

INTERNATIONAL STANDARD

NORME INTERNATIONALE



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

**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**



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CONTENTS

FOREWORD.....	11
1 Scope.....	13
2 Normative references	14
3 Terms and definitions	14
4 Specification of the function.....	18
4.1 General.....	18
4.2 Input energizing quantities/energizing quantities	19
4.2.1 General	19
4.2.2 Connections	19
4.3 Binary input signals.....	19
4.4 Functional logic.....	22
4.4.1 General	22
4.4.2 Phase biased differential protection	22
4.4.3 Biased restricted earth fault protection	24
4.4.4 Compensation of energizing quantities	25
4.4.5 Additional restraint or blocking methods	26
4.5 Binary output signals	27
4.5.1 General	27
4.5.2 Start (pick-up) signals.....	27
4.5.3 Operate (trip) signals.....	27
4.5.4 Other output signals	27
4.6 Additional influencing functions and conditions	27
4.6.1 General	27
4.6.2 Operation during CT saturation.....	28
4.6.3 Switch onto fault.....	28
4.6.4 Energizing quantity failure (CT supervision).....	28
4.6.5 Off-nominal frequency operation	28
4.6.6 Geomagnetically induced currents (GIC).....	28
5 Performance specification	29
5.1 General.....	29
5.2 Effective and operating ranges.....	29
5.3 Steady state accuracy tests in the effective range.....	29
5.3.1 General	29
5.3.2 Test related to the declared thermal withstand current.....	30
5.3.3 Basic characteristic accuracy.....	30
5.3.4 Ratio compensation accuracy	30
5.3.5 Phase (vector) compensation validity.....	31
5.3.6 Zero sequence compensation validity	31
5.3.7 Harmonic restraint basic accuracy	31
5.3.8 Basic accuracy of time delay settings	31
5.3.9 Disengage time.....	31
5.4 Dynamic performance in operating range	32
5.4.1 General	32
5.4.2 Typical operate time	32
5.4.3 Relay stability for external faults	32
5.4.4 Relay behaviour for internal fault preceded by an external fault	33
5.5 Stability during magnetizing inrush conditions	33

5.6	Stability during overexcitation conditions	33
5.7	Presence of harmonics on load	33
5.8	Performance during saturation of current transformers	33
5.9	Behaviour of differential protection with digital interface for the energizing quantities	34
6	Functional tests	34
6.1	General	34
6.2	Test related to the declared thermal withstand current	35
6.3	Steady state accuracy tests in effective range	35
6.3.1	General	35
6.3.2	Basic characteristic accuracy	37
6.3.3	Ratio (magnitude) compensation accuracy	44
6.3.4	Phase (vector) compensation validity	45
6.3.5	Zero sequence compensation validity	47
6.3.6	Harmonic restraint basic accuracy test under steady state conditions at nominal frequency	50
6.3.7	Accuracy related to time delay setting	52
6.3.8	Determination and reporting of the disengage time	54
6.4	Dynamic performance tests	55
6.4.1	General	55
6.4.2	Operate time for double infeed network model (restrained operation)	57
6.4.3	Operate time for double infeed network model (unrestrained operation)	68
6.4.4	Operate time for radial single infeed network model (restrained operation)	73
6.4.5	Operate time for radial single infeed network model (unrestrained operation)	86
6.4.6	Reporting of typical operate time	89
6.4.7	Stability for external faults	95
6.5	Relay behaviour for internal fault preceded by an external fault	112
6.5.1	General	112
6.5.2	Application specific considerations: transformer differential	112
6.5.3	Application specific considerations: biased restricted earth fault	115
6.5.4	Application specific considerations: generator differential	119
6.5.5	Reporting	122
6.6	Stability during inrush conditions	123
6.6.1	General	123
6.6.2	Application specific considerations: transformer differential	123
6.7	Stability during overexcitation conditions	128
6.7.1	General	128
6.7.2	Application specific considerations: transformer differential	128
6.8	Performance with load harmonics	133
6.8.1	General	133
6.8.2	Application specific considerations: transformer differential	133
6.8.3	Application specific considerations: generator or motor differential	137
6.8.4	Application specific considerations: biased restricted earth fault	140
6.8.5	Reporting	142
7	Documentation requirements	143
7.1	Type test report	143
7.2	Other user documentation	143

Annex A (informative) Examples of phase (vector) compensation and zero sequence compensation schemes.....	144
A.1 General.....	144
A.2 Y→d conversion.....	145
A.2.1 Current conversion	145
A.2.2 Three-phase fault at Y (star/wye) side	146
A.2.3 Phase-phase fault at Y (star/wye) side.....	147
A.2.4 Single-phase fault at Y (star/wye) side.....	147
A.2.5 Three-phase fault at delta side	148
A.2.6 Phase-phase fault at delta side.....	149
A.2.7 Single-phase fault at delta side.....	149
A.2.8 Ratio between start currents under different fault types	152
A.3 d→Y conversion.....	152
A.3.1 Current conversion	152
A.3.2 Three-phase fault at Y (star/wye) side	153
A.3.3 Phase-phase fault at Y (star/wye) side.....	153
A.3.4 Single-phase fault at Y (star/wye) side.....	153
A.3.5 Three-phase fault at delta side	154
A.3.6 Phase-phase fault at delta side.....	154
A.3.7 Single-phase fault at delta side.....	155
A.3.8 Ratio between start currents under different fault types	155
Annex B (normative) Calculation of mean, median and mode.....	156
B.1 Mean	156
B.2 Median.....	156
B.3 Mode	156
B.4 Example	156
Annex C (normative) CT requirements	157
C.1 General.....	157
C.2 Transformer differential protection	161
C.2.1 General	161
C.2.2 Fault 1	161
C.2.3 Fault 2.....	162
C.2.4 Fault 3	162
C.3 Transformer restricted earth fault protection	163
C.3.1 General	163
C.3.2 Fault 1	163
C.3.3 Fault 2.....	164
C.3.4 Fault 3	164
C.4 Generator differential protection.....	165
C.4.1 General	165
C.4.2 Fault 2.....	165
C.4.3 Criteria and additional conditions.....	166
C.5 Motor differential protection	166
C.5.1 General	166
C.5.2 Fault 1	166
C.5.3 Criteria and additional conditions.....	166
C.5.4 Start of motor, security case	167
C.5.5 Criteria and additional conditions.....	167
C.6 Reporting.....	167

Annex D (informative) CT saturation and influence on the performance of differential relays	168
Annex E (informative) Guidance on dimensioning of CTs for transformer differential protection	173
E.1 General.....	173
E.2 Example 1.....	174
E.2.1 General	174
E.2.2 Verification of CT1 – Internal fault	175
E.2.3 Verification of CT1 – External fault	175
E.2.4 Verification of CT2.....	176
E.3 Example 2.....	177
E.3.1 General	177
E.3.2 Dimensioning of CT1	178
E.3.3 Dimensioning of CT2	179
Annex F (informative) Examples of test procedures to determine CT sizing requirements for differential protection.....	181
F.1 General.....	181
F.2 Test data	183
F.2.1 General	183
F.2.2 Network model for CT requirement tests for the transformer differential protection	183
F.2.3 Network model for CT requirement tests for the transformer restricted earth fault protection.....	187
F.3 CT data and CT models	189
F.4 Test summary	197
Annex G (normative) Ramping methods for testing basic characteristic accuracy.....	199
G.1 General.....	199
G.2 Pre-fault condition.....	199
G.3 Pseudo-continuous ramp	199
G.4 Ramp of shots.....	201
Annex H (informative) Example of COMTRADE file for an evolving fault test case	203
Annex I (normative) Definition of fault inception angle.....	204
Bibliography.....	205
Figure 1 – Explanatory diagram for start time, operate time and disengage time	17
Figure 2 – Simplified biased differential functional block diagram.....	18
Figure 3 – Primary current reference direction	21
Figure 4 – Typical restrained element (biased) characteristic.....	23
Figure 5 – Typical unrestrained element characteristic.....	23
Figure 6 – Example of combined characteristic using restrained and unrestrained elements.....	24
Figure 7 – Basic error of the operating characteristic	30
Figure 8 – Example of an operating characteristic in the I_{DIFF}/I_{REST} plane with a tolerance band.....	37
Figure 9 – Test cases for differential characteristic basic accuracy	39
Figure 10 – Example of a differential characteristic with test lines "a" to "h"	40
Figure 11 – Machine differential protection	40
Figure 12 – Test sequence for basic characteristic accuracy.....	42

