocking		PHAR

This document does not specify the functional description of additional features often associated with biased differential relays such as current transformer (CT) supervision (CTS), switch onto fault (SOTF) and detection of geo-magnetically induced currents (GIC).

This document does not cover differential relays designed for bus bar protection (including high impedance differential protection and low impedance differential protection) or line protection. Additionally, this document does not explicitly cover generator incomplete longitudinal differential protection, generator split-phase transverse differential protection, self-balancing or magnetic balanced protection scheme, differential protection of phase-shifting transformers, directional restricted earth fault protection, railway transformers, convertor transformers and reactors. However, the principles covered by this document can be extended to provide guidance on these applications.

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The general requirements for measuring relays and protection equipment are defined in IEC 60255-1.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60255-1, *Measuring relays and protection equipment – Part 1: Common requirements*

IEC 61850-8-1, *Communication networks and systems for power utility automation – Part 8-1: Specific communication service mapping (SCSM) – Mappings to MMS (ISO 9506-1 and ISO 9506-2) and to ISO/IEC 8802-3*

IEC 61869-2, *Instrument transformers – Part 2: Additional requirements for current transformers*

IEC 61869-9, *Instrument transformers – Part 9: Digital interface for instrument transformers*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
differential relay
measuring relay that is intended to respond to the difference of the phasors and/or instantaneous values between specified incoming and outgoing electric currents

[SOURCE: IEC 60050-447:2020, 447-01-40]

3.2
biased relay
measuring relay, the characteristic of which is changed by means of an electrical bias

[SOURCE: IEC 60050-447:2020, 447-01-37]

3.3
percentage relay
biased relay, the characteristic of which is changed according to a percentage relationship of given input energizing quantity(ies)

[SOURCE: IEC 60050-447:2020, 447-01-38]

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3.4
longitudinal differential protection
protection the operation and selectivity of which depend on the comparison of magnitude or the phase and magnitude of the currents at the ends of the protected section

[SOURCE: IEC 60050-448:1995, 448-14-16, modified – The second preferred term "line differential protection (US)" has been deleted.]

3.5
transverse differential protection
protection applied to parallel connected circuits and in which operation depends on unbalanced distribution of currents between them

[SOURCE: IEC 60050-448:1995, 448-14-17]

3.6
high impedance differential protection
current differential protection using a current differential relay whose impedance is high compared with the impedance of the secondary circuit of a saturated current transformer

[SOURCE: IEC 60050-448:1995, 448-14-22]

3.7
low impedance differential protection
current differential protection using a current differential relay whose impedance is not high compared with the impedance of the secondary circuit of a saturated current transformer

[SOURCE: IEC 60050-448:1995, 448-14-23]

3.8
characteristic quantity
electric quantity, or one of its parameters, the name of which characterizes a measuring relay or protection equipment and the values of which are the subject of accuracy requirements

Note 1 to entry: For restrained differential protection, the characteristic quantities are the differential current and the restraining current. For unrestrained differential protection, the characteristic quantity is the differential current.

[SOURCE: IEC 60050-447:2020, 447-07-01, modified – The examples have been deleted, and a note to entry has been added.]

3.9
differential current
current which is the phasor and/or instantaneous value difference between specified incoming and outgoing currents

Note 1 to entry: Differential current is the characteristic quantity of differential protection.

3.10
restraining current
bias current
combination of incoming and outgoing currents, which restrains operation of the relay

3.11
through current
portion of the total incoming current that is also present in the outgoing current

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3.12
start current
pick-up current
value of differential current at which a differential function starts

3.13
restraint percentage
ratio, expressed as a percentage, between the differential current and the restraining current up to which the relay does not operate

Note 1 to entry: The definition of restraint percentage ignores an error, which may not be negligible, due to the finite characteristic quantity required under zero restraint conditions. This may be taken into account when necessary.

3.14
restrained operation
operation originated from the differential current exceeding a variable threshold formed by other energizing quantities and/or derived signals of energizing quantities, for example the through current

3.15
unrestrained operation
operation originated from the differential current exceeding a constant threshold

3.16
operating range
interval for which the measuring relay or protection equipment under specified conditions is able to perform its intended function(s) in accordance with the specified requirements

Note 1 to entry: When accuracy requirements have to be met, see "effective range" (3.17).

[SOURCE: IEC 60050-447:2020, 447-03-16]

3.17
effective range
interval of an input energizing quantity or characteristic quantity within which the accuracy requirements are met

Note 1 to entry: The effective range is part of the operating range.

[SOURCE: IEC 60050-447:2020, 447-07-08]

3.18
start time
pick-up time
duration between the instant a specified change is made in the value(s) of the input energizing quantity(ies) that will cause the measuring relay or protection equipment in initial condition or reset condition to start (pick up) and the instant it starts (picks up)

SEE: Figure 1.

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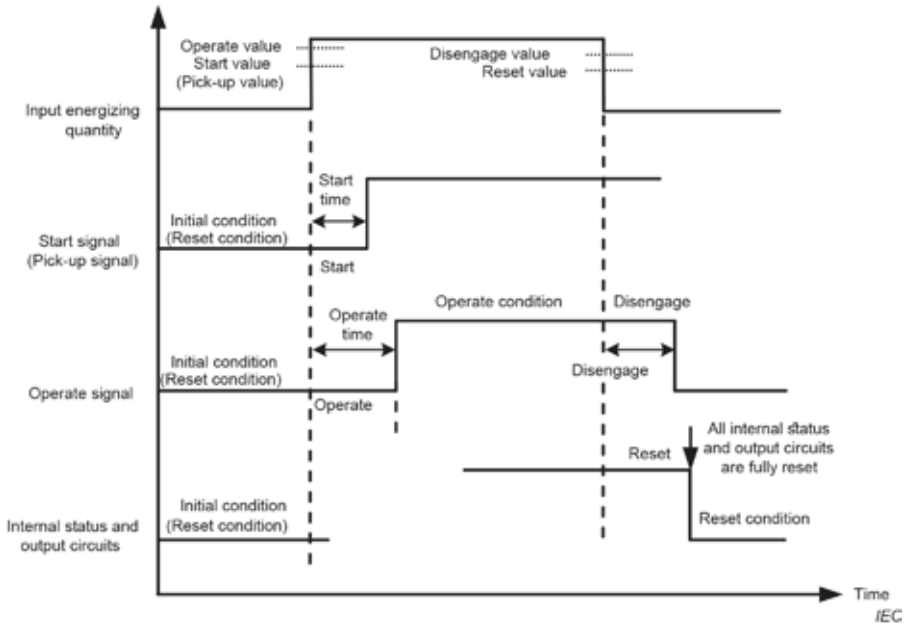

Figure 1 – Explanatory diagram for start time, operate time and disengage time

[SOURCE: IEC 60050-447:2020, 447-05-11, modified – The figures have been removed and replaced by Figure 1, the Note to entry has been deleted.]

3.19
operate time
duration between the instant a specified change is made in the value(s) of the input energizing quantity(ies) that will cause the measuring relay or protection equipment in initial condition to operate and the instant it operates

SEE: Figure 1.

[SOURCE: IEC 60050-447:2020, 447-05-05, modified – The figure has been removed and reference to Figure 1 has been added.]

3.20
disengage
terminate a function previously effected in a given output circuit

SEE: Figure 1.

[SOURCE: IEC 60050-447:2020, 447-02-17, modified – The figure has been removed and reference to Figure 1 has been added.]

3.21
disengage time
duration between the instant a specified change is made in the value(s) of the Input energizing quantity(ies) that will cause the measuring relay or protection equipment in operate condition to disengage and the instant it disengages

SEE: Figure 1.

[SOURCE: IEC 60050-447:2020, 447-05-10, modified – The figure has been removed and reference to Figure 1 has been added.]

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3.22
reset
switch to a reset condition

SEE: Figure 1.

[SOURCE: IEC 60050-447:2020, 447-02-05, modified – The figure has been removed and reference to Figure 1 has been added.]

3.23
reset condition
condition when all internal states (of moving parts and/or integrators,etc.) and output circuits of a measuring relay or protection equipment are either fully reset or at a specified condition in relation to the operate condition

SEE: Figure 1.

[SOURCE: IEC 60050-447:2020, 447-02-02, modified – The figure has been removed and reference to Figure 1 has been added.]

4 Specification of the function

4.1 General

The conceptual biased differential protection function with its input energizing quantities, binary input signals, functional logic, settings and binary output signals is shown in Figure 2. The manufacturer shall provide the functional block diagram of the specific implementation.

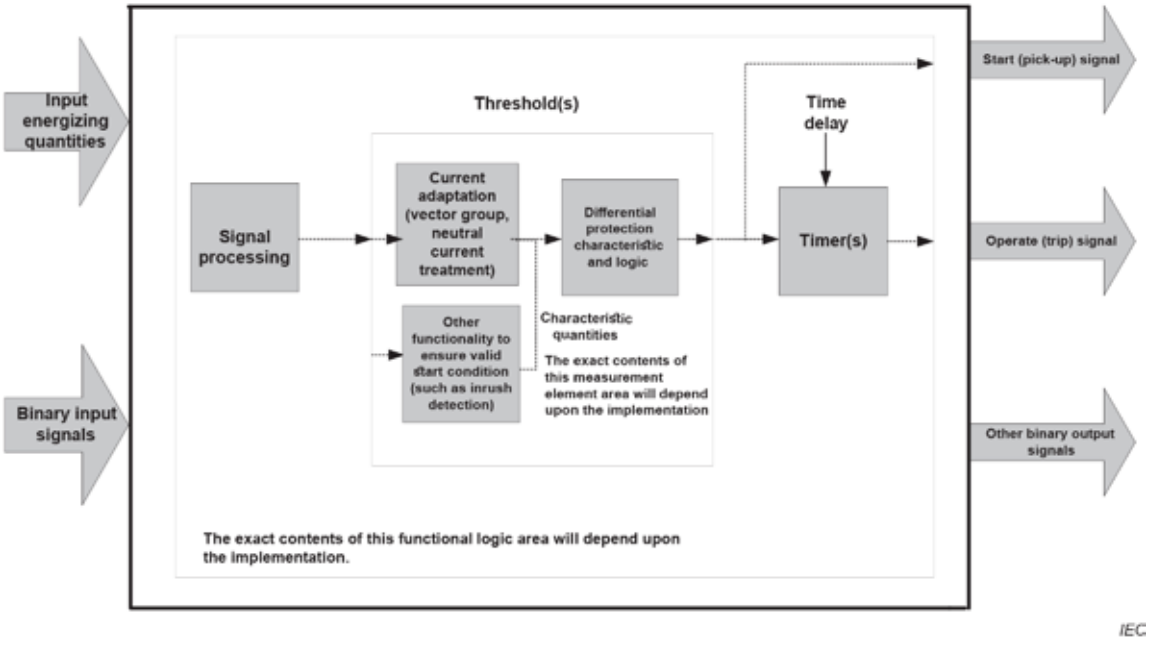

Figure 2 – Simplified biased differential functional block diagram

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4.2 Input energizing quantities/energizing quantities

4.2.1 General

The input energizing quantities are measuring signals, such as phase currents and neutral currents of the different windings or sides of the protected object. Their ratings and relevant requirements are specified in IEC 60255-1.

