ANSI/IEEE C37.91-1985

An American National Standard

IEEE Guide for Protective Relay Applications to Power Transformers

Sponsor

Power System Relaying Committee
of the
IEEE Power Engineering Society

Approved March 22, 1984
Reaffirmed December 6, 1990

IEEE Standards Board

Approved March 8, 1985
Reaffirmed May 20, 1991

American National Standards Institute

The Institute of Electrical and Electronics Engineers, Inc

345 East 47th Sreet, New York, NY 10017, USA

IEEE Standards documents are developed within the Technical Committees of the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Board. Members of the committees serve voluntarily and without compensation. They are not necessarily members of the Institute. The standards developed within IEEE represent a consensus of the broad expertise on the subject within the Institute as well as those activities outside of IEEE which have expressed an interest in participating in the development of the standard.

Use of an IEEE Standard is wholly voluntary. The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE Standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard. Every IEEE Standard is subjected to review at least once every five years for revision or reaffirmation. When a document is more than five years old, and has not been reaffirmed, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE Standard.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of all concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason IEEE and the members of its technical committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration.

Comments on standards and requests for interpretations should be addressed to:

Secretary, IEEE Standards Board
345 East 47th Street
New York, NY 10017
USA

Foreword

(This Foreword is not a part of ANSI/IEEE C37.91-1985, IEEE Guide for Protective Relay Applications to Power Transformers.)

This revision of ANSI/IEEE C37.91 incorporates a number of changes since the original guide was issued in 1967. Some of the more significant changes were made in the sections dealing with differential and overcurrent protection. Other changes were made to bring this guide up-to-date and more in line with present-day requirements.

This guide was revised by the Transformer Protection Guide Revision Working Group of the Transformer and Bus Protection Subcommittee of the Power System Relaying Committee of the IEEE Power Engineering Society. The working group membership at the time of completion of this revision was as follows:

R. W. Haas, *Chair*

E. J. Emmerling
S. E. Grier
F. O. Griffin
D. K. Kaushal
J. R. Linders
W. K. Morrison *
V. A. Nosko *
G. P. Palmer
G. C. Parr
J. W. Walton

*Honorary Member—Retired

At the time this guide was approved, the Power System Relaying Committee of the IEEE Power Engineering Society had the following membership:

W. A. Elmore, *Chair*
D. R. Volzka, *Vice Chair*
C. H. Griffin, *Secretary*

J. C. Appleyard
R. F. Archart
C. W. Barnett
E. A. Baumgartner
J. Berdy
J. L. Blackburn
J. J. Bonk
J. R. Boyle
B. Bozoki
W. D. Breingan
J. A. Bright
H. J. Calhoun
J. W. Chadwick, Jr
D. M. Clark
D. H. Colwell
D. Dalasta
H. DiSante
E. J. Emmerling
W. E. Feero
R. J. Fernandez
C. M. Gadsden
A. T. Giuliante
S. E. Grier
R. W. Haas
R. E. Hart
M. Hirakami
R. W. Hirtler
F. B. Hunt
R. H. Jones
T. L. Kaschalk
D. K. Kaushal
W. C. Kotheimer
R. J. Kuhr
K. J. Khunkhun
L. E. Landoll
J. R. Latham
H. Lee
J. R. Linders
W. R. Lund
C. J. Marieni
C. A. Matthews
F. N. Meissner
J. Miller
R. J. Moran
J. J. Murphy
T. J. Murray
K. K. Mustaphi
G. R. Nail
T. Niessink
S. L. Nilsson
G. C. Parr
C. J. Pencinger
A. G. Phadke
A. C. Pierce
H. B. Pitzer
J. W. Pope
G. D. Rockefeller
B. D. Russell
M. S. Sachdev
E. T. Sage
D. E. Sanford
L. Scharf
H. S. Smith
J. E. Stephens
A. Sweetana
J. R. Turley
E. A. Udren
C. L. Wagner
J. E. Waldron
L. N. Walker
J. W. Walton
E. J. Weiss
S. E. Zocholl
D. Zollman
J. A. Zulaski

When the IEEE Standards Board approved this standard on March 22, 1984, it had the following membership:

James H. Beall, *Chair*
John E. May, *Vice Chair*
Sava I. Sherr, *Secretary*

J. J. Archambault
John T. Boettger
J. V. Bonucchi
Rene Castenschiold
Edward Chelotti
Edward J. Cohen
Len S. Corey
Donald C. Fleckenstein
Jay Forster
Daniel L. Goldberg
Donald N. Heirman
Irvin N. Howell, Jr
Jack Kinn
Joseph L. Koepfinger *
Irving Kolodny
George Konomos
R. F. Lawrence
Donald T. Michael *
John P. Riganati
Frank L. Rose
Robert W. Seelbach
Jay A. Stewart
Clifford O. Swanson
W. B. Wilkens
Charles J. Wylie

* Member emeritus

Corrected Edition

CLAUSE PAGE

An American National Standard

IEEE Guide for Protective Relay Applications to Power Transformers

1. Introduction

1.1 Purpose

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.

1.2 References

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.[1]

[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.

[6] IEEE Std 32-1972(R 1978), IEEE Standard Requirements Terminology and Test Procedure for Neutral Grounding Devices.

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

---

[1] ANSI 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.

[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.

[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.

[14] ROCKEFELLER, G.D., SONNEMANN, W.K., and WAGNER, C.L. Magnetizing Inrush Phenomena in Transformer Banks. *AIEE* Transactions , vol 77, pt III, pp 884–892, Oct 1958.

[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.

2. Philosophy and Economic Considerations

Protective relaying is applied to components of a power system for several reasons:

1) To separate the faulted equipment from the remainder of the system so that the system can continue to function
2) To limit damage to the faulted equipment
3) Minimize the possibility of fire
4) Minimize hazards to personnel

In protecting some components, particularly high-voltage transmission lines, the limiting of damage 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 aspects of relays shall be considered when protecting transformers, particularly in the larger sizes.

Faults internal to the transformer quite often involve a magnitude of fault current which is low relative to the transformer rating. This indicates a need for 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 not 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 plan selected shall balance the best combination of these factors against the overall economics of the situation while holding to a minimum:

1) Cost of repairing damage
2) Cost of lost production
3) Adverse effects on the balance of the system
4) The spread of damage to adjacent equipment
5) The period 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 would not be practical. When the fault spreads due to nonclearing by the transformer protection, remote line relays or other protective relaying may operate. Part of the evaluation of the type of protection applied to a transformer should include how the system integrity may be affected by such a failure. In this determination, since rare but costly failures are involved, a diversity of opinion on the degree of protection required by transformers might be expected among those familiar with power system relay engineering. The major economic consideration is not ordinarily the fault detection equipment but the 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 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].

Table 1—Causes of Transformer Failures

1. Winding Failures
    - 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
    - c. Flashover due to surges
    - d. Moisture
    - e. Low oil
4. Terminal Board Failures
    - 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 failures
    - h. Overvoltage
    - i. Overloads
    - j. Unidentified problems

---

[2] The 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

3. Types of Transformer Failures

Transformer failures can be grouped into six major categories. The major categories are detailed in Table 1. Summaries of failures in those catagories 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.

4. Relay Current

Two characteristics of power transformers combine to complicate detection of internal faults with current operated relays:

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

4.1 Minimum Internal Faults

The most difficult transformer winding fault for which to provide protection is the fault that initially involves one turn. With a two-winding transformer, a turn-to-turn fault will result in a terminal current of less than rated full-load current. Possibly, 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. Thus, a turn-to-turn fault may result in a terminal current of 10% or less of a transformer rating.

4.2 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 an internal terminal fault, 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 current transformer on a short time basis. This may be a factor if the transformer is small relative to the system fault and if the current transformer ratio is chosen to match the transformer.

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.

4.4 Performance of Current Transformers

4.4.1 Internal Faults

During an internal fault, or a fault external to the transformer but in the protected zone, the current transformers may saturate, perhaps severely. Severe current transformer saturation can result in failure of a transformer differential relay to operate or in a delay of its operation. The effect depends on the relay's response to distorted current. On a transient basis, with a saturated current transformer, 2nd and 3rd harmonics predominate initially, and each may be greater than the fundamental. Ultimately, the even harmonics disappear, depending upon the direct current time constant of the short-circuit current. Whether or not the odd harmonics disappear depends on the current transformers steady state saturation characteristic. Harmonic restrained relays usually contain an independent instantaneous overcurrent unit set to operate during saturation of the current transformer when differential relay operation is restrained.

4.4.2 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.

4.4.3 Current Transformer Connections

Current transformer performance is a function of the secondary burden. The method of connecting the current transformers 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.

4.5 Nonfault Relay Current

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

4.5.1 Unbalance Caused by Current Transformer Ratios

Even if a transformer has a fixed ratio, it is frequently difficult to match current transformer ratios exactly on the two (or more) sides of a transformer. Current transformer mismatch causes current flow in the operating circuit of the differential relay. If the transformer has a load tap changer, 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.

4.5.2 Magnetizing Current Inrush

This is a phenomenon which 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. Current occasioned by magnetizing inrush can reach many times the transformer rating and these currents appear in the differential relay. See [14] for an explanation of this mechanism.

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. 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 operative only when energizing a transformer may not be adequate.

There are several conditions that cause particularly severe magnetizing inrush phenomena [14]. One involves the energizing of a transformer at a station at which at least one other transformer is already energized. The inrush phenomenon [9] involves the already energized transformers and the one being energized and the inrush transient is of particularly long 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 fundamental frequency, and therefore not operate the harmonic restraint unit of a differential relay if it is protecting both parallel transformers. Another inrush phenomenon involves the energizing of a transformer by means of an air switch. Arcing of the switch can result in successive heft cycles of arc 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.

An important characteristic of magnetizing inrush current is that it contains substantial harmonics, particularly the second harmonic.

4.5.3 Magnetizing Current During Overvoltage

Sudden loss of load can subject the generator step-up transformer to substantial overvoltage. This can also occur during shutdown of the generator if voltage is maintained while speed decreases (an overexcitation condition). If saturation occurs, substantial exciting current will flow which may overheat the core. The waveform will be distorted and the harmonic content will be dependent on the generator connections and the transformer design and connections. Relay current harmonic content will also be altered by delta current transformer connections. (Because of the abrupt voltage change, there may also be a magnetizing current inrush, but this is of secondary importance.)

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.

5. Electrical Detection of Faults

Fuses are commonly used to provide fault detection for transformers with minimum name-plate ratings up to 5000 kVA, three phase (Category I and II). Transformers larger than 5000 kVA, three phase, minimum nameplate (Category III and IV) are generally protected by a combination of protective devices as shown in Fig 1.

