



IEEE Guide for Protecting Power Transformers

IEEE Power and Energy Society

Developed by the
Power System Relaying and Control Committee

IEEE Std C37.91™-2021
(Revision of IEEE Std C37.91-2008)



STANDARDS

IEEE Guide for Protecting Power Transformers

Developed by the

Power System Relaying and Control Committee
of the
IEEE Power and Energy Society

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IEEE SA Standards Board

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Abstract: Guidelines for protecting three-phase power transformers of more than 5 MVA rated capacity and operating at voltages exceeding 10 kV is provided to protection engineers and other readers in this guide. 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 properly applying relays and other devices to protect transformers used in transmission and distribution systems is also provided. General philosophy, practical applications, and economic considerations involved in power transformer protection are discussed, with an emphasis 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, as well as associated problems, such as fault clearing and post trip reenergization.

Keywords: current transformer, differential protection, gas accumulator relay, grounding transformer, IEEE C37.91™, magnetizing inrush, overcurrent protection, power transformer, regulating transformer, sudden pressure relay, transformer overexcitation, transformer protection, volts-per-hertz protection

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Introduction

This introduction is not part of IEEE Std C37.91-2021, IEEE Guide for Protecting Power Transformers.

This document is a revision of IEEE Std C37.91-2008 and is intended to provide aid in the effective application of relays and other devices for the protection of power transformers.

In this revision, the following notable changes have been made.

- Added converter, Scott, and Le Blanc transformers to special-purpose transformers clause.
- Added information on negative sequence differential protection
- Removed information on topics that are now adequately addressed in other IEEE guides, such as phase-angle regulating transformers and transformer gas analysis.
- Removed outdated annex on transformer failure statistics.
- Corrected errors in Annex A related to through fault protection curves and their application.
- Updated information on multiple topics throughout the guide.

Contents

1. Overview	12
1.1 General	12
1.2 Scope	12
1.3 Word usage	12
1.4 Purpose	13
1.5 Device numbers	13
2. Normative references	13
3. Definitions, acronyms, and abbreviations	14
3.1 Definitions	14
3.2 Acronyms and abbreviations	15
4. Philosophy and economic considerations	15
5. Types of failures in transformers	16
6. Relay currents	17
6.1 General	17
6.2 Minimum internal faults	18
6.3 Maximum internal faults	18
6.4 Performance of CTs	18
6.5 Reasons for mismatch	20
7. Electrical detection of faults	22
7.1 General	22
7.2 Fuse protection and self-powered resettable fault interrupters	23
7.3 Differential protection	25
7.4 Overcurrent relay protection	46
7.5 Ground-fault protection	48
7.6 Fault detection for special-purpose transformers	54
7.7 Backup and external fault protection	64
7.8 Temperature relays	67
7.9 Miscellaneous relays	67
8. Mechanical detection of faults	67
8.1 General	67
8.2 Gas accumulator relay	67
8.3 Gas detector relay	67
8.4 Pressure relays	68
9. Thermal detection of abnormalities	71
9.1 General	71
9.2 Winding hot-spot measurement thermal relays	71
9.3 Calculated thermal model relays	72
9.4 Top-insulating liquid temperature protection	72
9.5 Fuses or overcurrent relays	73
9.6 Thermal relays for tank temperature	73
9.7 Overexcitation protection	73

10. Fault clearing	75
10.1 General	75
10.2 Relay tripping circuits.....	76
10.3 Circuit breakers.....	76
10.4 Tripping of remote circuit breakers	76
10.5 Circuit switcher.....	78
10.6 Fuses	79
10.7 Self-powered resettable fault interrupters	79
11. Post-trip analysis prior to re-energizing	79
12. Gas analysis	80
13. Special protective schemes	80
13.1 General	80
13.2 Grounding transformer inside the main transformer differential zone	81
13.3 Unbalanced voltage protection for wye-connected, three-legged core-type transformers.....	84
13.4 Differential protection of single-phase transformers connected in three-phase banks.....	85
14. Other considerations.....	89
Annex A (informative) Application of the transformer through-fault-current duration guide to the protection of power transformers	90
Annex B (normative) Examples of setting transformer protection relays	111
Annex C (informative) Thermal overload protection	131
Annex D (informative) Phase shift and zero-sequence compensation in differential relays	140
Annex E (informative) Bibliography.....	150

IEEE Guide for Protecting Power Transformers

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1. Overview

1.1 General

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.

1.2 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.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (shall equals is required to).^{1, 2}

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

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

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

1.4 Purpose

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

1.5 Device numbers

The device numbers used in this guide are listed in Table 1. Detailed definitions of these devices are given in IEEE Std C37.2TM,³ ~~IEEE Standard Electrical Power System Device Function Numbers and Contact Designations.~~

¹ The word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

² The word *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

³ ~~5~~ Information on references can be found in Clause 2.

Table 1 – Device numbers and device identification

Device number	Identification
24	Volts-per-hertz (V/Hz) relay
26	Apparatus thermal device
46	Reverse-phase or phase-balance current relay
49	Machine or transformer thermal relay
50	Instantaneous overcurrent relay
50N	Instantaneous neutral overcurrent relay
51	AC inverse time overcurrent relay
51G	AC inverse time ground overcurrent relay
51N	AC inverse time neutral overcurrent relay
52	AC circuit breaker
59	Overvoltage relay
60	Voltage or current balance relay
63	Pressure switch
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

(New)

Device number	Identification
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
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

(Deleted)

2. Normative references

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

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

IEEE Std C37.2™, IEEE Standard Electrical Power System Device Function Numbers, [Acronyms](#), and Contact Designations. [4](#), [5](#)

IEEE Std C57.12.00™, IEEE Standard [for](#) General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

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

[3. Definitions, acronyms, and abbreviations](#)

3.1 Definitions

For the purposes of this [document](#) ~~guide~~, the following terms and definitions apply. The ~~Authoritative Dictionary of IEEE Standards~~ [Dictionary Online](#) ~~Terms [B11]~~⁴ should be [consulted](#) ~~referenced~~ for terms not defined in this clause. ~~6 Definitions of several terms used in this guide are provided in IEEE Std C37.100.~~⁵

differential current: [The sum of all currents entering and leaving a section of the electrical system; measured with consistent polarity. Also referred to as an operating current. See: restraining current.](#)

digital relay: [A static relay or relay unit in which the designed response is developed by converting the inputs into numeric form and manipulating them mathematically or logically.](#)

⁴ ¹ IEEE publications are available from The Institute of Electrical and Electronics Engineers, ~~445 Hoes Lane, Piscataway, NJ 08854, USA~~ (<http://standards.ieee.org/>).

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⁶ [IEEE Standards Dictionary Online](#) is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

harmonic sharing: A modification of the general harmonic blocking technique for preventing misoperations of a transformer differential relay during inrush; where the magnitude of the harmonic content of the operating currents in all three phases is summed before it is compared in ratio with that of the fundamental current in each phase element. Operation is blocked if the ratio exceeds a prespecified threshold. ~~The principle of summing the magnitudes of the harmonic contents of a the three operating currents in 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.~~

microprocessor-based relay: A relay in which the designed response is developed by using one or more microprocessors. *See:* **digital relay**.

protective relay: A relay whose function is to detect defective lines or apparatus or other power system conditions of an abnormal or dangerous nature and to initiate appropriate control circuit action.

NOTE—A protective relay may be classified according to its operating principle or performance characteristics.⁷

restraining current: A current in a low-impedance differential relay which is derived from all currents of the differential zone to make the differential function more secure when current transformers are saturated due to external faults. It is used in conjunction with a percentage differential characteristic to desensitize the effect of the differential current and reflects the severity of external faults. *See:* **differential current**.

~~The term “restricted earth~~ **fault protection:** ~~” is an expression referring to~~ A sensitive ground relay system that is designed to detect ground faults in ~~within~~ a well-defined protective zone ~~(similar to Figure-17).~~

⁷ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

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.