Input energizing quantities can be presented to the functional protection logic algorithm either hardwired from current transformers or as a data packet over communication ports using an appropriate data communication protocol, such as IEC 61850-9-2.

The energizing quantities used by the biased differential protection function need not be directly the current at the secondary side of the current transformer. Therefore, the measuring relay documentation shall state the type of energizing quantities used by the biased differential function. Examples of energizing quantities include:

- three-phase current measurement (two or more groups),
- negative sequence current,
- neutral current or residual current measurement,
- voltage (example usage: frequency tracking).

The type of measurement of the energizing quantity and its method of calculation shall be stated by the manufacturer. Examples include:

- RMS value of the signal,
- RMS value of the fundamental component of the signal,
- RMS value of a specific harmonic component of the signal,
- peak values of the signal,
- instantaneous value of the signal.

4.2.2 Connections

The manufacturer shall describe the assumed reference direction for all measured primary currents.

It is recommended to use the "node equations notation" for the positive reference direction as indicated in Figure 3. With this notation, a positive primary current is a current flowing into the protected object.

The connection of the current transformers (star or delta), the earthing of the secondary windings and/or the polarity of the secondary signals and any relevant settings shall be specified by the manufacturer. Settings including the sign of the values associated with connection parameters, if any, can be included within the compensation of energizing quantities discussed in 4.4.4.

Where the input energizing quantity is a data packet received via a communication port(s) using a suitable communication protocol (such as IEC 61869-9), all relevant settings shall be specified by the manufacturer.

4.3 Binary input signals

If any binary input signals (externally or internally driven) are used, their influence on the biased differential function shall be clearly described on the functional logic diagram in the manufacturer's documentation. Additional textual description may also be provided if this can further clarify the functionality of the input signals and their intended usage.

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Binary input signals to this function may emanate from a number of different sources. Examples include:

- traditionally wired to physical (typically optically isolated) inputs,
- via a communications port from external devices,
- via internal logical connections from other functional elements within the relay, and
- via internal logical connections within the biased differential element.

The method of receiving the signal is largely irrelevant except to conform to operational requirements. For example, inrush blocking should prevent biased differential function tripping and hence the time taken to generate the blocking signal and deliver it to the biased differential element should be faster than the biased differential protection function operate time. Definitions, ratings and standards for physical binary input signals are specified in IEC 60255-1.

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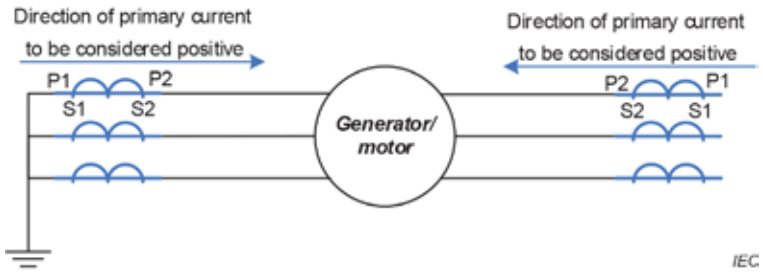
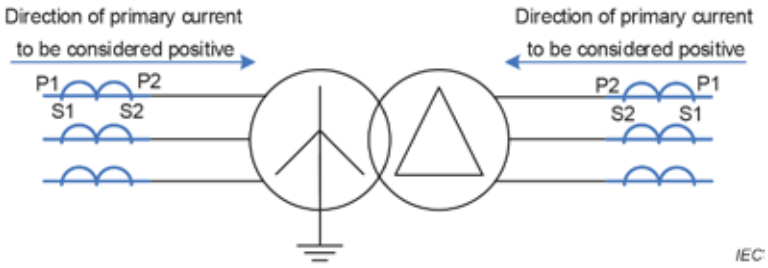
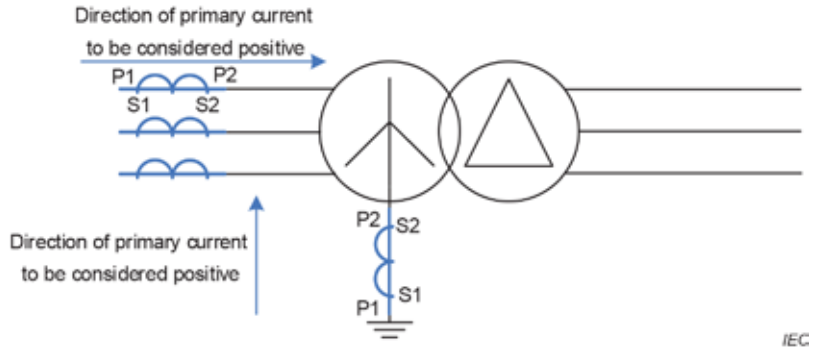


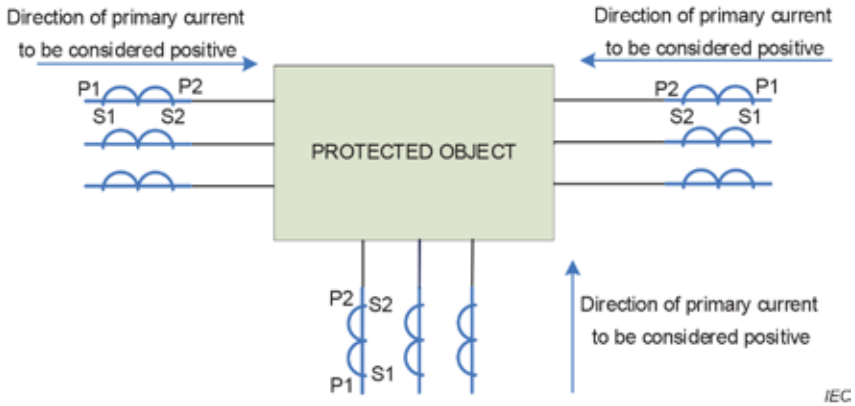
(a) Generator or motor differential



(b) Transformer differential



(c) Restricted earth fault differential



(d) Generic differential

Figure 3 – Primary current reference direction

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4.4 Functional logic

4.4.1 General

For the purpose of this document, a partial functional decomposition is considered in the interest of traditional implementation and ease of understanding. As such, features traditionally associated with transformer biased differential schemes, such as ratio (magnitude) and phase (vector) compensation, inrush and overexcitation restraint/blocking, are considered in 4.4.4. Other features that may influence the operation of the biased differential element are considered in 4.6.

4.4.2 Phase biased differential protection

Biased differential protection is defined in its simplest terms as an element where the differential (operating) current required for operation is increased according to some function of the through (bias or restraining) current. Typically, the differential current is defined as the vector sum of all the currents measured at the boundary of the protected zone whereas the restraining current is half of the scalar sum of the currents measured at the boundary of the protected zone. Other definitions are equally valid. For phase biased differential protection, the currents would be evaluated on a per phase basis.

For three-phase power transformer applications, vector and zero sequence compensation may be performed by mixing currents from two or more phases. In this case, it may be considered incorrect to consider phase differential protection but rather three systems relating to the three phases. However, the operating characteristic is still represented with reference to the three-phase, balanced system, i.e. positive sequence system.

The manufacturer shall declare how the differential (operating) and restraining (bias) currents are derived within the implementation of the biased differential function.

The increase in differential current required for element operation in relation to the restraining current defines the operating characteristic of the biased differential element. This operating characteristic shall be declared by the manufacturer by means of a graphical representation in the bias-differential plane using percentage or per unit quantities, and/or by means of mathematical formulae. An example of a typical biased (restrained element) characteristic is shown in Figure 4, where a percentage relay is demonstrated, K_1 and K_2 are restraint percentages.

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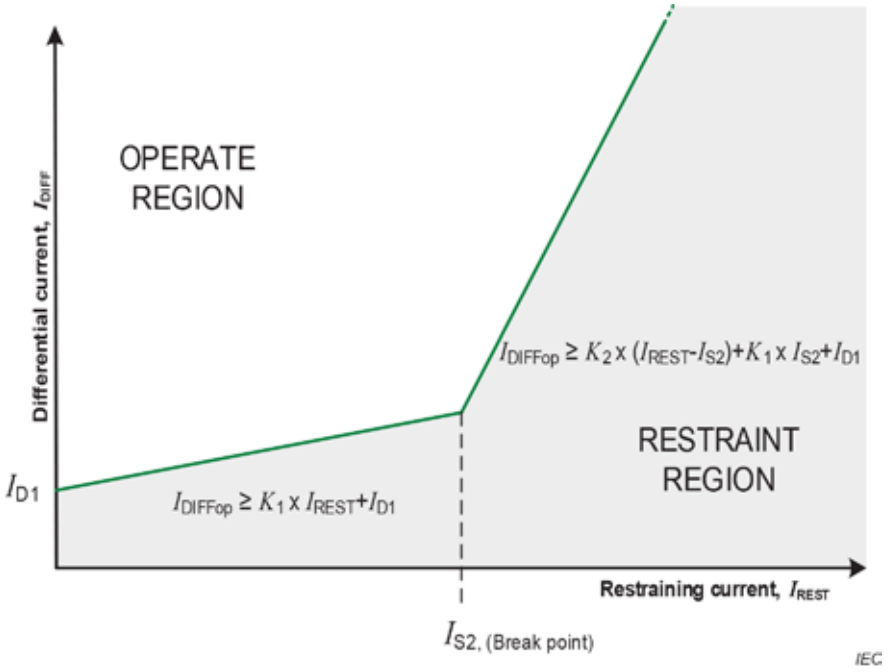

Figure 4 – Typical restrained element (biased) characteristic

In addition to the restrained element, the traditional implementation may also include one or more unrestrained elements that are not influenced by the restraining (bias) current and operate when the measured differential current exceeds the set threshold. An example of an unrestrained element is shown in Figure 5.