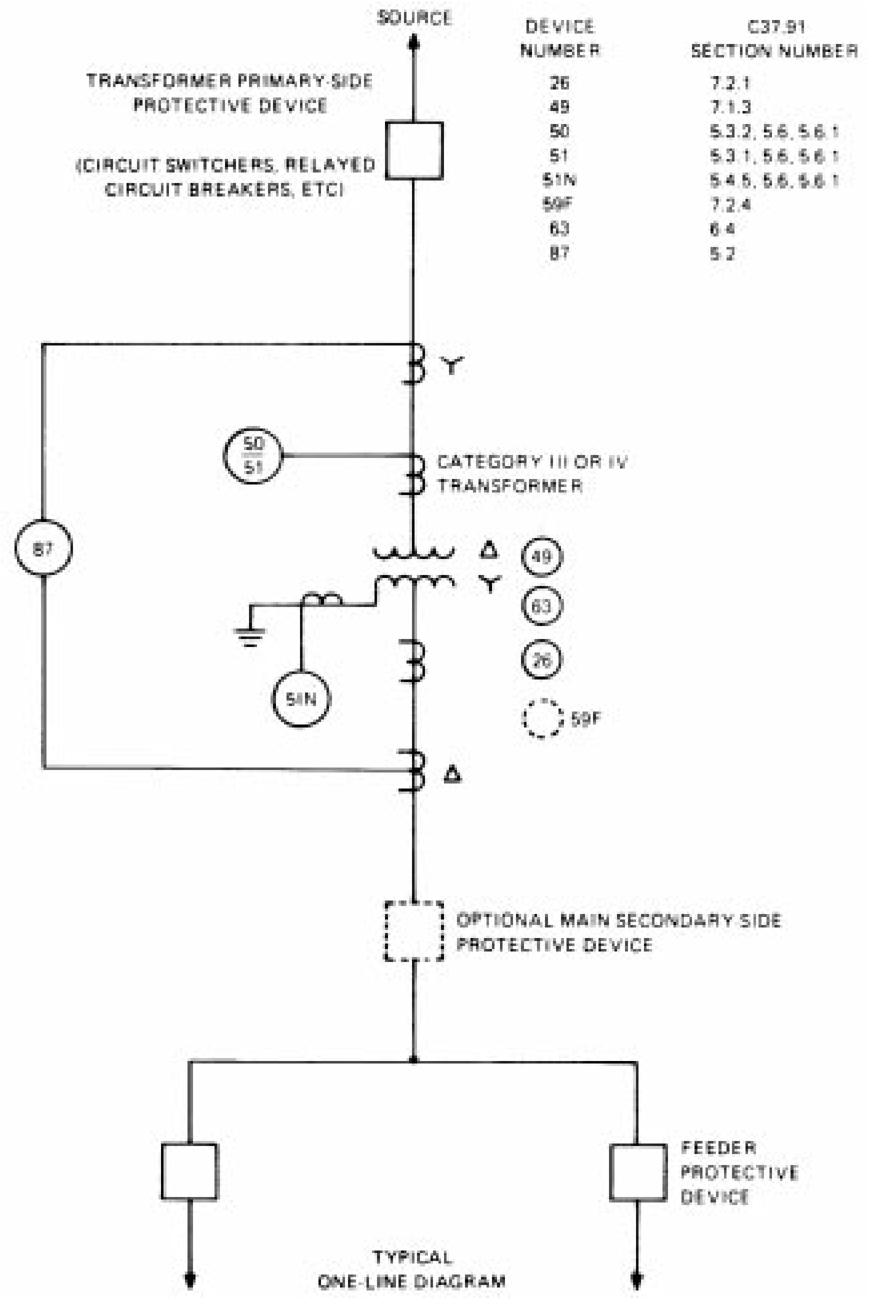
5.1 Fuse Protection

Fuses have the merits of being economical and requiring little maintenance. No dc battery supply is needed. Fuses can reliably protect some power transformers against primary and secondary external faults. They will provide limited protection for internal faults. Generally, more sensitive means for protection from internal faults are provided for transformers of 10 MVA and higher. 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.

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

1) Fuse fault interrupting capability and available system fault current
2) 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 Appendix)
3) 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)
4) Available primary system fault current and transformer impedance
5) Coordination with source side protection equipment
6) Coordination with low side protection equipment
7) Maximum allowable fault time on the low side bus conductors
8) Transformer connections and grounding impedance as they affect the primary current for various types of secondary faults
9) Maximum degree of sensitivity for protection from high impedance faults
10) Transformer magnetizing inrush

Ampere 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 the Appendix.



DEVICE NUMBER	C37.91 SECTION NUMBER
26	7.2.1
49	7.1.3
50	5.3.2, 5.6, 5.6.1
51	5.3.1, 5.6, 5.6.1
51N	5.4.5, 5.6, 5.6.1
59F	7.2.4
63	6.4
87	5.2

Figure 1—Protection for a Delta-Wye Transformer

5.2 Differential Protection

Current differential relaying is the most commonly used type of protection for transformers of approximately 10 MVA (self-cooled rating) and above [10]. 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.

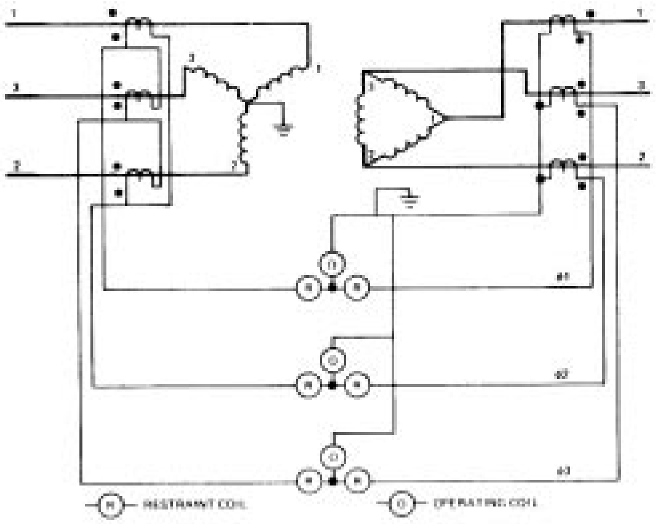
Current transformer connections and ratios must be such that the net current in the relay operating coil for any type or location of external fault is effectively zero, unless relay current matching taps are available. Various types of current transformer connections are shown in Figs 2, 3, and 4. Paralleling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

5.2.1 Differential Protection Using Time Overcurrent Relays

Overcurrent relays without restraint are seldom used in present day applications due to their susceptibility to false operation from causes such as: (1) Inrush magnetizing current when energizing the transformer, and (2) saturation errors or mismatch errors of current transformers.

5.2.2 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.



NOTE: See 5.2

Figure 2—Typical Schematic Connections for Percentage Differential Protection of a Wye-Delta Transformer

The amount of restraint is stated as a percent slope relating the operating (differential) current and the restraint current. Each manufacturer uses a slightly different definition for slope. Also, the amount of restraint may be fixed, adjustable, or variable, 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.

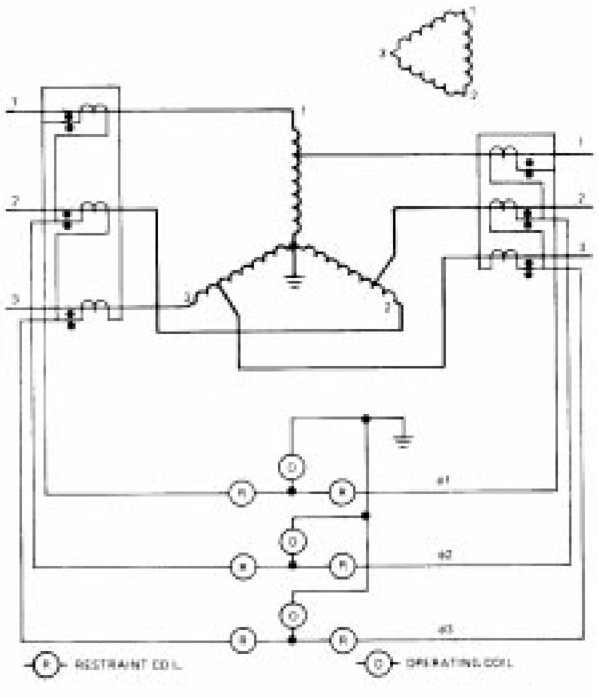
While a differential relay is more expensive than an overcurrent relay, the installed cost is usually no more. It is sometimes provided with taps which make auxiliary current transformers to balance currents unnecessary. The overcurrent relay in many instances requires an auxiliary current transformer and additional wiring which increases its installed cost.

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.

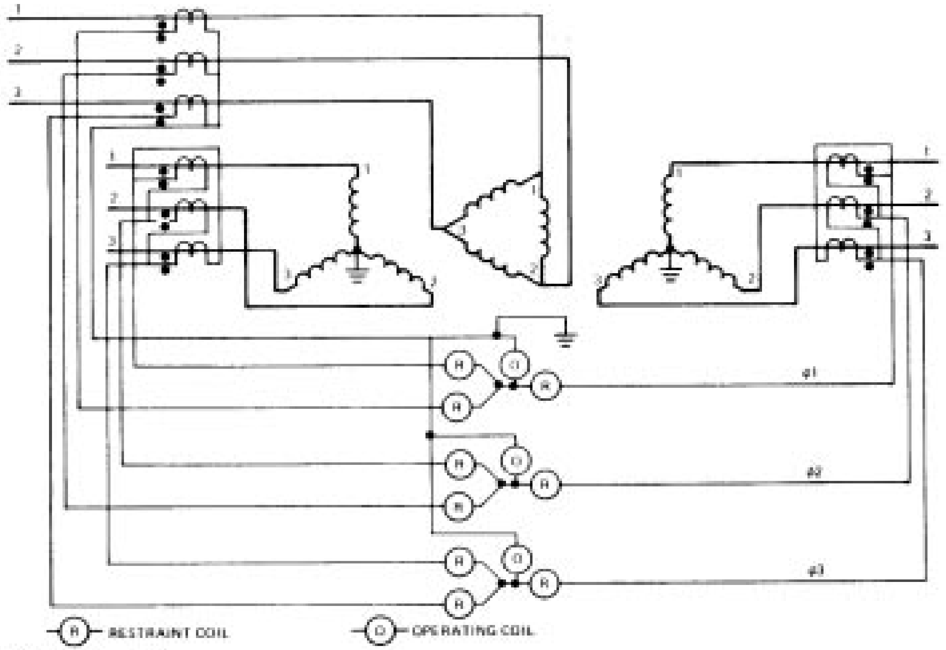
The purpose of all of these designs is to provide a relay which properly restrains regardless of the amount of inrush and yet permits operation if an internal fault occurs during the inrush period. Another design objective is not to have excessive restraint resulting from the harmonic distortions of 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.



NOTE: See 5.2

Figure 3—Typical Schematic Connections for Percentage Differential Protection of a Wye Autotransformer with an Unloaded Tertiary



NOTE: See 5.2

Figure 4—Typical Schematic Connections for Percentage Differential Protection of a Wye-Delta-Wye Transformer with a Loaded Delta Tertiary

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)

5.2.4 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 all of the 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.

5.2.5 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 current transformer ratio required for satisfactory sensitivity may result in severe current transformer 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 to operate. An additional current transformer with a high ratio, supplying an overcurrent relay with 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 current transformer connection shall be provided for the overall differential scheme. A connection from the overall differential to the low side current transformers of the unit auxiliary transformer avoids the saturation problem that may occur with high side current transformers. 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 and the generator and the 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 current transformer ratios.

5.2.6 Multiple Winding Transformer Differential

Differential relays for three 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.

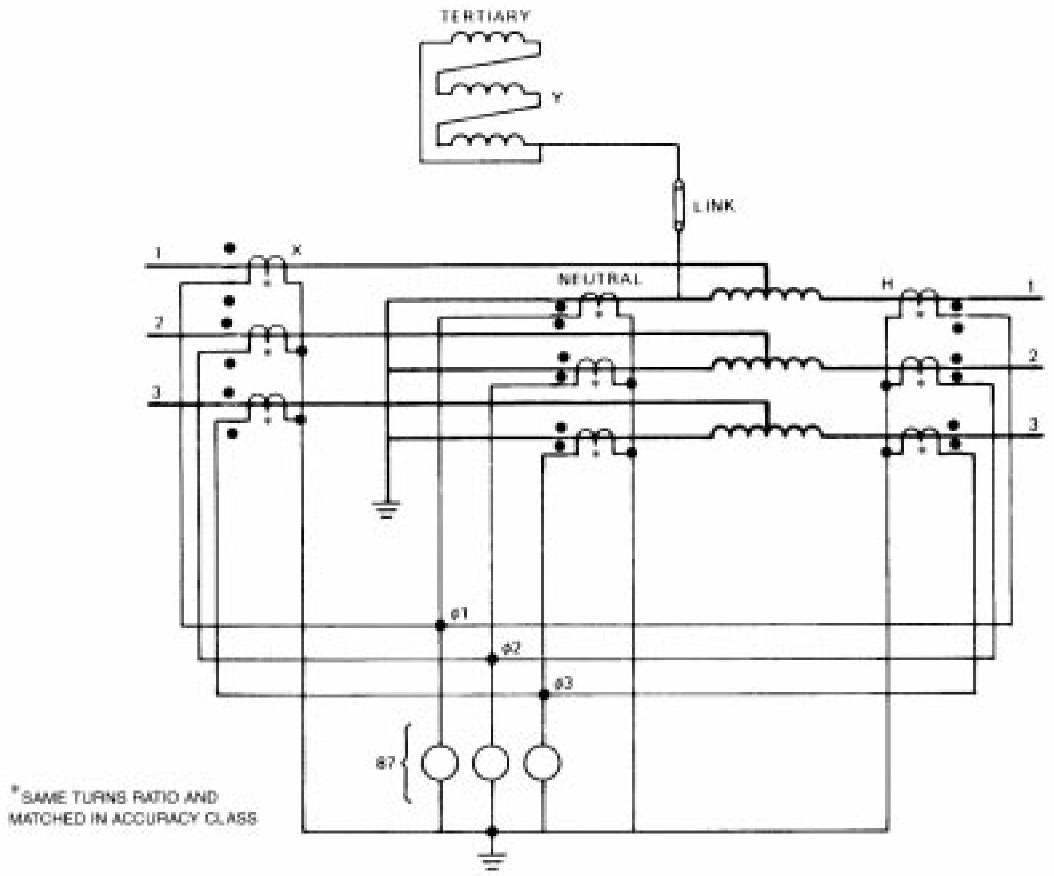
Multiple winding transformers frequently have different capacity ratings on the individual windings. For example, a three winding transformer may have a high side rating of 90 MVA with the other two windings each rated at 50 MVA. The sum of the small windings' ratings can be greater than the main (input) winding rating. Care should be taken in selecting current transformer ratios and selecting differential relay current balancing taps. 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 current involving only the high side and one other winding is studied at a time.

