



IEEE Guide for Protecting Power Transformers

IEEE Power Engineering Society

Sponsored by the
Power System Relaying Committee



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IEEE Guide for Protecting Power Transformers

Sponsor

**Power System Relaying Committee
of the
IEEE Power Engineering Society**

Approved 31 January 2008

IEEE-SA Standards Board

Abstract: This guide is intended to provide protection engineers and other readers with guidelines for protecting three-phase power transformers of more than 5 MVA rated capacity and operating at voltages exceeding 10 kV. In some cases, a user may apply the techniques described in this guide for protecting transformers of less than 5 MVA ratings or operating at voltages less than 10 kV. Information to assist protection engineers in applying properly relays and other devices to protect transformers used in transmission and distribution systems is provided in this guide. General philosophy, practical applications, and economic considerations involved in power transformer protection are discussed. Emphasis is placed on practical applications. Types of faults in transformers are described. Technical problems with the protection systems, including the behavior of current transformers during system faults, are discussed. Associated problems, such as fault clearing and reenergization, are discussed as well.

Keywords: analysis of dissolved gases in transformer oil, application of multifunction relays for transformer protection, differential protection, failures of transformers, overcurrent protection, protection of phase-shifting transformers, protection of transformers, volts-per-hertz protection

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Introduction

This introduction is not part of IEEE Std C37.91-2008, IEEE Guide for Protecting Power Transformers.

This document is a revision of IEEE Std C37.91™-2000, IEEE Guide for Protective Relay Applications to Power Transformers. This guide is intended to provide aid in the effective application of relays and other devices for the protection of power transformers.

In this revision, several areas have been improved. Most notably:

- Several clauses have been revised.
- Differential protection has been augmented to include the techniques used in numerical relays. Techniques now being used in numerical relays, such as harmonic restraint and harmonic blocking, wave shape recognition, low-current detection, and direct-current blocking methods, are included.
- An example of the relay blocking logic is included.
- New figures have been included to reflect the practice of connecting all current transformers (CTs) in wye configuration when numerical relays are used.
- The possibility of CT saturation when faults occur outside the protection zone of differential relays and the current does not flow through the differential zone is explained.
- Protection of transformers for faults in the grounded wye-connected windings has been expanded to include the use of restricted earth-fault relays.
- The practice of remote tripping of circuit breakers to protect transformers used to tap transmission and subtransmission lines is explained.
- The clause on gas analysis has been revised to bring it in line with the current practices. The use of rate of change of total dissolved combustible gases is incorporated.
- New annexes have been created. Annex B lists the transformer failure statistics collected by the Canadian Electrical Association. Annex C outlines the procedure for setting relays for protecting three transformers. The first transformer is a step-up transformer, the second transformer is a network autotransformer, and the third transformer is used for supplying energy to a distribution system. Annex D describes the need for monitoring current on the high-voltage and low-voltage windings, when automatic tap changing is used, for determining the hot-spot temperature of a transformer. Annex E outlines the methods that are used in differential relays for compensating for the phase shift in delta-wye transformers.

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~~An American National Standard~~

IEEE Guide for Protecting ~~Protective~~ Relay ~~Applications to~~ Power Transformers

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1. Overview ~~Introduction~~

This guide is intended to provide protection engineers and other readers with guidelines for protecting three-phase power transformers of more than 5 MVA rated capacity and operating at voltages exceeding 10 kV. In some cases, a user may apply the techniques described in this guide for protecting transformers of less than 5 MVA ratings or operating at voltages less than 10 kV.

1.1 Scope

The scope of this guide includes general philosophy, practical applications, and economic considerations involved in power transformer protection.

Emphasis is placed on practical applications. General philosophy and economic considerations in protecting transformers are reviewed. Types of faults in transformers are described. Technical problems with the protection systems, including the behavior of current transformers (CTs) during system faults, are discussed. Associated problems, such as fault clearing and reenergization, are discussed as well.

1.2 Purpose

The purpose of this guide is to provide protection engineers with information that helps them to properly apply relays and other devices to protect transformers used in transmission and distribution systems.

~~The purpose of this guide is to aid in the effective application of relays and other devices for the protection of power transformers. Emphasis is placed on practical applications, the general philosophy and economic considerations involved in transformer protection are reviewed, the types of faults experienced are described, and technical problems with such protection, including current transformer behavior during fault conditions are discussed. Various types of electrical, mechanical, and thermal protective devices are also described and associated problems such as fault clearing and re-energizing considerations are discussed.~~

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

~~When the following American National Standards referred to in this standard are superseded by a revision approved by the American National Standards Institute, the revision shall apply:~~

~~[1] ANSI/IEEE C37.2-1979, IEEE Standard Electrical Power System Device Function Numbers.[†]~~

~~[2] ANSI/IEEE C57.12.00-1980, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.~~

~~[3] ANSI/IEEE C57.91-1981, IEEE Guide for Loading Mineral-Oil-Immersed Overhead and Pad-Mounted Distribution Transformers Rated 500 kVA and Less with 55 °C or 65 °C Average Winding Rise.~~

~~[4] ANSI/IEEE C57.92-1981, IEEE Guide for Loading Mineral-Oil-Immersed Power Transformers Up to and Including 100 MVA with 55 °C or 65 °C Winding Rise.~~

~~[5] ANSI/IEEE C57.109-1985, IEEE Guide for Transformer through Fault Current Duration.~~

IEEE Std 32™-1972, IEEE Standard Requirements Terminology and Test Procedure for Neutral Grounding Devices.^{1,2}

~~[10] IEEE COMMITTEE REPORT. Protection of Power Transformers, *IEEE Transactions on Power Apparatus and Systems*, vol PAS-80, Dec 1963, pp 1040-1044.~~

~~[11] IEEE COMMITTEE REPORT. Transient Response of Current Transformers. *IEEE Special Publication*, 76CH1130-4PWR.~~

IEEE Std C37.2™, IEEE Standard Electrical Power System Device Function Numbers and Contact Designations.

IEEE Std C37.100™, IEEE Standard Definitions for Power Switchgear. IEEE Std C37.102™, IEEE Guide for AC Generator Protection.

IEEE Std C37.103™, IEEE Guide for Differential and Polarizing Relay Circuit Testing. IEEE Std C37.108™, IEEE Guide for the Protection of Network Transformers.

IEEE Std C37.110™, IEEE Guide for Application of Current Transformers Used for Protective Relaying Purposes.

IEEE Std C37.112™, IEEE Standard Inverse-Time Characteristic Equations for Overcurrent Relays. IEEE Std C37.113™, IEEE Guide for Protective Relay Applications to Transmission Lines.

IEEE Std C37.119™, IEEE Guide for Breaker Failure Protection of Power Circuit Breakers.

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

IEEE Std C57.13.3™, IEEE Guide for Grounding of Instrument Transformer Secondary Circuits and Cases.

IEEE Std C57.91™-1995 (Reaff 2004), IEEE Guide for Loading Mineral-Oil-Immersed Transformers.

[IEEE Std C57.104™-1991, IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers.](#)³

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

~~[7] *Applied Protective Relaying Reference Book*, East Pittsburgh, PA: Westinghouse Electric Corporation, Relay Instrument Division, 1979.~~

³ANSI documents are available from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

~~[8] BALERIAUX, H., and BROHET, F. Buchholz Relays. *CIGRE*, Paper no 321, June 1960, pp 1–10.~~

~~[9] HAYWARD, C.D. Prolonged Inrush Current with Parallel Transformers Affect Differential Relaying. *AIEE Transactions*, vol 60, Dec 1941, pp 1096–1101.~~

~~[12] MASON, C.R. *The Art and Science of Protective Relaying*. New York: Wiley 1956.~~

~~[13] PUGH, P.S., and WAGNER, H.H. The Detection of Incipient Faults on Transformers by Gas Analysis, *AIEE Transaction on Power Apparatus and Systems*, vol 80, pt III, pp 189–95, June 1961.~~

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~~[15] STERNER, V. The Protection of Large Transformers. *CIGRE Paper*, no 348, pp 24–37, June 1958.~~

~~[16] STERNER, V. The Protection of Large Transformers. *CIGRE Paper*, no 334, pp 8–21, June 1960.~~

~~[17] VORA, J.P., and AICHER, L.C. Transformer Fault—Gas Analysis and Interpretation. *IEEE Transactions on Power Apparatus and Systems*, vol no 1, Feb 1965, p 84.~~

~~[18] WAGNER, H.H. Survey of TCC Tests on Transformers, *IEEE Conference Paper Feb 1964*, pp 64–209.~~

~~[19] WARRINGTON, A.R. van C. *Protective Relays, Their Theory and Practice*, vol 1, New York: Wiley, 1963. Vol 2, London, Chapman and Hall Ltd, 1969.~~

3. Definitions

For the purposes of this guide, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms* [B11]⁴ should be referenced for terms not defined in this clause. Definitions of several terms used in this guide are provided in IEEE Std C37.100.⁵

3.1 harmonic sharing: The principle of summing the magnitudes of the harmonic contents of the three operating currents in a differential application and checking if the ratio of the sum of the harmonic components and the fundamental frequency component of the operating current in each phase exceeds a prespecified threshold.

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

⁵ Information on references can be found in Clause 2.

3.2 time-limited cross-blocking: A restraint in a differential relaying application based on blocking of tripping of all three phases when the operating current of any one phase has sufficient harmonic content for blocking during inrush. Adjacent phase blocking is removed after a predetermined time delay.

4. Device numbers

The device numbers used in this guide are listed in Table 1. [Detailed definitions of these devices are given in IEEE Std C37.2, IEEE Standard Electrical Power System Device Function Numbers and Contact Designations.](#)

Table 1—Device numbers and device identification

<u>Device number</u>	<u>Identification</u>
24	Volts-per-hertz (V/Hz) relay
26	Apparatus thermal device
46	Reverse-phase or phase-balance current relay (negative-sequence current relay)
49	Machine or transformer thermal relay
50	Instantaneous overcurrent relay
50N	Instantaneous neutral overcurrent relay
51	AC time overcurrent relay
51G	AC time ground overcurrent relay
51N	AC time neutral overcurrent relay
51NB	AC time neutral overcurrent backup relay
51NT	AC time neutral overcurrent torque-controlled relay
52	AC circuit breaker
59	Overvoltage relay
60	Voltage or current balance relay
63	Pressure switch ~~or relay~~
64	Ground detector relay
67	AC directional overcurrent relay
67G	AC directional ground overcurrent relay
86	Lockout relay
87	Differential protective relay
87G	Ground differential protective relay

~~26—Thermal device~~

~~49—Thermal relay~~

~~51—Alternating current time overcurrent relay~~

~~51N—Alternating current time neutral overcurrent relay~~

~~51NB—Alternating current time neutral overcurrent relay, backup~~

~~51NT—Alternating current time neutral overcurrent relay, torque-controlled~~

~~52—Alternating current circuit breaker~~

~~67—Alternating current directional overcurrent relay~~

~~67N—Alternating current directional overcurrent relay, neutral~~

5. Philosophy and economic considerations

Protective relays are applied to ~~components~~ [elements](#) of a power system for several reasons. Some of the reasons are as follows:

- To ~~separate~~ [isolate](#) the faulted equipment from the remainder of the system so that the system can continue to function [properly](#)
- To limit damage to the faulted equipment

- c) Minimize the possibility of fire
- d) Minimize hazards to personnel
- e) Minimize the risk of damage to adjacent high-voltage apparatus

In protecting some system elements, particularly high-voltage transmission lines, high speed is often critical for preserving the integrity of the system; limiting damage to equipment sometimes becomes a ~~by-product of the system protection function of the relay. However, since the cost of repairing faulty transformers may be great and since high speed, highly sensitive protective devices can reduce damage and therefore repair cost, the equipment protective secondary benefit.~~ With transformers, however, the high cost of repair or replacement, and the possibility of a violent failure or fire involving adjacent equipment, may make limiting the damage a major objective. Since sensitive, high-speed protection systems can reduce damage, and consequently reduce repair cost. The protection aspects of relays should be considered carefully when protecting transformers, particularly those of larger sizes.

Faults internal to the transformer quite often involve ~~a magnitude of fault current which is low relative to the transformer rating a few turns. While the currents in the shorted turns are large in magnitude, the changes of the currents at the terminals of the transformer are low compared to the rating of the transformer.~~ This indicates a need for the protection systems that have high sensitivity and high speed ~~to obtain good protection.~~

~~Transformers with modern surge protection are generally reliable. However, if a possibility of failure exists, protection shall be provided.~~

There is no one standard way to protect all transformers, or even identical transformers that are applied differently. Most installations require individual engineering analysis to determine the best and most cost-effective scheme. Usually more than one scheme is technically feasible, and the alternatives offer varying degrees of sensitivity, speed, and selectivity. The selected plan should balance the best combination of these factors against the overall economics of the situation while minimizing

- a) Cost of repairing damage
- b) Cost of lost production
- c) Adverse effects on the balance of the system
- d) Spread of damage to adjacent equipment
- e) Duration of unavailability of the damaged equipment

In protecting transformers, backup protection needs to be considered. The failure of a relay or breaker during a transformer fault may cause such extensive damage to the transformer that its repair may not remain a practical alternative. When a fault in the transformer protection zone is not cleared by the transformer protection system, remote line relays or other protective ~~may~~ relays operate. Part of the evaluation of the type of protection applied to a transformer should include how the system integrity would be affected by such a failure contingency. In this determination, because rare but costly failures are involved, a diversity of opinion on the degree of protection required by transformers might be expected among those individuals familiar with power system ~~relay protection~~ engineering.