Traditionally, the restrained (biased) element and the unrestrained element(s) will operate independently, forming a characteristic that observes the operate characteristics of the two types of elements.

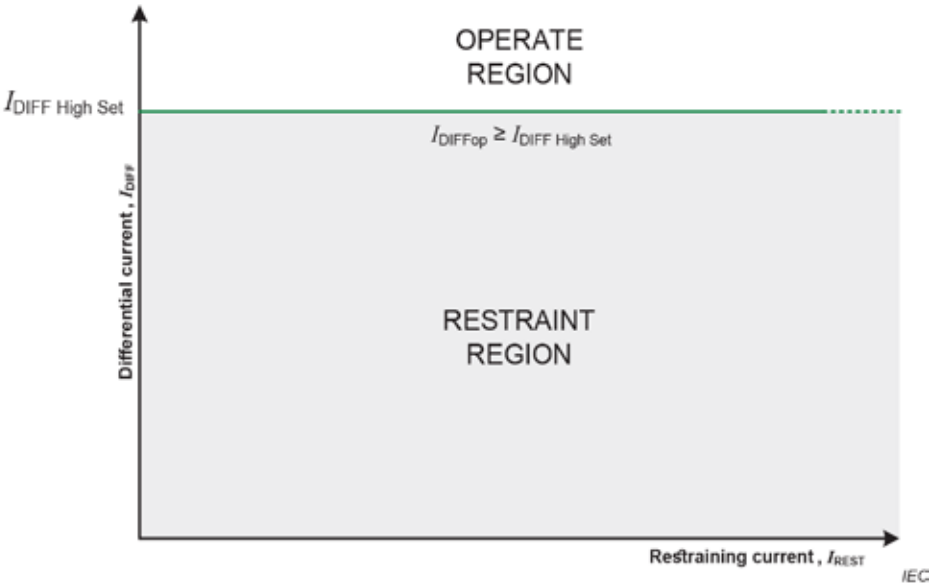

Figure 5 – Typical unrestrained element characteristic

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Figure 6 shows a possible example where a low set unrestrained element is used to prevent operation below a defined differential threshold, $I_{\text{DIFF Low Set}}$.

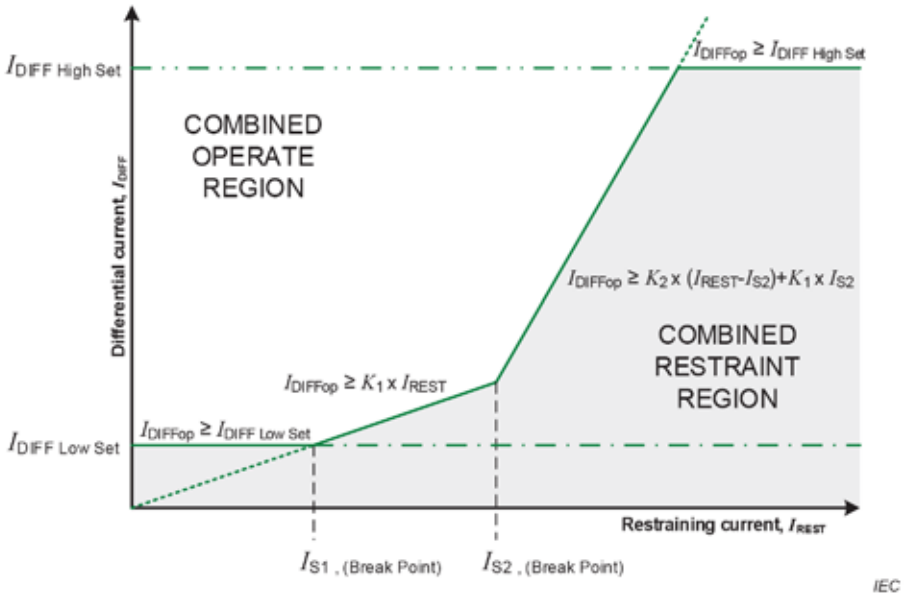

Figure 6 – Example of combined characteristic using restrained and unrestrained elements

When the restraining current exceeds a threshold I_{S1}, the amount of differential current required for operation, I_{DIFFop}, is controlled by the restrained element and follows this characteristic until the measured differential current exceeds the unrestrained high set element, $I_{\text{DIFF High Set}}$. At this point, any further increase in restraining current has no effect on the operation of the relay, and the operation is controlled by the unrestrained element. It should be considered that since the elements are usually independent, the restrained element may still operate, but usually the unrestrained element will be faster.

The manufacturer shall declare all setting parameters associated with the operating characteristic and provide guidance on their use. For the example shown in Figure 6, this would include the basic differential operating thresholds, break points of the characteristic and differential thresholds where restraining effects are ignored, in accordance with the supplied operating characteristic.

In some implementations, the characteristic can change based on certain conditions such as start up of a motor. The manufacturer shall declare if the characteristic is adapted in certain conditions. These conditions shall be described in detail. The tests done to verify this function shall be declared by the manufacturer.

4.4.3 Biased restricted earth fault protection

Biased restricted earth fault protection is a particular case of biased differential protection that is designed to provide increased earth fault sensitivity. It would typically be applied to earthed star transformer windings but could be used to protect any object requiring fast and sensitive earth fault protection.

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For biased restricted earth fault protection, the differential (operating) current would typically be the vector sum of the residual current evaluated from the phase CTs and the current measured in the neutral earthing connection. The restraining (bias) current would typically be half of the scalar sum of the largest phase current and the current measured in the earthing connection. Other definitions are equally valid and it is noted that there is generally more variability in the method of restraining current calculation than for phase differential protection.

The manufacturer shall declare how the differential (operating) and restraining (bias) currents are derived within the implementation of the biased restricted earth fault function.

The increase in differential current required for element operation in relation to the restraining current defines the operating characteristic of the biased restricted earth fault element. This operating characteristic shall be declared by the manufacturer by means of a graphical representation in the bias-differential plane using percentage or per unit quantities, and/or by means of mathematical formulae. Examples of typical bias characteristics and how they are generated are shown in Figure 4 and Figure 6.

The manufacturer shall declare all setting parameters associated with the operating characteristic and provide guidance on their use. For the example in Figure 6, this would include the basic differential operating thresholds, break points of the characteristic and differential thresholds where restraining effects are ignored, in accordance with the supplied operating characteristic.

4.4.4 Compensation of energizing quantities

4.4.4.1 Ratio (magnitude) compensation

The currents measured on the different terminals of the protected object may have different magnitudes, either due to different CT ratio selection, or in the case of power transformer applications due to different voltage levels. The manufacturer shall declare how the currents used by the biased differential element may be compensated. The currents may be compensated either within the protection relay, or externally, in order to have the current magnitudes balanced. All settings required to perform the compensation shall be specified with guidance on their use.

For power transformers with tap changers, the selected tap will affect the power transformer ratio thus causing a false differential current in the relay. This is traditionally overcome by desensitizing the relay and calculating settings at a mid-tap point. However, if the relay uses any feature to automatically compensate for the actual tap changer position, the manufacturer shall declare its operation and provide advice on its usage.

4.4.4.2 Phase (vector) compensation

In power transformer applications, the currents measured on the different terminals of the protected object may have different phase angles due to the power transformer winding configuration. The manufacturer shall declare how the currents used by the biased differential element may be compensated either within the protection relay, or externally, in order to ensure the currents used by the differential element are in phase under normal conditions, for use with all winding configurations that the relay may be applied. All settings required to perform the compensation shall be specified with guidance on their use. An example of a phase (vector) compensation method is shown in Annex A.

As a consequence of the phase (vector) compensation, it is likely that the biased differential element will have different sensitivities depending upon the fault type. However, if the relay uses any feature to achieve constant sensitivity for different fault types, the manufacturer shall declare its operation, any setting parameters required for use and provide advice on its usage.

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4.4.4.3 Zero sequence compensation

In power transformer applications, the zero sequence currents may not be transferred through all terminals due to the power transformer winding configuration. The manufacturer shall declare how the currents used by the biased differential element may be compensated either within the protection relay, or externally, in order to appropriately eliminate the zero sequence currents. All settings required to perform the compensation shall be specified with guidance on their use. An example of a zero sequence compensation method is shown in Annex A.

As a consequence of the zero sequence compensation, it is likely that the biased differential element will have different sensitivities depending upon the fault type. However, if the relay uses any feature to achieve constant sensitivity for different fault types, the manufacturer shall declare its operation, any setting parameters required for use and provide advice on its usage.

4.4.5 Additional restraint or blocking methods

4.4.5.1 General

Magnetizing inrush, overexcitation restraint or blocking are considered in 4.4.5. The manufacturer shall detail any additional restraint or blocking methods used.

4.4.5.2 Magnetizing inrush restraint or blocking

When energizing a transformer, the magnetizing current inrush will appear as differential current and is likely to give unwanted operation of the biased differential element. After transformer energization, magnetizing current inrush can be caused by any abrupt change of magnetizing voltage, such as the occurrence of a fault, the removal of a fault, the change of character of a fault type (for example, the change from a single-phase-to-earth fault to a two-phase-to-earth fault), network reconfiguration, etc.

The inrush current manifests itself as a differential current but differs significantly from an internal fault current. This difference can be used to distinguish between internal fault current and inrush current. Various methods are applied as countermeasures to detect the waveform, such as second and fourth harmonic detection, waveform recognition, etc.

The manufacturer shall declare the method used to characterize the inrush condition as well as any settings relevant to its use, along with guidance on its usage. It is preferable to use transformer manufacturer data regarding the inrush conditions to define the settings on the relay.

The manufacturer shall declare how the inrush detection prevents unwanted operation of the biased differential element, for example by providing additional restraining effect or by blocking operation of the element, and also whether inrush detection influences all three phase-elements of protection (cross blocking) or just the phase-element where inrush is detected.