Figure 13 – Machine restricted earth fault protection.....	44
Figure 14 – Example for documenting the test results for differential relay characteristic	45
Figure 15 – Ratio (magnitude) compensation accuracy test	46
Figure 16 – Secondary three-phase and double-phase injection for Winding 1 (example)	47
Figure 17 – Secondary single-phase and three-phase injections for Winding 1 (example)	49
Figure 18 – Zero sequence current injection on the Y side of the transformer	50
Figure 19 – Zero sequence current injection on the delta side of the transformer	50
Figure 20 – Example of a rated frequency harmonic restraint characteristic with visualization of test lines	53
Figure 21 – Sequence of events for testing the disengage time.....	55
Figure 22 – Double infeed network model for operate time tests	58
Figure 23 – Test sequence for double infeed network model – Restrained operation (transformer).....	62
Figure 24 – Double infeed network model for operate time tests	63
Figure 25 – Test sequence for double infeed network model – Restrained operation (REF).....	66
Figure 26 – Double infeed network model for operate time tests	67
Figure 27 – Test sequence for double infeed network model – Restrained operation (generator).....	70
Figure 28 – Test sequence for double infeed network model – Unrestrained operation (transformer).....	73
Figure 29 – Single infeed network model for operate time tests	74
Figure 30 – Test sequence radial single infeed network model – Restrained operation	78
Figure 31 – Single infeed network model for operate time tests	79
Figure 32 – Test sequence for radial single infeed network – Restrained operation (generator).....	82
Figure 33 – Single infeed network model for operate time tests	83
Figure 34 – Test sequence for radial single infeed network – Restrained operation (motor).....	86
Figure 35 – Test sequence for radial single infeed network – Unrestrained operation	89
Figure 36 – Example of distribution of the operate time for one application	93
Figure 37 – Operate time as a function of the off-nominal frequency values (effective range is the specified range of ± 10 % of nominal frequency).....	95
Figure 38 – Operate time as a function of the off-nominal frequency values (accuracy range beyond the specified range of ± 10 % of nominal frequency	96
Figure 39 – Double infeed network model for stability tests.....	97
Figure 40 – Sequence of fault injection for stability due to external faults (transformer)	100
Figure 41 – Double infeed network model for stability tests.....	101
Figure 42 – Sequence of fault injection for stability due to external faults (REF)	104
Figure 43 – Double infeed network model for stability tests.....	105
Figure 44 – Sequence of fault injection for stability due to external faults (generator)	108
Figure 45 – Double infeed network model for stability tests.....	109
Figure 46 – Sequence of fault injection for stability due to external faults (motor)	112

Figure 47 – Double infeed network model for internal fault preceded by an external fault....	112
Figure 48 – Double infeed network model for internal fault preceded by an external fault test	116
Figure 49 – Double infeed network model for internal fault preceded by an external fault test	119
Figure 50 – Power transformer inrush current waveform	124
Figure 51 – Comparison of waveforms	125
Figure 52 – Connection for the relay when current is injected from Y winding	126
Figure 53 – Connection for the relay when current is injected from delta winding	127
Figure 54 – Power transformer overexcitation current waveform injected from Y winding	129
Figure 55 – Overexcitation current waveform injected from delta winding.....	129
Figure 56 – Comparison of the waveforms injected from Y winding	130
Figure 57 – Comparison of the waveforms injected from delta winding.....	131
Figure 58 – Three-phase overexcitation current waveform injected from Y winding	132
Figure 59 – Three-phase overexcitation current waveform injected from delta winding.....	133
Figure 60 – Test with superimposed harmonics on load – Transformer protection	133
Figure 61 – Three-phase load current waveform on the Y side of the transformer with superimposed harmonics	137
Figure 62 – Three-phase load current waveforms on the delta side of the YNd1 transformer with superimposed harmonics	137
Figure 63 – Test with superimposed harmonics on load	138
Figure 64 – Test with superimposed harmonics on load – Restricted earth fault protection .	140
Figure A.1 – Example of a transformer.....	144
Figure A.2 – Current vectors	145
Figure A.3 – Three-phase injection at Y (star/wye) side	147
Figure A.4 – Phase-phase injection at Y (star/wye) side	147
Figure A.5 – Single-phase injection at Y (star/wye) side.....	148
Figure A.6 – Three-phase injection at delta side	149
Figure A.7 – Phase-phase injection at delta side.....	149
Figure A.8 – Internal single-phase fault at delta side with neutral grounding transformer in the system	150
Figure A.9 – Single-phase injection at delta side.....	150
Figure A.10 – External single-phase fault at delta side with neutral grounding transformer inside protected zone	151
Figure C.1 – Fault positions to be considered for specifying the CT requirements	160
Figure C.2 – Fault positions to be considered for transformer differential protection.....	161
Figure C.3 – Fault positions to be considered for the restricted earth fault protection.....	163
Figure C.4 – External fault position to be considered for the generator differential protection	165
Figure C.5 – Internal fault position to be considered for the motor differential protection.....	166
Figure D.1 – Fault positions to be considered for specifying the CT requirements	170
Figure D.2 – Additional fault position to be considered in case of summation of currents	170
Figure E.1 – Transformer differential relay example 1	174
Figure E.2 – Transformer differential relay example 2	177
Figure F.1 – Network models and fault positions for transformer differential protection	184

Figure F.2 – Network models and fault positions for transformer restricted earth fault protection	187
Figure F.3 – Excitation characteristic for the high-remanence basic CT	191
Figure F.4 – Magnetization curve for the high-remanence type basic CT.....	193
Figure F.5 – Secondary current at the limit of saturation caused by the AC component with no remanent flux in the CT	194
Figure F.6 – Secondary current in case of maximum DC offset	194
Figure F.7 – Excitation characteristics for non-remanence and high-remanence type basic CTs	196
Figure F.8 – Magnetization curve for non-remanence type basic CTs.....	197
Figure G.1 – Secondary injected currents for the simulation of a through load of 30 %	200
Figure G.2 – Pseudo-continuous ramp in the restraining current – Differential current plane in the time domain	201
Figure G.3 – Ramp of shots showing differential step change and the time step	202
Figure G.4 – Ramp of shots with binary search algorithm.....	202
Figure I.1 – Graphical definition of fault inception angle	204
Table 1 – Example of effective and operating ranges of differential protection	29
Table 2 – Frequencies for steady state accuracy tests when the frequency effective range is equal to ± 5 % of nominal frequency.....	36
Table 3 – Frequencies for steady state accuracy tests when the frequency effective range is larger than ± 5 % of nominal frequency	36
Table 4 – Example frequencies for steady state accuracy tests when the frequency effective range is narrower than ± 5 % of nominal frequency.....	36
Table 5 – Test points for differential characteristic basic accuracy	38
Table 6 – Test lines on the differential characteristic (Figure 10)	39
Table 7 – Basic characteristic accuracy	43
Table 8 – Example of start ratios resulting from phase (vector) compensation	47
Table 9 – Example of start ratios resulting from zero sequence compensation	50
Table 10 – Test points for rated frequency harmonic restraint.....	51
Table 11 – Reporting example of test results for harmonic restraint basic accuracy test	52
Table 12 – Results of time delay tests	53
Table 13 – Reported time delay	53
Table 14 – Results of disengage time for all the tests	55
Table 15 – Frequencies for dynamic performance tests when the frequency operating range is equal to ± 10 % of nominal frequency.....	55
Table 16 – Frequencies for dynamic performance tests when the frequency operating range is wider than ± 10 % of nominal frequency	55
Table 17 – Example frequencies for dynamic performance tests when the frequency operating range is narrower than ± 10 % of nominal frequency	56
Table 18 – Double infeed network model	58
Table 19 – Source impedances for double infeed network model – Restrained operation (e.g. 50 Hz ± 10 % operating range).....	59
Table 20 – Double infeed network model	62
Table 21 – Source impedances for double infeed network model – Restrained operation (e.g. 50 Hz ± 10 % operating range).....	63
Table 22 – Double infeed network model	66