5.2.7 Parallel Transformers

A major disadvantage of using one differential relay to protect two transformers is the reduction in sensitivity. The current transformer ratios are selected on the basis of total kilovoltampere, (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 4.5.2), 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.

5.2.8 Differential Protection of Autotransformers Using High Impedance Relays

In some countries, it is common practice to provide greater 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 Fig 5. This arrangement provides protection against all types of phase faults and ground faults but not turn-to-turn faults. In this application, three sets of three-phase current transformers 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 current transformers shall have the same turns ratio and should be reasonably matched in accuracy class. A single relay connected in a ground differential scheme is also applicable for autotransformer protection.



*SAME TURNS RATIO AND MATCHED IN ACCURACY CLASS

NOTE: See 5.2.8

Figure 5—Typical Schematic Connections for High Impedance Differential Relay Protection of a Wye Autotransformer with an Unloaded Tertiary

This protection is immune to the effects of magnetizing inrush current because inrush current is cancelled by the neutral current transformers. 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 tertiary delta winding. It should be noted that with this type of scheme no protection is afforded against faults occurring in the delta 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 current transformer. This connection is shown in Fig 5. 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. This scheme does not provide protection against 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 5.3.3.

5.3 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.

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 transformer 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 requirements 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 (Δ) 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.

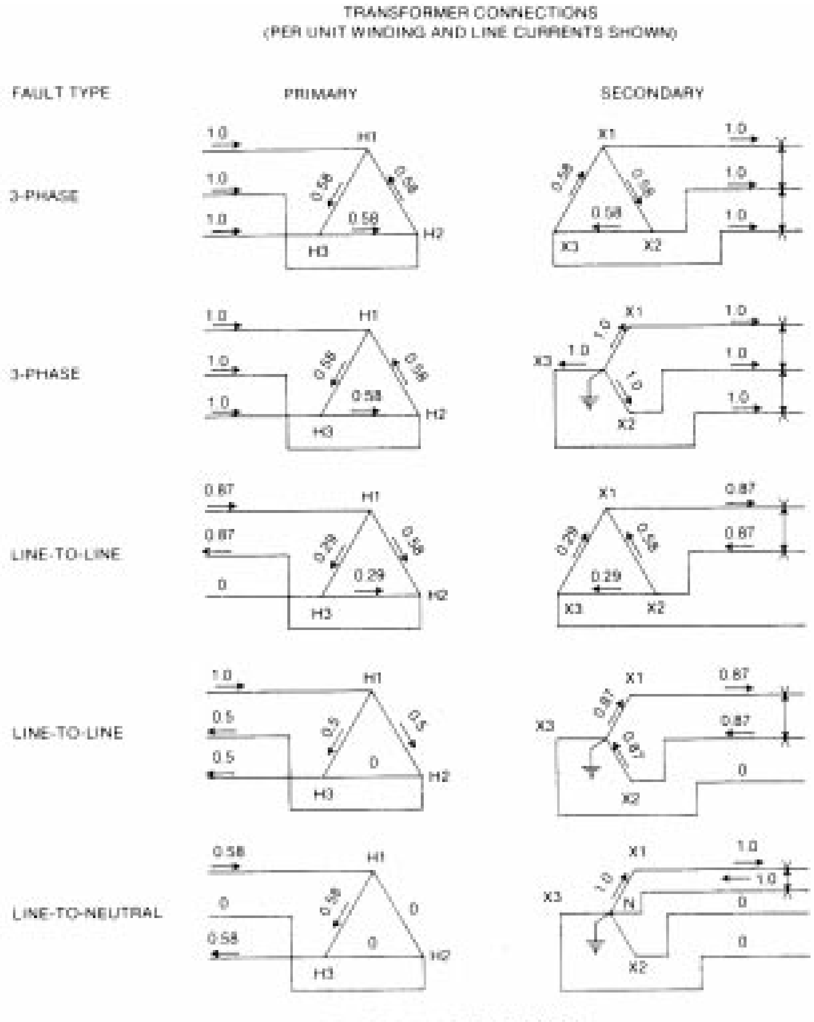
The time setting should coordinate with relays on downstream equipment. However, transformers are mechanically and thermally limited in their ability to withstand short-circuit current for finite periods of time. For proper backup protection, the relays should operate before the transformer is damaged 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.

5.3.2 Phase Instantaneous Overcurrent

Fast clearing of severe internal faults may be obtained through the use of instantaneous overcurrent units. Instantaneous overcurrent units, when used, 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 fault. For instantaneous units subject to transient overreach, a pickup of 175% (variations in settings of 125%–200% are common) of the calculated maximum low side three-phase symmetrical fault current 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 shall also be above the transformer inrush current to prevent nuisance tripping. In some cases, instantaneous trip relays cannot be used because the necessary settings are greater than the available fault currents. In these cases, a harmonic restraint instantaneous relay may be considered to provide the desired protection.



$$\text{3-PHASE FAULT CURRENT } I_f = \frac{\text{3-PHASE FULL LOAD CURRENT } I_{FL}}{\text{TRANSFORMER PER UNIT IMPEDANCE (Z)}} = 1.0 \text{ PER UNIT}$$

NOTE: See 5.3.1

Figure 6—Line and Transformer Winding Currents for Delta-Delta and Delta-Wye Connected Transformers

5.3.3 Tertiary Winding Overcurrent

The tertiary winding of an autotransformer, or three-winding transformer, is usually of much smaller kilovoltampere rating than the main windings. Therefore, fuses or overcurrent relays set to protect the main windings offer almost no protection to such tertiaries. During external system ground faults, these tertiary windings may carry very heavy currents. Hence, in the event of failure of the primary protection for external ground faults, separate tertiary overcurrent protection may be desirable.

The method selected for protecting the tertiary generally depends on whether or not the tertiary is used to carry load. If the tertiary does not carry load, protection can be provided by a single overcurrent relay connected to a current transformer in series with one winding of the Δ. This relay will sense system grounds and also phase faults in the tertiary or in its leads.

If the tertiary is used to carry load, partial protection can be provided by a single overcurrent relay supplied by three current transformers, one in each winding of the Δ and connected in parallel to the relay. This connection provides only zero sequence overload protection and does not protect for positive and negative sequence overload current. In this case, the relay will operate for system ground but will not operate for phase faults in the tertiary or its leads. Where deemed necessary, separate relaying such as differential type shall be provided for protection against phase faults in the tertiary or its leads.

The setting of the tertiary overcurrent relay can normally be based on considerations similar to those in 5.3.1. However, if the tertiary does not carry load, or if load is to be carried and the three current transformer zero sequence connection is used, the associated overcurrent relay can be set below the rating of the tertiary winding. This relay should still be set to coordinate with other system relays.

5.4 Ground Fault Protection

Sensitive detection of ground faults can be obtained by differential relays or by overcurrent relays specifically applied for that purpose. Several schemes are practical, depending on transformer connections, availability of current transformers, zero sequence current source, and system design and operating practices.

5.4.1 Faults in Delta-Connected Transformer Windings

A residual relay, device 51G, as shown in Fig 7 or 8, will detect ground faults within the Δ winding of the transformer and in the phase conductors between the current transformers and the winding, when an external source of zero sequence current is available. Instantaneous overcurrent relays may be used but sensitive settings will probably result in incorrect operations from dissimilar current transformer saturation and magnetizing inrush. This can be avoided by using a short time induction disc relay with a sensitive setting. The scheme is particularly valuable in plants or systems where the transformers are remote from the circuit breakers. By using current transformers at the circuit breaker, sensitive detection is obtained for cable, bus, Δ winding, and bushing faults. A single window or doughnut current transformer supplying an instantaneous relay (as commonly used in motor protection) is secure, but is limited to low and medium voltages where all three conductors can be fitted through the current transformer window.

5.4.2 Faults in Grounded Wye-Connected Transformer Windings

To successfully detect faults in grounded Y-connected transformer windings, the relay system shall discriminate between faults internal and external to the protected zone. The ground differential relay, device 87N, in Fig 7, or the directional ground relay, device 67N, connected as in Fig 8, is satisfactory. Both relay schemes will operate correctly for any internal ground faults with the circuit breaker in the circuit to the grounded Y winding open or closed. They will operate correctly with an external zero sequence current source, and they will not operate for external ground faults. Unequal current transformer action can produce residual error current during external *phase* faults. No transformer neutral current is produced and sensitive relays would misoperate. The auxiliary current transformer is necessary if the phase and neutral current transformers are of different ratio.

NOTES: (1) Zero sequence current arrows are for an external ground fault for which the relays will not operate.
(2) See: 5.4.1, 5.4.2, 5.4.5

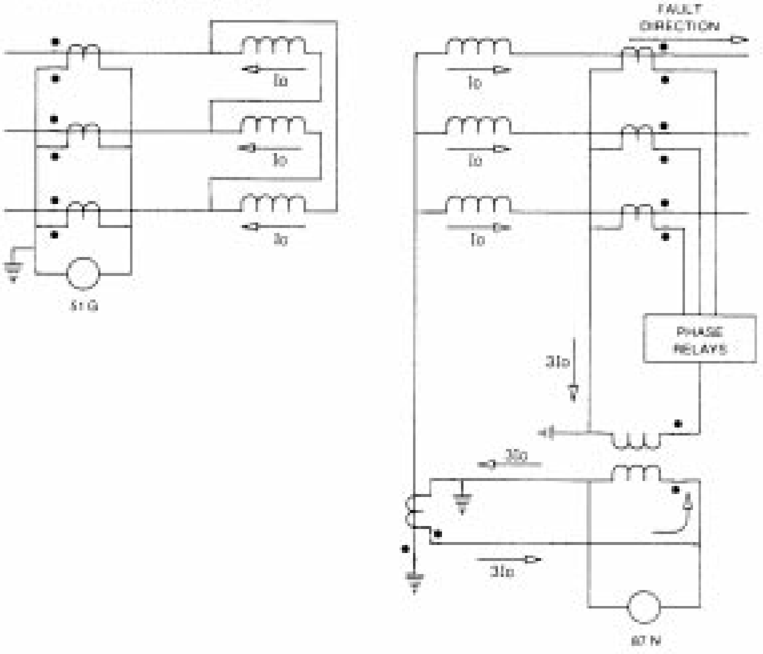
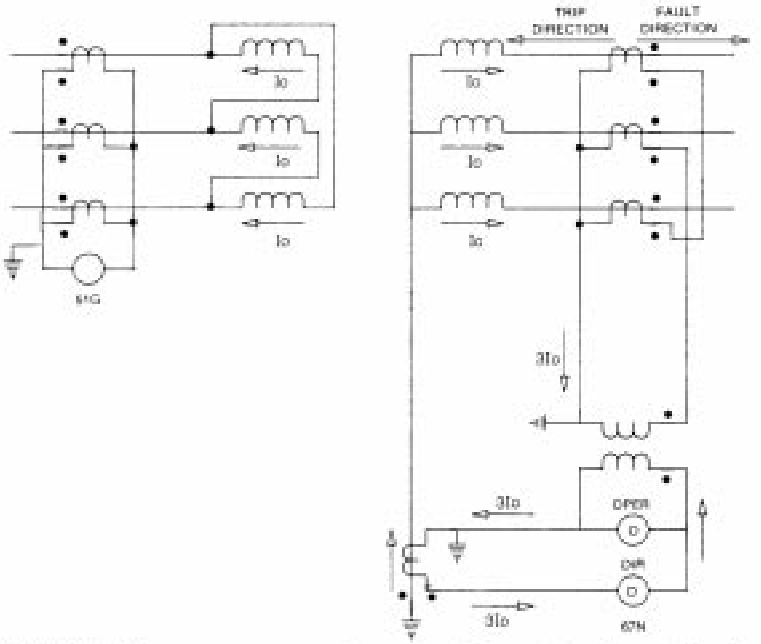


Figure 7—Complete Ground Fault Protection of a Delta-Wye Bank using Residual Overcurrent and Differentially Connected Ground Relay