4.4.5.3 Overexcitation restraint or blocking

During overexcitation (or over-fluxing) of a transformer, higher than normal levels of excitation currents will be measured by the biased differential element, which may cause unwanted operation. Typical methods of characterizing overexcitation include detection of elevated levels of 5^{th} harmonic current, or the V/Hz value.

The manufacturer shall declare the method used to characterize the overexcitation condition as well as any settings relevant to its use, along with guidance on its usage. It is preferable to use transformer manufacturer data regarding the overexcitation conditions to define the settings on the relay.

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The manufacturer shall declare how the overexcitation detection prevents unwanted operation of the biased differential element, for example by providing additional restraining effect or by blocking operation of the element, and also whether overexcitation detection influences all three phase-elements of protection (cross blocking) or just the phase-element (or system) where overexcitation is detected.

4.5 Binary output signals

4.5.1 General

Binary output signals from this function may be available in a number of different forms. Examples include:

- traditionally wired from physical relay output contacts,
- via a communications port to external devices,
- via internal logical connections to other functional elements within the relay,
- via internal logical connections within the biased differential element.

4.5.2 Start (pick-up) signals

The start signal is the output of measuring and threshold elements, with or without any additional verification of valid operate conditions but without any intentional time delay. In the context of biased differential protection, the start signal occurs when the measured differential current is greater than the differential current required for operation on the operating characteristic.

4.5.3 Operate (trip) signals

The operate signal is the output of measuring and threshold elements, after completion of any additional verification algorithms to confirm valid operate conditions. In the context of biased differential protection, this signal may occur at the same time as the start signal (if provided). When additional verification algorithms are used or an intentional time delay characteristic is provided, the manufacturer shall describe the characteristics and any corresponding settings.

It would be unusual to consider single-phase tripping for transformers, generators and motors, but phase-segregated operate signals may be provided for indication purposes.

4.5.4 Other output signals

If any other binary output signals are available for use, their method of operation shall be clearly shown on the functional logic diagram. Additional textual description may also be provided if this can further clarify the functionality of the output signal and its intended usage.

4.6 Additional influencing functions and conditions

4.6.1 General

The conditions in 4.6 may affect the behaviour of the differential protection function. These conditions can be detected by additional function elements which then interact with the differential protection relay through external inputs or signals from internal functional elements in pre-defined ways, for example blocking differential relay when CT supervision indicates a CT failure. The manufacturer shall describe the behaviour of the differential protection function during the following conditions.

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4.6.2 Operation during CT saturation

During internal and external faults, the CTs used to provide the input energizing quantities may become saturated due to large fault currents, extreme levels of remanence, sub-nominal frequency components, harmonics, internal fault preceded by an external fault, etc. As the current transformers saturate, the output measured by the relay will be of different wave shape from the primary current signals and can lead to either an unwanted operation for external faults, delayed operation or a failure to operate for internal faults. In addition, features utilized to prevent an unwanted operation under other conditions, for example inrush detection, may cause the differential element to be inadvertently blocked from tripping.

The manufacturer shall declare any additional features or techniques that are used in order to maintain fast, dependable tripping for internal faults and stability for external faults, including any settings relevant to its use, along with guidance on its usage.

4.6.3 Switch onto fault

The switch onto fault condition is defined as a closure of a circuit breaker (or other circuit switching device) onto a fault within the protected zone. For such conditions, fast instantaneous tripping is desired to minimize equipment damage. However, due to the energization conditions, it is likely that built-in blocking features may be activated, such as inrush blocking, and result in delayed operation of the relay. The manufacturer shall declare any additional features or techniques that are used in order to maintain fast tripping including any settings relevant to its use, along with guidance on its usage.

4.6.4 Energizing quantity failure (CT supervision)

Loss of one or several input energizing quantities without an equivalent loss of respective primary current signal(s) is called energizing quantity failure. Traditionally, this event will cause differential protection relays to operate due to the lack of the necessary balancing quantities. The manufacturer shall declare the behaviour of the differential element under an energizing quantity failure and, if any special techniques are used to prevent false operation, provide details of any settings relevant to its use, along with guidance on its usage.

4.6.5 Off-nominal frequency operation

Many applications of differential protection are required to operate over a wide frequency range and not solely at system nominal frequency. Depending upon the specific implementation, this can affect accuracy of operate times, ability to detect harmonic frequency components, or generally poor performance of the element.

The manufacturer shall declare the operating frequency range of the differential protection, including any features that may be used to improve performance at off nominal frequency. For any special techniques that are used, the manufacturer shall provide details of any settings relevant to its use, along with guidance on its usage.

4.6.6 Geomagnetically induced currents (GIC)

Presence of harmonics on the fundamental frequency load current can be caused by the induction of electric currents in the earth's crust as a result of increased solar activity and its interaction with the earth's magnetosphere. The effects of GIC are usually seen at high latitudes (Scandinavia, Canada, Russia, etc.) and the harmonics are caused by the saturation of the power transformers, but also of the current transformers feeding the protection relay. The differential protection may be affected by these harmonics and also the presence of quasi-DC currents ultimately causing unwanted relay operation. Simulation of GIC and its effect on power transformers and current transformers is a complex topic and no tests will be proposed in this document. If the GIC phenomenon has been considered in the design of the protection relay, the manufacturer shall declare the relay behaviour during such events.

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5 Performance specification

5.1 General

This document defines how the performance related to the minimum requirements shall be assessed and documented by the manufacturer. The manufacturer generally performs a much wider set of tests and produces a large amount of data to ensure the performance of its protection device. It is the responsibility of the end user, or their representative, to determine if the performance of the function as declared by the manufacturer is adequate for their application.

5.2 Effective and operating ranges

Table 1 shows, with an example, how effective range and operating range shall be declared by the manufacturer. Depending on the relay technology, the range can differ from Table 1 where the values are given as an example to indicate the format of the data. The effective and operating range shall be declared by the manufacturer and the data shall be published in accordance to the format given by Table 1.

Table 1 – Example of effective and operating ranges of differential protection

Input energizing quantity	Effective range	Operating range
Current	5 % to 1 000 % of rated current	0 % to 4 000 % of rated current
Voltage	5 % to 150 % of rated voltage	2 % to 200 % of rated voltage
Frequency deviation	–5 % to +5 % of rated frequency	–10 % to +10 % of rated frequency

For applications where the rated frequency is constant, the effective and operating ranges shall be declared as relative values (as shown). For applications where the rated frequency is not constant, for example generators and variable frequency drives, the ranges shall be declared in absolute values (Hz). Additional frequency ranges can be declared if frequency tracking is available.

Within the effective range of current (as per IEC 60255-1), the differential relay shall operate for internal fault conditions and remain stable for external fault conditions. Operation shall be in accordance with the manufacturer's claimed performance.

Within the operating range but outside the effective range of current (as per IEC 60255-1), the differential relay shall operate for internal fault conditions and remain stable for external fault conditions. Operation is not required to be in accordance with the manufacturer's claimed performance. The manufacturer shall declare the behaviour of the differential relay in the operating range.

5.3 Steady state accuracy tests in the effective range

5.3.1 General

Steady state conditions are defined as a non-varying level of the relay energizing quantities, such as constant through load. Steady state conditions often do not represent the electrical quantities that energize the protection relay in a realistic way, as the DC transient is not present, but they are very helpful for evaluating the basic accuracy.

Pseudo-continuous ramps created by slowly changing the energizing quantity using small discrete steps, or simulation of a number of steady state conditions sequentially applied to the device can also be considered as steady state testing. For example, applying a through load condition followed by application of a steady state fault condition.

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Steady state testing shall be performed and declared at both nominal frequency and within the limits of the effective range, unless specified otherwise. Details of the off-nominal frequencies to be used in the testing are described in the test methodologies. Any special features to improve performance, for example frequency tracking, shall be declared by the manufacturer, including input energizing quantities necessary for operation.

5.3.2 Test related to the declared thermal withstand current

The manufacturer shall declare the behaviour of the differential relay at the one second short time thermal withstand current (as per IEC 60255-1), according to the test methodologies described in 6.2.

5.3.3 Basic characteristic accuracy

The purpose of 5.3.3 is to provide a measure of the characteristic shape and its basic accuracy under steady state conditions. The test methods that shall be used for this assessment are described in 6.3.2 and the manufacturer shall declare the specific method used.

The manufacturer shall declare the basic accuracy either by graphically showing the maximum and the minimum line as in Figure 7 or percentage error over the effective range, under reference conditions. If required, the percentage error can be associated with a minimum absolute error, and the accuracy shall be defined by the maximum of both values (for example, ±2 % of the differential current start value or ±0,001 × I_r, with I_r equal to CT rated current). If the restrained and unrestrained elements have different basic accuracies, the manufacturer shall declare them separately for each element.

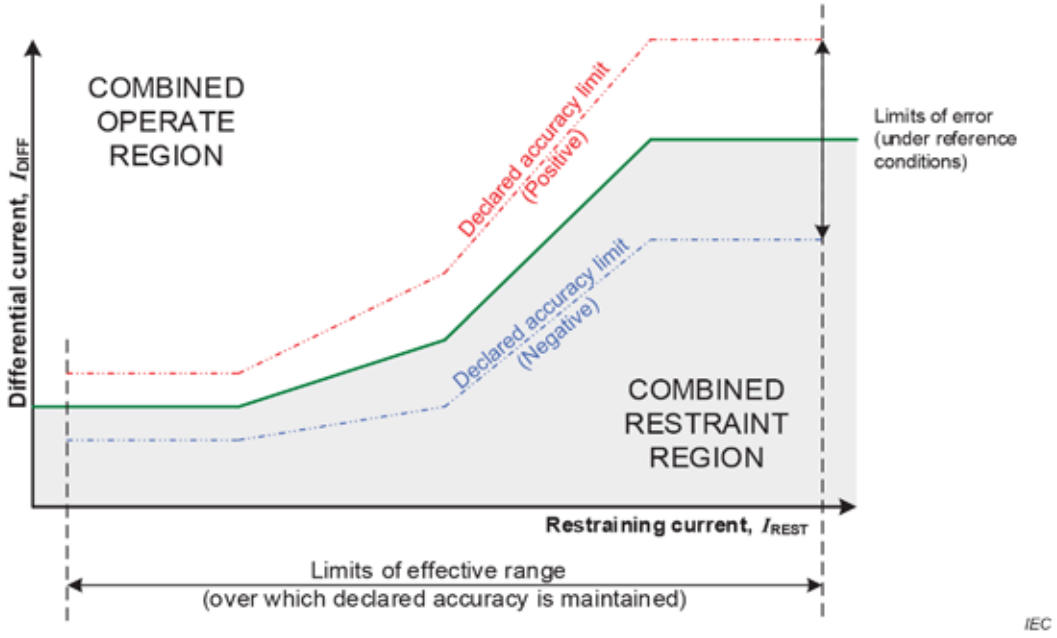

Figure 7 – Basic error of the operating characteristic

5.3.4 Ratio compensation accuracy

The validity of the ratio compensation shall be assessed according to the methodology described in 6.3.3. This is typically required for transformer differential elements but may be applied to compensate for different CT ratios in other applications.