Table 23 – Source impedances for double infeed network model – Restrained operation (e.g. 50 Hz $\pm$ 10 % operating range).....	67
Table 24 – Source impedances for double infeed network model – Unrestrained operation (e.g. 60 Hz $\pm$ 10 % operating range).....	70
Table 25 – Single infeed network model.....	74
Table 26 – Source impedances for radial single infeed network model – Restrained operation (e.g. 50 Hz $\pm$ 10 % operating range).....	74
Table 27 – Single infeed network model.....	78
Table 28 – Source impedances for radial single infeed network model – Restrained operation (e.g. 50 Hz $\pm$ 10 % operating range).....	79
Table 29 – Single infeed network model.....	82
Table 30 – Source impedances for radial single infeed network model – Restrained operation (e.g. 50 Hz $\pm$ 10 % operating range).....	83
Table 31 – Source impedances for radial single infeed network model – Unrestrained operation (e.g. 60 Hz $\pm$ 10 % operating range).....	86
Table 32 – Fault statistics for typical operate time of transformer protection (nominal frequency only).....	89
Table 33 – Fault statistics for typical operate time of biased restricted earth fault protection (nominal frequency only).....	90
Table 34 – Fault statistics for typical operate time of generator protection (nominal frequency only).....	90
Table 35 – Fault statistics for typical operate time of motor protection (nominal frequency only).....	90
Table 36 – Operate time classes.....	91
Table 37 – Corresponding operate time classes.....	91
Table 38 – Number of operate times and percentage.....	92
Table 39 – Example of typical operate time at nominal frequency (mode, median, mean).....	93
Table 40 – Examples of operate times (50 Hz nominal, CT configuration 500 A/1 A and 1 000 A/1 A, power transformer protection).....	94
Table 41 – Double infeed network model.....	96
Table 42 – Source impedances for double infeed network model stability tests (e.g. 50 Hz $\pm$ 10 % operating range).....	97
Table 43 – Double infeed network model.....	100
Table 44 – Source impedances for double infeed network model stability tests (e.g. 50 Hz $\pm$ 10 % operating range).....	101
Table 45 – Double infeed network model.....	104
Table 46 – Source impedances for double infeed network model stability tests (e.g. 50 Hz $\pm$ 10 % operating range).....	105
Table 47 – Double infeed network model.....	108
Table 48 – Source impedances for double infeed network model stability tests (e.g. 50 Hz $\pm$ 10 % operating range).....	109
Table 49 – Double infeed network model.....	113
Table 50 – Source impedances, fault resistances and pre-fault conditions for internal fault preceded by an external fault (e.g. for 50 Hz power system frequency).....	113
Table 51 – Double infeed network model.....	116
Table 52 – Source impedances, fault resistances and pre-fault conditions for internal fault preceded by an external fault tests (e.g. for 50 Hz power system frequency).....	117
Table 53 – Double infeed network model.....	120

Table 54 – Source impedances, fault resistances and pre-fault conditions for internal fault preceded by an external fault tests (e.g. for 50 Hz power system frequency).....	120
Table 55 – Operate time for internal fault preceded by an external fault and for internal fault when the relay always operated	122
Table 56 – Operate time for internal fault preceded by an external fault and for internal fault when the relay did not always operate.....	123
Table 57 – Coefficients of the inrush current waveforms	124
Table 58 – Nameplate data for test-transformers	125
Table 59 – Parameter k values.....	125
Table 60 – Coefficient of the overexcitation waveforms.....	130
Table 61 – Test data for the transformer	131
Table 62 – Transformer data for the superimposed harmonics on load test	134
Table 63 – Fundamental component of load current in pu	134
Table 64 – Harmonic content for superimposed harmonics on load test	134
Table 65 – Harmonic phase angles for superimposed harmonics on load test	134
Table 66 – Generator or motor data for the superimposed harmonics on load test	138
Table 67 – Harmonic phase angles for superimposed harmonics on load test	139
Table 68 – Transformer data for the superimposed harmonics on load test	141
Table 69 – Harmonic phase angles for superimposed harmonics on load test	141
Table A.1 – Transformer data	144
Table A.2 – Start currents under different fault types	152
Table A.3 – Start currents under different fault types	155
Table C.1 – Levels of remanent or remaining flux to be considered for external faults.....	159
Table C.2 – Levels of remanent or remaining flux to be considered for external faults when the difference of size between the CTs is limited	159
Table E.1 – Fault currents.....	174
Table E.2 – Fault currents.....	177
Table F.1 – Specification of test cases for the transformer differential protection – Internal and external faults with one saturated CT	185
Table F.2 – Specification of test cases for the transformer differential protection – External faults with two saturated CTs	186
Table F.3 – Example time constants with corresponding R/X ratios.....	186
Table F.4 – Specification of test cases for the transformer restricted earth fault protection – Internal and external faults with one saturated CT	188
Table F.5 – Specification of test cases for the transformer restricted earth fault protection – External faults with two saturated CTs	188
Table F.6 – Excitation characteristic data for the high-remanence basic CT	190
Table F.7 – Magnetization curve data for the high-remanence type basic CT	193
Table F.8 – Excitation characteristic data for the non-remanence type basic CT	196
Table F.9 – Magnetization curve data for non-remanence type CT	197
Table G.1 – Restraining and differential currents for different definitions of the restraining current.....	200
Table I.1 – Fault type and reference voltage	204

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- 8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
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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.

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.

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.

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]

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

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.

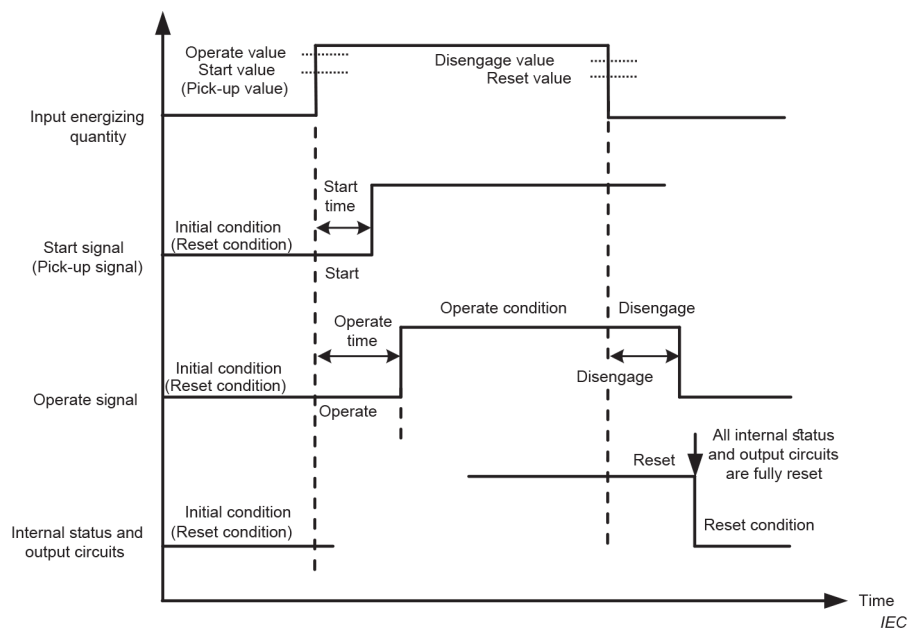


Figure 1 – Explanatory diagram for start time, operate time and disengage time

[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.]

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

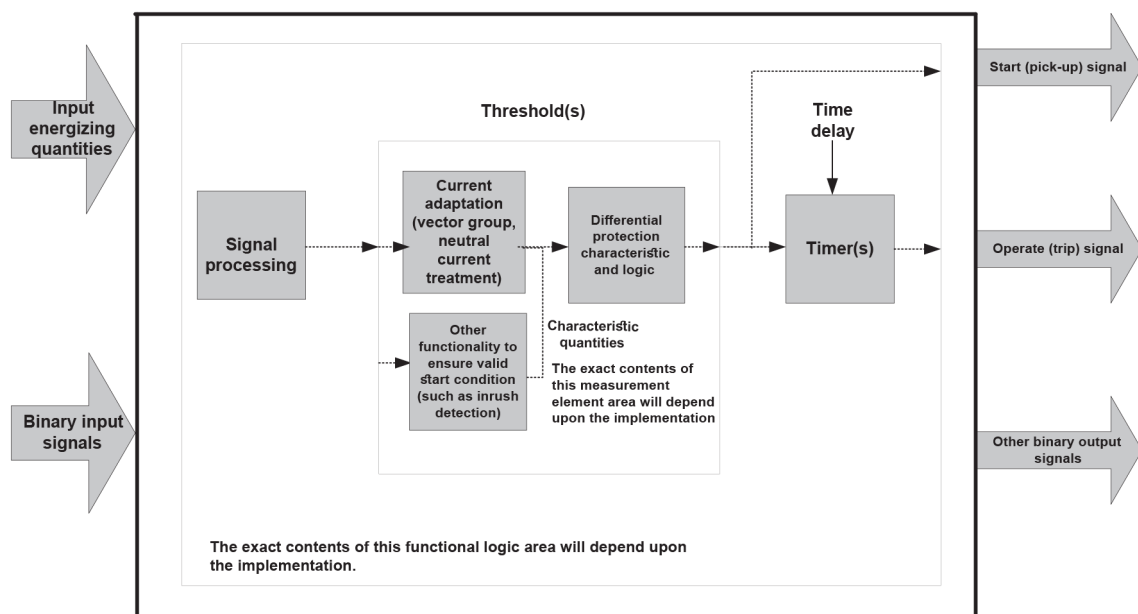
SEE: Figure 1.