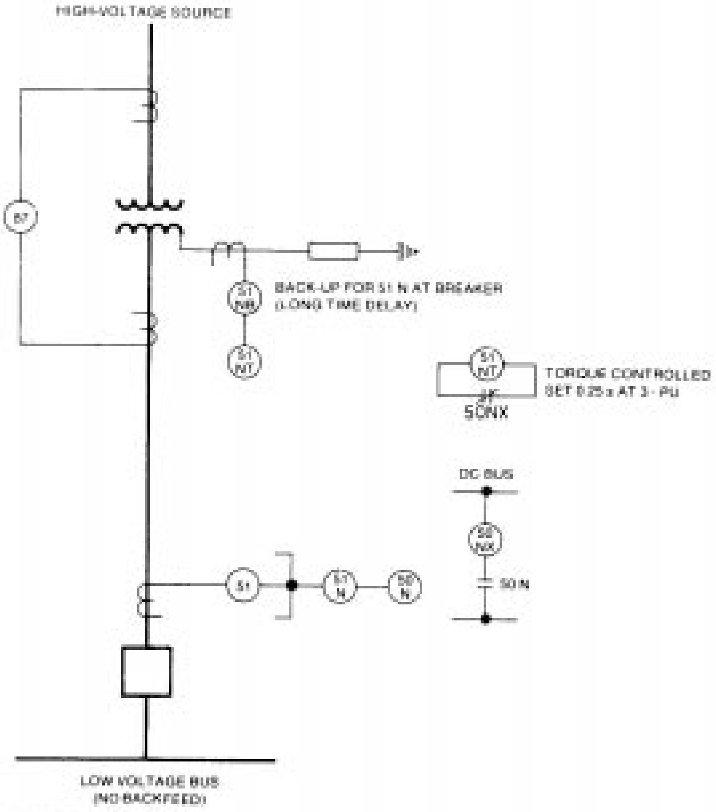


NOTES: (1) Zero sequence current arrows are for an external ground fault for which the relays will not operate.
(2) See: 5.4.1, 5.4.2

Figure 8—Complete Ground Fault Protection of a Delta-Wye Bank using a Residual Overcurrent and Directional Relay

5.4.3 Case Ground

On a grounded neutral system, it is possible to isolate the transformer case from ground except for a single point. A current transformer and overcurrent relay at this grounding point would detect any internal ground fault or bushing flashover. Although effective, several problems are encountered. The system shall be tested periodically to determine that no accidental grounds have been added. Incorrect operations can result from accidental grounds from power tools and transformer auxiliary equipment, or from a failed lightning arrester discharge if the arrestor is mounted on the transformer. Careful coordination between auxiliary equipment circuit breaker or fuse curves, arrester characteristics, and a time overcurrent trip relay can minimize this danger.



NOTE: See: 5.5.4

Figure 9—Sensitive High Speed Ground Fault Protection With Impedance Grounding (Alternate to Fig 7)

5.4.4 Impedance Grounded System

Transformer differential relays may not be sensitive enough to operate on ground faults where the transformer bank or system is grounded through an impedance. In these cases, it may be necessary to apply a sensitive time overcurrent relay in the transformer impedance grounded neutral or a time overvoltage relay connected across the neutral impedance. These relays shall be coordinated with feeder and line protection relays which they may overlap. It is possible to provide high-speed protection and to avoid the need for coordination by using sensitive product type relays which are connected to trip only for ground in the protected zone. Fig 9 is a method used when there is no other possible ground source. An overcurrent relay connected to a neutral current transformer is torque-controlled by the blocking contacts of a plunger type instantaneous relay in the neutral of the main breaker current transformers.

5.4.5 Ground Fault Relay Sensitivity

The primary advantage of ground relays over phase relays is their sensitivity. In systems where the ground fault current is purposely limited, their use may be vital. Ground relays can normally be applied with sensitivities of 10% or less of full load current. This compares very favorably with differential relays, whose pickup current may be from 20% to 60% of full load current under the most advantageous conditions. It is common European practice to protect all transformers with the *restricted earth* relays and a Buchholz gas relay [8], [15] and [16]. The term *restricted earth* is a British expression referring to a ground relay system sensitive to ground faults within a limited protective zone (similar to Fig 7).

5.5 Fault Detection for Special Purpose Transformers

5.5.1 Regulating Transformers

The exciting winding of a regulating transformer presents a special protection problem, since ordinary power transformer differentials are not sensitive enough to sense faults in this high-impedance winding. Regulating transformers can be either the most common *in-phase* type employing only voltage regulation, or the *phase-shifting* type which provides regulation of phase angle, or both.

Sudden pressure or fault-pressure relays will offer good protection for all three types. However, electrical protection may differ substantially between the in-phase type and the others. Fault-pressure relays generally are not used to protect the tap-changing mechanism because of large pressure variations during normal are interruption. However, fault-pressure relays may be used to protect tap changing mechanisms utilizing vacuum interrupter switches.

Transformer manufacturers usually provide special protection and monitoring schemes of their own design on regulating transformers. The scheme may stop the tap changing sequence or initiate a trip for a switch or mechanism malfunction.

5.5.1.1 In-Phase Type

Although overall differential relaying is usually provided for in-phase regulators, special purpose relays are also available to protect the exciting winding more sensitively. On each phase, this type of relay compares the exciting winding current (obtained from a current transformer in the high voltage lead or neutral end of the exciting winding) with one of the phase currents as shown in Fig 10a.

The relay has one operating coil and one restraint coil and is generally set to operate for a current imbalance of 15% greater than the imbalance due to maximum regulation. It should be noted that the exciting winding of a ±10% regulator has a full load current rating only 10% of the rating of the series winding; current transformer ratios should be chosen with this in mind. The use of Δ-connected current transformers is a necessary precaution to prevent tripping for external ground faults (if the neutral of the exciting winding is grounded). Because of the location of the current transformer in the exciting winding, the proper current transformer shall be specified when ordering the transformer.

5.5.1.2 Phase-Shifting or Combined Phase-Shifting and In-Phase Regulating Transformers

For these types of transformers neither type of protection shown in Fig 10(a) is suitable. For example, for a quadrature phase-shifting transformer, the exciting winding shown in Fig 10(a) might not introduce a voltage in the same phase. but rather, in each of the other two phases. Conversely, the series winding shown in Fig 10(a) would instead be two series windings deriving their voltages from the exciting winding of the other two phases.

The effects of these factors are as follows:

1) With respect to the normal percentage differential relay shown in Fig 10(a), an external fault on either one of the other two phases, or both, can produce current predominantly on only one side of the differential relay. This relay operates as though there was an internal fault if the fault current is above pickup.
2) With respect to the exciting winding protection of Fig 10(a), an external fault on either one of the other two phases, or both, can cause the exciting (operating) current to be substantially equal to the line (restraining) current. The relay, connected as shown, would operate.

The relay protection of the phase angle regulating transformer presents problems not common to a normal transformer. The primary winding, the series transformer, and the shunt transformer shall all be considered in determining a viable relay protection scheme. Because of the large number of possible varieties of phase-shifting transformers, specific electrical protection of them shall be considered to be beyond the scope of this guide. It is pertinent, however, to point out that electrical protection will probably require current transformers inside of the transformer rather than the usual bushing current transformers (see Fig 10(b)). Consequently, the protection must be decided upon early enough so that current transformers can be specified before the transformer design is started. For protection of this type of transformer, the sudden pressure or fault pressure relay shall be considered to be the first line of protection.

5.5.2 Combined Power and Regulating Transformers

A power transformer, such as a Y-Δ transformer, may also have regulating features either in-phase, out-of-phase (such as quadrature), or both. Such transformers are called *tap-changing-under-load*, or *load-tap-changing* transformers.

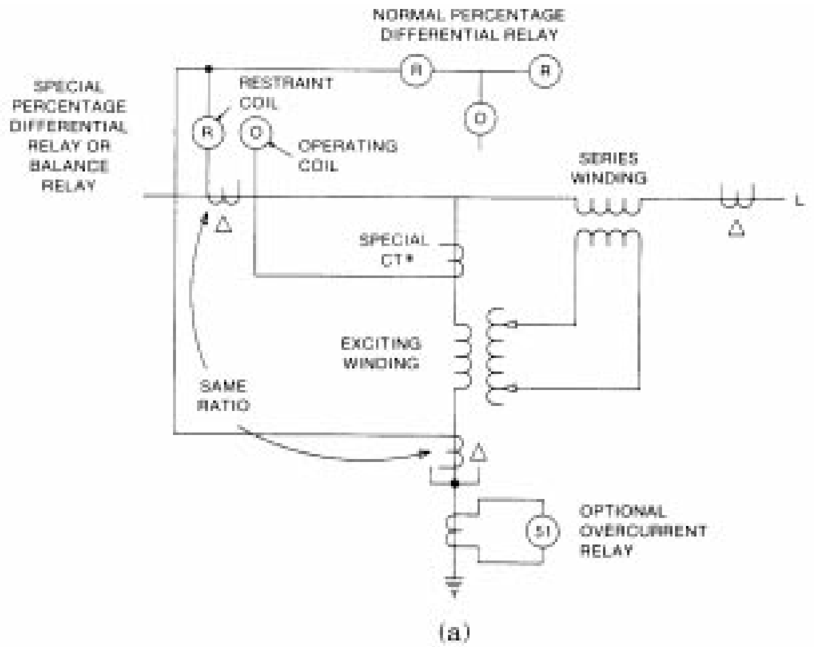
The protection of such a transformer of the in-phase variety has been previously covered in this guide. However, the electrical protection of the out-of-phase variety is even more difficult than the protection of the phase-shifting regulating transformer because the power transformer has no exciting winding as such since excitation is obtained from loaded windings. Comments with respect to phase-shifting regulating transformers apply equally well to this type of transformer (see 5.5.1.2). In any case, the sudden pressure or fault-pressure relay shall be considered the first line of protection.

5.5.3 Grounding Transformers

A grounding transformer can be either a zig-zag or a Y-Δ connected transformer. The electrical protection scheme is simple and consists of overcurrent relays connected to Δ connected current transformers as shown in Fig 11.

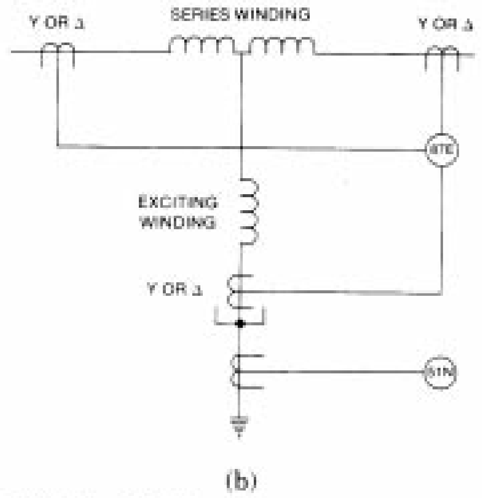
If the grounding transformer is of the zig-zag variety, internal faults, such as turn-to-turn faults, may be limited by the magnetizing impedance of an unfaulted phase. Consequently, a sudden pressure or fault-pressure relay should be considered to be the first line of protection, even though it may be marginal.

Grounding transformers are seldom switched by themselves. However, when they are switched, they are subject to magnetizing-inrush current as with any other type of transformer. Harmonic restrained overcurrent relays may be used to prevent inadvertent tripping upon energizing.



(a)

*CT Selection Example: If Main CT is 1500-5, Exciting Winding CT is 150-5 for a +/− 10%, 2500 kVA, 13.8 kV Reg.
NOTE: See 5.5.1.1, 5.5.1.2



(b)

NOTE: See: 5.5.1.2

Figure 10—Protection for Phase Shifting and Regulating Transformers
(a) Protection for In-Phase Regulating Transformers
(b) Protection for Phase Shifting Transformers

When a grounding transformer with a low or no neutral impedance is used, a phase-to-ground fault is normally not allowed to persist as it might when the current is restricted to a very low value by a high neutral impedance. Therefore, the selection of a current transformer ratio associated with the grounding transformer is more dependent on the pick-up of the ground relay than the rating of the grounding transformer. However, if a fault is allowed to persist then the current transformer ratio must be selected with the continuous current in mind. A grounding transformer has a continuous rating based on a set fraction of its thermal current rating according to IEEE Std 32-1972 [6].

If the continuous current rating is not available, it can be determined as follows:

1) Obtain the zero phase sequence impedance (ohms, or percent, or per unit on some base) from the transformer manufacturer.
2) Determine a kilovoltampere rating which will have approximately the same zero sequence impedance relative to the grounded neutral side by assuming a mean value of the *standard* range of impedances.
3) Having determined the fictitious kilovoltampere rating, choose the current transformer ratio based on full load current for that kilovoltampere.