3.2 Acronyms and abbreviations

ac alternating current

CT current transformer

dc direct current

DETC de-energized tap changer

GIC geomagnetic induced currents

HSGS high-speed ground switch

KCL Kirchhoff's Current Law

MOD motor-operated disconnect

OLTC on-load tap changer

REF restricted earth fault

rms root-mean-square

RTD resistance temperature detector

SPR Sudden-Pressure Relay

V/Hz volts per hertz

WTI winding temperature indicator

4. Philosophy and economic considerations

Protective relays are applied to elements of a power system for the following ~~several~~ reasons, among others. ~~Some of the reasons are as follows:~~

- To 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.
- To minimize the possibility of fire.
- To minimize hazards to personnel.
- To minimize the risk of damage to adjacent ~~high-voltage~~ apparatus.
- To prevent damage due to abnormal operating conditions.

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 secondary benefit. With transformers, however, the ~~excessive high~~ cost of repair or replacement, as well as ~~and~~ the possibility of a violent failure or fire involving adjacent equipment, may make limiting the damage a major objective. ~~Because~~ Since sensitive, high-speed protection systems can reduce damage, and consequently reduce repair cost, the protection aspects of relays are important considerations ~~should be considered carefully~~ when protecting transformers, particularly those of larger sizes.

Faults internal to the transformer quite often involve only 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.

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. A reasonable ~~The selected~~ plan balances ~~should balance~~ the best combination of these factors against the overall economics of the situation while minimizing the following factors:

- Cost of repairing damage
- Cost of lost production
- Adverse effects on the balance of the system
- Spread of damage to adjacent equipment
- Duration of unavailability of the damaged equipment

In protecting transformers, backup protection is an important consideration ~~needs to be considered~~. The failure of a relay or circuit 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 relays are set to operate. Part of the evaluation of the type of protection applied to a transformer includes ~~should include~~ how the system integrity would be affected by such a 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 protection engineering.

The major economic consideration ordinarily includes both the fault detection equipment and isolation devices. Circuit breakers often cannot be justified based ~~on the basis of~~ transformer protection alone. At least as much weight is ~~should be~~ given to the service requirements, the operating philosophy, and the system design philosophy. Evaluations of the risks involved and the cost effectiveness of the protection are necessary. ~~Further discussion on this subject is provided by Elmore [B5], McNutt et al. [B19], Sterner [B36], and Warrington [B41].~~

5. Types of failures in transformers

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

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

These different 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. Canadian and international ~~The~~ failure statistics have been collected by the Canadian Electrical Association [B32] and CIGRE [B21], ~~respectively are briefly reported in Annex B.~~⁸

This guide primarily addresses the application of electrical relays to detect fault currents that result from an insulation failure. Clause 6 ~~7~~ examines the current a relay can expect to see due to several ~~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:

- a) Monitoring devices ~~Temperature monitors~~ for winding and/or insulating liquid ~~oil~~ temperature are typically used to initiate an alarm requiring investigation by maintenance personnel ~~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.

⁸~~4~~ The numbers in brackets correspond to those of the bibliography in Annex E ~~F~~.

- b) Gas detection relays can detect the evolution of gases within the transformer insulating liquid ~~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 insulating liquid ~~oil~~ that are collected periodically. ~~A~~ Continuous gas analyzers are ~~analyzer is~~ available to allow online detection of insulation system degradation.
- c) Sudden-pressure relays located on the transformer tank below the insulating liquid level ~~under oil~~ respond to the pressure waves in the transformer insulating liquid ~~oil~~ caused by internal ~~the evolution of gas associated with~~ arcing.
- d) Sudden-pressure relays located on the transformer tank above the insulating liquid level ~~in the gas space~~ respond to sudden changes in ~~the~~ gas pressure due to the arcing in the insulating liquid ~~evolving gases from an arc under oil~~.
- e) Liquid ~~Oil~~ level detectors sense the insulating liquid ~~oil~~ level in the tank and are used to generate an alarm indicating minor reductions ~~in oil level~~ and trip for severe reductions in the liquid level.
- f) 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 can be ~~is~~ avoided. Details of ~~the modern~~ techniques for monitoring these components are given by Coffeen et al. [B23 ~~B3~~].

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

6. Relay currents

6.1 General

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.

6.2 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. For example, as much as 10% of the winding may have to be shorted to cause full-load terminal current to flow. Therefore, a single turn-to-turn fault results ~~will result~~ in an undetectable change of current at the transformer terminals. If the turn-to-turn fault is not quickly detected, it can escalate into a more serious ground fault involving the iron core and result in costly repairs.

6.3 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. A well-designed ~~The~~ relay system is ~~should be~~ capable of withstanding the secondary current of the CTs on a short-time basis. This may be a factor if the rated transformer load current is small relative to the system fault current and the CT ratio is chosen to match the transformer rating.

6.4 Performance of CTs ~~current transformers~~

6.4.1 Internal faults

During an internal fault, or a fault external to the transformer but in the protected zone of the relay system, one or more CTs may saturate. Severe CT saturation can cause a harmonic blocking element ~~restraint unit~~ to pick up or cause harmonic restraint to desensitize ~~thereby resulting in~~ the relay. As a result, ~~failure of~~ a transformer differential relay may fail to operate or ~~causing a delay in~~ its operation may be delayed. The effect depends on the relay's response to distorted currents. The direct current (dc) offset of fault current can cause CTs to go into saturation and then recover once the dc transient decays and the current waveform becomes symmetrical. This is called asymmetrical saturation. If a CT is severely underrated, it can experience saturation regardless of the presence of a dc transient. This is called symmetrical saturation. On a transient basis, second and third harmonics predominate initially when a CT saturates due to asymmetrical saturation. Even-numbered harmonics are also a characteristic of inrush current, and even-numbered harmonic restraint or blocking techniques can cause the loss of dependability during asymmetrical saturation. Ultimately, the even-numbered harmonics disappear with the decay of the offset ~~direct current (dc)~~ component of the short-circuit current. Whether ~~or not~~ the odd-numbered harmonics disappear depends on whether characteristic of the CT experiences symmetrical ~~the steady-state~~ saturation. The ratings of the CTs are normally ~~should be~~ selected to avoid symmetrical steady-state ~~saturation for internal faults and limit asymmetrical saturation as much as practical for through-faults. For severe internal faults, a high-set unrestrained element is often relied upon to provide dependability when asymmetrical saturation cannot be completely avoided.~~

6.4.2 External faults

Figure 1 shows three scenarios of external faults. The scenario in ~~part of~~ Figure 1(a) shows a transformer that is connected to single bus arrangements on the source and load sides and an external fault at location F1. In this scenario, the fault currents flow through the transformer. The scenario in ~~part of~~ Figure 1(b) 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 F1. 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™ [\[B67\]](#), ~~IEEE Guide for Application of Current Transformers Used for Protective Relaying Purposes.~~

The scenario in ~~part of~~ Figure 1(c) is the same as the scenario in ~~part of~~ Figure 1(b) except that the fault is at location F2. 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 [on CTs](#), ~~“Transient Response of Current Transformers”~~ [\[B53 B12\]](#).) 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, [the relays are](#) ~~they should be~~ applied with a restraint element in each CT circuit. Also, the burden of each CT secondary circuit [is checked to verify that the burden is](#) ~~must not be too~~ so high that [the permissible](#) 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.