[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.



IEC

Figure 2 – Simplified biased differential functional block diagram

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.

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.

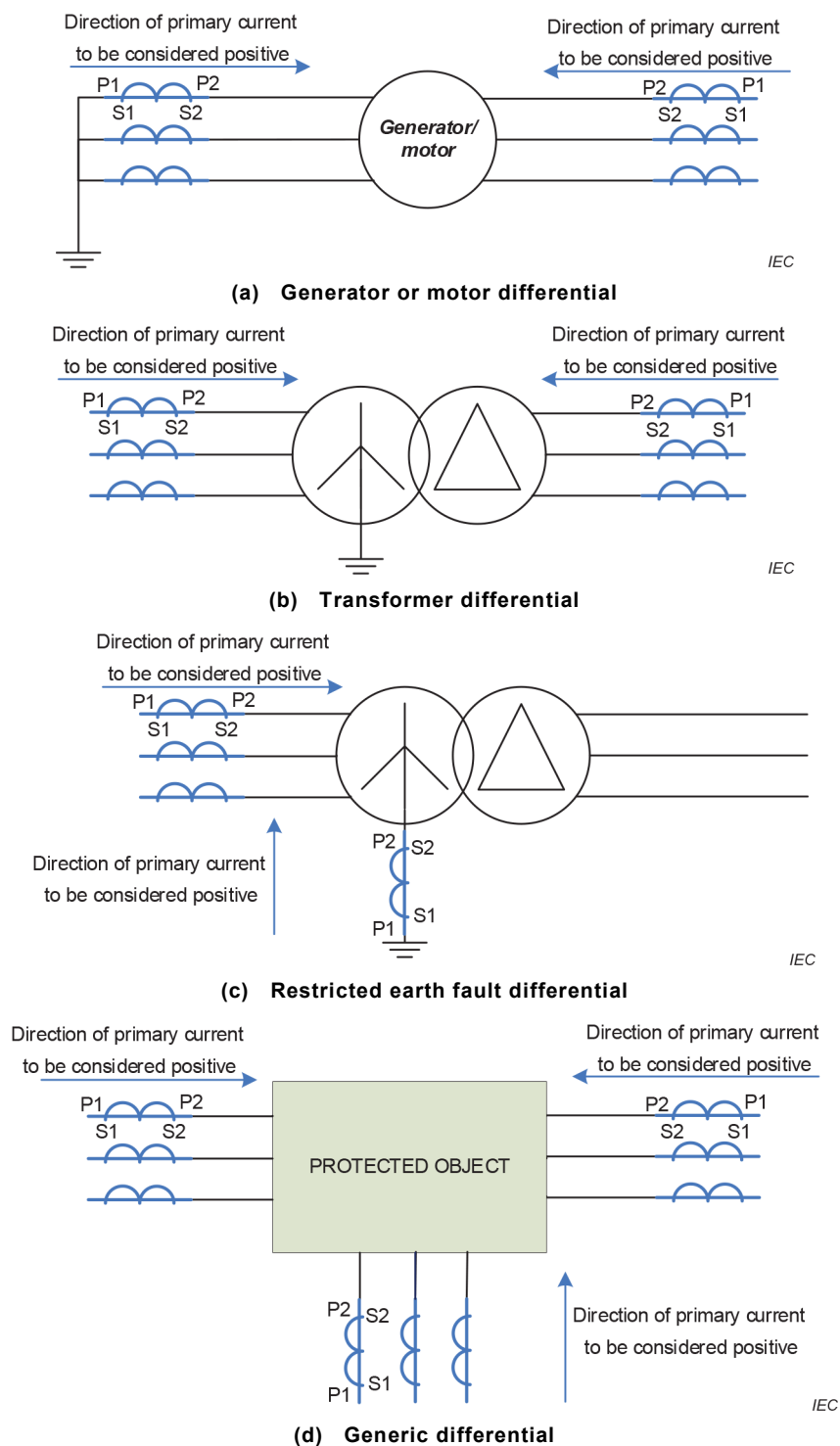


Figure 3 – Primary current reference direction

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.

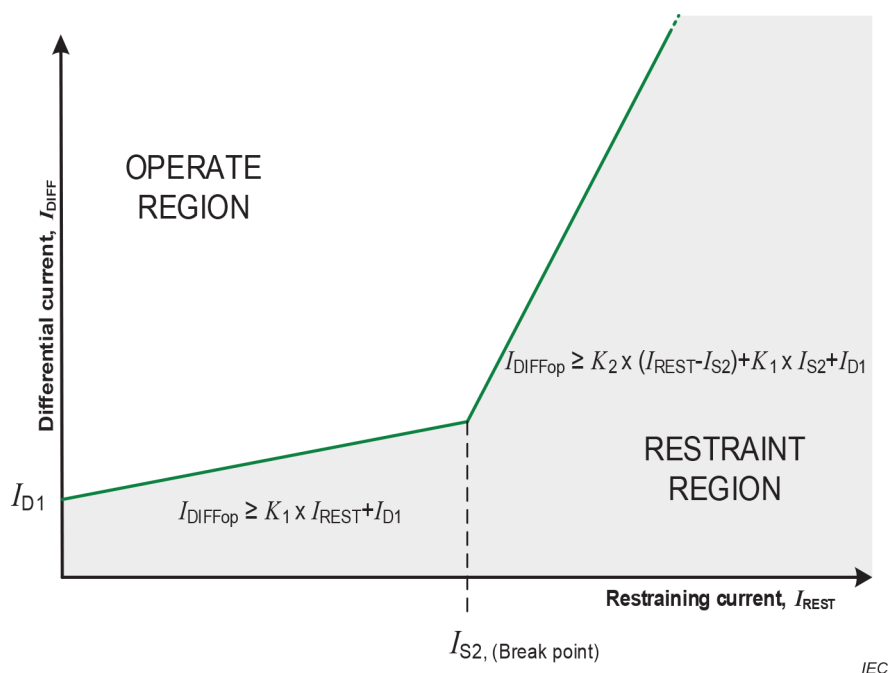


Figure 4 – Typical restrained element (biased) characteristic

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.