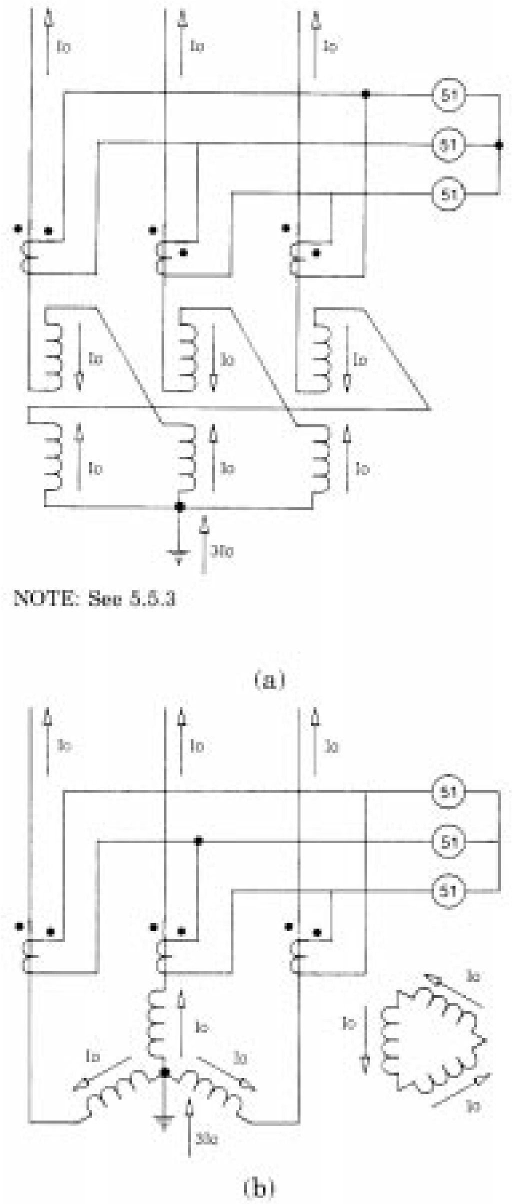


Figure 11—Protection of Grounding Transformers (a) Zig Zag (b) Wye-Delta

5.6 Backup and External Fault Protection

Protection of a transformer against damage due to the failure to clear an external fault should always be carefully considered.

This damage usually manifests itself as internal, thermal or mechanical damage caused by fault current flowing through the transformer. The curves in the Appendix show through fault-current duration curves to limit damage to the transformer. Through faults that can cause damage to the transformer include restricted faults or those some distance away from the station. The fault current, in terms of the transformer rating, tends to be low (approximately 0.5 to 5.0 times transformer rating) and the bus voltage tends to remain at relatively high values. The fault current will be superimposed on load current, compounding the thermal load on the transformer.

Several factors will influence the decision as to how much and what kind of backup is required for the transformer under consideration. Significant factors are the operating experience with regard to clearing remote faults, the cost effectiveness to provide this coverage considering the size and location of the transformer, and the general protection philosophies used by the company.

Backup protection for the transformer can be divided into several categories as follows:

5.6.1 Overcurrent Relays

When overcurrent relays are used for transformer backup, their sensitivity is limited because they shall be set above maximum load current. Separate ground relays may be applied with the phase relays to provide better sensitivity for some ground faults. Usual considerations for setting overcurrent relays are described in 5.3.

When overcurrent relays are applied to the high voltage side of transformers with three or more windings, they shall have pickup values which will permit the transformer to carry its rated load plus margin for overload. Locating phase overcurrent relays on the low-voltage side of each winding allows a gain in sensitivity since only the full load rating of an individual winding need be considered.

When two or more transformers are operated in parallel to share a common load, the overcurrent relay settings should consider the short time overloads on one transformer upon loss of the other transformer. Relays on individual transformers may require pickup levels greater than twice the forced cooled rating of the transformer to avoid tripping. Higher pickup levels result in a loss of backup protection sensitivity. To improve the sensitivity of backup protection, the current transformers on each transformer source to a bus may be paralleled so that one set of overcurrent relays receive the total current of the sources associated with the individual bus. Switching out a transformer, therefore, does not affect the relay sensitivity. However, all sources shall be tripped when the overcurrent relays operate. This is usually referred to as a *bus-overload* or partial differential scheme.

For sensitive ground protection, each transformer neutral may be grounded through a current transformer with a lower ratio than that used for the phase overcurrent relay. With due consideration for imbalanced line-to-ground load and time coordination, it may be possible to approach the sensitivity of the feeder ground relays. See 5.3 and 5.4 for a comprehensive discussion of overcurrent and ground protection, respectively.

5.6.2 Negative Sequence Relays

Since these relays do not respond to balanced load or three-phase faults, negative sequence overcurrent relays may provide the desired overcurrent protection. This is particularly applicable to Δ-Y grounded transformers where only 58% of the secondary per unit phase to ground fault current appears in any one primary phase conductor. Backup protection can be particularly difficult when the Y is impedance grounded. A negative sequence relay can be connected in the primary supply to the transformer and set as sensitively as required to protect for secondary phase-to-ground or phase-to-phase faults. This relay will also provide better protection than phase overcurrent relays for internal transformer faults. The relay should be set to coordinate with the low-side phase relays for phase-to-ground and phase-to-phase faults.

5.6.3 Fuses

Application of fuses to the high voltage or source windings of transformers present the same types of sensitivity problems discussed in 5.3. In addition, fuses are single-phase devices and operate individually. See 5.1 for discussion of the application of fuses.

5.6.4 Breaker Failure

Protection for the failure of a feeder breaker to clear a fault may be provided by addition of a timer started by the operation of feeder overcurrent relays in a breaker failure scheme. The principal advantage of this arrangement is that the back-up sensitivity is equal to that of the feeder protection The additional complication of this protection does increase the risk of inadvertant loss of the station load due to relay malfunction or testing errors. Breaker failure protection associated with a transformer requires a scheme that may have to recognize small fault currents. Breaker “a” switches may have to be used in combination with fault current selector relays. A transformer connected to a line without a line-side breaker requires transfer-trip or a ground switch to cause the remote breaker to trip. If the remote breaker fails to trip, the transformer fault probably was not cleared. See Section 13 for additional information.

5.6.5 Dual Input Relays

System voltages are lower during fault conditions than during load conditions with comparable current. This results from the fault current being highly reactive which causes larger voltage drops across the system. This fact is utilized in several different dual input relays.

5.6.5.1 Voltage Controlled Overcurrent Relay

In this relay the overcurrent unit is set based on the minimum fault-current condition independent of any load-current requirements. This relay is then torque controlled by an undervoltage relay. The undervoltage unit is set to operate below the normal minimum system load voltage, but above the maximum expected fault voltage. Thus, sensitive phase fault protection is provided with no hazard of tripping due to load current. Low-side potential should be used to allow the undervoltage unit to dropout for low-side faults. The potential supply should be monitored. There may be an application problem with this relay if the system voltage during a limited fault is not reduced substantially.

5.6.5.2 Voltage Restraint Overcurrent Relay

In this relay the overcurrent unit operating value is a function of the applied voltage. The relay is set so that maximum load current will not cause operation with the minimum expected system operating voltage. During fault conditions, the reduced voltage causes less restraint and the relay will operate at a lower current which varies with the voltage magnitude. There may be an application problem with this relay if the system voltage during a limited fault is not reduced substantially.

5.6.5.3 Impedance Relay Torque Controlling an Overcurrent Relay

This scheme is less dependent on the exact change in the level of system voltage than either of the above two methods. In this method, the impedance from the relay location to the most distant fault needing backup protection is set on the distance relay, with suitable margin. The overcurrent relay is then set at a current less than the minimum expected fault current. A mho-type distance relay characteristic provides improved fault/load discrimination over a straight impedance relay.

5.6.5.4 Overcurrent-Directional Relay

This relay, in contrast to a directional-overcurrent relay, responds only to the product of the current magnitude times the cosine of the angle between this current and a voltage reference. The magnitude of the voltage does not enter into the operating equation provided it is above a prescribed limit. In this application, the relay can be connected to respond only to the reactive component of current. It will not respond to the real component of any load current and hence has good loadability. The relay is set for the minimum expected fault current with suitable margin.

5.7 Temperature Relays

Transformer damage from remote low current faults which are not properly cleared may be similar to that from sustained overload causing thermal damage. The most direct solution to the backup problem is the use of thermal relays as discussed in Section 7

5.8 Miscellaneous Relays

In certain applications, advantages can be taken of relays not directly associated with the transformer. In the case of a unit connected generator, backup may be provided by protective relays essentially designed for generator backup. These include the voltage controlled overcurrent relay, a distance relay for remote faults (usually applied with a fixed time delay rather than inverse time delay), the generator negative sequence overcurrent relay and the generator overexcitation relay.

6. Mechanical Detection of Faults

There are two methods of detecting transformer faults other than by electric measurements. These methods are:

1) Accumulation of gases due to slow decomposition of the transformer insulation or oil. These relays can detect heating due to high resistance joints or due to high eddy currents between laminations.
2) Increases in tank oil or gas pressures caused by internal transformer faults.

Relays which use these methods are valuable supplements to differential or other forms of relaying, particularly for grounding transformers and transformers with complicated circuits that are not well suited to differential relaying, such as certain regulating and phase-shifting transformers. These relays may be more sensitive for certain internal faults than relays which are dependent upon electrical quantities, and thus can be very valuable in minimizing transformer damage due to internal faults.

6.1 Gas Accumulator Relay

This type of relay, commonly known as the Buchholz relay, is applicable only to transformers equipped with conservator tanks and with no gas space inside the transformer tank. The relay is placed in the pipe from the main tank to the conservator tank and is designed to trap any gas which may rise through the oil. It will operate for small faults by accumulating the gas over a period of time or for large faults which force the oil through the relay at a high velocity. This device is able to detect a small volume of gas and accordingly can detect arcs of low energy. The accumulator portion of the relay is frequently used for alarming only, it may detect gas which is not the result of a fault, but which can be evolved by gassing of the oil during sudden reduction of pressure. This relay may detect heating due to high-resistance joints or high eddy current between laminations.

6.2 Gas Detector Relay

The gas-detector relay can be used only on conservator transformers, either conventional or sealed. The relay will often detect gas evolution from minor arcing before extensive damage occurs to the windings or core. This relay may detect heating due to high resistance joints or high eddy current between laminations.

Essentially, the gas detector relay is a magnetic type liquid-level gage with a float operating in an oil-filled chamber. The relay is mounted on the transformer cover with a pipe connection from the highest point of the cover to the float chamber. A second pipe connection from the float chamber is carried to an eye level location on the tank wall. This connection is used for removing gas samples for analysis. The relay is equipped with a dial graduated in cubic centimeters and a snap action switch set to function to give an alarm when a specific amount of gas has beer collected.

6.3 Static Pressure Relay

The static pressure relay can be used on all types of oil-immersed transformers. They are mounted on the tank wall under oil and respond to the static or total pressure. These relays for the most part have been superseded by the sudden pressure relay, but many are in service on older transformers. However, due to their susceptibility to operate for temperature changes or external faults, the majority of the static pressure relays which are in service are connected for alarm only.

6.4 Sudden Gas Pressure Relay

The sudden gas-pressure relay is applicable to all gas cushioned oil-immersed transformers and is mounted in the region of the gas space. It consists of a pressure-actuated switch, housed in a hermetically sealed case and isolated from the transformer gas space except for a pressure-equalizing orifice.

The relay operates on the difference between the pressure in the gas space of the transformer and the pressure inside the relay. An equalizing orifice tends to equalize these two pressures for slow changes in pressure due to loading and ambient temperature change. However, a more rapid rise in pressure in the gas space of the transformer due to a fault results in operation of the relay. High energy arcs evolve a large quantity of gas which operates the relay in a short time. The operating time is longer for low energy arcs.

This relay has proven sufficiently free from false operations to be connected for tripping in most applications. It is important that the relay be mounted in strict accordance with the manufacturers specifications Further, a scheme similar to Figs 12(a) or 12(b), providing a shunt path around the auxiliary relay coil, is preferred to minimize the effects of control circuit electrical disturbances.

6.5 Sudden Oil-Pressure Relay

The sudden oil-pressure relay is applicable to all oil-immersed transformers and is mounted on the transformer tank wall below the minimum liquid level. Transformer oil fills the lower chamber of the relay housing within which a spring backed bellows is located. The bellows is completely filled with silicone oil and additional silicone oil in the upper chamber is connected to that in the bellows by way of two small equalizer holes.