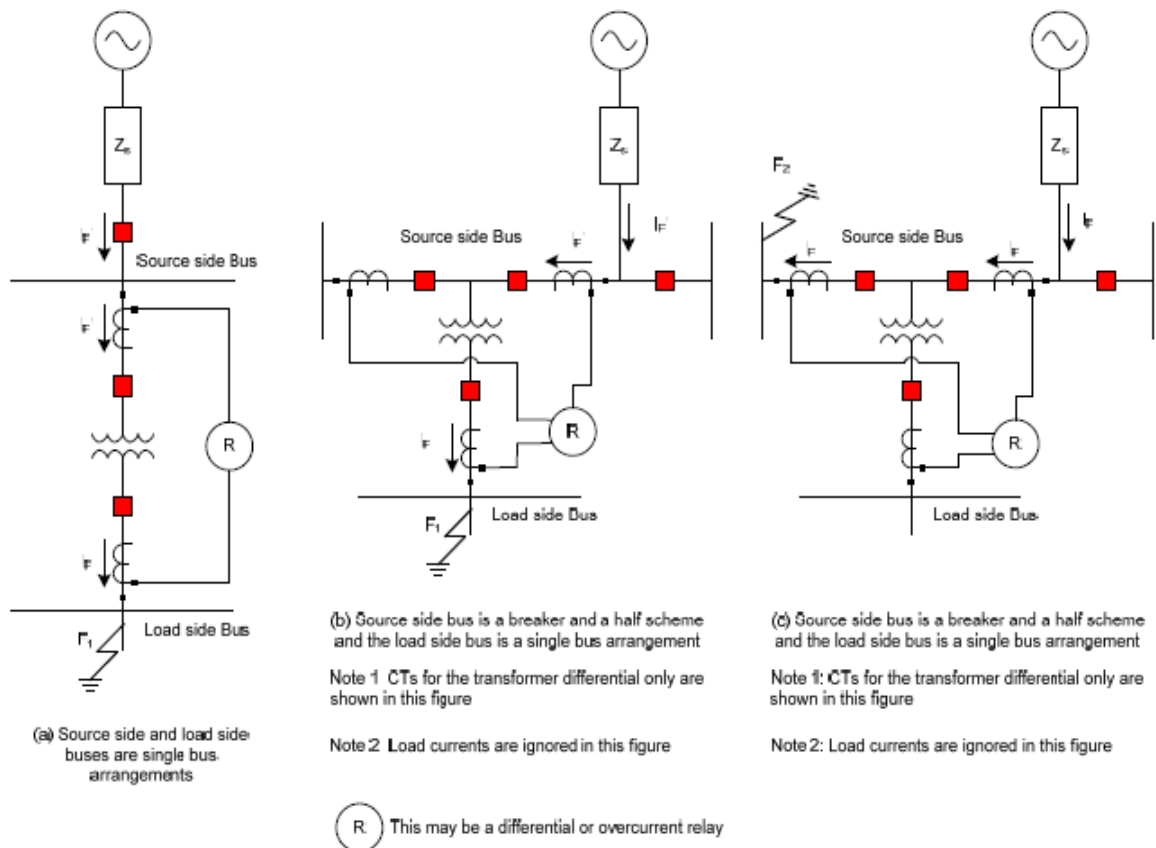


Figure 1—Three external fault scenarios

6.4.3 CT 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 ([e.g., delta connected CTs have an effective burden of three times the one-way lead resistance for three-phase faults as discussed in IEEE Std C37.110 \[B67\]](#)) 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 [\[B67\]](#), [IEEE Guide for Application of Current Transformers Used for Protective Relaying Purposes](#).

Capabilities of the relay will impact the ~~Before a~~ decision ~~on how is taken as~~ to ~~connect the manner~~ in which the CTs. ~~Many should be connected, capabilities of the relay should be evaluated.~~ Some differential relays can internally accommodate the phase shift of the transformer ~~and allow~~, allowing the engineer to choose CT connections that suit other devices connected to the same CTs. ~~Some Many~~ relays do not have this versatility; ~~and~~ in those cases, the CTs ~~are must be~~ connected to ~~compensate for create~~ the same phase shift ~~as the~~ transformer windings ~~created 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. ~~For proper phase shift, CAUTION~~ the delta connection of the CTs ~~is made to 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 ~~address 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 ~~address 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 ~~circuit windings of the CTs~~. The result is that the differential relays do not see the mismatch due to the flow of zero-sequence currents.

6.5 Reasons for mismatch

6.5.1 General

There are [non-fault](#) ~~nonfault~~ related currents or factors that may require compensation to prevent undesirable operation of differential relays. Subclauses [6.5.2](#) ~~7.4.1, 7.4.2~~, [6.5.3](#), and [6.5.4](#) ~~7.4.3~~ include a discussion of some of those situations.

6.5.2 Unbalance caused by [CT](#) ~~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 [an on-](#) ~~a~~ load tap changer ([OLTC](#) ~~LTC~~), the possible mismatch is increased further. [If a tap on a de-energized tap changer \(DETC\) is changed and the relay settings are not updated accordingly, the possible mismatch is also increased.](#) During a through-fault condition, the differential operating current due to mismatch can be very large.

6.5.3 Magnetizing inrush

[Magnetizing inrush](#) ~~This~~ is a phenomenon that causes the violation of the basic principle of differential relaying. 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 produced by magnetizing inrush can reach many times the transformer rating, and these currents appear in the differential relay. The inrush current duration can range from a few cycles to many seconds. Explanations of this phenomenon are given by Lin et al. [[B97](#) ~~B17~~] and Rockefeller et al. [[B121](#) ~~B27~~].

Although usually considered only in conjunction with the energizing of a transformer, magnetizing inrush current can be caused by any abrupt change of 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. [B121 B27]. One condition involves the energizing of a transformer at a station at which at least one other transformer is already energized (see Hayward [B46 B9]). The inrush phenomenon involves transformers that are already energized as well as the transformer being energized (see Lin et al. [B97 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~~ element of a differential relay, if it is protecting both parallel-connected transformers, will not operate. 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:

- a) 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).~~
- b) 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.

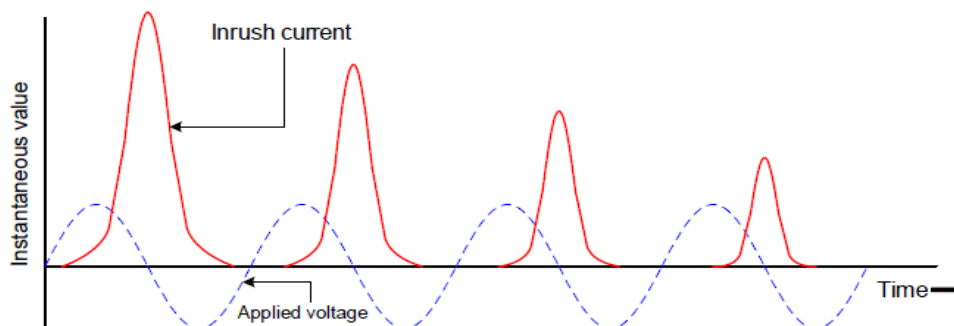


Figure 2—Typical magnetizing inrush current waveform

The harmonic content of the inrush current depends on [several](#) ~~various~~ factors, such as [remnant](#) ~~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. [[B97](#) ~~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.

6.5.4 Magnetizing current during overexcitation

A number of phenomena can subject a transformer to overexcitation, possibly coupled with substantial overvoltage at nominal frequency. At startup or shutdown of unit connected generators, the machine is brought up to speed and voltage prior to synchronizing to the system . If care is not taken the V/Hz rating of the step-up transformer may be exceeded. During static start, pumped hydro starting and rotor warming operations, the field can be applied at very low frequencies. Other overexcitation events at power plants include excitation system runaway, manual excitation control error, and sudden loss of load that may also involve overvoltage well above nominal.