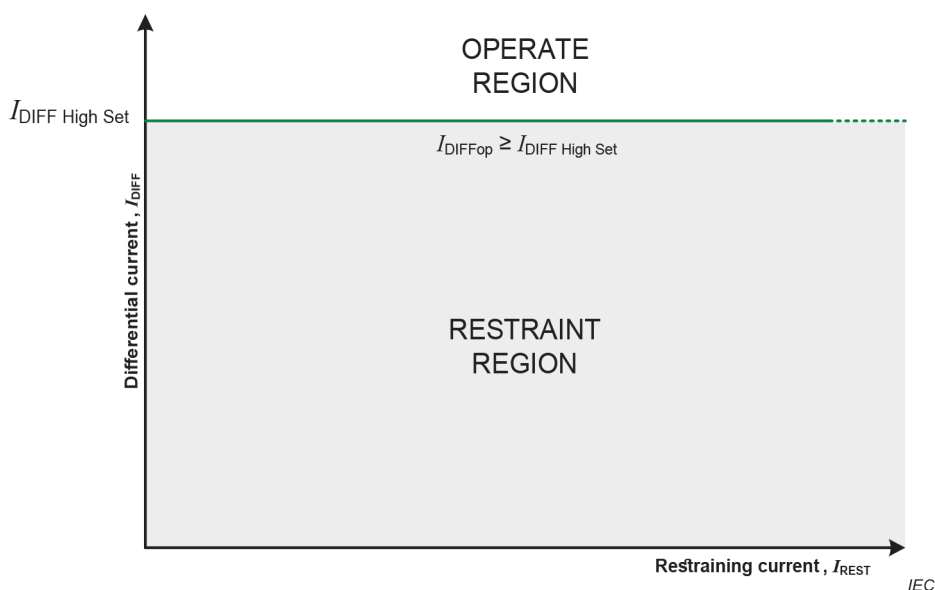


Figure 5 – Typical unrestrained element characteristic

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

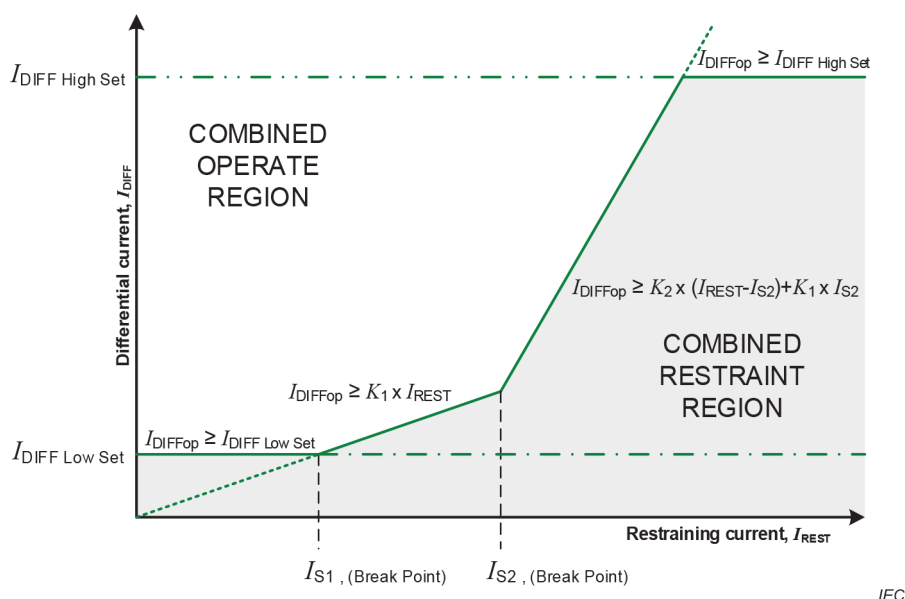


Figure 6 – Example of combined characteristic using restrained and unrestrained elements

When the restraining current exceeds a threshold I_{S1} , the amount of differential current required for operation, $I_{DIFF Op}$, is controlled by the restrained element and follows this characteristic until the measured differential current exceeds the unrestrained high set element, $I_{DIFF\ High\ Set}$. 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.

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.

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 5th 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.

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.

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.

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.

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.

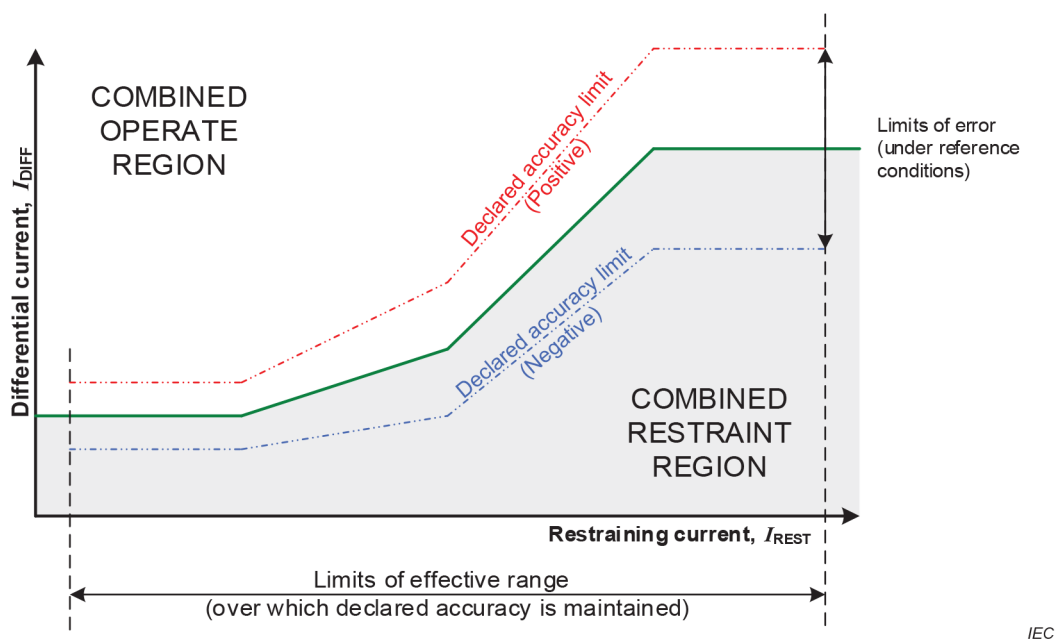
5.3.2 Test related to the declared thermal withstand current

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, $\pm 2\%$ of the differential current start value or $\pm 0,001 \times I_r$, 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.



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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.

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 $\pm 5\%$ 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.

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.

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:

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.

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)

$$I_{L1} \ 200, 0 \text{ A} \angle 0,00^\circ$$

$$I_{L2} \ 200, 0 \text{ A} \angle -180,00^\circ$$

$$I_{L3} \ 0,0 \text{ A} \angle 0,00^\circ$$

- 1-phase injection for case L3-E (amplitude/phase)

$$I_{L1} \ 0,0 \text{ A} \angle 0,00^\circ$$

$$I_{L2} \ 0,0 \text{ A} \angle 0,00^\circ$$

$$I_{L3} \ 200,0 \text{ A} \angle 00,00^\circ$$

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.

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
$(\text{Min. frequency of effective range} + 47,5) / 2$	$(\text{Min. frequency of effective range} + 57) / 2$
47,50	57,00
48,75	58,50
50,00	60,00
51,25	61,50
52,50	63,00
$(52,5 + \text{max. frequency of effective range}) / 2$	$(63 + \text{max. frequency of effective range}) / 2$
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

6.3.2 Basic characteristic accuracy

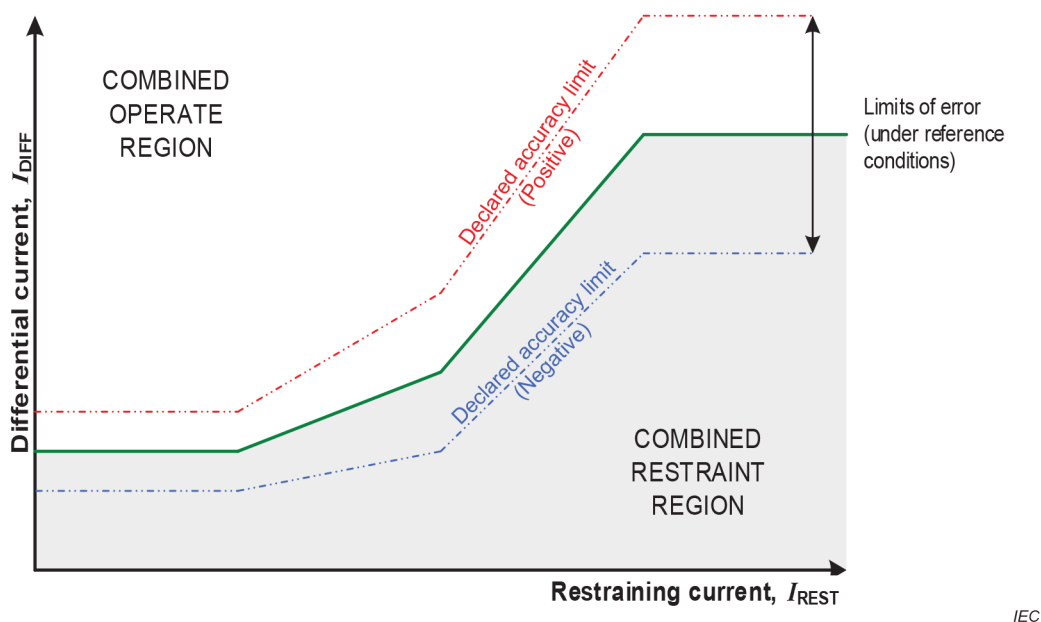
6.3.2.1 General methodology

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.



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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.

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.