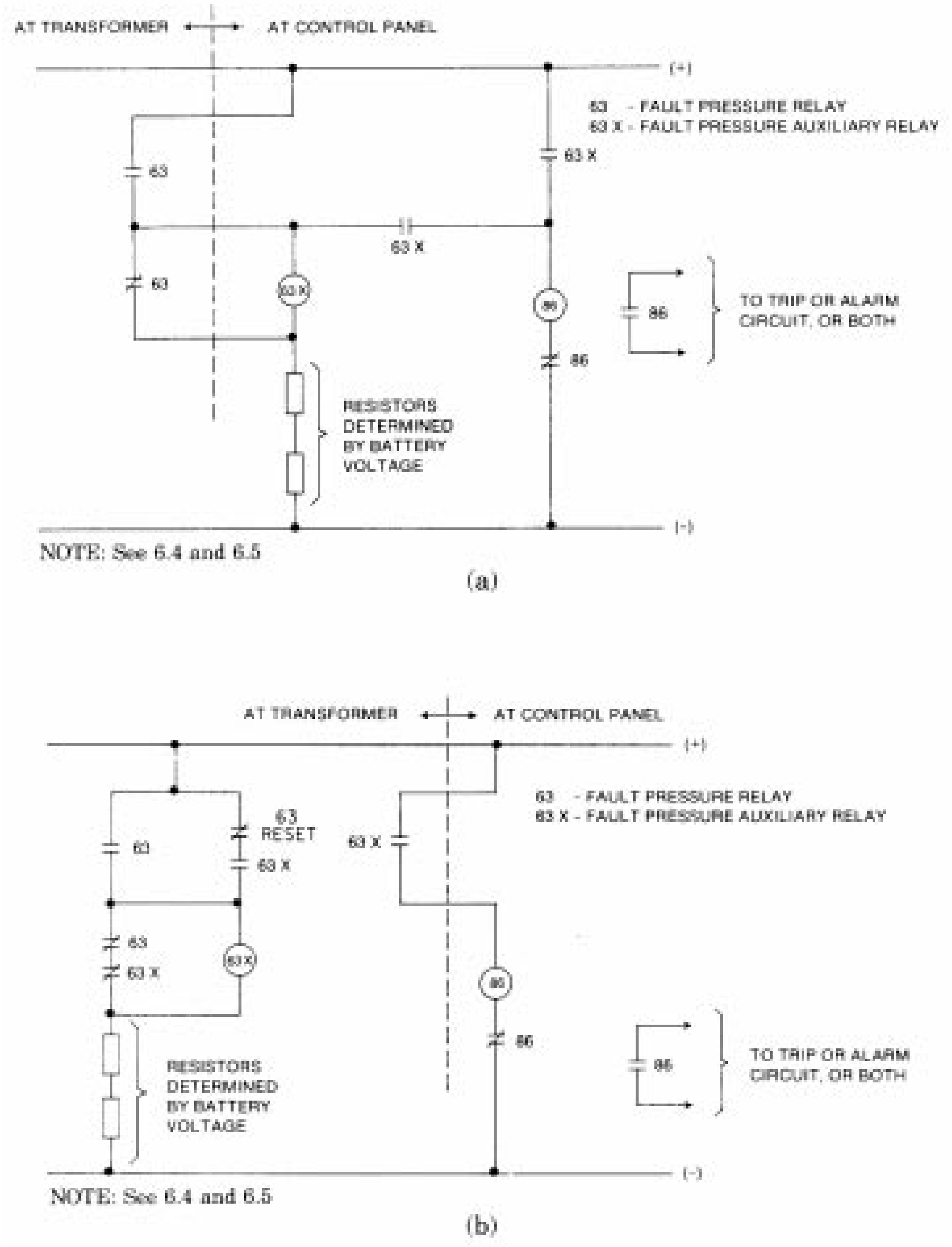


Figure 12—Fault Pressure Relay Schemes
(a) Auxiliary Relay at Control Panel
(b) Auxiliary Relay at Transformer with Manual Reset

A piston rests on the silicone oil in the bellows, but extends up into the upper chamber, separated from a switch by an air gap. Should an internal fault develop, the rapid rise in oil pressure or pressure pulse is transmitted to the silicone oil by way of the transformer oil and the bellows. This then acts against the piston which closes the air gap and operates the switch.

In the event of small rises in oil pressure, due to changes in loading or ambient for example, the increased pressure is also transmitted to the silicone oil. However, instead of operating the piston, this pressure is gradually relieved by oil which escapes from the bellows into the upper chamber by way of the equalizer holes. The bellows then contract slightly. The pressure bias on the relay is thus relieved by this differential feature. Relay sensitivity and response to a fault is thus independent of transformer-operating pressure.

This relay has proven sufficiently free from false operations to be connected for tripping in most applications. It is important that the relay be mounted in strict accordance with the manufacturers specifications. Further, a scheme similar to Figs 12(a) or 12(b), providing a shunt path around the 63X auxiliary-relay coil is preferred to prevent its operation due to surges.

6.6 Sudden Gas/Oil Pressure Relay

A more recent design of the above relays utilizes two chambers, two control bellows, and a single sensing bellows. All three bellows have a common interconnecting silicone-oil passage with an orifice and ambient temperature compensating assembly inserted at the entrance to one of the two control bellows.

An increase in transformer pressure causes a contraction of the sensing bellows thus forcing a portion of its silicone oil into the two control bellows and expanding them. An orifice limits the flow of oil into one control bellows to a fixed rate, while there is essentially no restriction to flow into the second control bellows. The two control bellows expand at a uniform rate for gradual rate of rise in pressure, but during high rates of transformer pressure rise, the orifice causes a slower rate of expansion in one bellows relative to the other. The dissimiliar expansion rate between the two control bellows will cause a mechanical linkage to actuate the snap action switch which initiates the proper tripping.

7. Thermal Detection of Abnormalities

7.1 Thermal Relays for Winding Temperature

7.1.1 Causes of Transformer Overheating

Transformers may overheat due to

1) High ambient
2) Failure of cooling system
3) External fault not cleared promptly
4) Overload
5) Abnormal system conditions such as low frequency, high voltage, nonsinusoidal load current or phase-voltage unbalance.

7.1.2 Undesirable Results of Overheating

1) Overheating shortens the life of the transformer insulation in proportion to the duration of the high temperature and in proportion to the degree of the high temperature.
2) Severe overtemperature may result in an immediate insulation failure.
3) Severe overtemperature may result in the transformer coolant heated above its flash temperature, with a resultant fire.

7.1.3 Hot-Spot Location

The location of the hottest spot within a transformer is predictable from the design parameters. It is customary to measure or to simulate this hot spot temperature and to base control action accordingly. The desired control action will depend on the users' philosophy, on the amount of transformer life he is willing to lose for the sake of maintaining service, and the priorities he places on other aspects of the problem. Transformer top-oil temperature may be used with or without hot-spot temperature, to establish the desired control action.

A common method of simulating the hot-spot temperature is with a thermal relay responsive to both top-oil temperature and to the direct heating effect of load current. In these relays, the thermostatic element is immersed in the transformer top oil. An electric heating element is supplied with a current proportional to the winding current, so that the responsive element tracks the temperature which the hot spot of the winding attains during operation. If this tracking is exact, the relay would operate at the same time as the winding reaches the set temperature. Since insulation deterioration is also a function of the duration of the high temperature, additional means are generally used to delay tripping action for some period of time. One common method is to design the relay with a time constant longer than that of the winding. Thus, the relay does not operate until some time after the set temperature has been attained by the winding. There are no standards established for this measuring technique, nor is information generally available for one to make an accurate calculation of the complete performance of such a relay. These relays can have from one to three contacts which close at successively higher temperature. With three contacts, the lowest level is commonly used to start fans or pumps for forced cooling, and the second level to initiate an alarm. The third step may be used for an additional alarm or to trip load breakers or to de-energize the transformer.

Another type of temperature relay is the *replica* relay. This relay measures the phase current in the transformer and applies this current to heater units inside the relay. Characteristics of these heaters approximate the thermal capability of the protected transformer. In the application of replica type relay, it is desirable to know the time constants of the iron, the coolant, and the winding. In addition, the relay should be installed in an ambient temperature approximately the same as the transformer and not be ambient compensated.

7.2 Other Means of Thermal Protection

7.2.1 Top Oil

Many transformers are equipped with a thermometer element immersed in the top oil. If this element is equipped with contacts which close at selected temperatures, these contacts can be used to start cooling fans or pumps, or to sound an alarm. Since the top-oil temperature may be considerably lower than the hot-spot temperature of the winding, especially shortly after a sudden load increase, the top-oil thermometer is not suitable for effective protection of the winding against overloads. However, where the policy toward transformer loss of life permits, tripping on top-oil temperature may be satisfactory. This has the added advantage of directly monitoring the oil temperature to ensure that it does not reach the flash temperature.

7.2.2 Fuses or Overcurrent Relays

Other forms of transformer protection such as fuses or overcurrent relays provide some degree of thermal protection to the transformer. Application of these is discussed in 5.1 and 5.3.

7.2.3 Thermal Relays for Tank Temperature

In Y-connected, three-legged core-type transformers without Δ windings, during imbalanced voltage conditions the transformer tank acts as a high-impedance Δ-tertiary winding (generally known as a phantom tertiary), and under severe conditions, damaging heat can be produced. A thermal relay mounted to sense tank temperature will detect this condition, and since this condition usually occurs because of an open phase which does not cause other protection to operate, the device should trip the transformer. The device can be a dial type temperature indicator with a switch or a direct acting thermostat. In either case, it should be placed in direct contact with the transformer tank. Settings of 105 °C to 125 °C will be above temperatures reached under normal operating conditions, and will correspond to temperatures reached in 1 min to 4 min under maximum heating conditions (one phase of supply open and grounded). See 11.4 for overcurrent relay application.

7.2.4 Overexcitation Protection

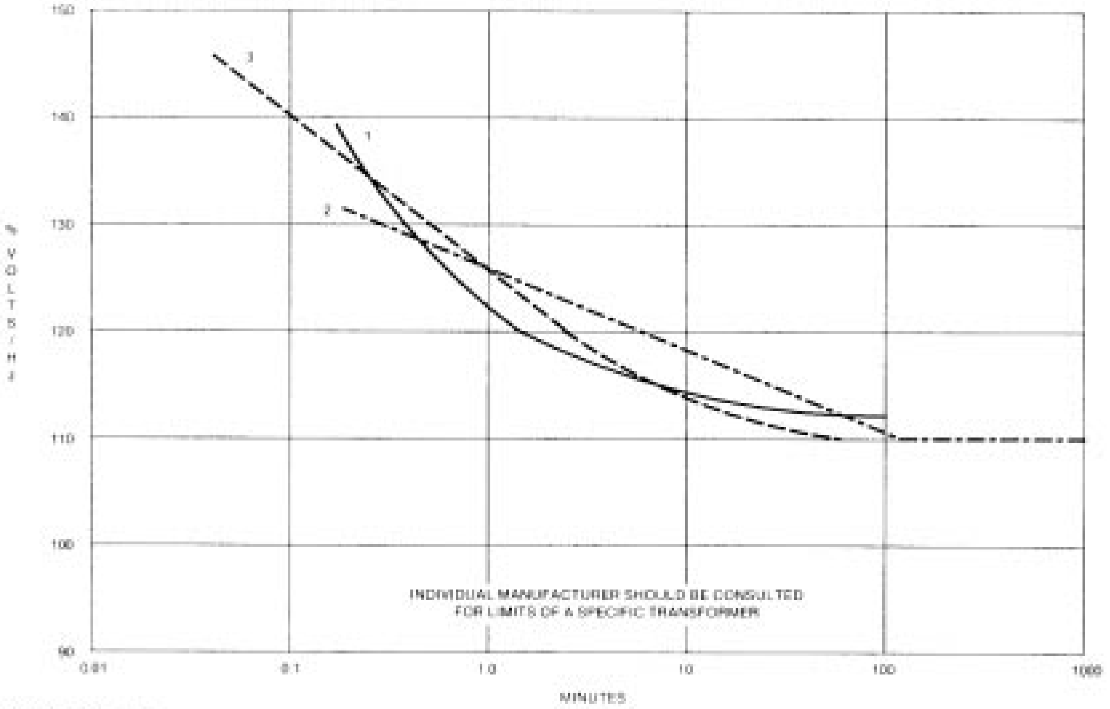
Overexcitation may be of concern on direct connected generator unit transformers. Excessive excitation current leads directly to overheating of core and unlaminated metal parts of a transformer, which in turn causes damage to adjacent insulation and leads to ultimate failure. ANSI/IEEE C57.12.00-1980 [2], requires that transformers shall be capable of operating continuously at 10% above rated secondary voltage at no load without exceeding the limiting temperature rise. The requirement applies for any tap at rated frequency.