In the transmission system a number of voltage and reactive support control failures can create overexcitation at nominal frequency with possibly substantial overvoltage. These are as follows:

- Capacitor banks on when they should be off
- Shunt reactor compensation off when it should be on
- Single-end breaker trip failures resulting in voltage rise at the open end of a long line (Ferranti Effect)
- Runaway load tap changers

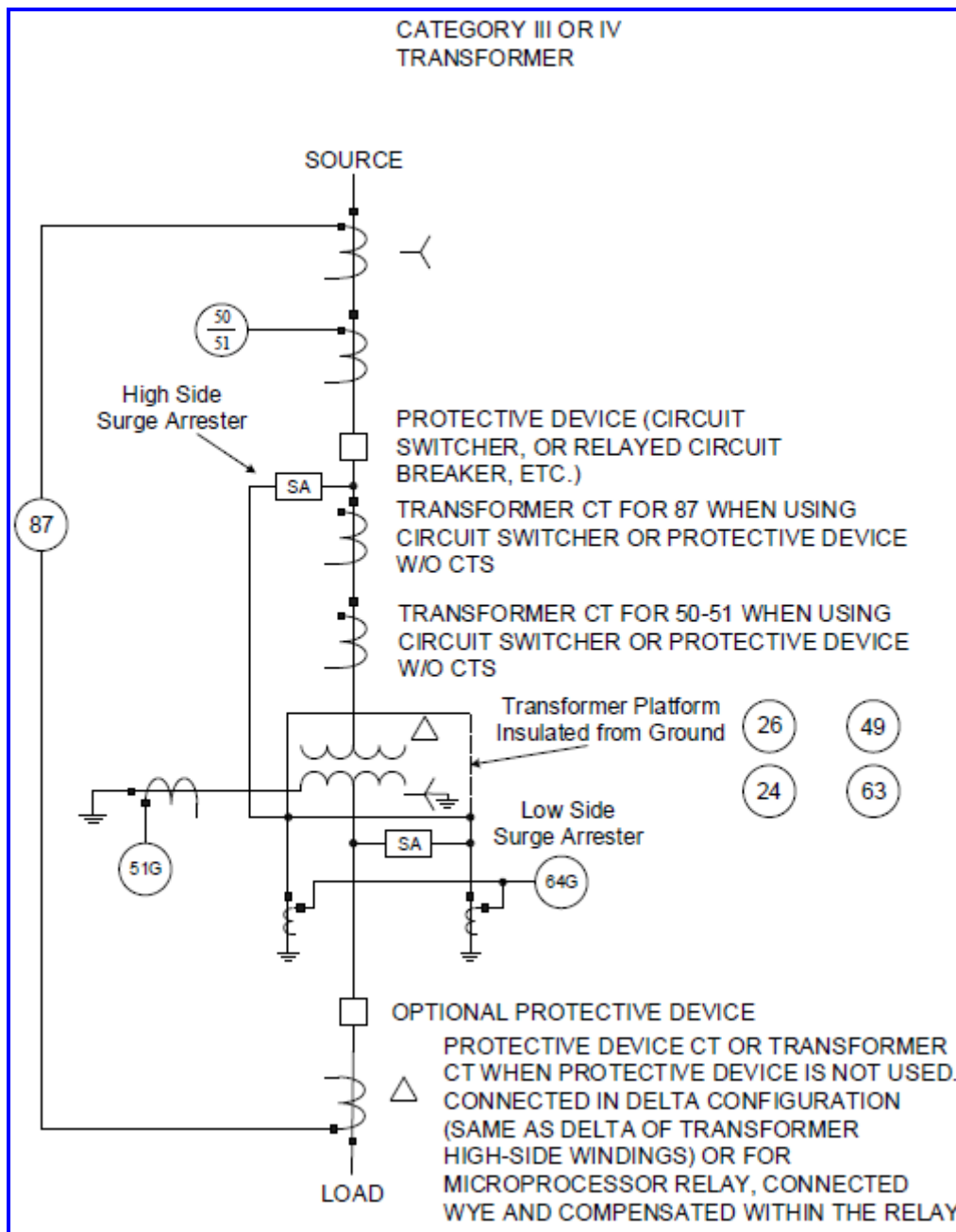
~~Sudden loss of load can subject a generator step-up transformer to substantial overvoltage. This can also occur during startup or shutdown of a generator if the generator is excited to nominal voltage while its speed is less than the specified normal value (an overexcitation condition). If transformer saturation occurs, substantial exciting current flows and will flow, which may overheat the transformer core, tank, or structure and damage the transformer. The waveform is will be distorted; it has will have harmonic content and near zero-current periods. With overexcitation, 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 only odd harmonics are present, with no appreciable even harmonics that appear during inrush. So the presence of third and fifth harmonics is a signature of overexcitation second harmonic is present.~~ The extent of these effects depends on the generator connections and the transformer design and connections. The third harmonic content of the relay current, but not the fifth is also altered by delta connections of CTs. The third Fifth harmonic (and other triplens) may blocking of tripping should be effectively canceled in delta transformer windings used to avoid tripping during overexcitation. A V/Hz relay is required if tripping is desired.

For information on how the fifth-harmonic is used in differential relay applications to avoid undesired operations due to overexcitation, see 7.3.4.2.2 and 7.3.4.3.2. Protection for excessive volts per hertz (V/Hz) in accordance with the transformer manufacturers' specifications is covered in 9.7.

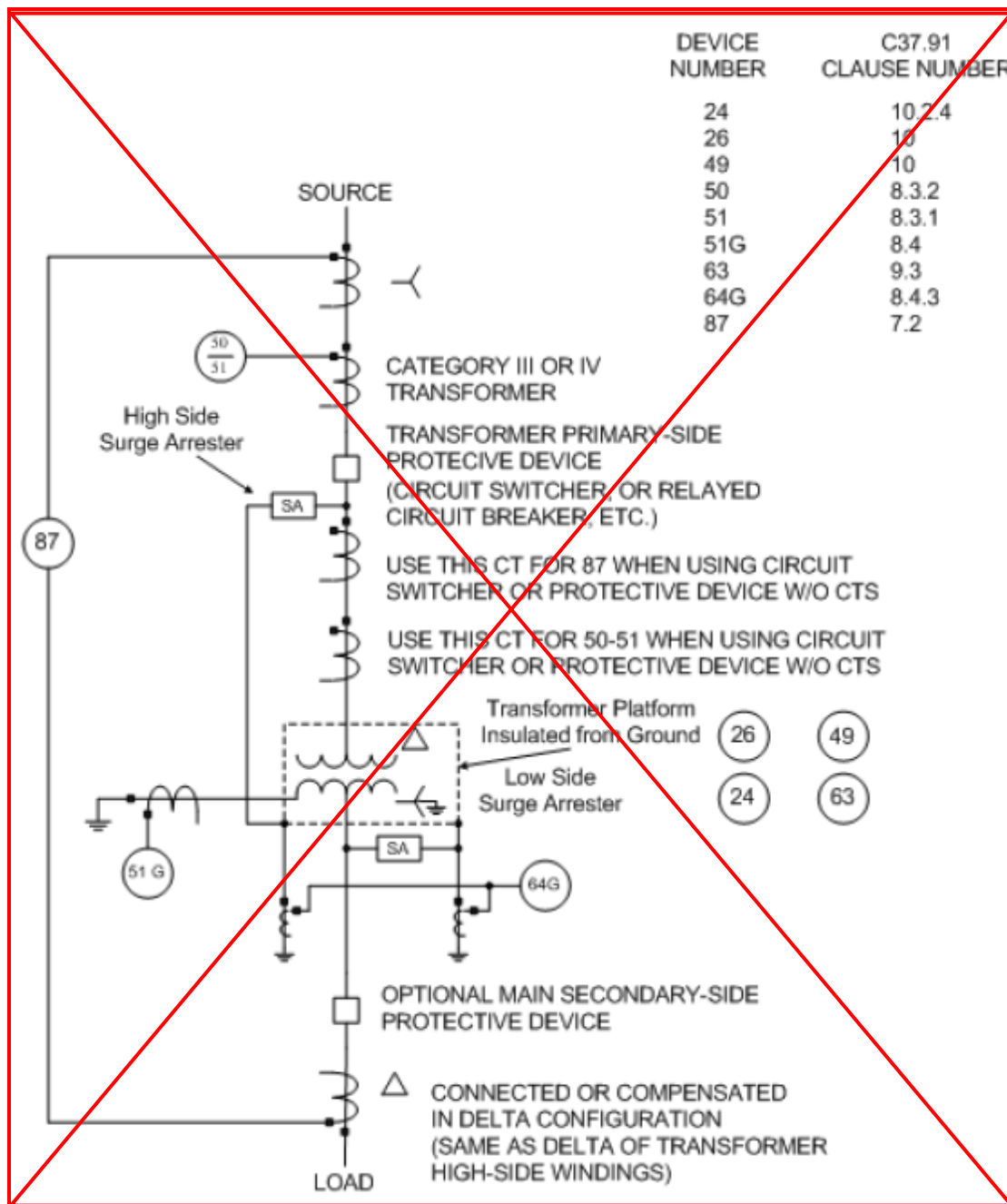
7. Electrical detection of faults

7.1 General

Fuses are commonly used to provide [protection](#) ~~fault-detection~~ for transformers with minimum nameplate ratings of up to 5 000 kVA, three-phase (Category I and Category II). Transformers 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 protected by either 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.