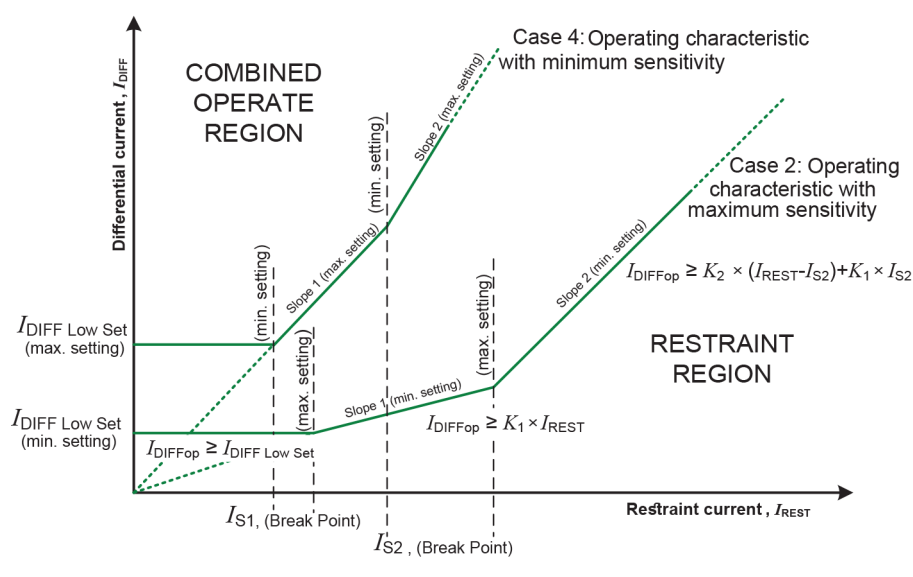


Figure 9 – Test cases for differential characteristic basic accuracy

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 $\times 1,2$
h	Point of I_{REST} where $I_{DIFF High Set}$ cuts the slope $\times 1,5$

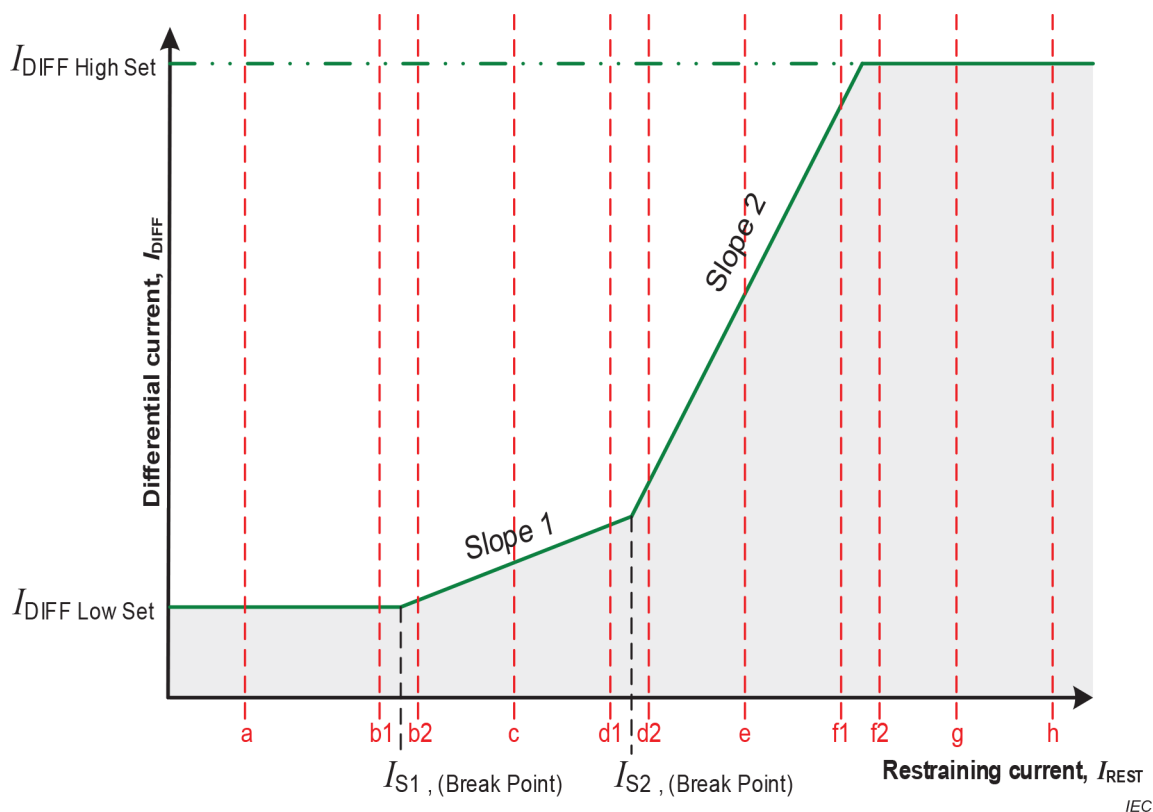


Figure 10 – Example of a differential characteristic with test lines "a" to "h"

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).

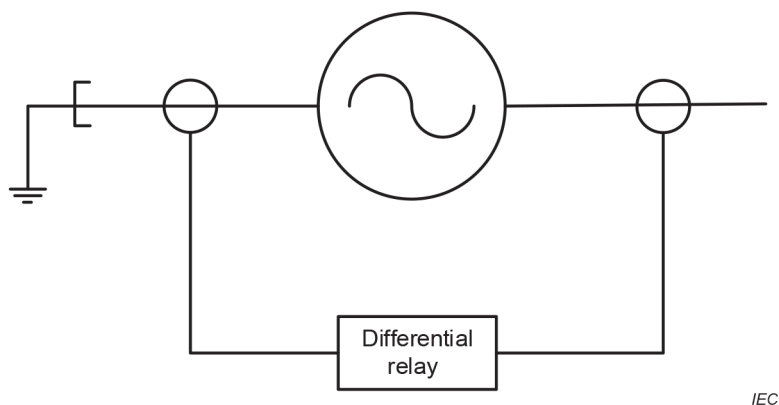


Figure 11 – Machine differential protection

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

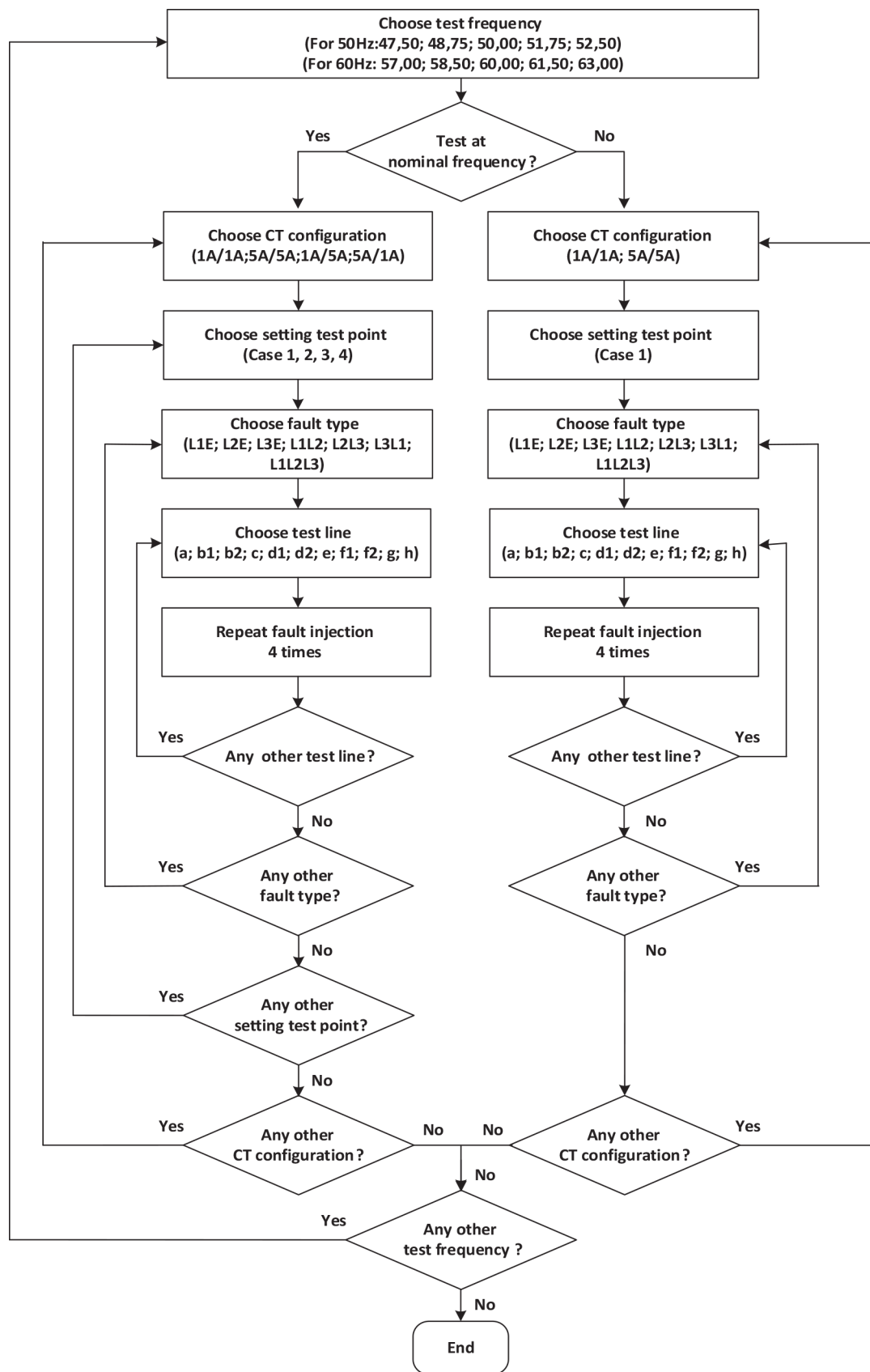
For this test, a simple machine as shown in Figure 13 is used requiring no transformation ratio compensation, no phase (vector group) compensation, no zero sequence compensation, etc.