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The manufacturer shall declare any additional error resulting from the effects of the ratio compensation. If this is not feasible due to the functionality of the element or relay, compliance to the testing methodology proposed shall be declared.

5.3.5 Phase (vector) compensation validity

The validity of the power transformer vector group compensation shall be assessed according to the methodologies described in 6.3.4. It is not generally required to perform this test for generator or motor differential elements, or for restricted earth fault elements.

The manufacturer shall declare the ratio between the double-phase start current (pick-up current, injection of current going "in" on one of the three phases of the selected winding and going "out" in one of the other phases of the selected winding) and the three-phase start current (pick-up current, positive sequence three-phase injection in all the three phases of the selected winding) for each winding connection. Refer to Annex A for the derivation of this ratio.

5.3.6 Zero sequence compensation validity

The validity of the power transformer zero sequence compensation shall be assessed according to the methodologies described in 6.3.5. It is not generally required to perform this test for generator or motor differential elements, or for restricted earth fault elements.

The manufacturer shall specify the ratio between the single-phase start current (pick-up current, injection of current in only one of the three phases of the selected winding) and the three-phase start current (pick-up current, positive sequence three-phase injection in all the three phases of the selected winding) for each winding connection (star, delta or zigzag as appropriate) and for each setting of the zero-sequence current compensation (enabled or disabled). Refer to Annex A for the derivation of this ratio.

5.3.7 Harmonic restraint basic accuracy

The manufacturer shall declare the basic accuracy of the harmonic restraint functionality of the differential protection. The test methods and how to determine the accuracy are described in 6.3.6. It is noted that this test is only performed at the rated frequency or rated frequencies of the function.

5.3.8 Basic accuracy of time delay settings

These tests are aimed at determining the accuracy of the timers for time delayed differential protection (if available). They are based on monitoring the time difference between the start (pick-up) and operate (trip) output signals of the relay. The maximum permissible error of the specified time delay shall be expressed as either:

- a percentage of the time delay setting value, or
- a percentage of the time delay setting value, together with a fixed maximum time error (where this may exceed the percentage value), whichever is greater (for example ±5 % or ±20 ms, whichever is greater), or
- a fixed maximum time error (generally used when there is no time delay setting).

Details on how these tests shall be performed are given in 6.3.7.

5.3.9 Disengage time

The manufacturer shall declare the maximum disengage time according to the test procedure described in 6.3.8.

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5.4 Dynamic performance in operating range

5.4.1 General

Dynamic performance represents the response of the protection function to various power system conditions (such as electrical faults). Testing to verify the response of the protection relay for dynamic power system conditions requires a power system simulator. When the relay inputs are energized with electrical quantities representing steady-state pre-fault conditions, followed by the fault condition (with correctly represented DC transient and final steady state condition), the test is called a "dynamic test". The response of the protection function to the above tests is called "dynamic performance".

Also, the performance of the protection function during dynamic fault conditions (such as internal fault preceded by an external fault, superimposing of load currents on fault currents during faults) needs to be declared by the manufacturer.

The relay performance is reported for the following dynamic performance tests:

- typical operate time;
- stability for external faults;
- behaviour for internal fault preceded by an external fault.

Dynamic performance testing shall be performed and declared at both nominal frequency and within the limits of the operating range, unless specified otherwise. Details of the off-nominal frequencies to be used in the testing are described in the test methodologies.

5.4.2 Typical operate time

The operate time (trip time) of a differential protection function depends upon a number of factors:

- fault current level;
- magnitude and time constant of DC component;
- type of fault.

The typical operate time shall be published by the manufacturer as a result of dynamic performance tests not taking into consideration the effects of CT performance (saturation, remanence, magnitude and angle errors, etc.). Two network models are used in these tests, one for double infeed network and one for radial single infeed network. The operate time shall be declared at the rated power system frequencies for which the device is designed and in accordance with IEC 60255-1 and for each network application. Additionally, the operate time for off nominal frequencies within the declared operating range shall also be published.

The manufacturer shall provide the median operate time which is a statistical indicator of the typical operate time. In addition, a graphical representation (histogram) of the complete set of tests shall be provided with the mean, mode and median values indicated.

More comprehensive information about test methodology is provided in 6.4.2 to 6.4.5 with reporting requirements in 6.4.6. Clarification of the statistical terminology is provided in Annex B.

5.4.3 Relay stability for external faults

Vector group compensation, ratio compensation and zero sequence current elimination algorithms may show unexpected results during transient conditions, causing the relay to become unstable for external faults. Based on the double infeed network model, the stability of the protection function for a number of external fault cases shall be evaluated. Subclause 6.4.7 provides detailed description of the tests to be executed.

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The manufacturer shall declare if any operations occur during the testing.

5.4.4 Relay behaviour for internal fault preceded by an external fault

External faults, if not cleared in time, may cause both thermal and mechanical damage to equipment that may in turn evolve into internal faults, and the protection relay shall operate for this condition.

The relay behaviour for faults changing from the external position into the internal position is assessed in terms of stability for the first fault and operate time for the second fault. The test methodologies are described in 6.5.

The manufacturer shall declare the operate time in accordance with 6.5, which provides a comparative detail of the operate time with and without the initial external fault. Additionally, the manufacturer shall declare if the relay failed to operate during any of the tests.

5.5 Stability during magnetizing inrush conditions

Under magnetizing inrush conditions during transformer energization, the differential relay may misoperate. The manufacturer shall verify the relay stability for inrush conditions, according to the tests provided in 6.6, which utilizes injection of current waveforms of a similar wave shape as may be expected during the inrush period.

The manufacturer shall declare if any operations occur during the testing, as well as the test method used.

5.6 Stability during overexcitation conditions

Under overexcitation conditions of a transformer, the differential relay may misoperate. The manufacturer shall verify the relay stability for overexcitation conditions, according to the tests provided in 6.7, which utilizes injection of current waveforms of a similar wave shape as may be expected during the overexcitation conditions.

The manufacturer shall declare if any operations occur during the testing, as well as the test method used.

5.7 Presence of harmonics on load

Nonlinear load conditions or presence of nearby HVDC network can create harmonics superimposed on the fundamental frequency component of current. The presence of harmonics on the steady state load may cause the differential protection relay to issue an unwanted trip command.

The manufacturer shall verify the relay stability when superimposed harmonics (representing the current supplied into a 6-pulse rectifier bridge) are present on the load, according to the tests described in 6.8.

5.8 Performance during saturation of current transformers

Saturation of CTs will cause distortion of the secondary current, and the performance of differential protection may degrade. The measuring errors due to current transformer saturation can cause incorrect operations, such as unwanted operation for external faults and failure to operate or unacceptable delayed operation in case of internal faults. The degree of degradation depends upon the dimensioning of the CTs. The relay manufacturers shall declare CT requirements in accordance with Annex C (normative).

The following informative annexes are included to provide additional guidance:

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Annex D (informative) provides background on CT saturation and its influence on the performance of differential relays.

Annex E (informative) provides guidance on dimensioning CTs for transformer differential protection.

Annex F (informative) provides examples of test procedures to determine CT sizing requirements for differential protection.

5.9 Behaviour of differential protection with digital interface for the energizing quantities

When the input energizing quantities are data packets received via a communication port(s) using a suitable communication protocol such as the profile of IEC 61850-9-2 defined in IEC 61869-9, additional declarations are required.

The examples of these declarations include:

- the behaviour of the protection function when invalid or questionable sampled values are received from the process bus interface, and
- the behaviour of the protection function when the synchronization of the received sampled values is lost or changing.

6 Functional tests

6.1 General

Clause 6 gives a detailed description of the tests to be performed to verify the relay accuracy and performance specification described in Clause 5. These tests are not intended for protection relay field commissioning or routine tests, where the manufacturer's instructions shall be used as a reference. Several test methodologies and performance requirements described in this document are also applicable for commissioning or routine tests.

These tests are, as explained in Clause 5, a mandatory part of the type tests for the protection relay. Detailed description of the test conditions and how test results shall be published in the manufacturer's documentation are provided in Clause 6. This will allow a comparison of the technical requirements of the user with the protection relay specifications given in the manufacturer's documentation. In some cases, default settings are used for the test in this document. The default setting is the setting that is applied to the relay when it is shipped from the factory.

The tests described in this document are designed for applications for which conventional current transformers are directly connected to the differential relay. Application of low-level signals of the input energizing quantities that would bypass the CTs on the relay is not acceptable. For installations when any low power instrument transformers and/or merging units are utilized, these tests should be adapted by mutual agreement of all of the parties involved for their use in testing differential protection relays for a specific project.

All testing described in Clause 6 refers to generator, motor, transformer and restricted earth fault applications. Only the tests applicable should be performed for the particular protection device under test. For example, for testing a generator differential function without vector compensation, only the tests detailed for generator applications should be performed.

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6.2 Test related to the declared thermal withstand current

For each group of current inputs (e.g. a transformer phase differential relay that protects a 3-winding transformer has three current input groups), the following tests shall be performed:

- for each provided nominal input current (e.g. 1 A, 5 A);
- for each provided nominal frequency (e.g. 50 Hz, 60 Hz).

The differential function is set active with default settings. Each of the defined test cases will lead in theory to an operation of the function (because the current injection to the other current input groups is zero and the resulting differential current will be very high). The manufacturer shall report the operation (with operate time) or non-operation for each of the defined test cases. This report shall be used to declare the behaviour of the differential relay at the one second short time thermal withstand current. The manufacturer shall declare the cooling and recovery time.

The following tests shall be performed:

- for L1L2, 2-phase injection of the thermal withstand current for 1 s (simulating a 2-phase fault);
- for L3E, 1-phase injection of the thermal withstand current for 1 s (simulating a 1-phase fault).