Direct-connected generator transformers are subjected to a wide range of frequency during the acceleration and deceleration of the turbine. Under these conditions the ratio of the actual generator terminal voltage to the actual frequency shall not exceed 1.1 times the ratio of transformer rated voltage to the rated frequency on a sustained basis:

$$\left(\frac{\text{Generator terminal voltage}}{\text{Actual frequency}}\right) \le \left[\frac{(1.1)\text{Transformer rated voltage}}{\text{Transformer rated frequency}}\right]$$

Generator manufacturers now recommend an overexcitation protection system as part of the generator excitation system. This system may also be used to protect the transformer against overexcitation. These systems may alarm for an overexcitation condition, and if the condition persists they may decrease the generator excitation, or trip the generator and field breakers, or both. The generator manufacturer should be requested to provide their recommendation for overexcitation protection.

Overexcitation (V/Hz) relays are for use on transformers located either at, or remote from, generating stations. They are available with a definite time delay or an inverse time V/Hz characteristic and may be connected for trip or alarm.



NOTE: See 7.2.4

Figure 13—Transformer Overexcitation Limits of Three Manufacturers

Fig 13 shows three manufacturers' curves for permissible short time overexcitation of a transformer for determining V/Hz relay settings. Specific data for a particular transformer should be requested from the transformer manufacturer.

7.3 Testing Thermal Relays

Manufacturers recommendations should be followed in testing and calibrating these devices. One method with one design is to remove the relay from the transformer and immerse the temperature sensitive element in a controlled temperature oil bath. The heating element which provides the load current effect is an integral part of the well in which the relay sensing element is mounted, and provision is made to circulate current from a test source through this heater to check the operation of this element. These relays consist of dial-type temperature indicators with shaft operated switches and the design shall ensure that the high-temperature contact, which is used for tripping, cannot be operated by reverse rotation under very low temperature conditions.

Calibration procedures should ensure that the relay contacts and the temperature-dial indication are within specified limits. The thermal time constant of the system is not usually field adjustable. It can be confirmed by plotting the indicated temperature versus time duration of a constant load current. The time constant is the time it takes for the reading to reach 63.2% of the total change of temperature readings. This should relate to the 5 – 15 min time constant of the transformer winding, rather than to the 1 h to 2 h time constant of the oil. The calibration cannot be considered complete without confirming the ratio of the current transformer used to provide current to the relay heating element. These current transformers are generally made to saturate at high-fault current, so as to avoid heater damage and to ensure that the thermal relay does not operate before planned protective-relay action occurs. Should severe overloads also cause current transformer saturation, the thermal relay will not respond in the desired manner.

8. Fault Clearing

A faulted transformer can be separated from its power source by devices such as circuit breakers, power operated disconnect switches, circuit switchers, fuses, or by remote tripping of fault interrupting devices. In addition to separating the transformer from its power source, due consideration should be given to tripping oil pumps and fans to reduce their possible adverse effects in sustaining or spreading a transformer oil fire. Determination of the type of fault clearing devices to be used should involve considerations such as:

1) Installation and maintenance cost
2) Fault clearing time relative to fire hazard and repair or replacement costs of the transformer
3) System stability and reliability
4) System operating limitations
5) Device interrupting capability

8.1 Circuit Breakers

Circuit breakers directly actuated by a protective relay system are usually provided where it is desirable to isolate a faulted transformer with minimum effect on other segments of the power system. They offer the fastest fault clearing time and highest interrupting capability.

8.2 Remote Tripping of Circuit Breakers

In some situations it may be difficult to justify the cost of local circuit breakers. Tripping of remote source circuit breakers by use of local relays and a communications channel, or by use of fault-initiating switches (high-speed ground switch) are alternatives.

8.2.1 Transfer Trip Schemes

Three types of communication channels are in general use for transferring a trip signal to remote circuit breakers: wire, power-line carrier, and microwave or radio. In direct-transfer trip schemes, the receipt of a signal will trip remote circuit breakers independently of remote relays. The signal may be a simple application of voltage or audio tones on a pair of wires or may utilize frequency-shift type audio tones, or frequency-shift carrier. Frequency-shift equipment employs a *guard* frequency for channel monitoring and added security against trips by spurious signals. Transformer protective relays will actuate the shift to *trip* frequency. These schemes have the advantage of speed and the capability to block reclosing of the remote circuit breakers until the faulted transformer is isolated from the system.

8.2.2 Fault Initiating Switch (High Speed Ground Switch)

Remote tripping of circuit breakers can be accomplished by applying a fault t usually solid single phase-to-ground) to the source line so that the remote line relays will detect it and trip the remote circuit breakers. A disadvantage of this scheme is the additional time involved while the ground switch is closing and remote relays in turn detect the fault. Another consideration is that the ground switch phase and the faulted phase on the transformer may be different, thus imposing a multi-phase fault on the system.

8.2.3 Disconnecting Switch

When remote tripping is used, a power-operated disconnecting switch is usually connected on the source side of the transformer to isolate it from the system. The switch is arranged to open automatically and cancels the remote transfer trip signal, or isolates the ground switch from the system. In both cases, this permits the remote breakers to reclose.

8.3 Circuit Switcher

A circuit switcher is a mechanical switching device with a limited fault interrupting rating. Internal faults or secondary faults limited by transformer impedance, where the magnitude of current is below the interrupting rating of the circuit switcher, can be cleared. It should be possible to coordinate remote line relays to avoid remote tripping for the lower magnitude faults. High magnitude source side faults on the transformer exceeding the interrupting rating of the circuit switcher must be detected by remote line relays and cleared by the remote breakers before the circuit switcher opens. The circuit switcher may be blocked from tripping using an instantaneous overcurrent relay or it may be allowed to attempt interruption depending on user preference.

8.4 Fuses

When applicable, power fuses are used due to their low installation cost and simplicity. See 5.1.

8.5 Other Practices

It is not uncommon to adapt permissive-overreaching tone or carrier-blocking line protection schemes to permit the remote line relaying to operate to clear a faulted transformer from the electric system. If line protection schemes employ impedance measuring types of relays, however, they may not respond to low side or winding faults.

Another practice involves the use of the source side motor operated disconnect switch with no-fault interrupting capability as a backup for one of the above applications. The transformer protective relays initiates opening of the switch independently of other protective devices on the basis that should it fail, a fault develops of a magnitude sufficient to cause remote relay operation. These switches are usually quite slow in opening (2 sec or more) depending on the motor operator used.

9. Re-energizing Policy

There is no universal policy with respect to re-energizing a transformer that has been disconnected from the system by relay action that may have been caused by a transformer fault. Since no one would intentionally energize a transformer knowing it to be faulted internally, the differences in practice seem to be based on the lack of knowledge of where the fault was or, if there was a fault.

Consider a transformer differential arrangement that includes external leads. A fault within the differential zone may not be an internal fault. If the transformer has a pressure relay, this may give indication of an internal fault. If not, one has to rely on the presence or lack of evidence indicating an external fault. In the absence of this definite information that a fault was external, most operating companies will not re-energize the power transformer without a complete check.

Now consider a form of transformer protection that includes just the transformer. This may be a differential relay (operating from transformer bushing current transformers) or a pressure relay. The one reason to re-energize a transformer so protected is the lack of confidence in the relays. While a few may re-energize a transformer so protected, it may be argued that such a practice does not appear to be warranted with modern relays.

The use and location of the transformer will affect the decision whether or not to re-energize. One is less likely to re-energize a generator step-up transformer or a large system tie transformer than a small substation transformer. The presence of a spare transformer would lessen the necessity to re-energize right away. A history of failures of a certain type transformer may affect the decision by operating companies to re-energize that type of transformer.

If a user's policy is not to re-energize after a protective relay has disconnected the transformer from the system, a real and continuing problem is how to proceed after such a relay operation; that is, if no fault is evident upon visual inspection, what should be done to determine whether or not an actual fault exists. Several tests are available to check a transformer prior to re-energization. Turns ratio tests, resistance tests, and low-voltage impulse tests are available, but gas analysis is now the most used test. Gas analysis has become increasingly popular and found to be quite reliable when properly performed [10], [13].

Normally, power transformers are not re-energized by automatic reclosing schemes except where the transformer may be connected to a line or bus which may be re-energized following a relay trip by the line or bus-protective relays. The transformer protective relays usually operate a lock-out relay which trips the local interrupting devices (power circuit breaker, circuit switcher or disconnect switch) and prevents the devices from closing. Where a local interrupting device is not present, transfer trip may be used to operate a remote interrupting device. The transfer trip may also be used to lock out the remote interrupting device, thus preventing re-energizing the transformer (Section 8). If an automatic grounding-switch is used on the high side of a transformer and high-speed reclosing is used on the line, the transformer will probably be re-energized before a high-side motor operated disconnect switch (MODS) can open. However, if delayed reclosing is used on the line, the MODS will have time to open and the transformer will not be re-energized.

If a transformer tapped on a line is fused on the high side, there is no way to prevent its re-energization if the line relays detect the fault and trip, unless all three fuses blow.

Philosophies have changed somewhat in recent years, in that operating companies seem to have an increasing reluctance to re-energize transformers following a protective-relay operation where the transformer might be subjected to a second fault. This reluctance is partly because of recent transformer failure rates and partly because of increased cost and time to repair internal failures. Also, operating companies are gaining more, confidence in protective relays, particularly pressure relays.

10. Gas Analysis

Electrical faults in oil-filled transformers usually generate gases, some of which are combustible. Many transformer faults in their early stages are incipient and deterioration is gradual, but sufficient quantities of combustible gases are usually formed to permit detection and allow corrective measures to forestall a serious outage. To determine if combustible gases have been formed, a sample from the gas space of a transformer may be analyzed. This can be done in the field by utilizing commercial gas detectors. At the time this method was first developed [13], a classification table of total combustible gas readings was published as a guide for evaluation of test results. This method was admittedly approximate since a single reading has relatively small value and its use was recommended to be tempered with judgment and influenced by previous records. It has proved to be a reliable criterion [18]. However, specific transformer manufacturers should be consulted.

Classification of gas detector readings is as follows:

1) 0% to 0.5%, no indication of incipient fault
2) 0.5% to 1.0%, take periodic gas samples two weeks to one month apart, until possible upward or downward trend of readings is established
3) 1.0% to 5.0%, take immediate additional gas samples and prepare to investigate the cause, preferably by internal inspection of transformer
4) Higher than 5.0%, remove the transformer from service until the cause is located and remedied

Gas analysis on transformers should be made periodically by manual or automatic methods. The interval between tests may be varied according to size, importance, loading, and exposure to faults. This test should also be made following protective relay or relief diaphragm operation and before re-energizing, if practical. It should be made on new transformers following installation and original loading.

If combustible gases are found, gas samples may be further analyzed by a mass spectrometer for identification of the various components which may indicate more directly the source of the combustibles [17].

11. Special Protective Schemes

Many transformer protection problems can be solved by means of special current transformer connections. The applications presented are in industry use but are not readily found in the published literature.

11.1 Overall Unit Generator Differential

11.1.1 Configuration

This consists of a unit generator and a transformer with the winding of the generator in wye, high impedance grounded through a transformer with secondary resistor. The unit transformer low side winding is in Δ with the high side winding in a solidly grounded Y.