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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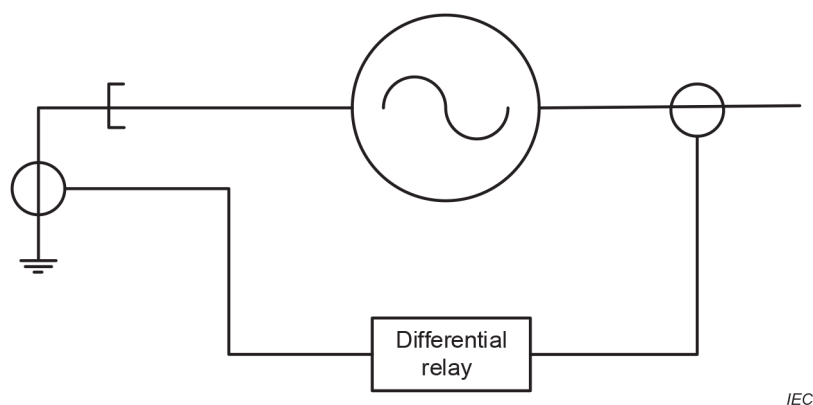
Figure 12 – Test sequence for basic characteristic accuracy

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**

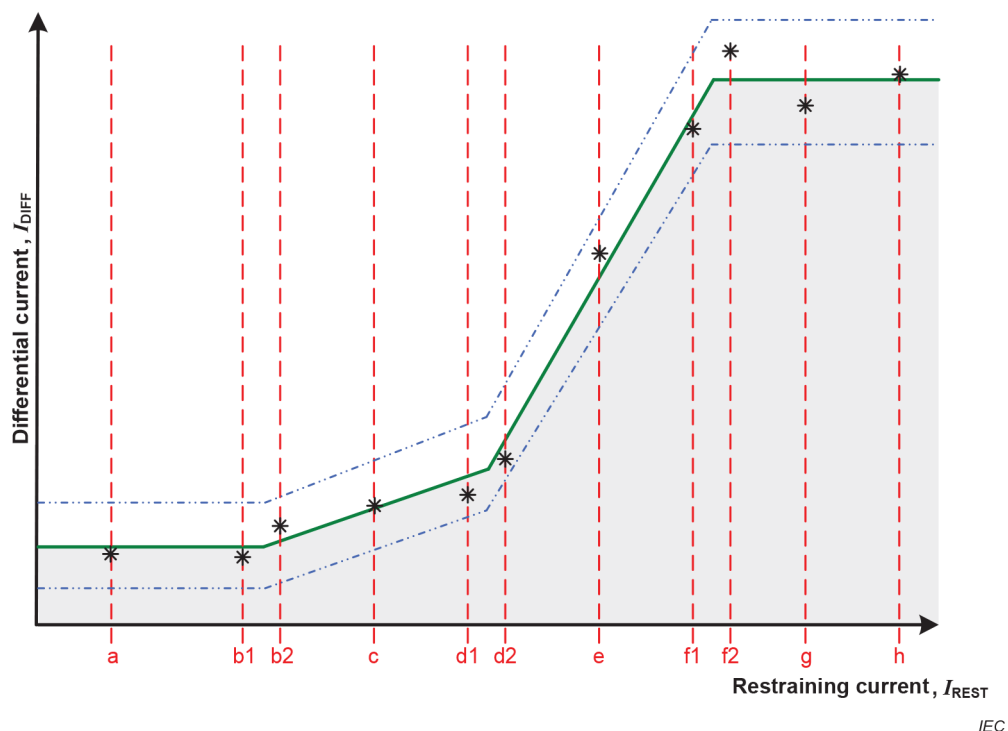


Figure 14 – Example for documenting the test results for differential relay characteristic

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.

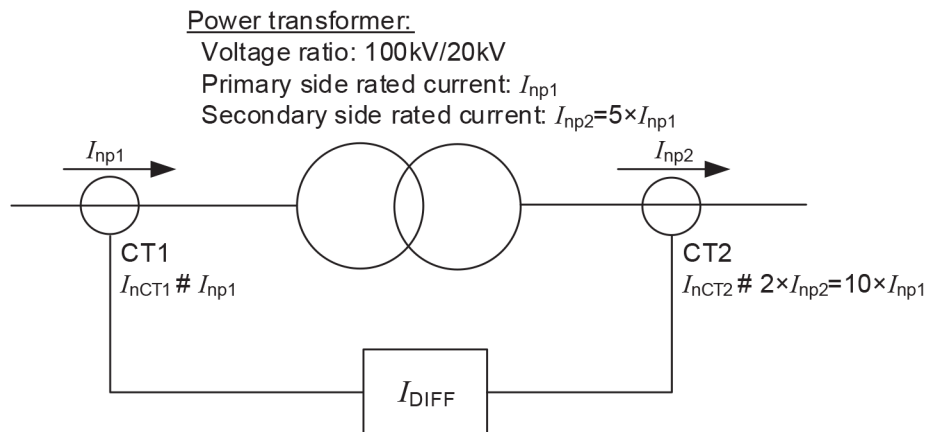
6.3.3.2 Application specific considerations: transformer differential

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).

- 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.



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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.

Figure 16 shows the three-phase and double-phase winding current injections to establish the ratio between the double-phase and three-phase start current. Balanced three-phase current shall be injected onto the relay winding input under test and increased until relay operation occurs. Double-phase current shall then be injected onto the same relay winding input and increased until relay operation occurs. For both of these cases, no current is injected into the analog inputs for the other windings of the relay. If the ratio of double-phase start current to three-phase current is within the manufacturer's basic accuracy of the theoretical value of this ratio, then the performance of the compensation is considered to have passed the test.

In the example for the star winding shown, the double-phase to three-phase start ratio is theoretically analysed to be $\sqrt{3}/2$. The manufacturer claims an accuracy of $\pm 5\%$ which allows for the measured ratio to lie within the range of 0,823 to 0,909.

The test shall be repeated for each winding connection supported by the relay.