The major economic consideration ordinarily includes both the fault detection equipment and isolation devices. Circuit breakers often cannot be justified on the basis of transformer protection alone. At least as much weight should be given to the service requirements, the operating philosophy, and the system design philosophy ~~as to the protection of the transformer.~~ Evaluations of the risks involved and the cost effectiveness of the protection are necessary ~~to avoid going to extremes. Such considerations involve the art rather than the science of protective relaying. See [7],² [12], [16], and [19]. Further discussion on this subject is provided by Elmore [B5], McNutt et al. [B19], Sterner [B36], and Warrington [B41].~~

- a. Turn-to-turn insulation failure
 - b. Surges due to lightning, switching, etc.
 - c. Moisture
 - d. External faults (producing insulation failure)
 - e. Overheating
 - f. Open winding
 - g. Deterioration
 - h. Improper blocking of turns
 - i. Grounds
 - j. Phase-to-phase failures
 - k. Mechanical Failures
2. Tap Changer Failures
- a. Mechanical
 - b. Electrical
 - c. Contacts
 - d. Leads
 - e. Tracking
 - f. Overheating
 - g. Short Circuits
 - h. Oil Leak
 - i. External fault
3. Bushing Failures
- a. Aging, Contamination, and cracking
 - b. Flashover due to animals
- a. Loose connections
 - b. Leads (opened)
 - c. Links
 - d. Moisture
 - e. Insufficient insulation
 - f. Tracking
 - g. Short Circuit
5. Core Failures
- a. Core Insulation Failures
 - b. Ground strap burned away
 - c. Shorted laminations
 - d. Loose clamps, bolts, wedges
6. Miscellaneous Failures
- a. Bushing current transformer failure
 - b. Metal particles in oil
 - c. Damage in shipment
 - d. External faults
 - e. Bushing flange grounding
 - f. Poor tank weld
 - g. Auxiliary system
 - h. Overvoltage
 - i. Overloads
 - j. Unidentified problems

²The numbers in brackets correspond to the references listed in 1.2 of this standard.

Table 2—Failure Statistics for Two Time Periods

	1955–1965		1975–1982	
	Number	% of Total	Number	% of Total
1. Winding failures	134	51	615	51
2. Tap-changer failures	49	19	231	19
3. Bushing failures	41	15	114	9
4. Terminal board failures	19	7	71	6
5. Core failures	7	3	24	2
6. Miscellaneous failures	12	5	72	13
	262	100	1217	100

6. Types of failures in transformers

The electrical windings and the magnetic core in a transformer are subject to a number of different forces during operation, for example

- a) Expansion and contraction due to thermal cycling
- b) Vibration
- c) Local heating due to magnetic flux
- d) Forces due to the flow of through-fault currents
- e) Excessive heating due to overloading or inadequate cooling

These forces can cause deterioration and failure of the electrical insulation of the transformer windings. Statistics for the causes of transformer failures experienced in U.S. utilities are not readily available. The failure statistics collected by the Canadian Electrical Association are briefly reported in Annex B.

~~Transformer failures can be grouped into six major categories. The major categories are detailed in Table 1. Summaries of failures in those categories reported by groups of utilities are given in Table 2.~~

~~Transformer failure statistics are available through various organizations that periodically survey owners and users of transformers~~

This guide primarily addresses the application of electrical relays to detect fault currents that result from an insulation failure. Clause 7 examines the current a relay can expect to see due to various types of winding insulation failures.

The detection systems that monitor other transformer parameters can be used to indicate an incipient electrical fault. Prompt response to these indicators may help avoid a serious fault. Some examples of actions taken to detect undesirable operating conditions are as follows:

- 1) Temperature monitors for winding or oil temperature are typically used to initiate an alarm requiring investigation by maintenance staffs. At this stage, the operators may start to reduce the load on the transformer to avoid reaching a condition where tripping the transformer would be required.
- 2) Gas detection relays can detect the evolution of gases within the transformer oil. Analysis of the gas composition indicates the mechanism that caused the formation of the gas, e.g., acetylene can be caused by electrical arcing; other gases are caused by partial discharge and thermal degradation of the cellulose insulation. The gas detection relays may be used to trip or to generate an alarm depending on the utility practice. Generally, gas analysis is performed on samples of the oil that are collected periodically. A continuous gas analyzer is available to allow online detection of insulation system degradation.
- 3) Sudden-pressure relays under oil respond to the pressure waves in the transformer oil caused by the evolution of gas associated with arcing.
- 4) Sudden-pressure relays in the gas space respond to sudden changes in the gas pressure due to evolving gases from an arc under oil.
- 5) Oil-level detectors sense the oil level in the tank and are used to generate an alarm indicating minor reductions in oil level and trip for severe reductions.
- 6) Online devices monitor bushings of the transformers, CTs installed in those bushings, and surge arresters installed on the transformers and generate an alarm indicating that repair is needed urgently so that major damage is avoided. Details of the modern techniques for monitoring these components are given by Coffeen et al. [B3].

These and other relays are discussed in greater detail in later clauses of this guide.

7. Relay currents

The following two characteristics of power transformers combine to complicate detection of internal faults with relays actuated with currents [available at the terminals of a transformer](#):

- a) The change in magnitude of current at the transformer terminals may be very small when a limited number of turns of a winding are shorted within the transformer.
- b) When a transformer is energized, magnetizing inrush current that flows in one set of terminals may be equal to many times the transformer rating. These and other considerations require careful thought to obtain relay characteristics best suited to a particular application.

4.3 Through Faults

~~A favorable aspect for the protection of transformers is that fault current through a transformer is limited by the transformer impedance. While current through a transformer thus limited by its impedance can still cause incorrect relay operations or even transformer failure, current transformer saturation is less likely to occur than with unlimited currents.~~

~~The above favorable aspect may disappear if the transformer protective zone includes a bus area with two or more breakers on the same side of the transformer through which external fault current can flow with no relationship to the transformer rating. An example is a transformer connected to a section of a ring bus with the transformer protection including the ring bus section.~~

7.1 Minimum internal faults

The most difficult transformer winding fault for which to provide protection is the fault that initially involves one turn. A turn-to-turn fault results in a terminal current change of much less than rated full-load current. ~~Possibly, 10% For example, as much as 10% of the winding may have to be shorted to cause full-load terminal current to flow. If the transformer is an autotransformer or a regulating transformer, there are fewer total number of turns in the coils than a two-winding transformer of the same rating. Consequently, a greater percentage of the exciting winding will have to be shorted to provide full-load current at the transformer terminals. Therefore, a single turn-to-fault will result in a terminal current of 10% or less of a transformer rating~~ [an undetectable change of current at the transformer terminals](#).

7.2 Maximum internal faults

There is no limit to the maximum internal fault current that can flow, other than the system capability when the fault is on the source-side terminals of the transformer, or a fault external to the transformer but in the relay zone. The relay system should be capable of withstanding the secondary current of the CTs on a short-time basis. This may be a factor if the transformer is small relative to the system fault and the CT ratio is chosen to match the transformer [rating](#).

7.3 Performance of current transformers

7.3.1 Internal faults

During an internal fault, or a fault external to the transformer but in the protected zone, ~~the current transformers of the relay system, one or more CTs~~ may saturate, ~~perhaps severely~~. Severe CT saturation can cause ~~a harmonic restraint unit to pick up, thereby resulting~~ in the failure of a transformer differential relay to operate or ~~causing~~ a delay in its operation. The effect depends on the relay's response to distorted currents. On a transient basis, ~~with a saturated current transformer, second and third harmonics predominate initially, and each may be greater than the fundamental, when a CT saturates~~. Ultimately, the even harmonics disappear ~~depending upon the~~ with the decay of the offset direct-current time constant-current (dc) component of the short-circuit current. Whether or not the odd harmonics disappear depends on the ~~current transformers~~ steady-state saturation characteristic of the ~~current transformer when differential relay operation is restrained~~ CT. The ratings of the CTs should be selected to avoid steady-state saturation.

7.3.2 External faults

~~If a single set of current transformers is used at each voltage, the current transformer current will be limited by the transformer impedance. If current can flow through the differential zone at the same voltage (for example, ring bus, or breaker and a half applications), then the current is not limited by the transformer impedance. In either case, any deficiency of current output caused by saturation [11] of one current transformer that is not matched by a similar deficiency of another current transformer will cause a difference current to appear in the operating circuit of a differential relay. Time overcurrent relays, without restraint, can overcome this problem only by having their tap and time dial settings made sufficiently high, to override this false differential current. Percentage differential relays offer the advantage of faster speed and security with reasonable sensitivity. Ideally they should be applied with a restraint element in each current transformer circuit. Also, the burden of each current transformer secondary circuit as related to the relaying accuracy class rating of the current transformers involved should not exceed the values established by the relay manufacturer.~~

Figure 1 shows three scenarios of external faults. The scenario in part (a) of Figure 1 shows a transformer that is connected to single bus arrangements on the source and load sides and an external fault at location F_1 . In this scenario, the fault currents flow through the transformer. The scenario in part (b) of Figure 1 shows a transformer that is connected to a breaker-and-a-half bus arrangement on the source side and a single bus arrangement on the load side, and an external fault at location F_1 . In this scenario, the fault currents flow through the transformer as well. (These fault-current flows are also referred to as through-currents.) These fault currents are limited by a series combination of the source impedance, Z_s , and the transformer impedance. The currents are not likely to cause the CTs to saturate if the CTs are selected after considering the levels of the fault currents and the relay burden (including the burden due to the leads connecting the CTs with the relay) as discussed in IEEE Std C37.110, IEEE Guide for Application of Current Transformers Used for Protective Relaying Purposes.

The scenario in part (c) of Figure 1 is the same as the scenario in part (b) of Figure 1 except that the fault is at location F_2 . In this scenario, the fault current does not flow through the transformer but flows through the two CTs provided on the breaker-and-a-half bus that form part of the transformer protection scheme. The levels of primary currents in CTs would be substantially large because they are limited by the source impedance only. One or both CTs through which the fault current or currents flow may saturate. The unequal outputs of the CTs cause the difference currents to flow in the operating coils of the differential relay. (For more details, see the IEEE PSRC Report, "Transient Response of Current Transformers" [B12].) Time overcurrent relays, without restraint, can overcome this problem only by having their pickup and time dial settings made sufficiently high, to override this false differential current. Percentage differential relays offer the advantage of faster speed and security with reasonable sensitivity. Ideally, they should be applied with a restraint element in each CT circuit. Also, the burden of each CT secondary circuit must not be too high so that ratio errors recommended by the relay manufacturer are not exceeded.

[Using the approach described in these scenarios, problems associated with CT performance can be reviewed for other scenarios](#)

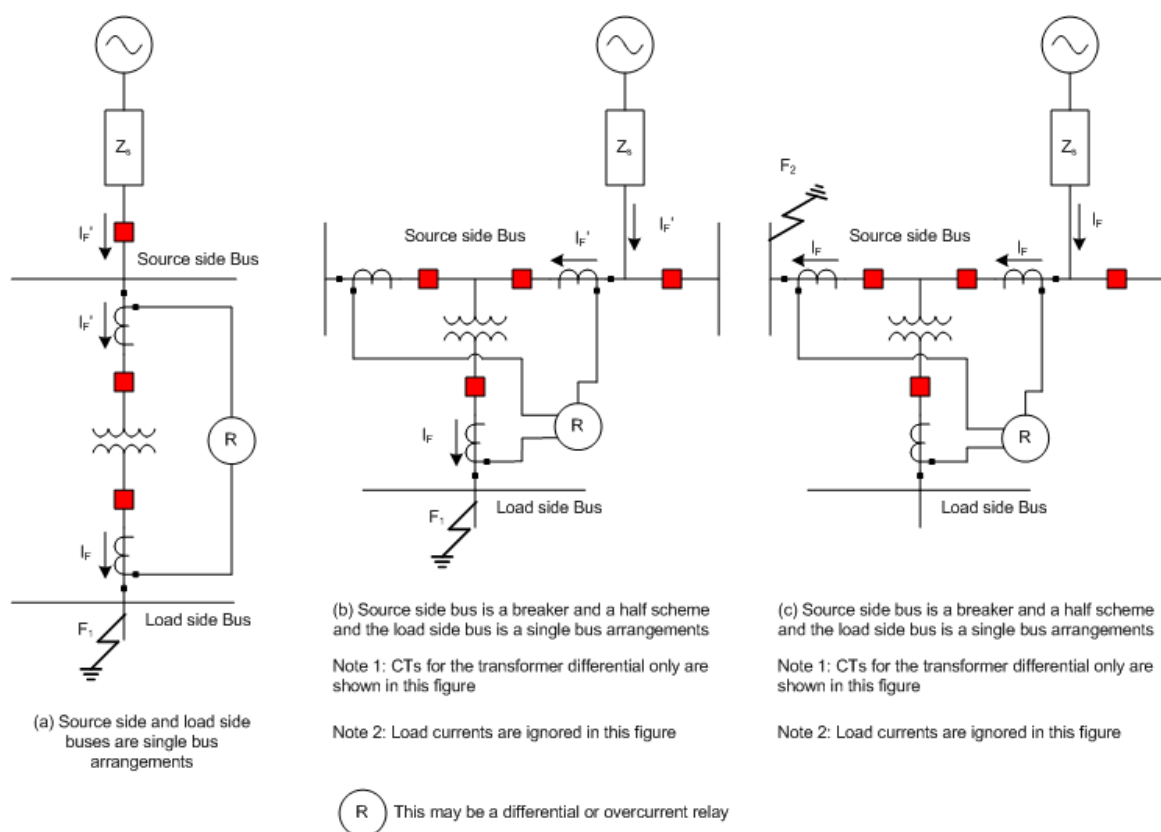


Figure 1—Three external fault scenarios

7.3.3 Current-transformer connections

The performance of a CT is a function of the burden connected to the secondary winding of the CT. The method of connecting the CTs and [the impedances of the secondary circuit and the relay determine the total burden](#). [Also, the physical and electrical locations of auxiliary CTs affect the burden](#). [For more information on the effect of CT connections, see IEEE Std C37.110, IEEE Guide for Application of Current Transformers Used for Protective Relaying Purposes](#). ~~and the burden can affect the effective burden (for example, the lead burden of the delta-connected current transformers is three times that of wye-connected current transformers). Also, current transformers paralleled at the current transformer terminals to obtain zero sequence current have no lead burden for three phase or phase-to-phase faults. The physical and electrical locations of auxiliary current transformers can similarly affect the effective burden.~~

[Before a decision is taken as to the manner in which the CTs should be connected, capabilities of the relay should be evaluated](#). [Some differential relays can internally accommodate the phase shift of the transformer, allowing the engineer to choose CT connections that suit other devices connected to the same CTs](#). [Many relays do not have this versatility, and, in those cases, the CTs must be connected to create the same phase shift as the transformer windings create](#).