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Figure 3—Protection of a delta-wye transformer

7.2 Fuse protection and self-powered resettable fault interrupters

Fuses have the merits of being economical and ~~requiring~~ ~~require~~ little maintenance. Battery ~~supplies~~ ~~supply~~ and ~~a~~-relay ~~enclosure buildings~~ ~~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 ~~with~~ ratings of 10 MVA and higher. Fuses have been used at higher transformer ratings depending on the 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 ~~have~~ three-phase tripping capability. Like fuses, self-powered fault interrupters are economical and require little maintenance. A battery supply ~~is 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 ~~does will~~ not necessarily de-energize the fault. If the fault is not de-energized, the resulting single-phase service may be detrimental to the connected polyphase motors and other loads. If required, special protection ~~can should~~ be added for detecting and protecting from single-phasing conditions.

A typical transformer that exhibits this protection ~~issue 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 ~~operates will-operate~~ first ~~and leaves 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 ~~persists will-persist~~ until the second fuse opens. [See Jensen \[B85\] for more in-depth discussion of issues related to fuse protection of power transformers.](#)

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

(New)

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

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The selection of the [source side](#) fuse and proper current rating [involves considering](#) ~~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 [several](#) ~~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 [include](#) ~~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.~~

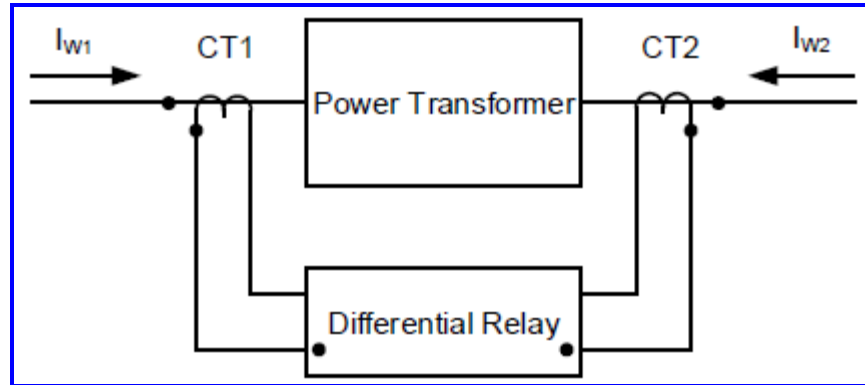
7.3 Differential protection

7.3.1 General

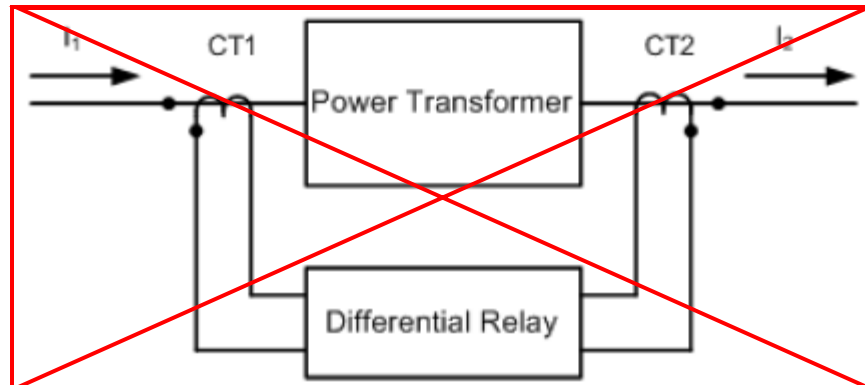
While fuse protection is a simple and minimal-cost approach, many advantages are realized with differential protection (see Blackburn [B15 B2], Elmore [B29 B5], and Hayward [B46 B9]). These advantages include the following:

- Differential protection provides faster detection of faults that can reduce damage due to the flow of fault currents.
- The location of the fault is determined more precisely depending on the “size” of the protection zone (e.g., transformer only, transformer [and](#) + bus, transformer [and](#) + bus [and](#) + feeder breakers~~, etc.~~).
- Accurate fault location allows the application of automation techniques, such as rapid isolation of faulted components, and restoring load.
- 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 [on protecting](#) ~~“Protection of~~ power transformers” [B55 B14]). Figure 4 shows a typical differential relay connection diagram for a single~~-~~phase transformer of ratio 1:1.



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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_{op} , which is the difference between the current entering one winding and the current leaving the other winding, can be [represented as the sum of the currents entering both windings as](#) expressed [as](#) in Equation (1):

$$I_{op} = I_{w1} - I_{w2} \quad (1)$$

where

I_{op} is the operating current

I_{w1} is the current [in the primary winding of](#) ~~entering~~ the transformer

I_{w2} is the current [in the secondary winding of](#) ~~leaving~~ the transformer

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

- Time overcurrent relays with or without an instantaneous trip unit
- Percentage differential relays with restraint actuated by the currents going into and out of the protection zone
- 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 is considered ~~should be taken into account~~ and CT connections and ratios are selected ~~must be~~ such that the net current in the relay operating coil for any external fault is effectively zero, unless matching or scaling current taps are available in the relay. 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 is ~~usually should be~~ avoided for the most effective restraint action.