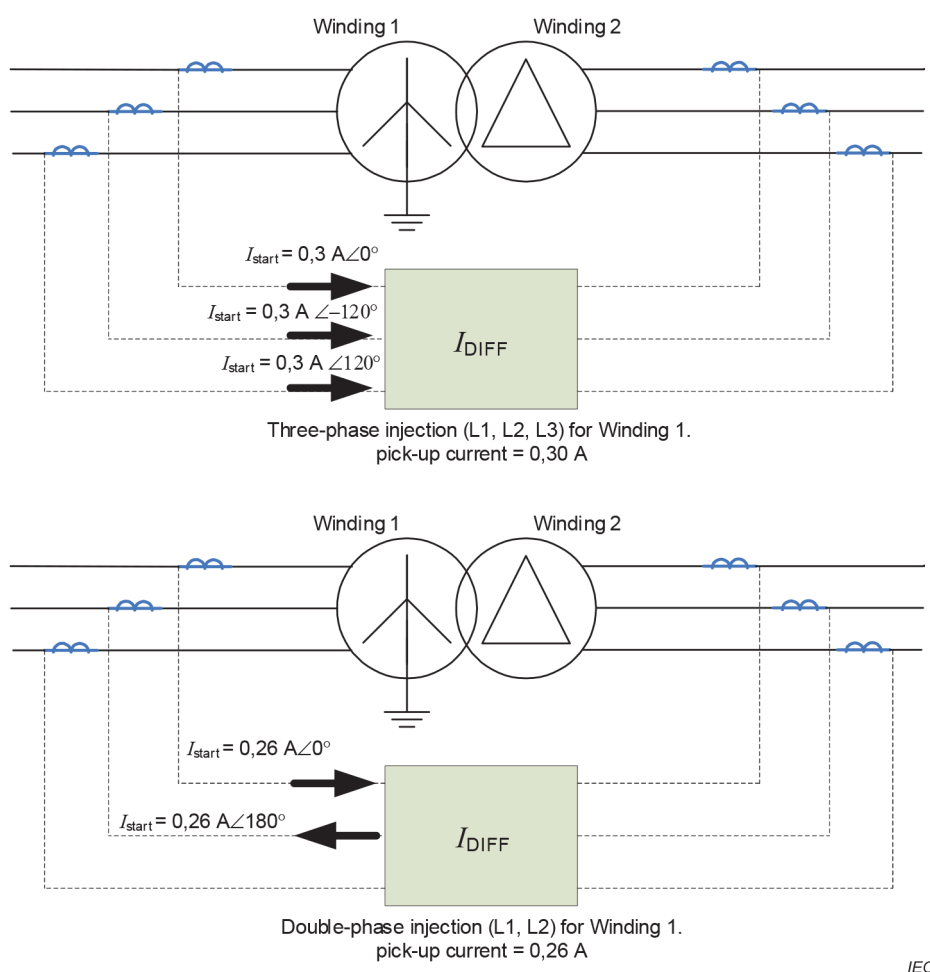


Figure 16 – Secondary three-phase and double-phase injection for Winding 1 (example)

6.3.4.3 Additional errors resulting from phase (vector) compensation

Applying the ratio setting of 6.3.3.2, all vector groups supported by the relay shall be tested by the injection of 100 % symmetrical through load currents (referred to power transformer nominal power). Vector group compensation shall be set in accordance with the specification of the manufacturer.

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 for a period greater than 1 s.

6.3.4.4 Reporting

The manufacturer shall report the start ratios as per Table 8 resulting from the testing of 6.3.4.2.

Table 8 – Example of start ratios resulting from phase (vector) compensation

Winding type	Three-phase start value	Phase-phase start value	Start ratio (theoretical)
Star ("Y")	I_{start}	$I_{\text{start}} \times \sqrt{3}/2$	$\sqrt{3}/2$
Delta ("Δ")	I_{start}	I_{start}	1

The manufacturer shall report whether the protection function has passed the test of 6.3.4, reporting the measured differential current and measured ratios where possible.

6.3.5 Zero sequence compensation validity

6.3.5.1 General methodology

The purpose of these tests is to confirm the validity of the zero sequence 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 (if shown by the relay HMI or other interface) the differential current 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.

6.3.5.2 Start ratios resulting from zero sequence compensation – Application specific considerations: transformer differential

The start ratios resulting from the zero sequence (and phase) 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 to actual performance.

Figure 17 shows the three-phase and single-phase winding current injections to establish the ratio between the single-phase and three-phase start current. Balanced three-phase current shall be injected onto the relay winding input under test and increased until relay operation occurs. Single-phase current shall then be injected onto the same relay winding input and increased until relay operation occurs. If the ratio of single-phase start current to three-phase current is within the manufacturer's basic accuracy of the theoretical value of this ratio, then the performance of the compensation is considered to have passed the test.

In the example for the star winding shown, the single-phase to three-phase start ratio is theoretically analysed to be 1,5. The manufacturer claims an accuracy of $\pm 5\%$ which allows for the measured ratio to lie within the range of 1,425 to 1,575.

The test shall be repeated for each winding connection supported by the relay and for each setting of the zero sequence compensation (enabled and disabled).

6.3.5.3 Additional errors resulting from zero sequence compensation

Applying the ratio setting of 6.3.3.2, all vector groups supported by the relay shall be tested by injecting currents with equal magnitude (100 % referred to power transformer nominal power) and phase angle into three phases to one side of the transformer only. The primary rated value of phase CTs shall be equal to or just above the power transformer rated current (with 1 A or 5 A secondary rated value). Vector group compensation and zero sequence current elimination shall be set in accordance with the specification of the manufacturer.

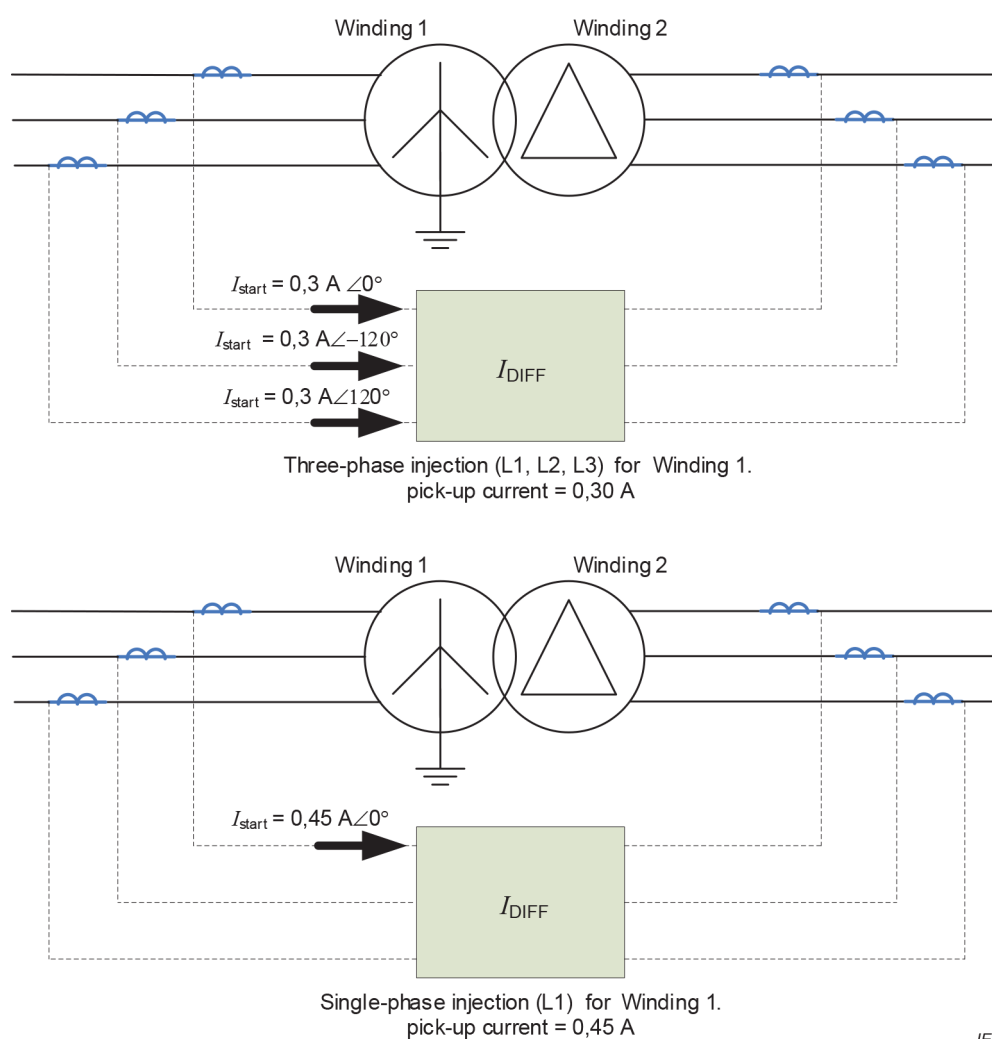


Figure 17 – Secondary single-phase and three-phase injections for Winding 1 (example)

Injecting pure zero sequence current on the Y side of the transformer as shown in Figure 18 simulates an earth fault occurring on the Y side of an unloaded transformer. Injecting pure zero sequence current on the Δ side of the transformer as shown in Figure 19 simulates a neutral grounding transformer (e.g. zigzag transformer) inside the protected zone with an earth fault on the Δ side network. More details regarding single-phase and three-phase winding current injection are provided in Annex A.