For example, a transformer using both delta and wye connections create a 30° phase shift between the current entering and leaving the transformer. By connecting the CTs in delta on the wye side of the transformer and connecting the CTs in wye on the delta side of the transformer, the 30° phase shift can be matched between the transformer and the CT currents. Therefore, the relay does not see any phase shift between the input and output currents when current flows through the transformer.

CAUTION

The delta connection of the CTs should have the same configuration as the delta connection of the transformer winding. If the configurations of the delta connections are not identical, the phase angles of the currents contributed from the two windings will not match.

The grounded wye winding of a delta-wye transformer allows zero-sequence currents to flow in the wye winding when a ground fault occurs on the circuit connected to it. The zero-sequence currents in the grounded wye-connected winding circulate in the delta-connected winding and are not present at the terminals of the delta-connected winding. Some relays take care of this problem by removing the zero- sequence currents as part of the internal phase-shift accommodation. On the other hand, many other relays do not accommodate this function and must use the CT connections to filter out the ground current. The connections used in the example from the previous paragraph take care of this problem as well. The delta connection of the CTs on the wye side of the transformer trap the zero-sequence currents and prevent them from flowing in the secondary windings of the CTs. The result is that the differential relays do not see the mismatch due to the flow of zero-sequence currents.

4.5 Nonfault Relay Current

~~There are nonfault related currents or factors which may result in incorrect or undesirable relay operation. following sections include a discussion of some of those situations.~~

7.4 Reasons for mismatch

There are nonfault-related currents or factors that may require compensation to prevent undesirable operation of differential relays. Subclauses 7.4.1, 7.4.2, and 7.4.3 include a discussion of some of those situations.

7.4.1 Unbalance caused by current-transformer ratios

Even if a transformer has a fixed ratio, it is frequently difficult to match CT ratios exactly on the two (or more) sides of a transformer. CT mismatches result in current flows in the operating circuits of differential relays. If a transformer has a load-tap changer (LTC), the possible mismatch is increased further. During a through-fault condition, the differential operating current due to mismatch can ~~approach the current rating of the transformer~~ be very large.

7.4.2 Magnetizing inrush

This is a phenomenon that causes the violation of the basic principle of differential relaying. ~~since the magnetizing branch of the transformer can have a very low impedance without a transformer fault. If the primary winding of a transformer is connected to a source and the secondary winding is connected to loads, magnetizing inrush currents flow from the source to the primary winding while no currents (or much smaller load currents) flow out of the transformer secondary windings.~~ Current ~~occasional~~ produced by magnetizing inrush can reach many times the transformer rating, and these currents appear in the differential relay. Explanations of this phenomenon are given by Lin et al. [B17] and Rockefeller et al. [B27].

Although usually considered only in conjunction with the energizing of a transformer, magnetizing current inrush can be caused by any abrupt change of ~~magnetizing~~ voltage at the transformer terminals. Such transients include the occurrence of a fault, the removal of a fault, the change of character of a fault (for example, the change from a single-phase-to-ground fault to a two-phase-to-ground fault), and out-of-phase synchronizing. Thus, a desensitizing scheme that is effective only when a transformer is being energized is not an adequate countermeasure.

There are several conditions that cause particularly severe magnetizing inrush phenomena. [More details are given by Rockefeller et al. \[B27\].](#) One condition involves the energizing of a transformer at a station at which at least one other transformer is already energized (see Hayward [B9]). The inrush phenomenon involves transformers that are already energized as well as the transformer being energized (see Lin et al. [B17]). This inrush transient may be particularly long in duration. It is important to realize that the inrush into the transformer being energized occurs during the opposite half-cycle to that of the already energized transformer. Thus, the net inrush into all transformers may approximate a sine wave of the fundamental frequency, and, therefore, the harmonic restraint unit of a differential relay, if it is protecting both parallel-connected transformers, will not operate. ~~Another inrush phenomenon involves the energizing of a transformer by means of an air switch. Arcing of the switch can result in successive half cycles of are of the same polarity. Thus if the first half cycle results in substantial residual magnetism in a transformer core, succeeding half cycles can cause a cumulative increase in residual magnetism, each time resulting in a more severe inrush. However, the inrush is no more severe in this case than for a normal inrush. The problem is that there is inrush current from the previously energized transformer to the adjacent incoming transformer. The net inrush to both transformers contains little second harmonic. It is, therefore, desirable to provide a separate differential relay for each parallel-connected transformer.~~

[The two important characteristics of magnetizing inrush current are as follows:](#)

- Magnetizing inrush currents contain substantial harmonics, particularly the second harmonic. [These harmonics are not always present in high quantities in all the phases \(see 8.2.3.1\).](#)
- [There is always a time during each cycle when the current magnitude is almost zero. This time is always greater than a quarter-cycle. A typical magnetizing inrush current waveform is shown in Figure 2.](#)

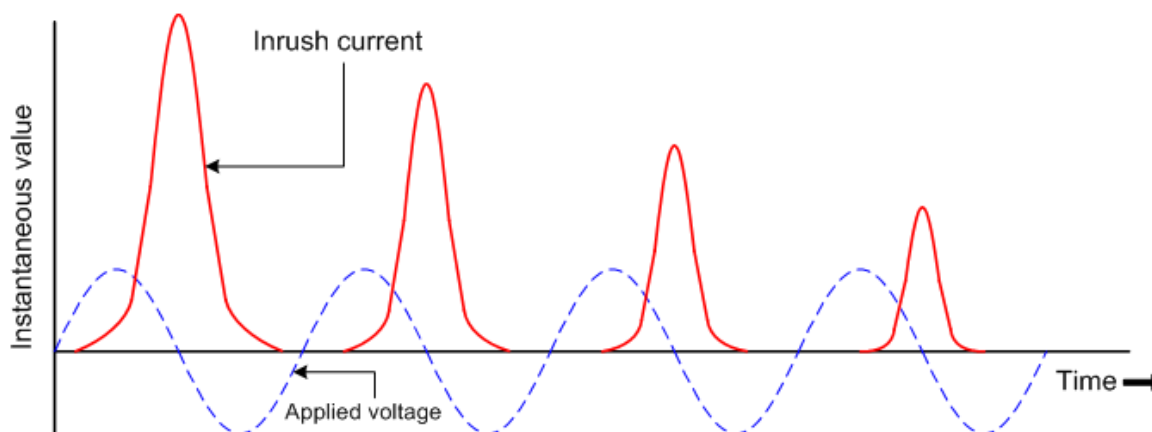


Figure 2 —Typical magnetizing inrush current waveform

[The harmonic content of the inrush current depends on various factors, such as remanent flux in the core, switching angle, and load on the transformer. Harmonic analysis of the inrush current for such cases shows that the second-harmonic content of the inrush current is sensitive to all these conditions. The second-harmonic content reduces appreciably with increasing load at lagging power factor \(see Lin et al. \[B17\]\).](#)

[If three single-phase point-on-the-wave closing circuit breakers are used for switching on circuit breakers, controlling a transformer, substantial reduction in magnetizing inrush currents can be achieved. The approach used in such applications is to estimate the residual flux in the transformer core for each phase and close the](#)

circuit breaker of that phase at an instant the maximum flux in that core does not substantially increase from the normal maximum flux.

7.4.3 Magnetizing current during over ~~voltage~~excitation

Sudden loss of load can subject a generator step-up transformer to substantial overvoltage. This can also occur during startup or shutdown of a generator if the generator is excited to nominal voltage while its speed is less than the specified normal value (an overexcitation condition). If saturation occurs, substantial exciting current will flow, which may overheat the core and damage the transformer. The waveform will be distorted; ~~and the harmonic content will be dependent on the generator connections and the transformer design and connections.~~ it will have harmonic content and zero-current periods. The waveform is distorted, but the behavior on the positive-going half-cycle is the same as on the negative-going half-cycle, and therefore no appreciable second harmonic is present. The extent of these effects depends on the generator connections and the transformer design and connections. The harmonic content of the relay current is also altered by delta connections of CTs. ~~(Because of the abrupt voltage change, there may also be a magnetizing current inrush, but this is of secondary importance.)~~ Fifth-harmonic blocking of tripping should be used to avoid tripping during overexcitation. A V/Hz relay is required if tripping is desired.

~~4.5.4 Phase-Shifting Transformers~~

~~A phase-shifting transformer, as its name implies, has a purposely introduced angular voltage difference, usually adjustable in steps, between the primary and secondary voltages. If the angular difference is a fixed 30°, such as with the familiar Y-Δ transformer, current transformer connections for proper differential relaying are easy to obtain. However, if the phase angle shift is some other angle (15°), orthodox connections of current transformers, either Y or Δ, to a differential relay will not provide proper current balance and an operating (differential) current will flow.~~

~~If the 15° phase shift were fixed, it is possible to develop current transformer connections that would provide proper operation for that one phase shift. However, each angle of shift would require different considerations such as a different ratio of auxiliary current transformers. Thus, it may not be practical to apply the usual percentage differential relay to a given phase-shifting transformer.~~

8. Electrical detection of faults

Fuses are commonly used to provide fault detection for transformers with minimum nameplate ratings of up to 5000 kVA, three-phase (Category I and Category II). Transformers ~~larger than 5000 kVA, 10 000 kVA and larger~~, three-phase, minimum nameplate (Category III and Category IV), are generally protected by a combination of protective devices as shown in Figure 3. Transformers that fall between these two ratings are either protected by fuses or relays; self-powered resettable fault interrupters can be used for transformers up to 50 000 kVA at 69 kV or up to 83 000 kVA at 138 kV. The choice of protection depends on the criticality of the load, the relative size of the transformer compared to the total system load, and potential safety concerns. System considerations, such as ability to coordinate fuses with upstream relays or with transformer damage curves, may determine what protection is used. Some other considerations include types of faults, personnel safety issues, speed of clearing, single phasing of load, and ferroresonance. More details of the definition of these categories are given in Annex A.

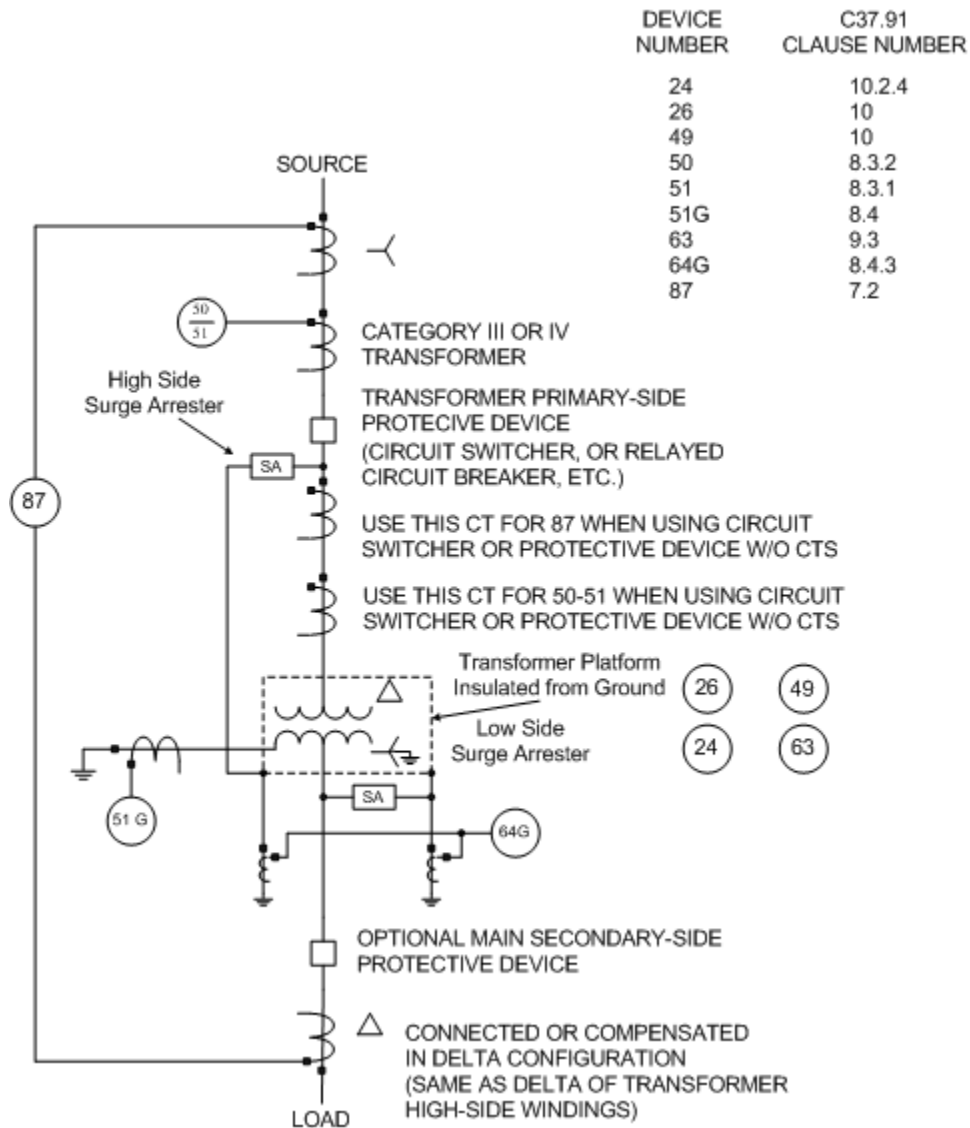


Figure 3 —Protection of a delta-wye transformer

8.1 Fuse protection and self-powered resettable fault interrupters

Fuses have the merits of being economical and require little maintenance. Battery supply and a relay building are not needed. Fuses can reliably protect some power transformers against damage from primary and secondary external faults. They, however, provide limited protection for internal faults. Generally, more sensitive means for protection from internal faults are provided for transformers of 10 MVA and higher ratings. Fuses have been used at higher transformer ratings depending on the ~~currently available fuse ampere ratings~~. ~~Primary fuses for power transformers are not applied for overload protection, their main purpose being fault protection (see 5.6.1). It should be recognized that the blowing of one fuse on a three-phase system will not necessarily deenergize the fault. If the fault is not deenergized, the resulting single-phase service may be detrimental to the connected polyphase motors and other loads. If required, special protection should be added for single phasing conditions~~availability of fuses that have the needed current ratings.