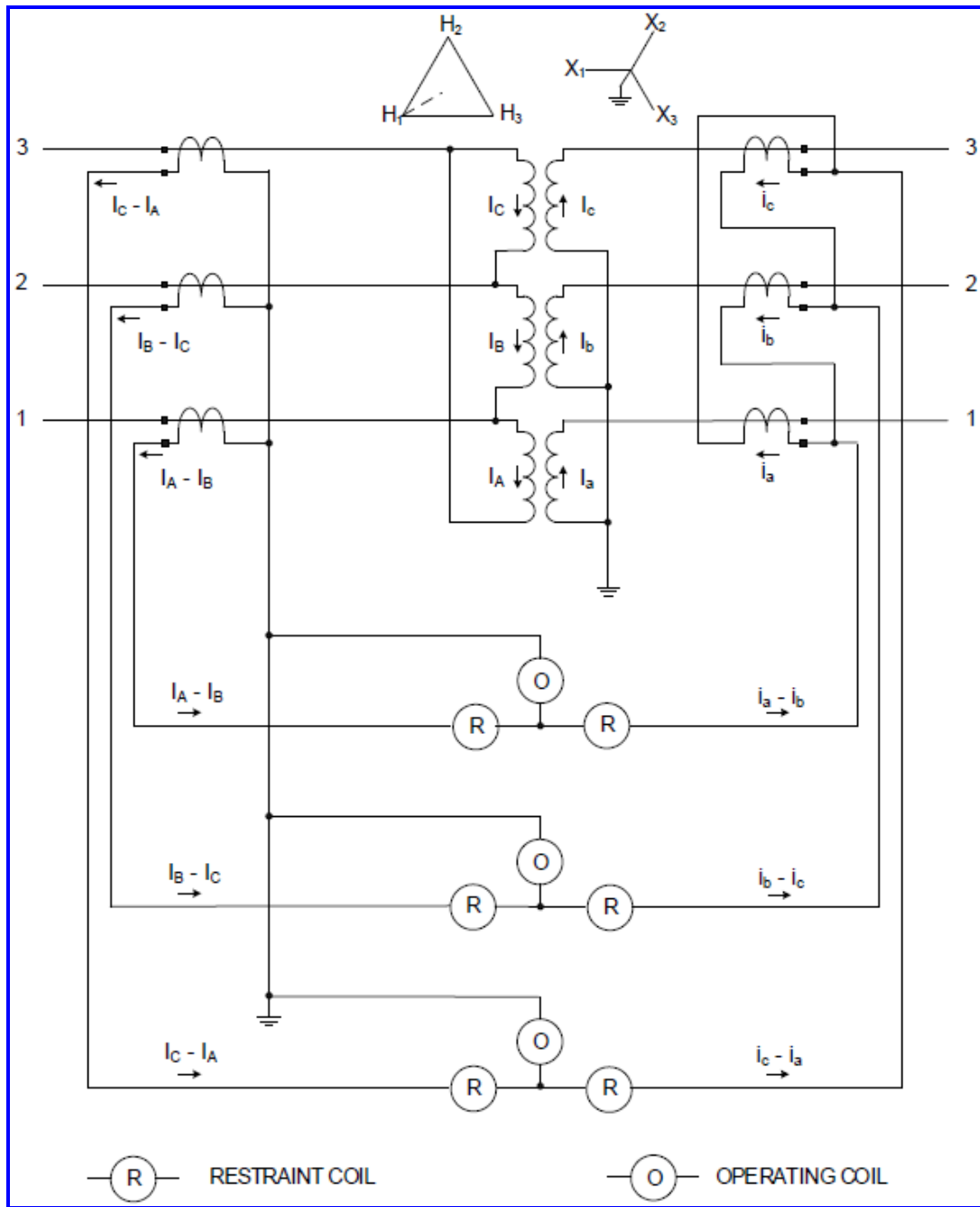
The arrangements ~~arrangement~~ shown in Figure 5, Figure 6, Figure 7, and Figure 8 are typical CT connections when electromechanical relays and some types of solid-state relays are used for differential protection. In these types of applications, when configurations such as delta-wye transformations are used, care is needed ~~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. Proper grounding of the secondary circuits of CTs is ~~should be grounded as~~ explained and discussed in IEEE Std C57.13.3TM [B76], ~~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.

On the other hand, for microprocessor-based relays and some types of solid-state relays, all CTs are connected in wye as shown in Figure 9. The phase compensations are done by the software or circuit board jumpers (for analog relays) in the relay. The magnitude compensation in microprocessor-based ~~numerical~~ relays is also done in the relay. Each set of CTs in this case is provided with a separate ground. Because the inputs to the relay are from wye-connected CTs, the inputs can be used for other protection functions, such as overcurrent and ground overcurrent protection.

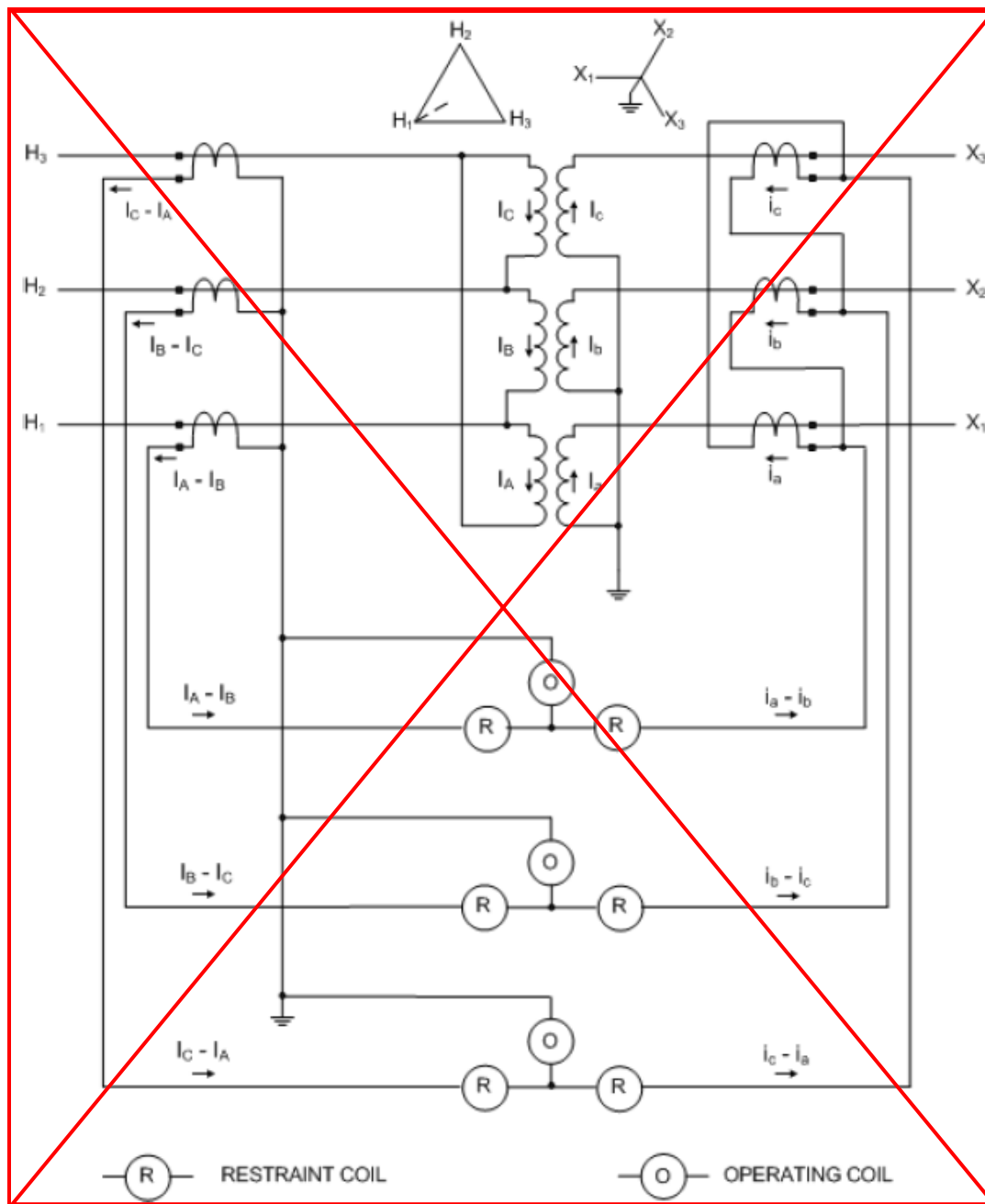
Differential protection of transformers and its implementation in [microprocessor-based numerical](#) relays ~~are~~ [is](#) discussed in several books and published papers, [e.g.](#), ~~;-some-of-these-are~~ Guzmán et al. [B41 B7] [and](#) [B42 B8], Murty and Smolinski [B108 B20], Murty et al. [B109 B21], Phadke and Thorp [B112 B22] [and](#) [B113 B23], Sachdev [B122 B28], [B123 B29], [and](#) [B124 B30], Sachdev and Nagpal [B125 B31], Sachdev and Shah [B126 B32], Sachdev et al. [B127 B33], Sidhu et al. [B134 B35], Thorp and Phadke [B147 B38], and Ziegler [B159 B42].

The issue of testing the differential circuits is not included in this guide; [it](#) ~~-This~~ is discussed in detail in IEEE Std C37.103TM [B65], ~~IEEE Guide for Differential and Polarizing Relay Circuit Testing~~.

If [circuit](#) breaker CTs are used for input to the transformer differential, bypassing the [circuit](#) breaker ~~affects~~ ~~will-affect~~ the inputs for the differential relays. ~~If Assuming-that~~ the differential relay is removed from service and ~~there-are~~ other relay schemes [are](#) protecting the transformer, care [is](#) [needed](#) ~~so 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 [is not normally bypassed because a fault in the protected zone may](#) ~~should~~ not be [removed properly](#) ~~bypassed~~.