The following examples illustrate currents that shall be injected for the declared thermal withstand current of 200 A for 1 s:

- 2-phase injection for case L1-L2 (amplitude/phase)

  I_{L1} 200, 0 A∠0,00º

  I_{L2} 200, 0 A∠–180,00º

  I_{L3} 0,0 A∠0,00º
- 1-phase injection for case L3-E (amplitude/phase)

  I_{L1} 0,0 A∠0,00º

  I_{L2} 0,0 A∠0,00º

  I_{L3} 200,0 A∠00,00º

After the injection, the relay shall prove that its performance and accuracy is still within the defined limits. This can be achieved by starting the type test of the device with the thermal withstand current test sequences.

6.3 Steady state accuracy tests in effective range

6.3.1 General

The intention of the tests described in 6.3 is to define the accuracy of the operating characteristic, the operate time and the stability performance of differential protection relays when the electrical system is operating within the relays effective frequency range, as described in Clause 5.

In order to provide fixed, comparative test points, the effective ranges have been chosen as ±5 % of the nominal frequency for accuracy tests as per Table 2.

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Table 2 – Frequencies for steady state accuracy tests when the frequency effective range is equal to ±5 % of nominal frequency

50 Hz nominal frequency (Hz)	60 Hz nominal frequency (Hz)
47,50	57,00
48,75	58,50
50,00	60,00
51,25	61,50
52,50	63,00

If the effective range of the protection function is wider than the ±5 % range, the tests shall be executed for the frequencies shown in Table 3.

Table 3 – Frequencies for steady state accuracy tests when the frequency effective range is larger than ±5 % of nominal frequency

50 Hz nominal frequency (Hz)	60 Hz nominal frequency (Hz)
Min. frequency of effective range	Min. frequency of effective range
(Min. frequency of effective range + 47,5) / 2	(Min. frequency of effective range + 57) / 2
47,50	57,00
48,75	58,50
50,00	60,00
51,25	61,50
52,50	63,00
(52,5 + max. frequency of effective range) / 2	(63 + max. frequency of effective range) / 2
Max. frequency of effective range	Max. frequency of effective range

If the effective range of the frequency of the protection function is narrower than the proposed ±5 % of the nominal frequency, then the tests shall be executed for the frequencies listed in Table 2 that are included in the relay's effective range. Additional tests shall be executed for the minimum and maximum values of the effective range. Table 4 shows an example where the protection relay has an effective range of 48 Hz to 52 Hz for 50 Hz nominal frequency. A note in the test report shall state that the frequency effective range is narrower than 5 % of the nominal frequency.

Table 4 – Example frequencies for steady state accuracy tests when the frequency effective range is narrower than ±5 % of nominal frequency

50 Hz nominal frequency (Hz)
Min. frequency of effective range = 48,00
48,75
50,00
51,25
Max. frequency of effective range = 52,00

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6.3.2 Basic characteristic accuracy

6.3.2.1 General methodology

The purpose of these tests is to measure the basic accuracy of the differential characteristic under quasi steady-state conditions. These tests are not intended to prove the performance of the differential protection relay for a real application.

These tests may not be realistic from a power system protection perspective, but they determine the inherent characteristic accuracy of the device. The proposed tests should not be used as criteria for performance evaluation of the relay for a specific protection application.

The proposed test methods are recommended. If a particular protection algorithm does not allow the use of the proposed approach, the manufacturer shall propose and describe an alternative test procedure and present the results in the format given in this document. Tests are performed for the effective range of frequency of the protection relay, as outlined in 6.3.1.

The differential characteristic basic accuracy tests shall be performed in the I_{DIFF}/I_{REST} plane shown in Figure 8.

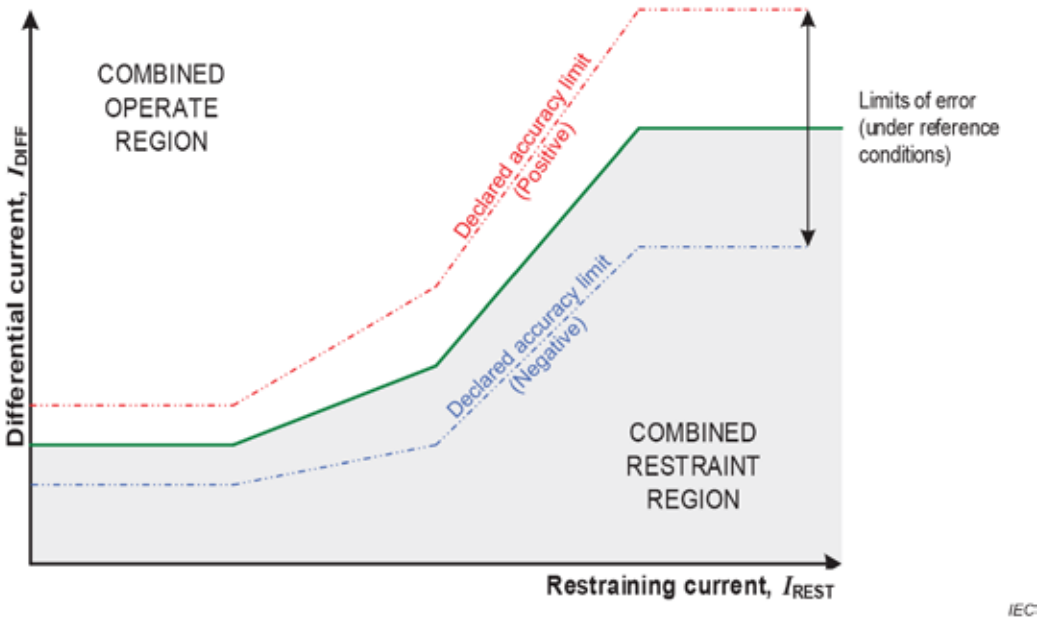

Figure 8 – Example of an operating characteristic in the I_{DIFF}/I_{REST} plane with a tolerance band

At rated frequency, the tests shall be repeated and documented for all possible combinations of rated currents as per the specification of the protection relay under test (e.g. all combinations of the HV and LV sides: 1 A/1 A; 1 A/5 A; 5 A/1 A; 5 A/5 A).

At all other test frequencies within the effective range, the tests shall be repeated and documented for the identical rated currents as per the specification of the protection relay under test (e.g. combinations of the HV and LV sides: 1 A/1 A and 5 A/5 A only).

Some devices under test may allow combinations of conventional current inputs (1 A, 5 A) on the one side and low power instrument transformers (LPITs) on the other side. Verification of such combinations is not covered by this document.

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All settings of the differential characteristic shall be varied in the settings range (default/minimum/50 %/maximum) as shown in Table 5. The test settings to be used are expressed in a percentage of the available range with 0 % representing the minimum available setting and 100 % representing the maximum available setting. Similarly, 50 % would represent the mid-point of the available setting range.

Table 5 – Test points for differential characteristic basic accuracy

Case	$I_{\text{DIFF Low Set}}$	Slope 1	$I_{\text{S1, (Break Point)}}$	Slope 2	$I_{\text{S2, (Break Point)}}$	$I_{\text{DIFF High Set}}$
1	Default setting	Default setting	Default setting	Default setting	Default setting	Default setting
2	Minimum (0 %)	Minimum (0 %)	Maximum (100 %)	Minimum (0 %)	Maximum (100 %)	Minimum (0 %)
3	50 %	50 %	50 %	50 %	50 %	50 %
4	Maximum (100 %)	Maximum (100 %)	Minimum (0 %)	Maximum (100 %)	Minimum (0 %)	Maximum (100 %)

The actual setting to be used can be calculated using the following formula:

$$S_{\text{AV}} = (S_{\text{MAX}} - S_{\text{MIN}})X + S_{\text{MIN}}$$

where

S_{AV} is the actual setting value to be used in the test (or closer applicable setting value);

S_{MAX} is the maximum available setting value;

S_{MIN} is the minimum available setting value;

X is the test point percentage value divided by 100.

For example, for slope setting in Table 5, assuming the available setting range is 20 % to 100 %, the actual slope settings to be used (minimum/medium/maximum settings) would be: 20 %, 60 % and 100 %.

Table 5 and Figure 9 provide the test cases to be used for tests at nominal frequency. At all other test frequencies within the effective range, the tests shall be performed for case 1 only.

The setting values defined in Table 5 are chosen to perform accuracy tests in four conditions:

- case 1 with default settings;
- case 2 based on settings which gives an operating characteristic corresponding to the maximum sensitivity;
- case 3 to get a test case between minimum and maximum sensitivity cases (2 and 4);
- case 4 based on settings which gives an operating characteristic corresponding to the minimum sensitivity.

The setting values defined for cases 2 and 4 are illustrated in Figure 9. If some settings are not available to define the operating characteristic, the four test cases shall be performed with the same approach and with settings proposed by the manufacturer. If any method of frequency tracking is implemented within the protection relay, it shall be activated. For each setting combination, test lines shall be placed at the points defined in Table 6 on the I_{REST} axis (see also Figure 10). For each defined test point, a ramp perpendicular to the I_{REST} axis will be performed to determine the corresponding pick-up value of the differential characteristic. The ramp can be a pseudo-continuous ramp or a ramp of shots (pulse ramp or any search algorithm). The ramping methods and the associated simulated currents are described in Annex G.