Self-powered resettable fault interrupters are applied similarly to fuses, but the interrupters generally have higher continuous current flow and fault-interrupting capabilities. They also have the capability of sensing neutral current and three-phase tripping capability. Like fuses, self-powered fault interrupters are economical and require little maintenance. A battery supply and relay building are not required because tripping power is derived from the CTs (usually, transformer bushing CTs) that provide current sensing. Fault interrupters are resettable after the occurrence of a fault. Transformers up to 50 MVA at 69 kV or up to 83 MVA at 138 kV can be protected with self-powered resettable fault interrupters.

Primary fuses for power transformers are not applied for overload protection; their main purpose is to protect during faults (see 8.6.1). It should be recognized that the operation of one fuse on a three-phase system will not necessarily deenergize the fault. If the fault is not deenergized, the resulting single-phase service may be detrimental to the connected polyphase motors and other loads. If required, special protection should be added for detecting and protecting from single-phasing conditions.

A typical transformer that exhibits this protection shortfall is a station transformer whose primary winding is connected in delta and the secondary winding is connected in wye configuration with neutral connected to ground. If a phase-to-phase-to-ground fault occurs on the secondary side between the transformer terminals and the low-side protective device, then the fault is cleared by the high-side fuses. The fuse with the highest current will operate first leaving the transformer energized through the remaining two fuses. At this point, the secondary fault is further limited by twice the transformer impedance and, depending on the fuse size, transformer impedance and system impedance, the remaining fuses may or may not operate. This condition could overload the transformer and may severely overload the neutral connection because the currents in the secondary windings are in phase and their sum flows in the neutral connection. Table 2 shows the magnitude of currents for a typical 69 kV/13.2 kV, 8.4 MVA power transformer before and after the first fuse clears. This transformer would normally be protected by a 100E fuse. Table 2 clearly shows that the current in the neutral connection remains essentially the same after the first fuse opens; this current will persist until the second fuse opens.

Table 2—Currents for a typical distribution station delta-wye power transformer

Phase B-C-ground fault on the low-voltage side before first fuse opens				Phase B-C-ground fault on the low-voltage side after first fuse opens			
High side		Low side		High side		Low side	
Phase	Current (A)	Phase	Current (A)	Phase	Current (A)	Phase	Current (A)
A	415	A	0	A	226	A	0
B	415	B	3764	B	226	B	2050
C	697	C	3764	C	0	C	2050
		Neutral	4100			Neutral	4100

The selection of the fuse and proper current rating should be based on the following factors:

- a) Fuse fault-interrupting capability and available system fault current
- b) Maximum anticipated peak load current, daily peak loads, emergency peak loads, maximum permissible transformer load current, and the applicable transformer through-fault-current duration curve (see Annex A)
- c) Hot-load pickup (inrush current upon instantaneous reclosing of source-side circuit breaker) and cold-load pickup (inrush current and undiversified load current after an extended outage)
- d) Available primary system fault current and transformer impedance
- e) Coordination with source-side protection equipment
- f) Coordination with low-side protection equipment
- g) Maximum allowable fault time on the low-side bus conductors
- h) Transformer connections and grounding impedance as they affect the primary current for various types of secondary faults
- i) Sensitivity for high-impedance faults
- j) Transformer magnetizing inrush

Current rating selection is facilitated by data published by fuse manufacturers. Such data includes time- current characteristic curves, ambient temperature, and preloading adjustment curves, plus daily and emergency peak-loading tables. Coordination examples are included in Annex A.

8.2 Differential protection

While fuse protection is a simple and minimal cost approach, many advantages are realized with differential protection (see Blackburn [B2], Elmore [B5], and Hayward [B9]). These advantages include the following:

- a) Differential protection provides faster detection of faults that can reduce damage due to the flow of fault currents.
- b) The location of the fault is determined more precisely depending on the “size” of the protection zone (i.e., transformer only, transformer + bus, transformer + bus + feeder breakers, etc.).
- c) Accurate fault location allows the application of automation techniques, such as rapid isolation of faulted components, and restoring load.
- d) The high-speed clearing of in-zone faults can significantly lower the arc flash incident energy levels and the associated clothing and personnel protective equipment needed for energized work.

Current differential relaying is the most commonly used practice for protecting transformers that are rated approximately 10 MVA (three-phase, self-cooled rating) or more (see IEEE PSRC Report, “Protection of Power Transformers” [B14]). Figure 4 shows a typical differential relay connection diagram for a single-phase transformer of ratio 1:1.

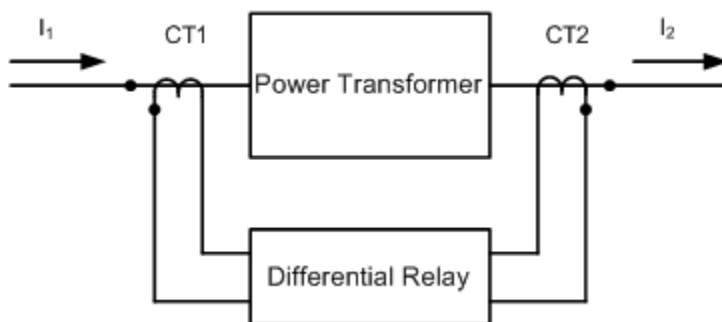


Figure 4 —Typical differential relay connection diagram for a single-phase transformer

If the ratios of CT1 and CT2 are 1:1, the operating current, I_o , which is the difference between the current entering one winding and the current leaving the other winding, can be expressed in Equation (1):

$$I_o = I_1 - I_2 \quad (1)$$

where

I_o is the operating current

I_1 is the current entering the transformer

I_2 is the current leaving the transformer

Relays of three general classes are used in current differential schemes. They are as follows:

- a) Time overcurrent relays with or without an instantaneous trip unit
- b) Percentage differential relays with restraint actuated by the currents going into and out of the protection zone
- c) Percentage differential relay with restraint actuated by one or more harmonics in addition to the restraint actuated by the currents flowing into and out of the protection zone

Power transformers of 1:1 ratio are rarely used. The transformation ratio of the power transformer should be taken into account and CT connections and ratios must be such that the net current in the relay operating coil for any external fault is effectively zero, unless matching current taps are available in the relay. ~~Current differential relaying is the most commonly used type of protection for transformers of approximately 10 MVA (self-cooled rating) and above [10].~~ Various types of CT connections are used and some are shown in Figure 5 through Figure 9. Paralleling of two or more CTs for connection to a single restraint coil or element usually should be avoided for the most effective restraint action.

The arrangement shown in Figure 5, Figure 6, Figure 7, and Figure 8 are typical CT connections when electromechanical relays and some solid-state relays are used for differential protection. In these types of applications, when configurations such as delta-wye transformations are used, care must be taken while connecting the CTs. For example, in a typical delta-wye power transformer, the CTs would be connected as wye-delta. Another feature involves correction for CT ratios, which in the electromechanical world may require external auxiliary CTs. The secondary circuits of CTs should be grounded as explained and discussed in IEEE Std C57.13.3, IEEE Guide for Grounding of Instrument Transformer Secondary Circuits and Cases. As shown in Figure 5, Figure 6, Figure 7, and Figure 8, the secondary circuits and the circuits connected to them are grounded at a single physical location.

~~The term refers to the connection of current transformers so that the net operating current to the relay is the difference between input and output currents to the zone of protection.~~

~~Relays of three general classes are used with this current differential. They are:~~

- ~~1) Time overcurrent relay, which may include an instantaneous trip unit having a high current setting.~~
- ~~2) Percentage differential relay, with restraint actuated by the input and output currents.~~
- ~~3) Percentage differential relay, with restraint actuated by one or more harmonics in addition to the restraint actuated by the input and output currents.~~

~~Current transformer connections and ratios must be such that the net current in the relay operating coil for any type or location of external fault is effectively zero, unless relay current matching taps are available. Various types of current transformer connections are shown in Figs 2, 3, and 4. Paralleling of two or more current transformers for connection to a single restraint coil usually should be avoided for the most effective restraint action.~~

On the other hand, for microprocessor relays and some solid-state relays, all CTs are connected in wye as shown in Figure 9. The phase compensations are done by the software in the relay. The magnitude compensation in numerical relays is also done in the relay. Each set of CTs in this case is provided a separate ground. Because the

inputs to the relay are from wye-connected CTs, the inputs can be used for protection functions, such as overcurrent and ground overcurrent protection.

Differential protection of transformers and its implementation in numerical relays is discussed in several books and published papers; some of these are Guzmán et al. [B7], [B8], Murty and Smolinski [B20], Murty et al. [B21], Phadke and Thorp [B22], [B23], Sachdev [B28], [B29], [B30], Sachdev and Nagpal [B31], Sachdev and Shah [B32], Sachdev et al. [B33], Sidhu et al. [B35], Thorp and Phadke [B38], and Ziegler [B42].

The issue of testing the differential circuits is not included in this guide. This is discussed in detail in IEEE Std C37.103, IEEE Guide for Differential and Polarizing Relay Circuit Testing.

If breaker-CTs are used for input to the transformer differential, bypassing the breaker will affect the inputs for the differential relays. Assuming that the differential relay is removed from service and there are other relay schemes protecting the transformer, care must be taken to insure that other breakers will trip in lieu of the bypassed breaker. If this alternative tripping is not available, the transformer breaker should not be bypassed.

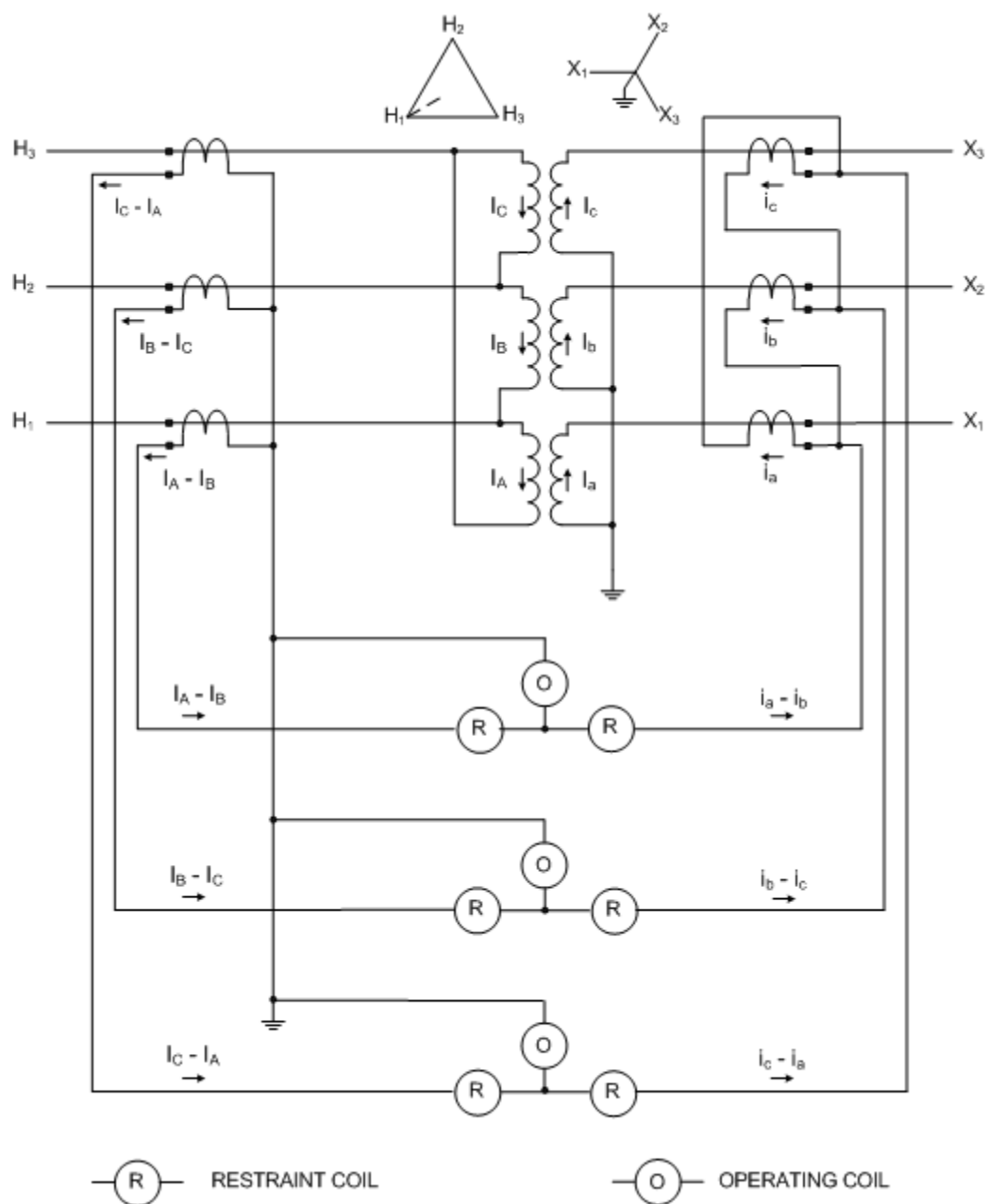


Figure 5—Typical schematic connections for percentage differential protection of a delta-wye transformer