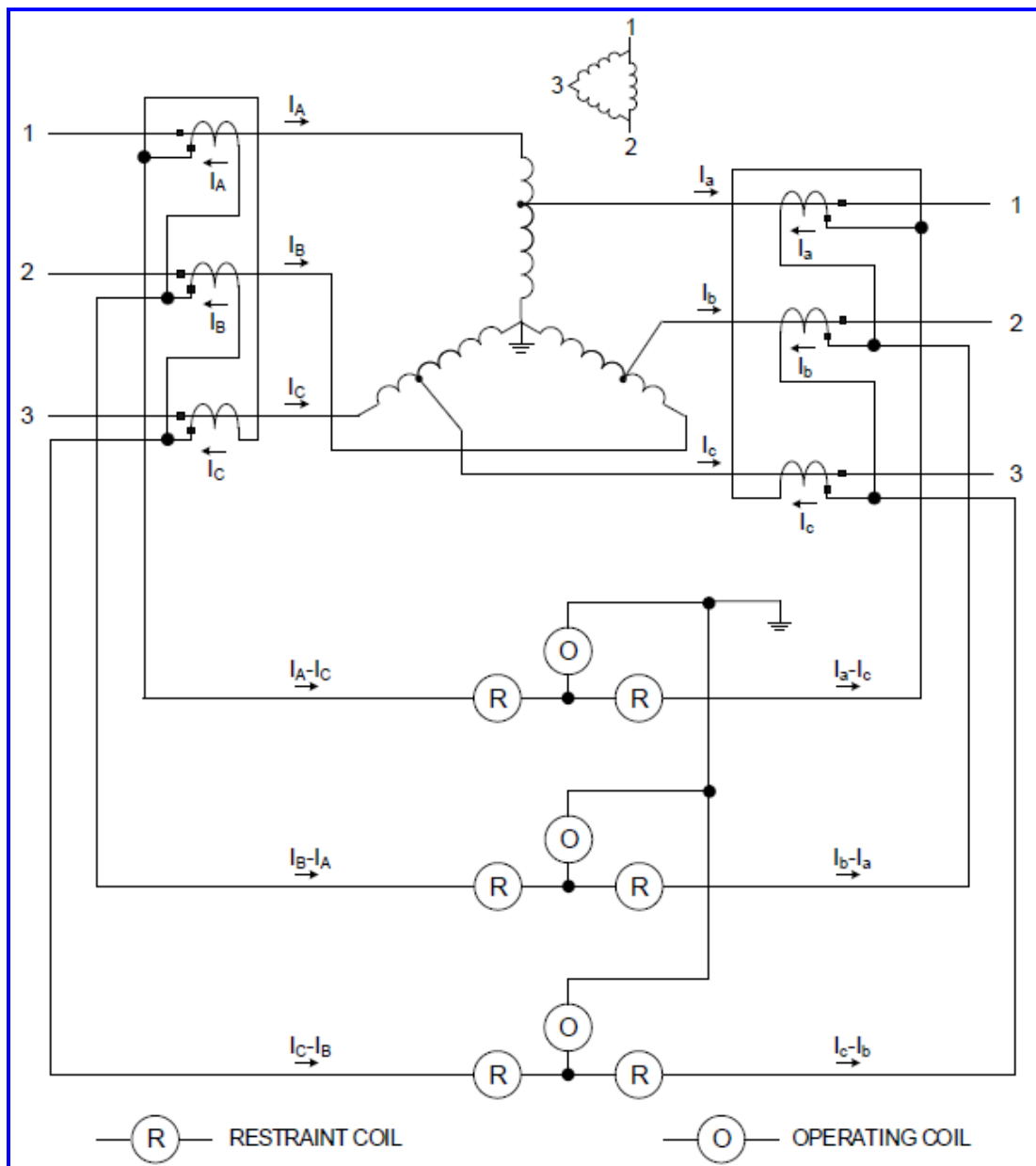


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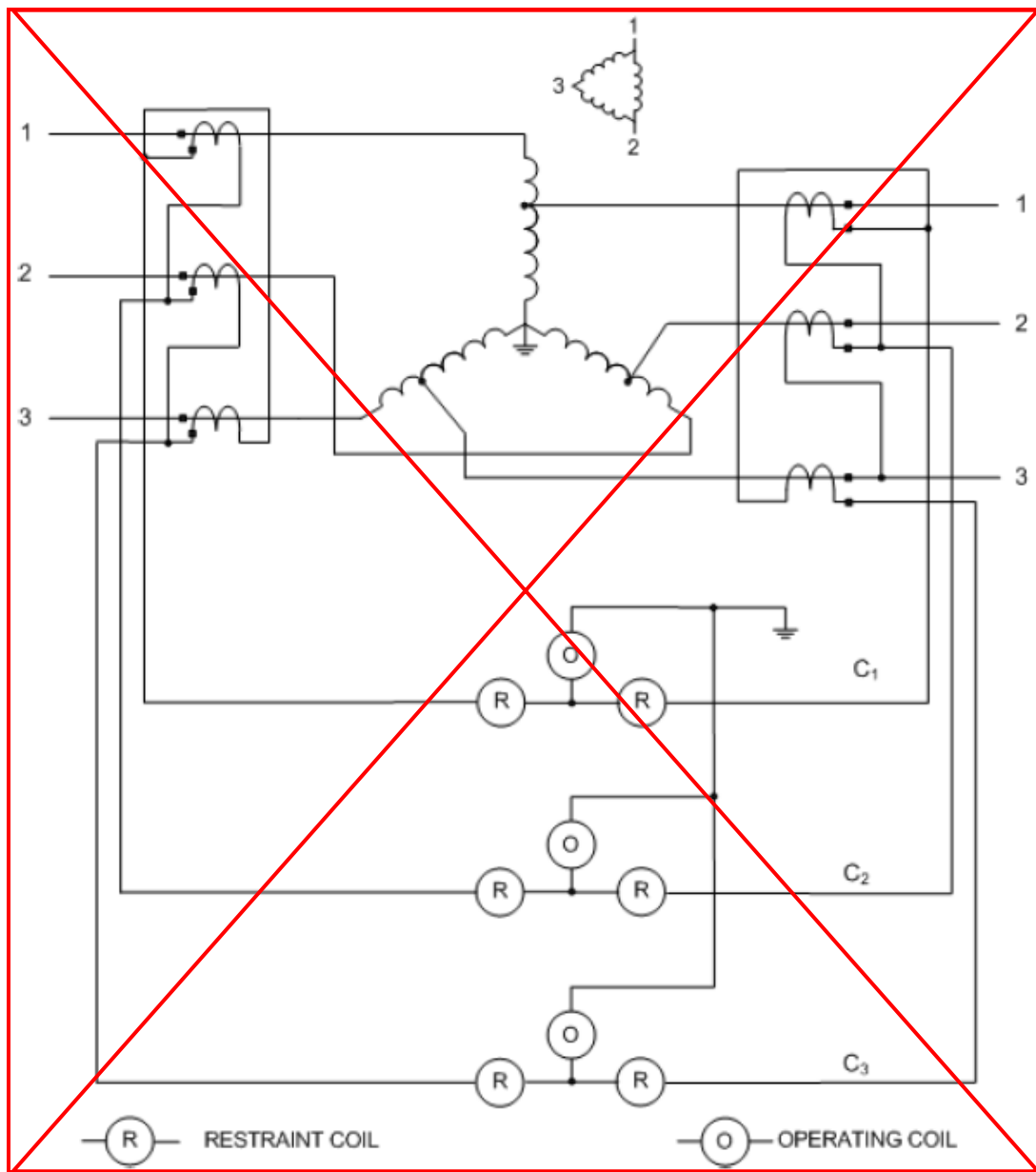