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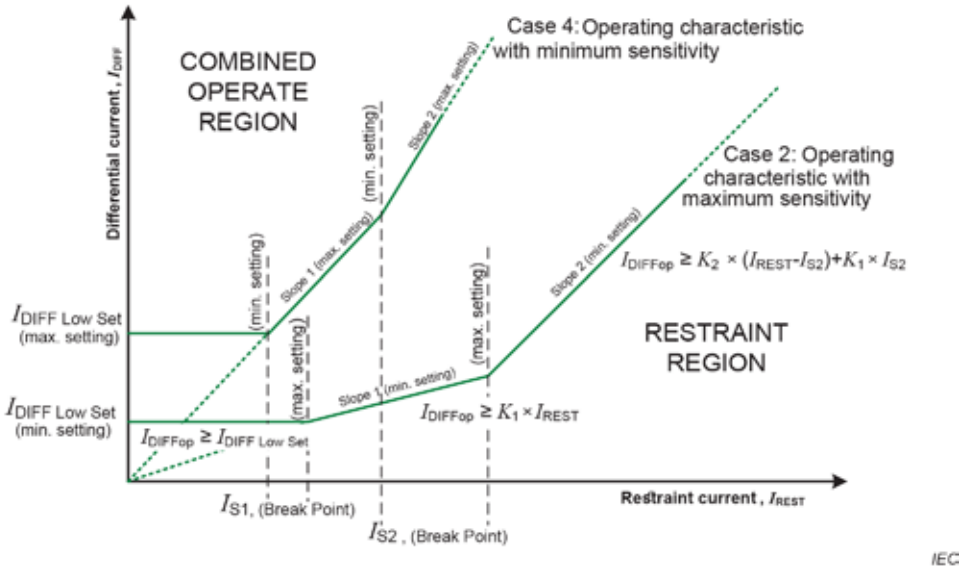

Figure 9 – Test cases for differential characteristic basic accuracy

Table 6 – Test lines on the differential characteristic (Figure 10)

Test point (line)	I_{REST}
a	Minimum possible I_{REST} that allows a test
b1	Reference point for slope 1, $I_{S1,\ (Break\ Point)}$ –2 %
b2	Reference point for slope 1, $I_{S1,\ (Break\ Point)}$ +2 %
c	Reference point 1, $I_{S1,\ (Break\ Point)}$ + 50 % of ($I_{S2,\ (Break\ Point)} - I_{S1,\ (Break\ Point)}$)
d1	Reference point for slope 2, $I_{S2,\ (Break\ Point)}$ –2 %
d2	Reference point for slope 2, $I_{S2,\ (Break\ Point)}$ +2 %
e	Reference point 2, $I_{S2,\ (Break\ Point)}$ + 50 % of (point of I_{REST} where $I_{DIFF\ High\ Set}$ cuts slope 2 – $I_{S2,\ (Break\ Point)}$)
f1	Point of I_{REST} where $I_{DIFF\ High\ Set}$ cuts the slope –2 %
f2	Point of I_{REST} where $I_{DIFF\ High\ Set}$ cuts the slope +2 %
g	Point of I_{REST} where $I_{DIFF\ High\ Set}$ cuts the slope × 1,2
h	Point of I_{REST} where $I_{DIFF\ High\ Set}$ cuts the slope × 1,5

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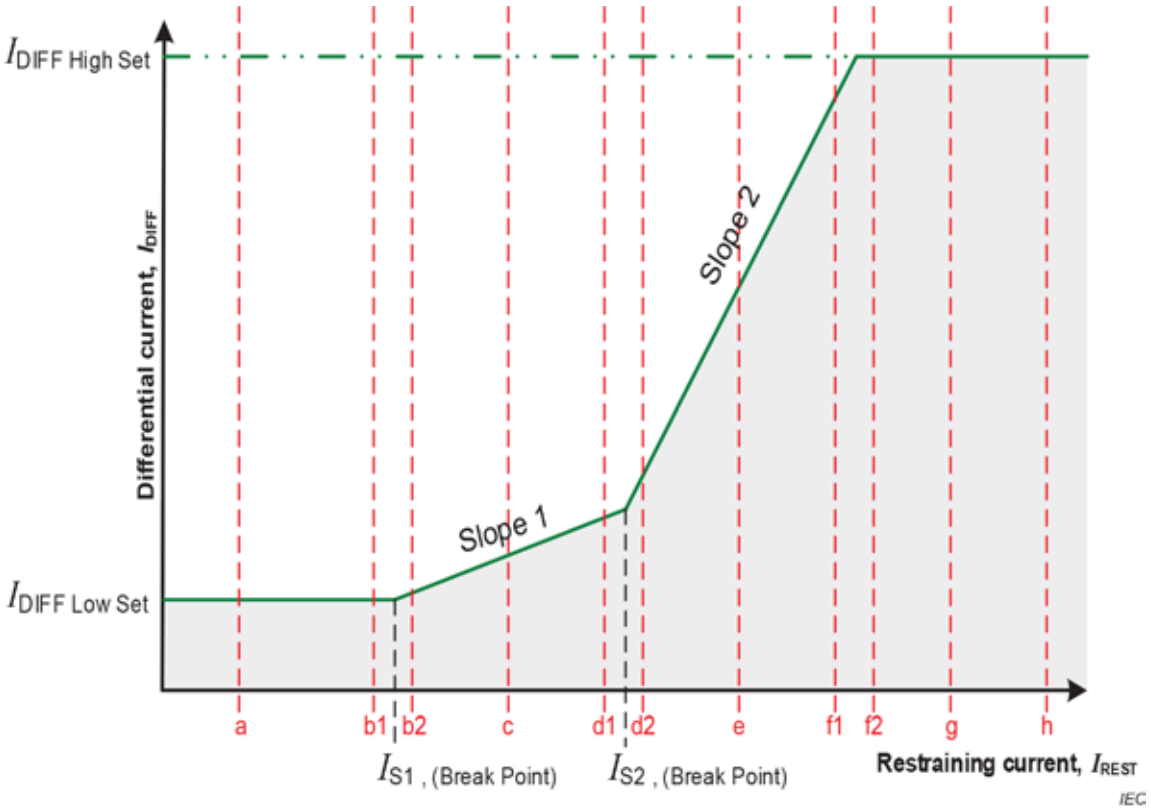

Figure 10 – Example of a differential characteristic with test lines "a" to "h"

6.3.2.2 Application specific considerations: phase biased differential

For this test, a simple machine as shown in Figure 11 is used requiring no transformation ratio compensation, no phase (vector group) compensation, no zero sequence compensation, etc. All relevant settings shall be specified by the manufacturer, using the following information:

- primary nominal voltage: 10 kV;
- primary nominal current: 1 000 A;
- nominal power: 17,32 MVA;
- CT ratios: CT1: 1 000 A/1 A (5 A); CT2: 1 000 A/1 A (5 A).

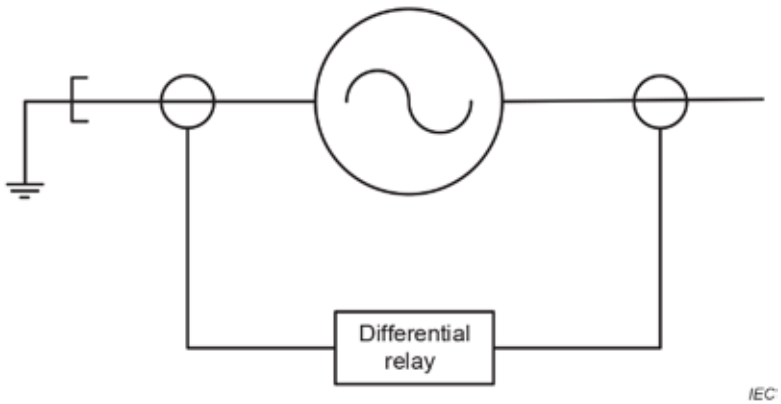

Figure 11 – Machine differential protection

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All tests shall be repeated and documented for the following faults (L1E, L2E, L3E, L1L2, L2L3, L3L1, L1L2L3). If the characteristic changes for different types of faults, the manufacturer shall document this accordingly.

Faults will be injected according to the example test sequence described by the flowchart shown in Figure 12. However, other test sequences can be used to reduce overall test time. The total number of tests is 7 392 for one rated frequency (i.e. 50 Hz or 60 Hz) and all possible combinations of rated currents.

6.3.2.3 Application specific considerations: biased restricted earth fault

For this test, a simple machine as shown in Figure 13 is used requiring no transformation ratio compensation, no phase (vector group) compensation, no zero sequence compensation, etc.

All tests shall be repeated and documented for the following faults (L1E, L2E, L3E).

Faults will be injected according to the sequence described by the flowchart shown in Figure 12. However, other test sequences can be used to reduce overall test time.The total number of tests is 3 168 for one rated frequency (i.e. 50 Hz or 60 Hz) and all possible combinations of rated currents.

6.3.2.4 Reporting

Table 7 provides example test results for a single test point. Test results for all test points shall be documented using the format of Table 7.

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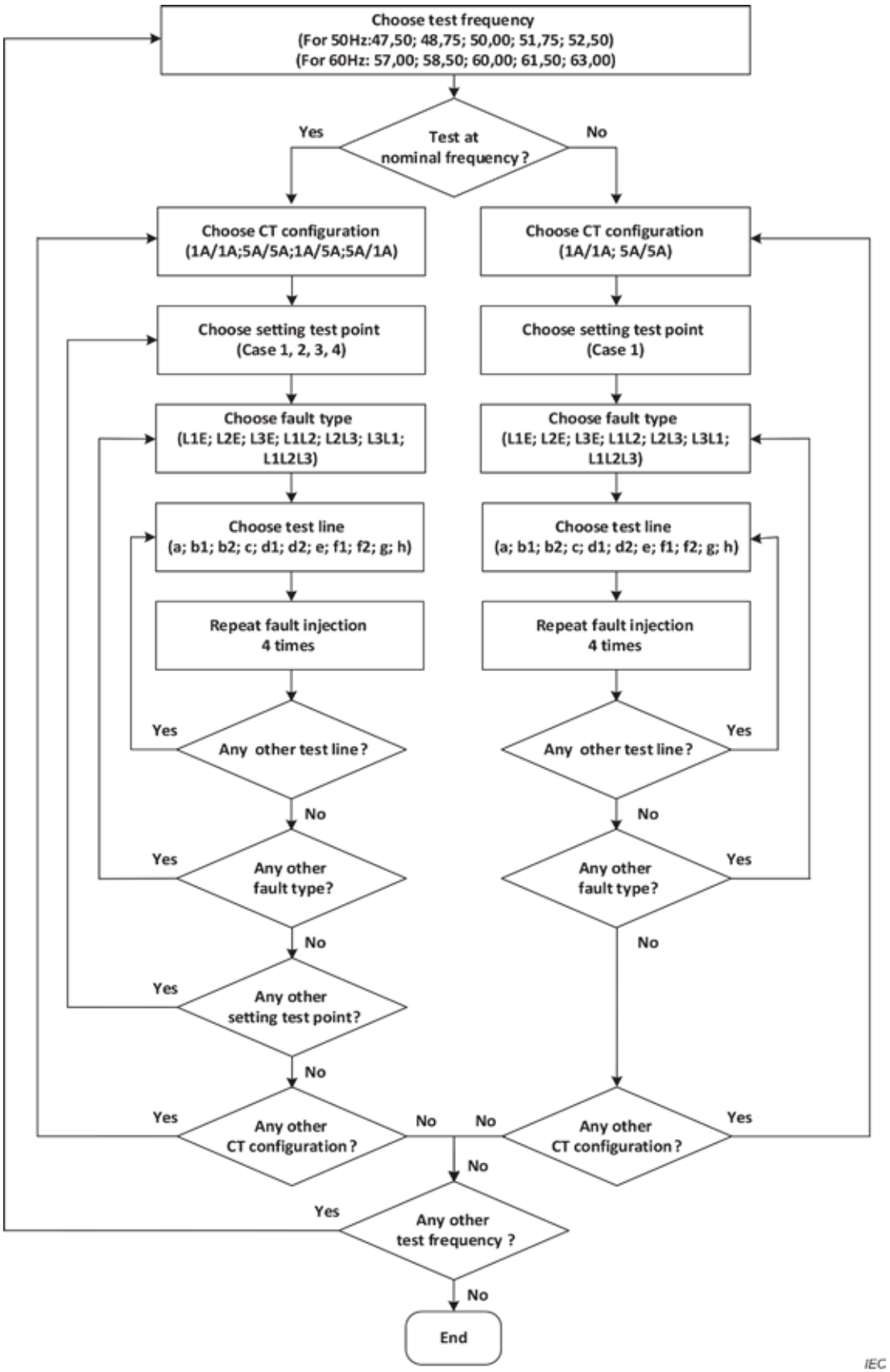