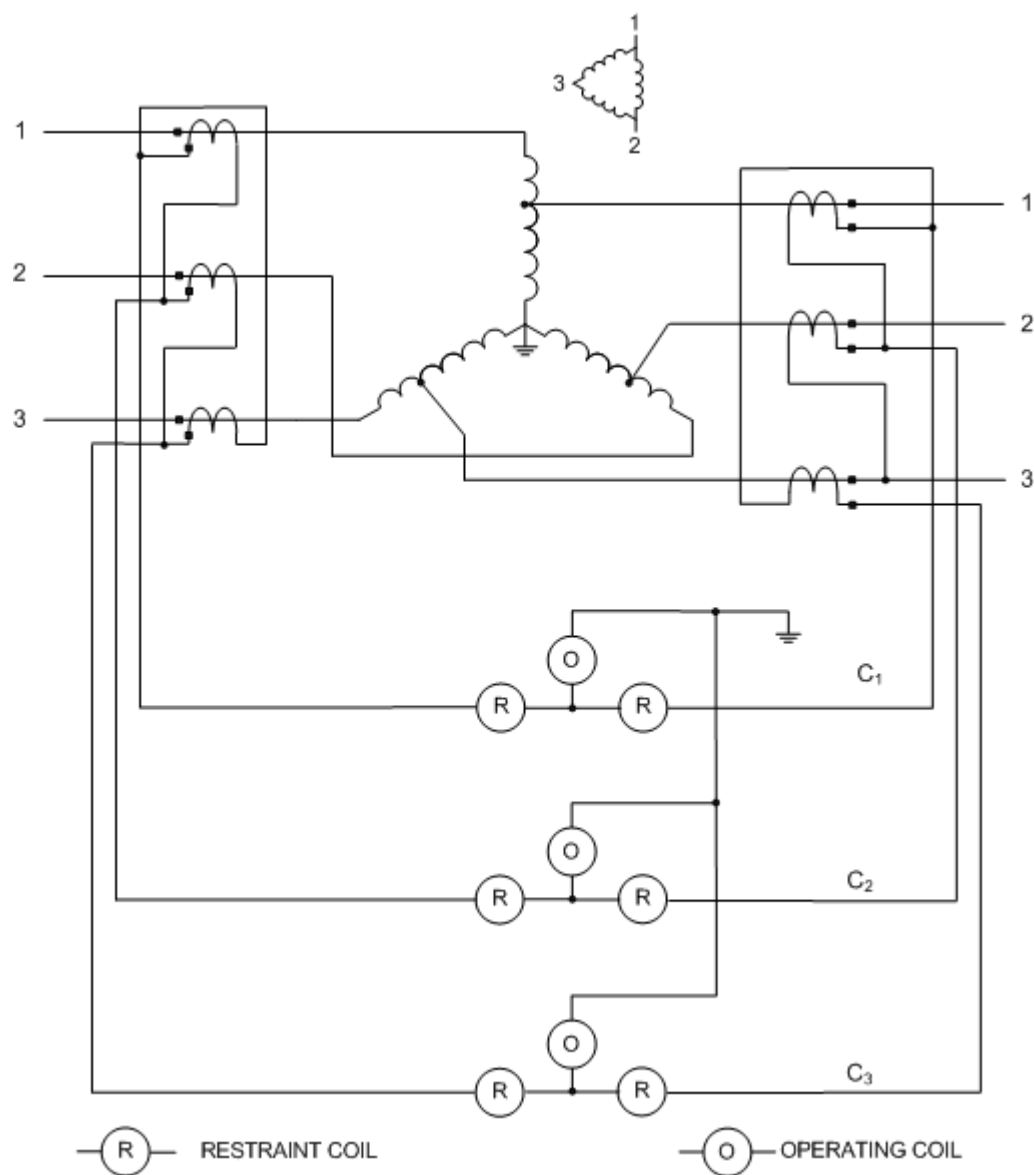


Figure 6 —Typical schematic connections for differential protection of a wye autotransformer with unloaded tertiary

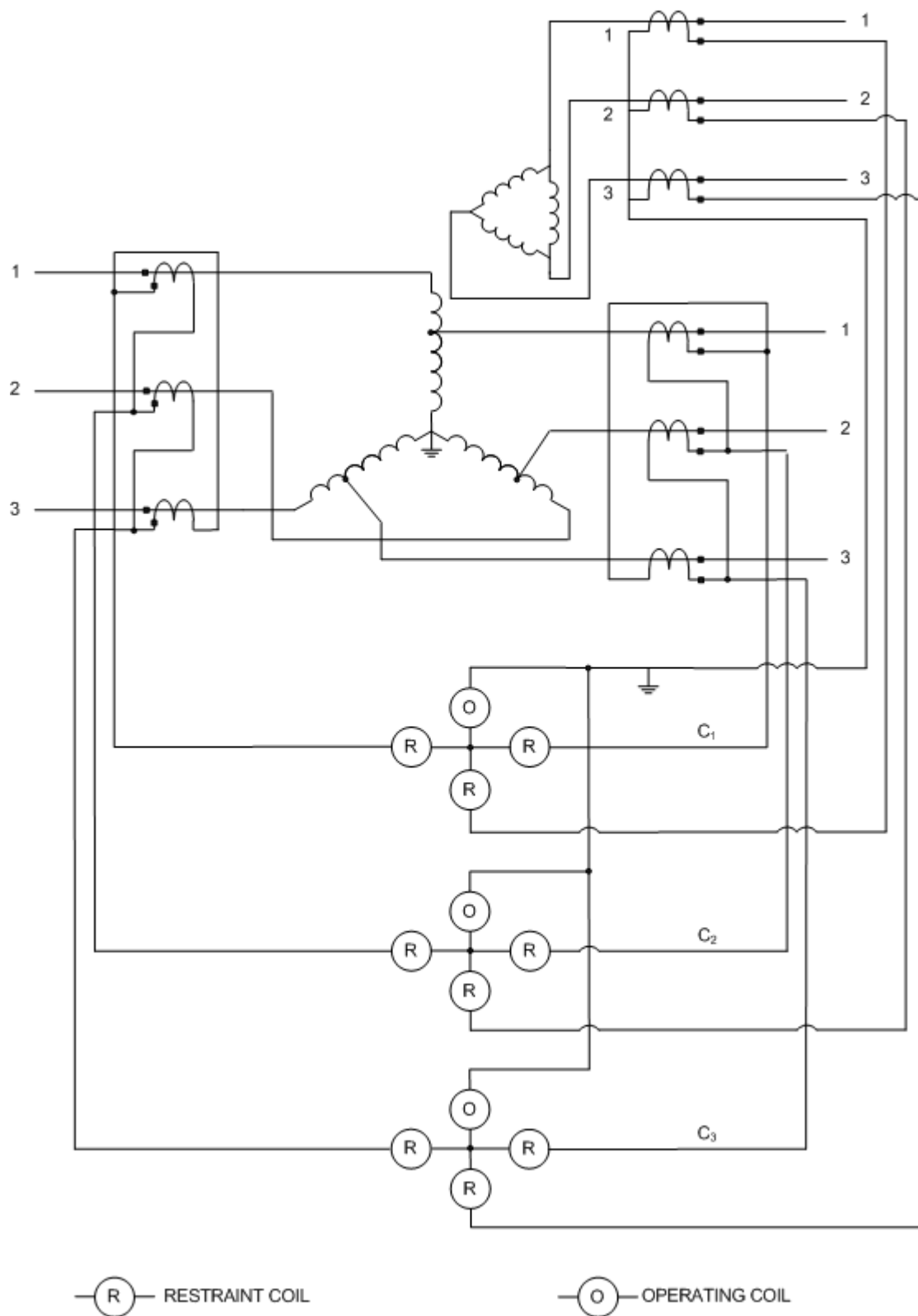


Figure 7—Typical schematic connections for differential protection of a wye autotransformer with loaded tertiary



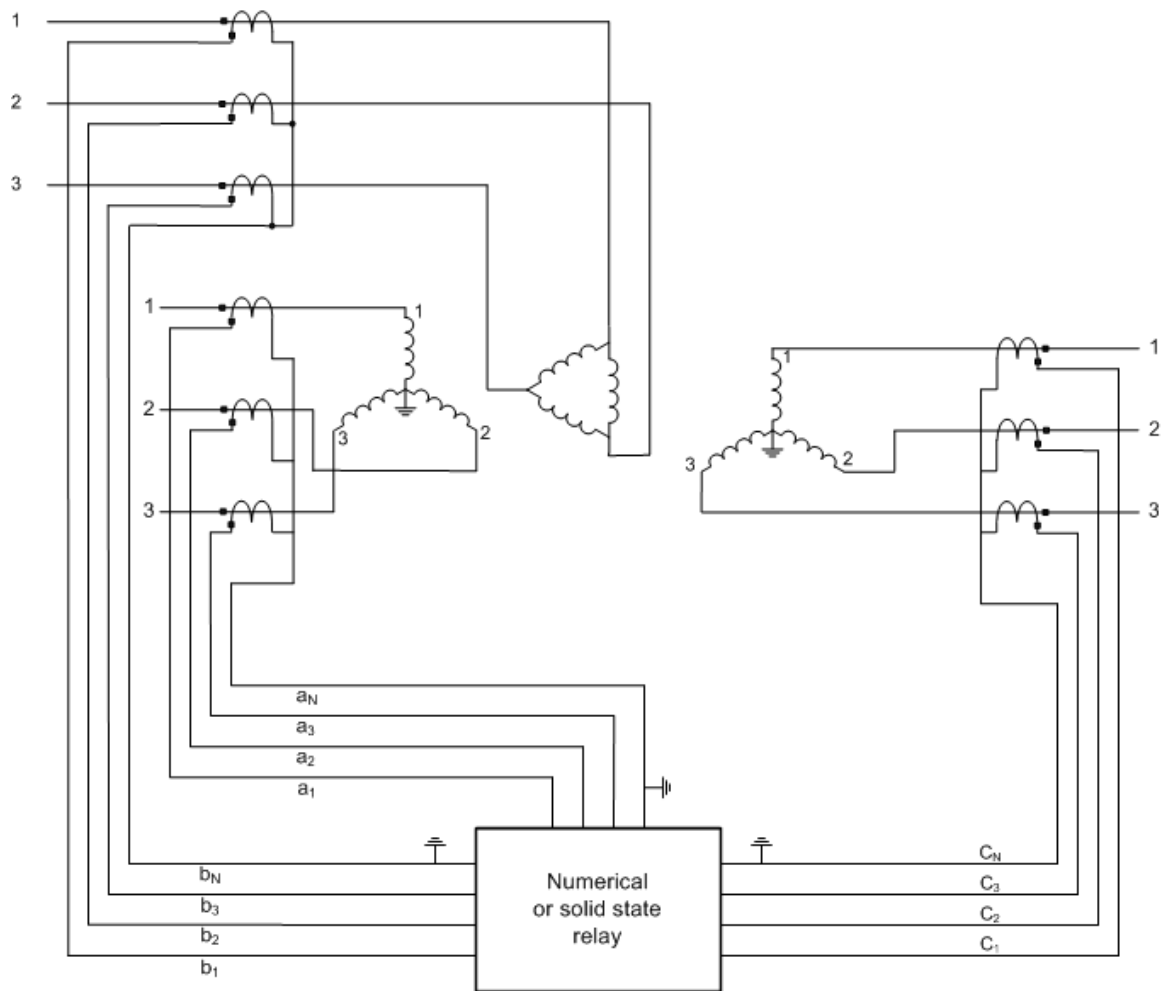


Figure 9 —Typical schematic connections for differential protection of a three-winding transformer using solid-state or numerical relays

8.2.1 Differential protection using time overcurrent relays

Overcurrent relays without restraint are seldom used due to their susceptibility to false operation from causes such as follows:

- a) Saturation errors or mismatch errors of CTs
- b) Magnetizing inrush current [flow from the source end](#) when energizing the transformer

[To compensate for the saturation and mismatch errors, overcurrent relays should be set to operate above the anticipated inrush values. Time delay to override inrush is also necessary. Due to power transformer saturation, caution is advised against the use of this relay where exposure to geomagnetically induced currents \(GICs\) is possible.](#)

8.2.2 Differential protection using percentage differential relays

~~To avoid undesired tripping due to a mismatch of relay currents or relay taps, restraint is added for through (external) faults. This permits increased speed and security with reasonable sensitivity at low fault currents. There is also some benefit in case of saturation errors. The restraining force disappears or is a much smaller percentage of the operating force, when the fault is internal. These relays are particularly applicable to power transformers of moderate size located at some distance from major sources of generation, depending upon the manufacturer. The variable percentage relay increases the restraint as the current increases so that a greater amount of current transformer error can be tolerated at high current levels. A percent slope or restraint characteristic shall be selected to accommodate error currents due to current transformer ratio imbalance and transformer ratio change due to tap changers. Various relays are available with slopes ranging from 15% to 60%. It should be noted that the simple percentage differential relay can misoperate on inrush currents. While a differential relay is more expensive than an overcurrent relay, the installed cost is usually no more. It is sometimes provided with taps which make auxiliary current transformers to balance currents unnecessary. The overcurrent relay in many instances requires an auxiliary current transformer and additional wiring which increases its installed cost.~~

To overcome the drawbacks of applying overcurrent relays for differential protection, manufacturers developed percentage differential relays. These relays offer sensitive differential protection at low currents and tolerate larger mismatches at high currents while still tripping for internal faults.