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Figure 5—Typical schematic connections for percentage differential protection of a delta-wye transformer

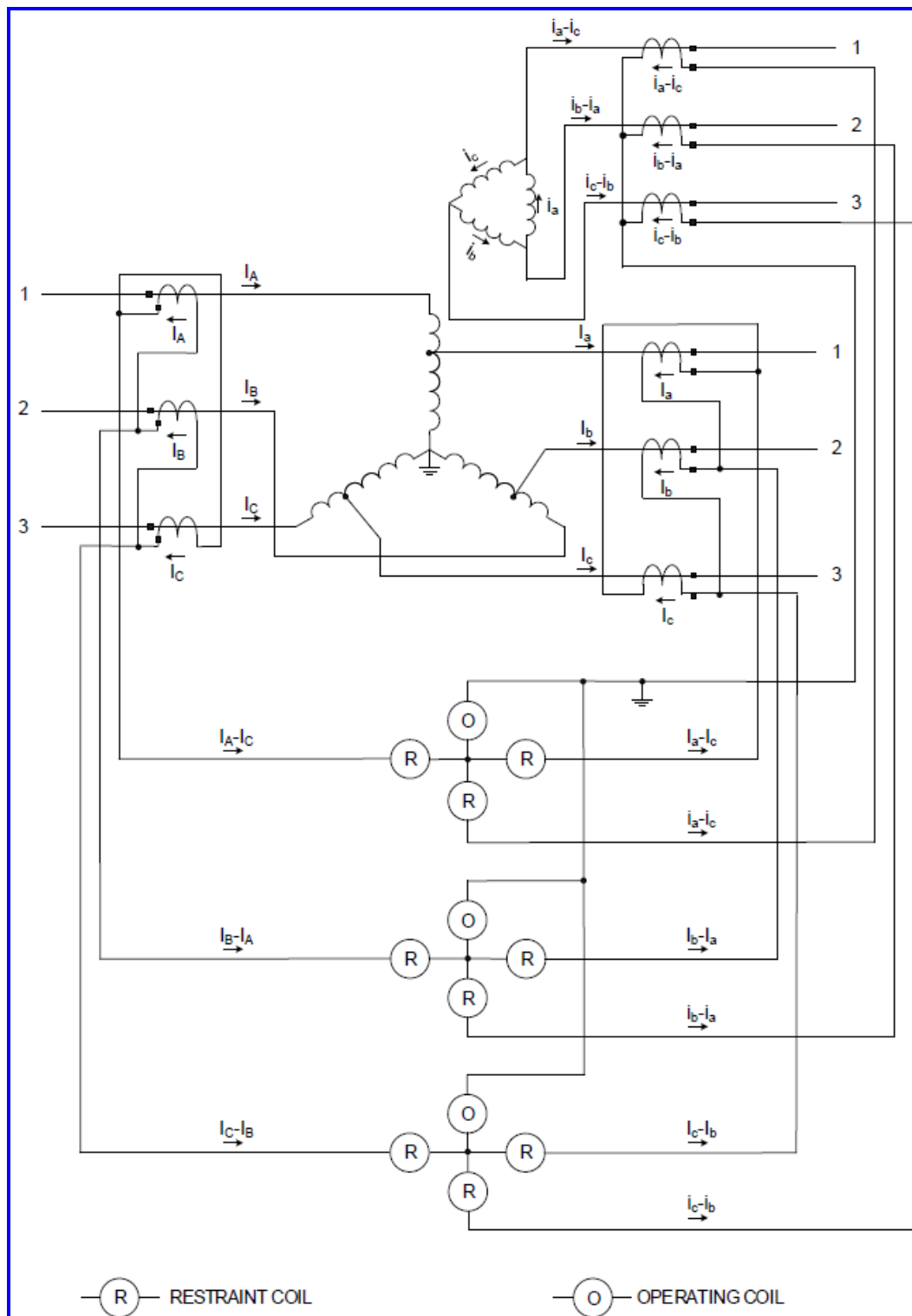


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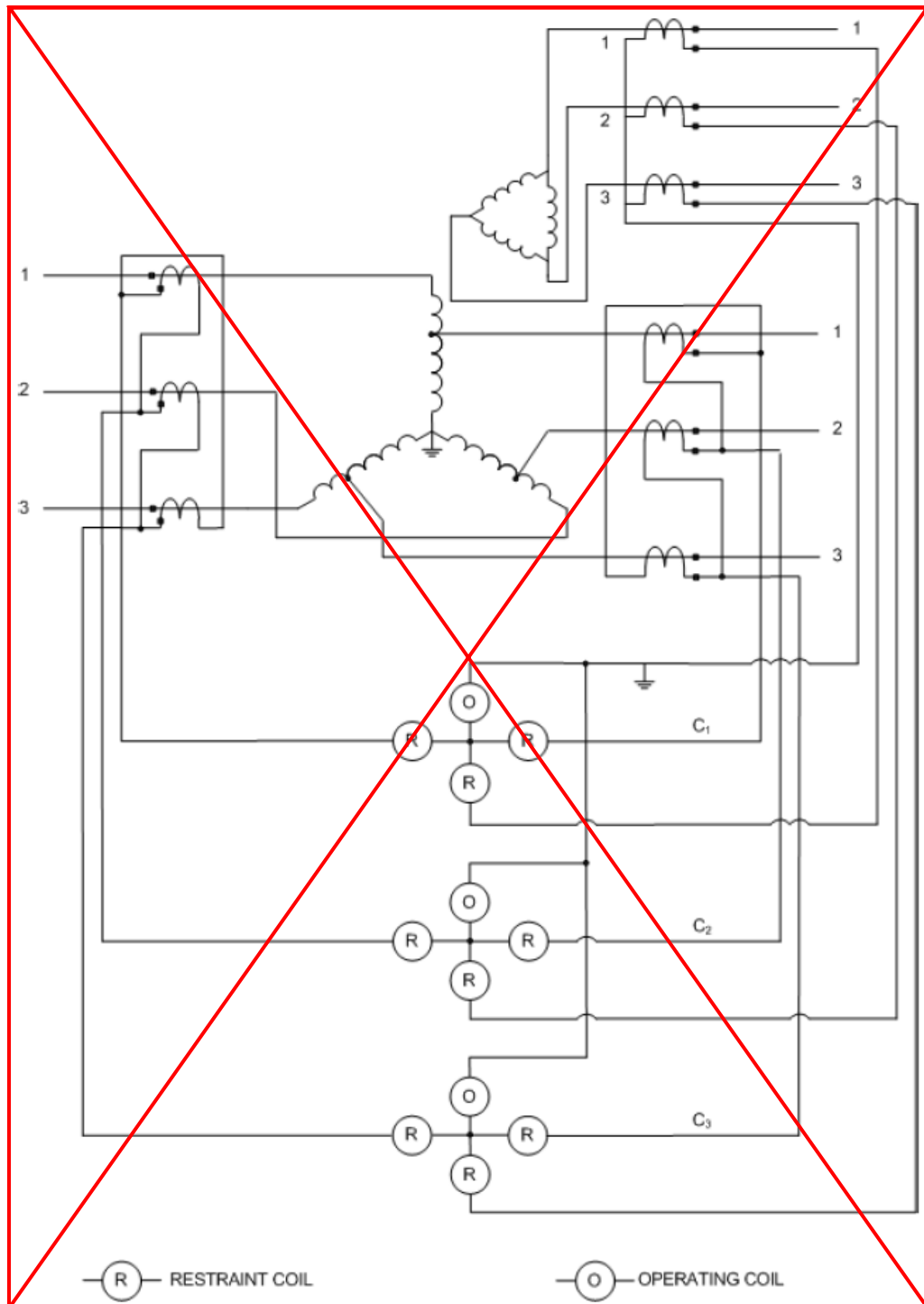


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Figure 6 — Typical schematic connections for differential protection of a wye autotransformer with unloaded tertiary



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