Figure 12 – Test sequence for basic characteristic accuracy

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Table 7 – Basic characteristic accuracy

I_{REST}	I_{DIFF} theoretical	I_{DIFF} measured	Error %	Tolerance –	Tolerance +
2,68 I_r	0,670 I_r	0,669 I_r	–0,15 %	–0,6 %	+0,6 %

"I_r" in Table 7 is the reference current defined by the manufacturer. For example, it can be the nominal current of the protected object or the nominal current of the CTs on either side of the protected object. For each fault type and combination of nominal currents and set of parameters for the characteristic, the differential characteristic with a graphical representation of the test results and the corresponding tolerance band shall be provided (refer to Figure 14).

The manufacturer shall declare the formulae or provide the graphical representation for the I_{DIFF} versus I_{REST} characteristic. The manufacturer shall declare the basic accuracy and specify which ramping method has been used to test the basic accuracy.

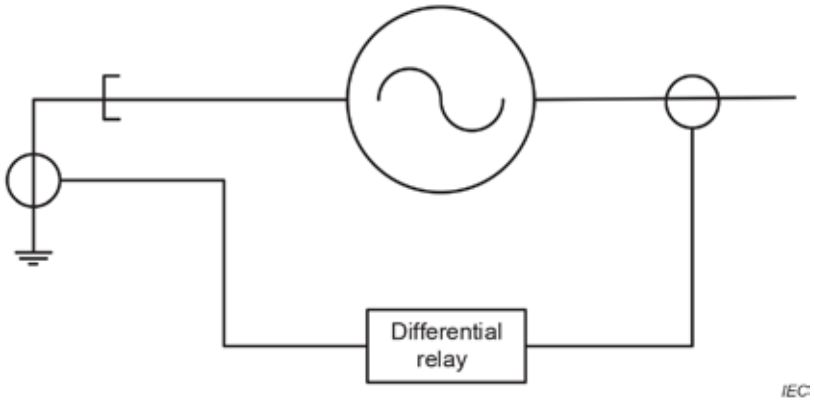

Figure 13 – Machine restricted earth fault protection

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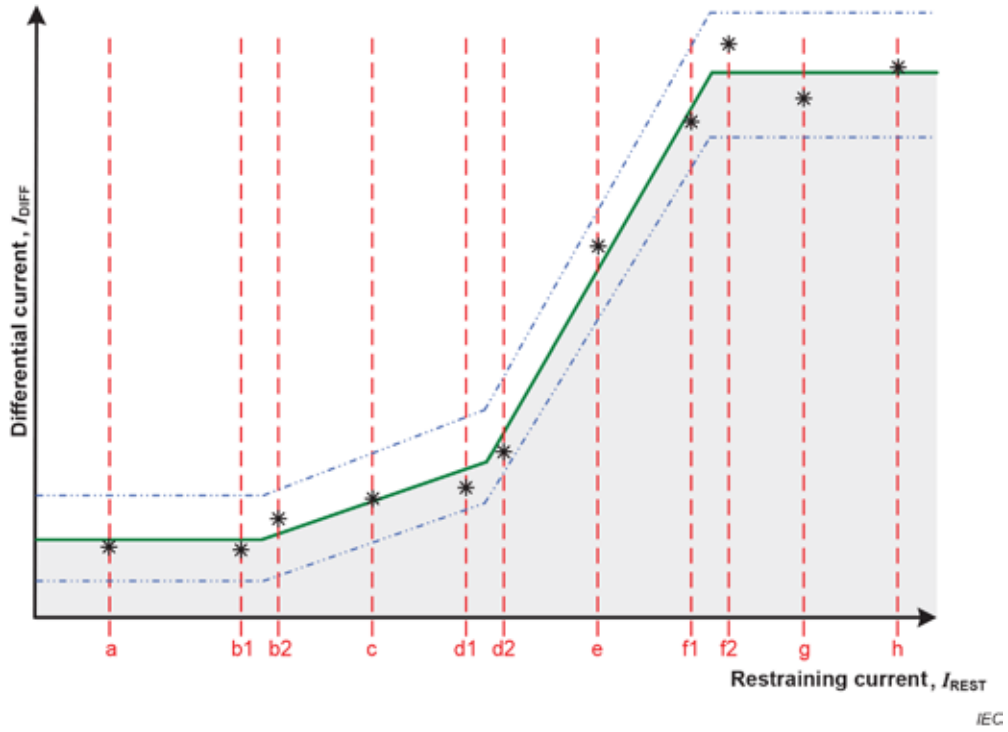

Figure 14 – Example for documenting the test results for differential relay characteristic

6.3.3 Ratio (magnitude) compensation accuracy

6.3.3.1 General methodology

The purpose of these tests is to confirm the accuracy of the ratio compensation settings that may exist in the protective function. For relays that do not provide this capability, this test is not required. These tests are conducted at one nominal frequency (50 Hz or 60 Hz).

During injection of the specified currents, the differential current (if shown by the relay human machine interface (HMI) or other interface) shall be less than half of the minimum differential pick-up threshold. For example, if the manufacturer declares that the minimum differential pick-up threshold is 20 %, then the differential current shall not be higher than 10 %.

For relays that do not display the differential current, the biased characteristic shall be configured with minimum slope and differential pick-up threshold settings. The relay shall remain stable for the test condition.

6.3.3.2 Application specific considerations: transformer differential

Select the "Yy" type transformer application. The relay shall be tested in the following conditions:

- Power transformer ratio equal to 5 (e.g. system voltage 100 kV/20 kV).
- Primary CT rated current value on HV transformer side (e.g. 100 kV side) shall be equal or just above the power transformer rated current (with 1 A or 5 A secondary rated value).
- Primary CT rated current value of LV transformer side (e.g. 20 kV side) shall be equal or just above two times the power transformer rated current, (with 1 A or 5 A secondary rated value). So this rated value is equal to 10 times the rated current of HV side CT (e.g. 100 kV side).

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- Calculate and set the ratio compensation and CT ratio according to the specification of the manufacturer.
- Injection of 100 % symmetrical through load current (referred to power transformer nominal power).

The test conditions are illustrated in Figure 15. During injection, the requirements of 6.3.3.1 shall be satisfied.

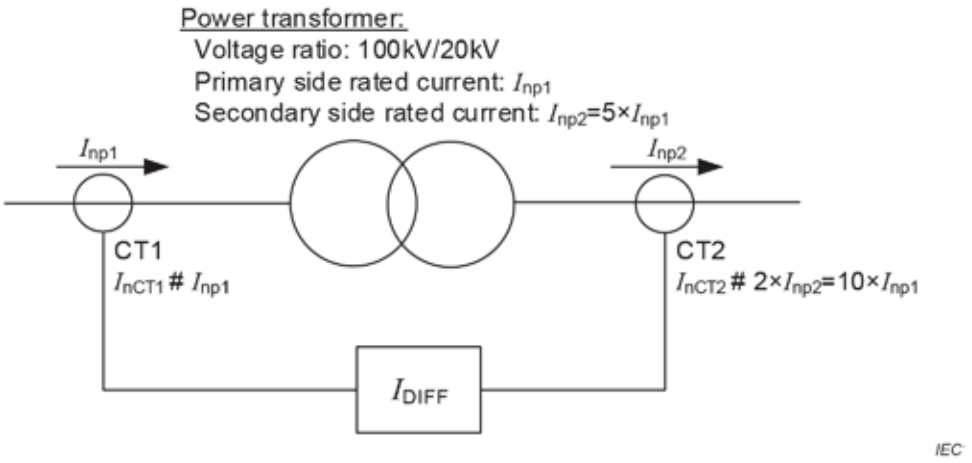

Figure 15 – Ratio (magnitude) compensation accuracy test

6.3.3.3 Reporting

The manufacturer shall report whether the protection function has passed this test.

6.3.4 Phase (vector) compensation validity

6.3.4.1 General methodology

The purpose of these tests is to confirm the validity of the phase compensation settings that may exist in the protective function. For relays that do not provide this capability, this test is not required. These tests are conducted at the nominal frequency (50 Hz or 60 Hz).

During injection of the specified currents, the differential current (if shown by the relay HMI or other interface) shall be less than half of the minimum differential pick-up threshold. For example, if the manufacturer declares that the minimum differential pick-up threshold is 20 %, then the differential current shall not be higher than 10 %. For relays that do not display the differential current, the biased characteristic shall be configured with minimum slope and differential pick-up threshold settings. The relay shall remain stable for the test condition.

6.3.4.2 Start ratios resulting from phase (vector) compensation

The start ratios resulting from the phase (vector) compensation may be established by theoretical analysis of the algorithms used by the biased differential protection function as highlighted in Annex A. This test shall be used to ascertain whether this analysis corresponds with actual performance.

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