The basis of the percentage differential relay is that the difference current (as measured at the ends of the protected zones) is more than a predetermined percentage of the restraint current. The basic arrangement for percentage differential protection of a single-phase two-winding transformer is shown in Figure 4.

Different alternatives are used for obtaining the restraining current, I_R . Several combinations of the currents at the two terminals of the transformer shown in Figure 4 are used for restraining differential relays; some of these are expressed in Equation (2), Equation (3), and Equation (4):

$$I_R = k |I_1 + I_2| \quad (2)$$

$$I_R = k (|I_1| + |I_2|) \quad (3)$$

$$I_R = \max(|I_1|, |I_2|) \quad (4)$$

In these equations, k is a constant that is usually 1 or 0.5. Equation (3) and Equation (4) offer the advantage of being applicable to differential relays with more than two restraints.

The percentage difference can be fixed or variable, based on the relay's design. There is also a minimum differential current threshold before tripping without regard to the restraint current. Details of minimum pickup, restraint current, and characteristic slope vary among manufacturers. Slope may not be a straight line but may curve up depending on the design of the percentage restraint system. This curve allows even larger percentage mismatches during heavy through-currents. These options are shown in Figure 10.

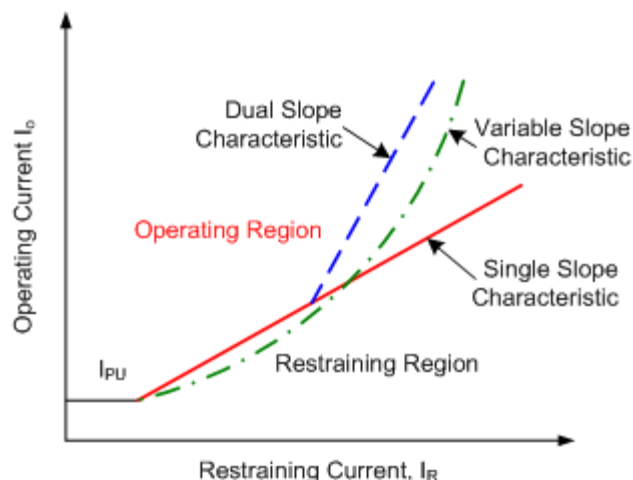


Figure 10—Typical options for the characteristics of percentage differential relays

High-voltage power transformers present several possibilities for current mismatch as seen by the differential relay. These mismatches, caused by different phenomena, can add to or offset each other, thus making the total mismatch difficult to predict. Therefore, the percentage differential relay must be tolerant of the worst-case addition of the mismatch errors.

First, the ratio of the high-voltage transformation inherently mandates different currents at the primary and secondary terminals. Depending on the transformer ratio, sometimes this difference is precisely compensated for by using offsetting ratio differences in the CT primary ratings. For example, a 138 kV/69 kV transformer could use 600:5 CTs on the 138 kV side and 1200:5 CTs on the 69 kV side.

For wye-delta transformer connections, the 30° phase shift is compensated by proper connection of the CT secondary windings when electromechanical relays are used, but the current ratio difference is affected by the multiplier for currents leaving the delta CT secondary connection. Alternatives used with electromechanical relays consist of using CTs with internal current taps to compensate for current input ratio differences and/or using special ratio auxiliary CTs. In solid-state and microprocessor relays, these differences are accounted for in the software/firmware of the relay. For more details, refer to Annex E of this guide.

Second, a large contribution to current mismatch is the application of LTCs for voltage regulation. A typical LTC range of ±10% voltage creates a ±10% variation in current. The differential must not operate for this substantial mismatch. In electromechanical relays, this was achieved by increasing the percentage slope, and this approach is also used in some numerical relays. However, in some modern microprocessor-based protection systems, the tap positions are monitored and the mismatches are taken care of in the software.

The third contributor to current mismatch is the difference in the performance of CTs applied to different voltage terminals of the transformer. At low currents, such as for load, the errors are very small and insignificant compared to the CT ratio and LTC errors. For heavy faults just outside the differential zone, CT saturation is a likely possibility. The difference in performance between the CTs on different transformer terminals appears as differential current in the relay. Some modern numerical relays can monitor the CTs for saturation and take remedial measures to remain secure from false differential current caused by CT saturation.

The fourth contributor to current mismatch during normal operation is the magnetizing inrush currents that flow when a transformer is energized, a parallel transformer is energized, or the system recovers from a fault outside the transformer protection zone. The magnetizing currents can be many times the rated current of the transformer.

The fifth and final reason for current mismatch is the overexcitation due to excessive voltage at the terminals of the transformer. When the voltage exceeds the rated value, the flux also exceeds the rated value.

Typically, a 10% increase is tolerated because the transformer is operating in the linear range of the magnetizing characteristic of the core. When the voltage exceeds further, the transformer operates partly in the saturated region of the magnetic circuit. This results in large magnetizing currents for parts of each period of the voltage. Because this current is at one terminal of the transformer, it appears as differential current in the relay.

5.2.3 Differential Protection Using Percentage Differential Relays With Harmonic Restraint

~~To avoid undesired tripping due to inrush currents, harmonic restraint is incorporated in certain differential relays. These relays utilize at least the 2nd harmonic current which is present in all transformer energizing surges to restrain or greatly reduce the sensitivity of the relay during this period. These relays use frequency selective circuits to develop the needed restraint. Several designs utilize harmonics in addition to the 2nd harmonic to develop the restraint, while others utilize only the 2nd harmonic.~~

~~The purpose of all of these designs is to provide a relay which properly restrains regardless of the amount of inrush and yet permits operation if an internal fault occurs during the inrush period. Another design objective is not to have excessive restraint resulting from the harmonic distortions of the secondary currents due to current transformer saturation during a severe internal fault. Thus, each relay design attempts to optimize the amount of harmonic restraint to ensure correct operation under all service conditions.~~

~~Frequently, the differential harmonic restraint relay will also include an instantaneous relay unit. The instantaneous unit is set above possible transformer inrush current, but below that current which might result in current transformer saturation. The usual factory setting is 8 to 10 times the tap value.~~

~~Another consideration in the use of harmonic restraint relays is the performance during transformer overexcitation (see 4.5.3). Whether or not a differential relay will operate on exciting current due to overexcitation depends on the magnitude of exciting current, the harmonic content of the current (predominately odd harmonics), and the restraint characteristic of the relay. A relay which restrains on odd harmonics is less likely to operate under such conditions. The relay application engineer should check Section 13 for assistance in defining his specific transformer protection objectives and hence preferred type of harmonic restraint relay characteristic.~~

~~Harmonic restraint differential relays often can be justified by considering the following points:~~

- ~~1) Fewer investigations of false trips due to inrush~~
- ~~2) Faster operating time (0.03 s to 0.05 s versus 0.1 s to 0.2 s for the percentage restraint type)~~
- ~~3) Lower pickup (20% to 40% of transformer rating versus 40% to 100% for the percentage restraint type)~~

8.2.3 Differential protection using percentage differential relays with inrush and overexcitation restraint

The addition of some type of restraint that recognizes the characteristics of the inrush current allows the relay to be set with greater sensitivity.

8.2.3.1 Harmonic restraint

Harmonic restraint is used to avoid undesired tripping by the percentage differential relay due to the flow of magnetizing inrush currents when a transformer is energized. In addition, the use of harmonic restraint allows the use of more sensitive settings. Different methods are used in the relays for harmonic restraint. Typical methods are described in this subclause.

The general principle of operation, when harmonic restraint is used, can be expressed as shown in Equation (5):

$$|I_o| > s |I_R| + k_2 |I_2| + k_3 |I_3| + \dots \quad (5)$$

where

I_o is the fundamental frequency component of the operating current

$I_2, I_3, \dots$ are the second-, third-, and higher harmonic components of the operating current

I_R is the unfiltered restraining current

k_2, k_3 are constants of proportionality

s is the slope of the percentage differential characteristics (nonvariable slope types)

The harmonic restraint is high when this approach is used and, therefore, it provides security for inrush conditions at the expense of operating speed for internal faults with CT saturation. In some relays, only the harmonic components of the operating current are used for restraining the relay. In other relays, the effect of the restraining current could become negligible. The operation of the differential relay can be expressed as shown in Equation (6):

$$|I_o| > k_1 |I_1| + k_2 |I_2| + \dots \quad (6)$$

8.2.3.1.1 Second- and fifth-harmonic restraints

A three-phase differential relay with second- and fifth-harmonic restraint is reported by Einvall and Linders [B4]. This relay uses only the second-harmonic component of the operating current to identify inrush currents (originally proposed by Sharp and Glassburn [B34]), and it uses the fifth-harmonic component of the operating current to avoid incorrect operations during overexcitation of the transformer. The relay includes a maximum current detector that produces the percentage differential restraint current, so the restraint quantity is of the form shown in Equation (4). The relay forms an additional restraint by summing the second- and fifth-harmonic components of the operating current. The basic equation for the operation of one phase of the relay can be expressed as shown in Equation (7):

$$|I_o| > s |I_R| + k_2 |I_2| + k_5 |I_5| \quad (7)$$

In some relays, the harmonic restraint is proportional to the sum of the second- and fifth-harmonic components of the three phase-elements of the relay; its operation, therefore, can be expressed as shown in Equation (8):

$$|I_o| > s |I_R| + \sum_{n=1}^3 (k_2 |I_{2n}| + k_5 |I_{5n}|) \quad (8)$$

Figure 11 shows the logic of a second- and fifth-harmonic restraint differential relay element defined by Equation (7) and a high set element for the fifth-harmonic component.

Note that in this harmonic restraint element, the operating current should overcome the combined effects of the restraining current, and the second and fifth harmonics of the operating current. As previously stated, the fifth-harmonic current is experienced when the transformer is overexcited due to excessive voltage applied to it. Excessive fifth-harmonic current can damage the transformer, and therefore many relays include a high-current setting for I_5 ; the fifth-harmonic restraint is removed if the I_5 exceeds the setting.

Common harmonic restraint or blocking increases the security of the differential relay, but it is likely to delay the relay operation for internal faults combined with inrush currents in the nonfaulted phases.

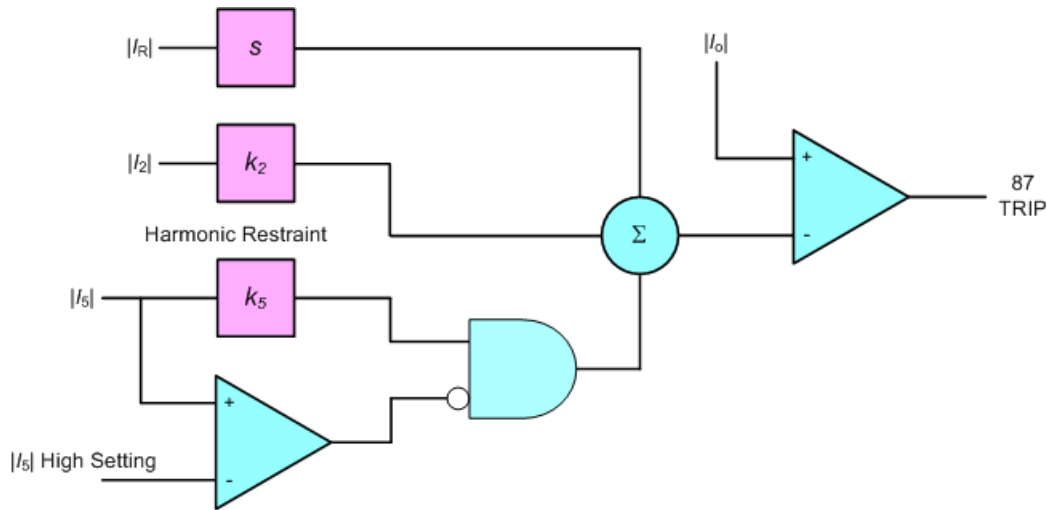


Figure 11—Second- and fifth-harmonic restraint logic of a differential element

8.2.3.1.2 Even-harmonic restraint

The use of even harmonics (second and fourth) in a restraint scheme is another method that ensures security during inrush currents that may have very low second-harmonic current. The equation that represents this differential function is shown in Equation (9):

$$|I_o| > s|I_R| + k_2|I_2| + k_4|I_4| \quad (9)$$

In contrast to the odd harmonics, which are generated by CT saturation caused by excessive alternating current (ac), even harmonics are a better indicator of magnetizing inrush. Even harmonics resulting from dc saturation of a CT are transient in nature. The use of even harmonics (and not only the second harmonic) usually provides better discrimination between inrush and internal fault currents.

8.2.3.2 Harmonic blocking

Harmonic blocking can also be used to avoid undesired tripping by the percentage differential relay due to the flow of magnetizing inrush currents when a transformer is energized. Typical methods are described in this subclause.

8.2.3.2.1 Second-harmonic blocking

In one design (see Sharp and Glassburn [B34] for more details), the relay consists of a differential unit and a harmonic unit. The operating current defined in Equation (1) is used in the differential unit. The current is rectified and applied to the operating coil of a polarized relay unit. The current applied to the restraint unit has the form of Equation (4). The polarized relay unit performs an amplitude comparison of the operating and the restraining currents and implements the percentage differential characteristic using Equation (10):

$$|I_o| > m|I_R| \quad (10)$$

The harmonic unit compares an operating signal formed by the fundamental component, plus the third- and higher-order harmonics of the operating current, with a restraint signal that is proportional to the second harmonic of the operating current. The operation of the harmonic blocking unit can be expressed by Equation (11):

$$|I_o| + k_3|I_3| + k_4|I_4| \dots > k_2|I_2| \quad (11)$$

8.2.3.2.2 Second- and fifth-harmonic blocking

Typically, numerical transformer differential relays use second- and fifth-harmonic blocking logic. The differential relay generates a trip if the condition defined by Equation (10) is satisfied and the blocking conditions defined in Equation (12) and Equation (13) are satisfied:

$$|I_o| > k_2|I_2| \quad (12)$$

$$|I_o| > k_5|I_5| \quad (13)$$

It is important to appreciate that, in this case, the operating current is independently compared with the restraint current and the second- and fifth-harmonic components of the operating current.

It is a common practice to use the fifth harmonic of the operating current to avoid the operation of the differential relay when the protected transformer experiences overexcitation. One solution may be to use a harmonic blocking scheme in which the fifth harmonic is independently compared with the operating current. In this scheme, a given relay setting, in terms of percentage of the fifth harmonic, always represents the same overexcitation condition. In a fifth-harmonic restraint scheme, a given setting may represent different overexcitation conditions, depending on the other harmonics that may be present.

8.2.3.2.3 Harmonic sharing

Harmonic sharing is a modification of the harmonic blocking technique; in this technique, the harmonic content of all three phases is summed before checking if the ratio of the fundamental frequency and harmonic components of the operating current is more than a prespecified threshold. This approach adds security in applications in which harmonic content on one or two phases is not sufficient to block the operation of the relay.

8.2.3.3 Wave shape recognition methods

Wave shape recognition techniques represent another alternative for discriminating internal faults from inrush conditions. However, these techniques fail to identify transformer overexcitation conditions as effectively as the presence of fifth harmonic does. Identification of the separation of differential current peaks represents a major group of wave shape recognition methods. Rockefeller [B26] proposed blocking relay operation if successive peaks of the differential current fail to occur at about 7.5 ms ~ 10 ms on a 60 Hz system.

8.2.3.3.1 Low-current detection method

A well-known principle recognizes the length of the time intervals during which the differential current is nearly zero (see Rockefeller et al. [B27]). Figure 12 depicts the basic concept behind this low-current detection method.

The differential current is compared with positive and negative thresholds of equal magnitudes. This comparison helps to determine the duration of the intervals during which the value of the current is less than the value of the threshold. The time intervals are then electronically compared with a threshold value equal to one-quarter cycle. For inrush currents shown in part (a) of Figure 12, the low-current intervals, t_A , are greater than one-quarter cycle, and the relay is blocked. For internal faults shown in part (b) of Figure 12, the low-current intervals, t_B , are less than one-quarter cycle, and the relay operates.

It is possible that the low-current intervals of a magnetizing inrush current may not be greater than one-quarter cycles in a specific case. If this happens, the low-current detection technique fails and remedial measures are needed to identify the situation as magnetizing inrush.

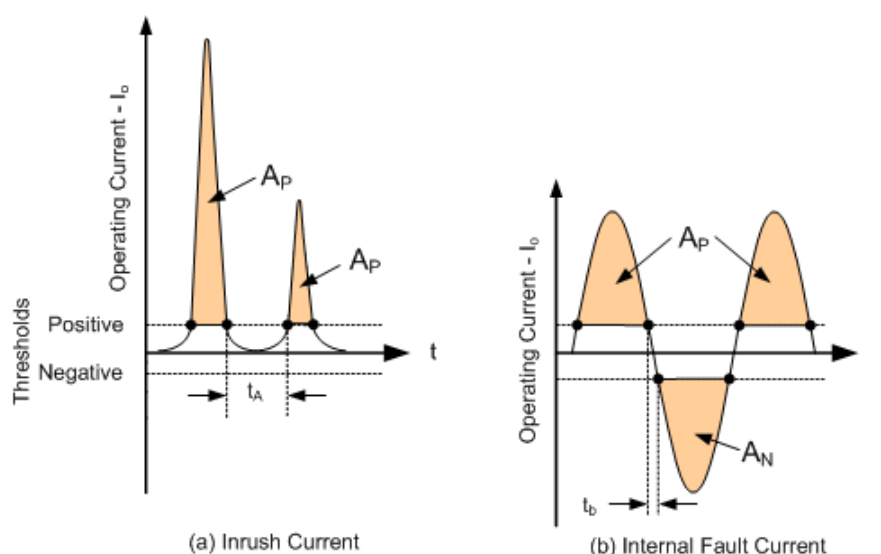


Figure 12—Differential relay blocking based on recognizing the duration of low-current intervals

8.2.3.3.2 DC blocking method

This waveform recognition method depends on the dc signal information apart from the harmonic content of the differential current. The dc component of inrush current typically has a greater time constant than that for internal faults. The presence of dc offset in the inrush current is an additional indicator that can be used to guarantee relay security during magnetizing inrush. This wave shape recognition method is relatively easy to apply in a digital relay because extraction of the dc component is a low-pass filtering process.

In the dc blocking method, the relay splits the differential current into its positive and negative half-cycles and calculates the one-cycle sums for both half-cycles. The one-cycle sum of the positive half-cycle is proportional to the area A_P shown in Figure 13, and the one-cycle sum of the negative half-cycle is proportional to the area A_N . The positive, S_P , and negative, S_N , one-cycle sums of the differential current are formed. Then the minimum and the maximum of the absolute values of the two one-cycle sums are determined, and the dc ratio, D_R , is calculated by dividing the smaller one-cycle sum value by the larger one-cycle sum value. When D_R is less than a threshold value, say 0.1, the relay issues a blocking signal. Figure 13 shows a logic diagram of the dc blocking method for a relay element.

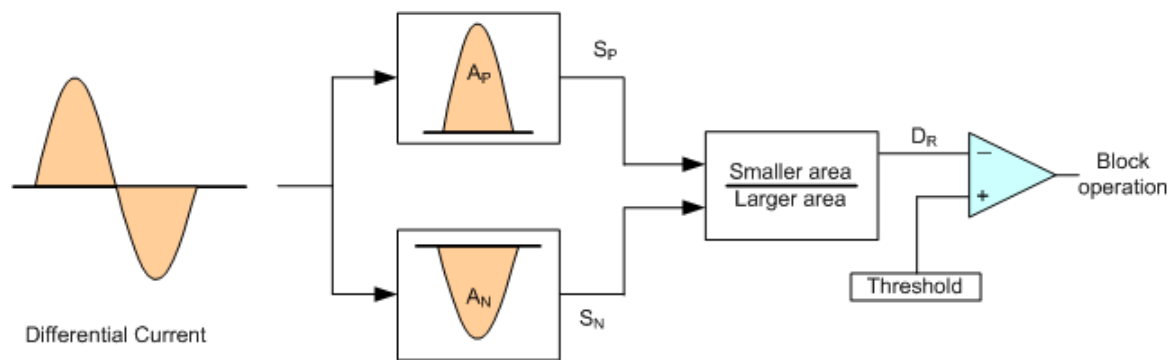


Figure 13—Logic diagram for dc blocking

8.2.3.4 Relay blocking logic

The security of harmonic restraint relays can be improved by using a time-limited, cross-blocking signal, which consists of restraining the whole unit when current in one phase is found to have sufficient harmonic content instead of requiring sufficient harmonics in all three phases. This may be desirable for transformers that have insufficient harmonics on some phases to block during inrush. However, common blocking has the downside of the possibility of delaying a trip when energizing a faulted transformer if the healthy phases sense inrush. The effect of cross-blocking can be limited to inrush by using a time limitation since harmonic blocking can also cause trip delays on internal faults with CT saturation.

Three-phase differential relays, which use independent harmonic restraint in each phase, take protective action when any of the three phase-elements operate. The three-phase differential relays, which use harmonic blocking, use two different approaches. One approach consists of using harmonic blocking in each phase-element of the relay; in these designs, the relay takes protective action when any of the phase-elements operate. The second approach is to block the operation of the three-phase relay if blocking function operates for any of the phase-elements.

Modern numerical transformer differential relays provide the user with choices to apply even-harmonic restraint or even-harmonic blocking to the fifth-harmonic and dc blocking functions. The logic, used for selecting these choices in one of the relays, is shown in Figure 14. If the even-harmonic restraint is not in use, switch S1 closes to add even-harmonic blocking to the fifth-harmonic and dc blocking functions. In this case, the differential elements operate in a blocking-only mode. Enabling or disabling of each blocking function is achieved by using switches S2, S3, S4, and S5. The output of the differential element blocking logic asserts when any one of the enabled logic inputs asserts.

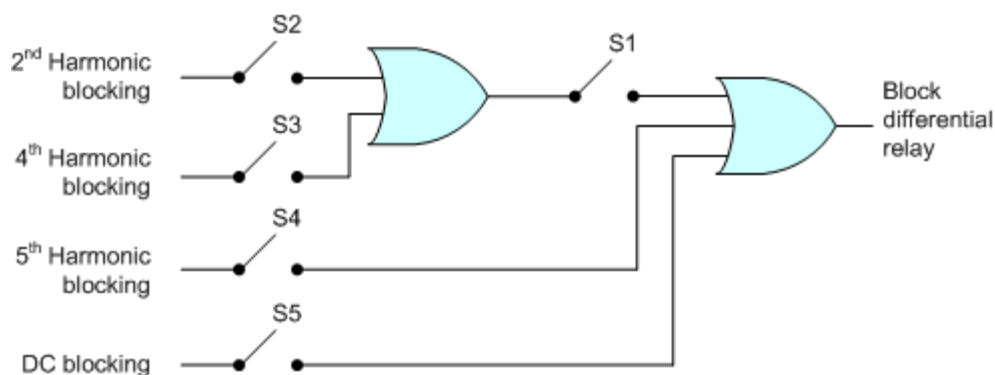


Figure 14—Example of blocking logic for a numerical differential relay

[The purpose of these designs is to provide a relay that properly restrains regardless of the amount of inrush but permits relatively high-speed operation if an internal fault occurs with or without simultaneous magnetizing inrush. Another design objective is not to have excessive restraint due to harmonic distortions of the CT secondary currents. The distortions might have occurred due to CT saturation during severe internal or external faults. To provide protection during CT saturation, modern differential harmonic restraint relays also include unrestrained instantaneous overcurrent relays that are set above the maximum expected magnetizing inrush currents but below that current that might result in CT ac saturation. The usual factory setting is eight to ten times the tap value. Refer to IEEE Std C37.110, IEEE Guide for Application of Current Transformers Used for Protective Relaying Purposes, for considerations regarding ac and dc saturation of CTs.](#)

[A consideration in the use of harmonic restraint relays is the performance during transformer overexcitation. Whether or not a differential relay will operate on exciting current due to overexcitation depends on the magnitude of exciting current, the harmonic content of the current \(predominately odd harmonics\), the shape of the waveform, and the restraint characteristic of the relay. A relay that restrains on odd harmonics \(in addition to the second harmonic present during initial inrush\) is less likely to operate under such conditions. On the other hand, transformers connected to rectifiers or variable-speed drive systems, whose currents contain relatively high levels of odd harmonics, would be better protected by the harmonic restraint relays using only the second harmonic. Relay application engineers should check the publications listed in Annex F for assistance in defining specific transformer protection objectives and hence preferred type of harmonic restraint relay characteristic.](#)

Harmonic restraint differential relays often can be justified by considering the following points:

- a) Fewer ~~investigations of~~ false trips due to inrush
- b) Faster operating time (0.01 s to 0.05 s versus 0.1 s to 0.2 s for the percentage restraint type)
- c) Lower pickup (10% to 50% of transformer rating versus 40% to 100% for the percentage restraint type)

[Occasional false trips by harmonic restraint differential relays have been observed when transformers with directly connected transmission lines were energized. Analysis of magnetizing inrush current waveforms for this configuration showed noticeable reduction in harmonic content when compared with energizing the transformer isolated from the line. The same point-on-wave closing signal was used for comparison. It was concluded that insufficient inrush harmonic content for this configuration was the cause of false trips.](#)

8.2.4 Unit generator transformer sets

On cross-compound generators, the fields may be applied while the generators are on turning gear, or at speeds of 15% to 35% of synchronous speed, depending on the design and users' preferences. Application of the fields to such machines normally excites the generator step-up and unit station service transformers and the generator so that protection is required for the [entire](#) unit system. The filter circuit of some harmonic restraint relays may block relay operation if a fault occurs before the machine is up to synchronous speed. Since relay designs vary, the relay performance at reduced frequency should be checked. [V/Hz relaying may be required to protect the transformer from damage due to overexcitation \(see 10.2.4 for further details\).](#)

8.2.5 Generator station service

Where a startup or station service transformer is connected to the high-voltage bus, high-speed fault clearing is usually required for stability reasons, even though the transformer is relatively small. The low CT ratio required for satisfactory sensitivity may result in severe CT saturation for high-side faults. If the burden is high, the high peak voltages could result in insulation breakdown and, thus, failure of the differential [relay](#) to operate. An additional CT with a high ratio, supplying an overcurrent relay, with an instantaneous unit, would then be required to back up the differential; ~~if such an instantaneous trip is not built into the differential relay~~. If high sensitivity is not required, the differential relay may be omitted.

When a unit auxiliary transformer is connected at a point between the generator and step-up transformer, a CT connection should be provided for the overall differential scheme. A connection from the overall differential to the low-side CTs of the unit auxiliary transformer avoids the saturation problem that may occur with high-side CTs. This saturation problem could prevent the operation of the unit auxiliary transformer differential relays. The overall differential thus connected provides protection for the unit auxiliary transformer, generator, and step-up transformer. It should be noted, however, that the relay sensitivity for the unit auxiliary transformer faults may be low due to the high CT ratios. If additional sensitivity is desired, time and instantaneous overcurrent relays are utilized on the high side of the auxiliary transformer.

8.2.6 Multiple-winding transformer differential protection

Differential relays for three or more winding transformers are available in the percentage differential and harmonic restraint relay types. ~~These relay types are also available to accommodate additional windings or terminals.~~ Multiple-winding transformers frequently have different capacity ratings for the individual windings. For example, a three-winding transformer may have a high-side rating of 90 MVA with the other two windings each rated at 50 MVA. The sum of the ratings of the small windings can be greater than the rating of the main (input) winding. Care should be taken in selecting CT ratios and selecting differential relay current balancing taps in electromechanical relays and ratio matching settings in numerical relays. These should be based on the through-flow of current equivalent to the largest winding rating regardless of the rating of the other winding considered. Proper restraint tap selection may be accomplished if through-~~fault-load~~ current involving only ~~the high side and one other winding~~ two windings is studied at a time.

8.2.7 Parallel transformers

A major disadvantage of using one differential relay to protect two transformers operating in parallel is the reduction in sensitivity. The CT ratios are selected on the basis of total kilovolt-ampere (kVA), and hence, the sensitivity for each transformer is less than one-half of what it would be if individual protection was provided. When a transformer is energized in parallel with an already energized transformer (see 7.4.2), the harmonic restraint unit on a differential relay protecting both transformers may not restrain. Thus, an undesired trip may occur. Therefore, each transformer should be protected by separate sets of differential relays.

8.2.8 Effect of overexcitation on differential relays

Overexcitation of a transformer could cause unnecessary operation of transformer differential relays. This situation may occur in generating plants when a unit-connected generator is separated (tripped) while exporting vars. The resulting sudden voltage rise impressed on the unit transformer windings from the loss of var load can cause a higher than nominal V/Hz condition, which causes overexcitation of the transformer. This could also occur in transmission systems when a large reactive load connected to a transformer is tripped while the primary winding remains energized.

When the primary winding of a transformer is overexcited and driven into saturation, more apparent power (voltamperes) appears to be flowing into the primary of the transformer than is flowing out of the secondary. A differential relay, with its inputs supplied by properly selected CTs to accommodate for ratio and phase shift, will perceive this as a current difference between the primary and secondary windings and, therefore, will operate. This would be an undesirable operation because there is no internal fault; the current imbalance is created from the overexcitation condition.

Three methods have been applied to prevent false transformer differential operations when overexcitation occurs. The methods would be in addition to the second harmonic or gap detection principle used for inrush detection and restraint (described in 8.2.3.1). These methods are as follows:

- Use a V/Hz relay to block the tripping of the differential relay, or to desensitize the differential relay when V/Hz reaches a certain level.

- Overexcitation manifests itself with the production of odd harmonics. As the third harmonic (and other triplens) may be effectively cancelled in delta transformer windings, the level of fifth harmonic is often used as a restraining quantity in the differential relay.
- Use of a modified differential scheme that extracts and uses the third-harmonic exciting current from the transformer delta winding to restrain the differential relay.

Instead of blocking the differential relay during an overexcitation condition (identified by the presence of the fifth-harmonic component of the differential current), the pickup setting of the differential current can be adaptively increased to prevent operation of the relay during overexcitation while disconnecting the transformer from the system if severe overexcitation occurs. The logic for this application is shown in Figure 11.

8.2.9 Differential protection of autotransformers using high-impedance relays

~~In some countries, it is common practice to~~ Some utilities provide protection for large, high-voltage and extra-high-voltage autotransformers by using voltage-operated, bus-type high-impedance differential relays. Typical connections of this protective system for autotransformers, with the neutral point of the wye winding solidly grounded, are shown in Figure 15. This arrangement provides protection for all types of phase faults and ground faults but not turn-to-turn faults. In this application, three sets of three-phase CTs are required—one set on the high-voltage side, another set on the low-voltage side, and the third set in the neutral ends of the winding. All CTs should have the same turns ratio and should be reasonably matched in accuracy class. A single high-impedance relay connected in a ground differential scheme is also applicable for autotransformer protection.

This protection is immune to the effects of magnetizing inrush current because inrush current is cancelled by the neutral CTs. Also, there is no imbalance current in the relay circuit due to the load-tap-changing equipment. Thus a high-impedance differential relay can be applied without any harmonic restraint, load bias, or time delay.

Autotransformers are often provided with a delta-tertiary winding. It should be noted that with this type of scheme no protection is afforded for faults occurring in the delta-connected tertiary winding. Where the terminals for this winding are not brought out to supply load, one corner of the delta can be connected between the end of one phase of the main winding and its neutral CT. This connection is shown in Figure 15. In such an arrangement, the tertiary winding is included in the differential protection zone and the relay would sense ground faults in the tertiary winding provided they are not close to the grounded terminal. This scheme does not provide protection for phase faults or turn-to-turn faults in the tertiary winding.

Where the tertiary winding is used to supply load, the delta winding corner connection cannot be used. Hence, separate protection is required. The tertiary winding overcurrent protection is described in 8.3.2.

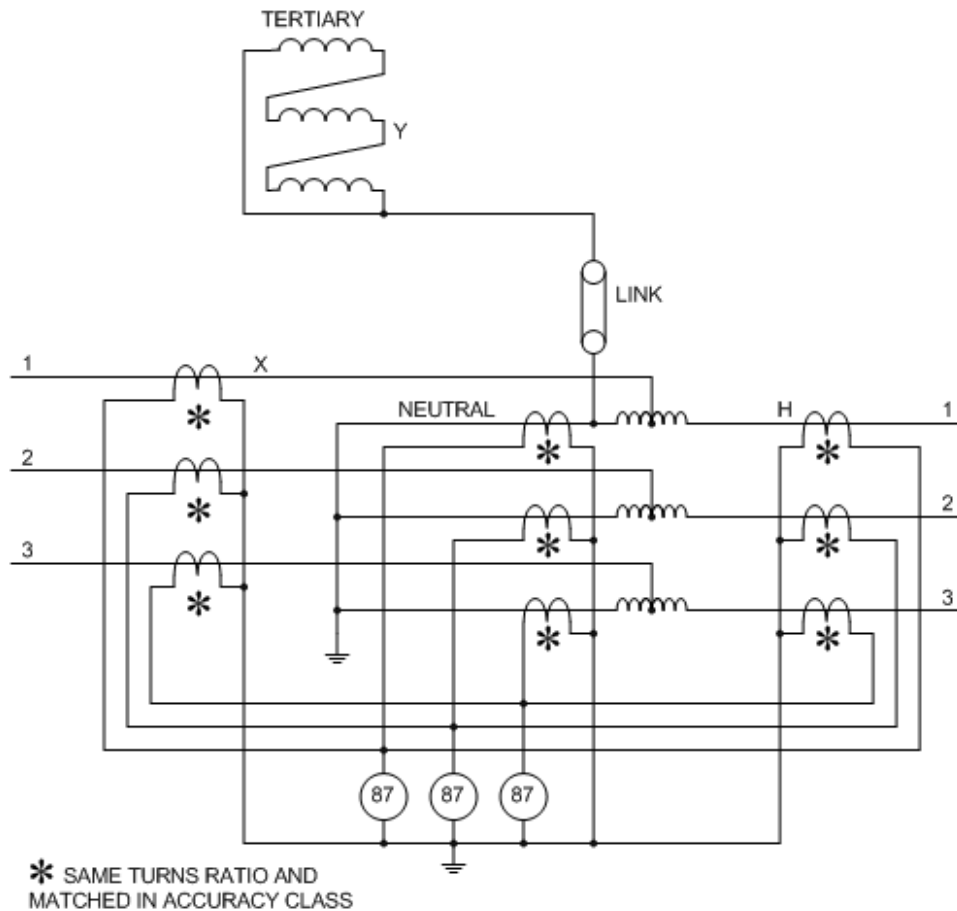


Figure 15—Typical schematic connection for high-impedance differential protection of a wye autotransformer with unloaded tertiary

8.2.10 Current-transformer requirements

The CT ratios and relay matching taps should be selected to minimize the unbalance current at the center of any applicable tap changer range. These should also be selected to avoid CT saturation during a maximum symmetrical through-fault (see IEEE Std C37.110, IEEE Guide for Application of Current Transformers Used for Protective Relaying Purposes). If saturation is likely to occur, burdens and capabilities of CTs should be matched so that all sets of CTs begin to saturate at about the same fault level. CT capability is increased and cable burden reduced by using the highest CT ratio compatible with relay taps. Cable burdens may be further reduced by using larger conductor or two conductors per phase. The risk of CT saturation may also be reduced by specifying higher “C-” ratings for the CTs at the time of purchase for initial installation or for retrofitting.

5.3.1 Phase Time Overcurrent

Time-overcurrent relays are inexpensive, simple, and reliable protective devices. Since sensitive settings and fast operation are usually not possible with overcurrent relays, they will provide limited protection for internal transformer faults. Since the pickup value of phase overcurrent relays must be high enough to take advantage of

~~the overload capabilities of the transformer and be capable of withstanding energizing inrush currents, insensitive settings result. Fast operation is not possible, since the~~

~~relays shall coordinate with load-side protection including consideration for reclosing cycles and service restoration inrush. Where time overcurrent relays are used for primary transformer protection, extensive damage to the transformer from an internal fault may occur.~~

~~Settings of phase overcurrent relays on transformers involve a compromise between the of operation and protection. The pickup setting should be high enough to permit overloading the transformer when necessary, but the higher the setting, the less the protection. A setting of 200% to 300% of the minimum nameplate rating of a transformer is common, although higher values are sometimes used. On multiple rated transformers, a higher setting may be necessary so as to utilize the full capability of the transformer at the higher forced-cooled rating.~~

~~If only overcurrent protection is applied to the high-voltage (A) side of a Δ-Y grounded transformer, it can have a problem providing sensitive fault protection for the transformer. For low-voltage (Y side) line-to-ground faults, the high-side line current will be only 58% of the low-voltage per-unit fault current. (See Fig 6 and Appendix Figs B6, B7, and B8.) When the Y is grounded through a resistor, the high-side fault current may be less than the maximum transformer load current. Similar concerns are applicable when the Y is grounded through a reactor~~

~~The time setting should coordinate with relays on downstream equipment. However, transformers are mechanically and thermally limited in their ability to withstand short-circuit current for finite periods of time. For proper backup protection, the relays should operate before the transformer is damaged by an external fault. (Refer to the Appendix for the transformer through-fault current duration limits and relay setting examples.) When setting transformer overcurrent relays, the short-time overload capability of the transformer in question should not be violated. Low values of 3.5 or less times normal base current may result from overloading rather than faults. For such cases see ANSI/IEEE C57.91-1981 [3] and ANSI/IEEE C57.92-1981 [4] since allowable time durations may be different from those in the through-fault current duration curves. Pending establishment of additional transformer standards, it is recommended that the manufacturer be consulted for the capability of a specific transformer.~~

~~Although electromechanical overcurrent relays have time-proven reliability, static (solid-state) relays with special features such as fast reset should be evaluated for these applications.~~

8.3 Overcurrent relay protection

~~A fault external to a transformer can result in damage to the transformer. If the fault is not cleared promptly, the resulting overload on the transformer can cause severe overheating and failure. Overcurrent relays (or fuses, see 5.1) may be used to clear the transformer from the faulted bus or line before the transformer is damaged. On some small transformers, overcurrent relays may also protect for internal transformer faults, and on larger transformers, overcurrent relays may be used to provide relay backup for differential or pressure relays. Thermal relays (Section 7) may also be used to protect transformers against overload. However, thermal relays often are used for alarm only. Coordination examples are included in the Appendix.~~

8.3.1 Phase instantaneous overcurrent

Fast clearing of severe internal faults may be obtained through the use of instantaneous overcurrent ~~units~~ [relays](#). Instantaneous overcurrent units, when used, When these relays are used, they should be set to pick up at a value higher than the maximum asymmetrical through-fault current. This is usually the fault current through the transformer for a low-side three-phase [short circuit](#). Instantaneous units that are subject to transient overreach, are set for pickup in the range of 125% to 200% (a 175% setting is often used) of the calculated maximum low-side three-phase symmetrical fault current. This setting generally provides sufficient margin to avoid false tripping ~~for a low-side bus fault, while still~~ providing protection for severe internal faults. For instantaneous units with negligible transient overreach, a lesser margin can be used. The settings in either case should also be above the transformer inrush current to prevent nuisance tripping. In some cases, instantaneous trip relays cannot be