11.1.2 Problem

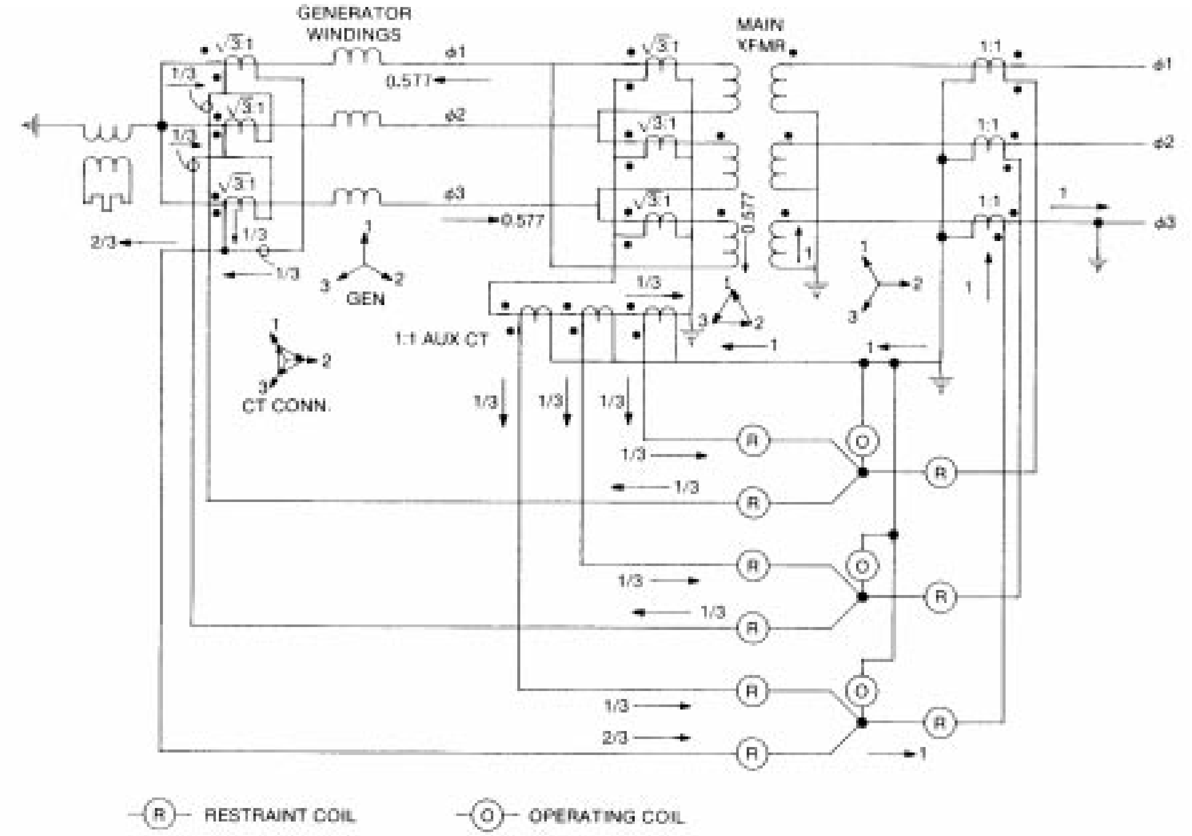
Overall unit-differential relay operation on sudden unloading of a machine is to be avoided. False tripping and indicating of unit trouble can cause operating confusion and delay restoration.

A sudden unit unloading during a fault may be caused by the clearing of a system fault and hence the machine may be at ceiling excitation if the fault has persisted for a second or more. The unit transformer may be excited with voltages exceeding 130% of normal. Because of transformer iron saturation with overexcitation, the exciting current can exceed 25% of the unit current rating. Hence, for relays without overexcitation restraint capability, normal differential relay connections could result in relay operation under these conditions.

11.1.3 Solution

As the transformer magnetizing current has appreciable harmonic content during overvoltage conditions, this current is used for additional restraint. Thus, the normal differential current transformer connections are altered as shown in Fig 14. The additional restraint is provided by inside-the-delta current transformers having the same ratio as those on the generator. The paralleling of the inside-the delta current transformers eliminates normal load current. Only zero sequence current, 3rd harmonics and odd multiples of the 3rd harmonic are supplied to the primaries of the three auxiliary-current transformers connected in series. The output of the auxiliary current transformers is connected in Y and each supplies a differential relay restraint coil.

Normally a three-restraint coil differential relay is used for the overall unit. The three-relay restraint coils are supplied from the generator, transformer high side, and station service transformers current transformers. To provide separate relay restraint from the inside delta-current transformers, the station service transformer differential current transformers are now paralleled with the generator current transformers.



*Adjust Ratio to Increase Relay Current Approximately 25% for 3 Legged Core Form Transformers to Avoid Undersired Tripping on Overexcitation

NOTES: (1) See 11.1 and 11.2

(2)For simplicity, the station service current transformer connections are not shown in Figure 14.

Figure 14—Special Differential Relay Connections for Over-all Protection of Unit Generator

The conventional differential connections have Y-current transformers on the Δ-winding side and Δ-current transformers on the high-side grounded-Y winding. Thus the Δ-current transformers on the high side normally act as zero-sequence filters. However, as zero-sequence current is now inserted in the low-side connections, it also shall be introduced in the high-side connections. This is done by connecting the high-side current transformers in Y. Then, for proper phasing relationship, the low-side current transformers are connected in Δ. Considering only the generator Δ current transformers and the transformer high-side Y current transformers, it is interesting to note that this connection is proper for load and external phase faults but not for external ground faults. The inside-the-delta current transformers provide the balance for external ground faults.

Thus, on overexcitation of an unloaded transformer, additional harmonic restraining current is provided to prevent misoperation of the relays. These current transformer connections to the harmonic restraining differential relays have been tested to 135% normal voltage. The transformer of one unit tested had a 150 MVA, 17/132 kV rating with exciting current of 23 A at normal voltage. With 135% of normal voltage applied, the exciting current was 604 A. On another 150 MVA, 17/132 kV unit, 135% of normal voltage resulted in 1175 amperes exciting current which is 23% of full-load current. The saturation characteristic of each transformer determines the magnitude of exciting current at ceiling generator voltages. Several installations have performed correctly following clearing of high-voltage bus faults.

Figure 14 also shows the proper balance for an external ground fault. The main transformer is given as 1:1 overall voltage ratio and the current transformer ratios are shown for this condition. The fault current is assumed as one per unit. Phasors for the current-transformer connections are also shown in Fig 14.

NOTE — This modification must be used with caution since transformers have been severely damaged by high temperatures from excessive magnetizing current. When this scheme is used, overexcitation relaying should be considered.

11.2 Unit Transformer of Three Legged Core Form Type

If the unit transformer has three-legged core form construction, the zero-sequence current contribution of the transformer case is not accounted for by the connections shown in Fig 14. In such core form transformers, the case may contribute as much as 20%–25% of the zero-sequence current. Thus the previously described differential connections require modification. While exact solutions are possible with additional auxiliary-current transformers, for simplicity, these are not discussed. A simple empirical solution is to adjust the ratio of the inside-the-delta auxiliary-current transformers so that the current to the relay is increased by 25% (Fig 14). The ratio of the auxiliary-current transformers can be determined more accurately from the transformer manufacturers zero-sequence impedance test data.

11.3 Grounding Transformer Inside the Main Transformer Differential Zone

11.3.1 Configuration

To establish a grounded system, a grounding transformer is frequently tapped on the low-side leads of the supply transformer and is thereby included in the transformer differential zone.

11.3.2 Problem

Zero-sequence current supplied by the grounding transformer may cause differential relay operation during an external ground fault.

11.3.3 Solution

Since external ground faults cause zero-sequence current to flow in the current transformer secondary circuits, a zero-sequence filter is provided for the low-side differential Y-connected transformers. This filter is composed of three auxiliary-current transformers and can be formed in several ways. The simplest form is to connect the primaries in Y and the secondaries in Δ. In Fig 15, the ratio of the auxiliary current transformers is not critical, but a 5/5 A ratio is suggested.

The alternate filter connection in Fig 15 requires a 1 to 3 ratio for the auxiliary-current transformers. The primaries are connected in Y and the junction or sum of the primaries is wired to the secondaries connected in series. Thus the secondaries carry three times the primary current.

NOTE: See 11.3

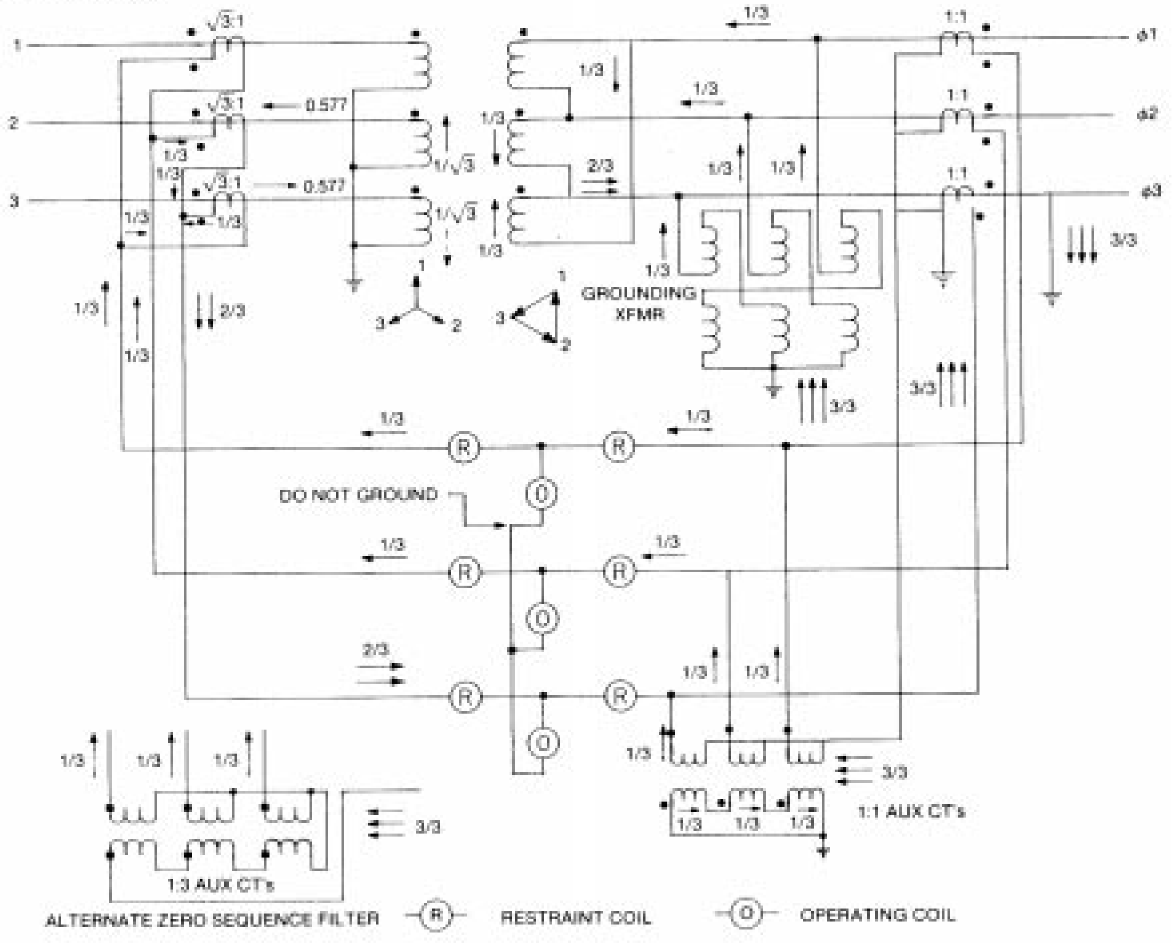


Figure 15—Grounding Transformer in Differential Zone (External Fault Condition Shown)

Both of these connections present relatively high-magnetizing impedance to all but zero-sequence current. However, modern differential relays are of even lower burden than the usual auxiliary current transformers. Thus, the common point of the relay connections should not be connected to the common point of the Y-connected transformers (a connection which is necessary without the zero-sequence filter). Only the filter neutral should be connected to the current transformer common point.

Figure 15 also shows the primary current and current-transformer secondary current for an external ground fault. The zero-sequence filter prevents a relay imbalance. A 1:1 overall voltage ratio is assumed in Fig 15 with one per unit of fault current flowing.

11.4 Unbalanced Voltage Protection for Wye-Connected Three-Legged Core-Type Transformers

11.4.1 Configuration

Three-phase three-legged core-type wye-wye-connected transformer or autotransformer.

11.4.2 Problem

In wye-connected core-type transformers, the transformer case acts as a high impedance delta winding during unbalance voltage conditions. Damaging heat can be produced by sustained circulating current in the case.

11.4.3 Solution

An overcurrent relay is energized by current transformers connected to duplicate the effective tertiary current in the case. For a two-winding transformer, the required zero-sequence current is obtained by the connection of high- and low-side neutral-current transformers as shown in Fig 16(a). An alternate method is shown in Fig 16(b) wherein the sum of the residuals of Y-connected high- and low-side current transformers is used. Fig 16(c) shows the connections for an autotransformer using the residual of Y-connected current transformers and a neutral-current transformer.

11.4.4 Relay Setting

The proper equivalent tertiary impedance of the case shall be used to determine the zero-sequence current for various faults. From this, the required relay sensitivity is established. A long time-dial setting for overcurrent relay operation will provide thermal protection and coordination with other relaying for external faults.

An application example using an inverse relay, has relay pickup at 30% of transformer rating and a time of 1.7 s at 300% of setting. The pickup depends on the effective contribution of the equivalent tertiary of the case. The transformer manufacturer should be consulted.

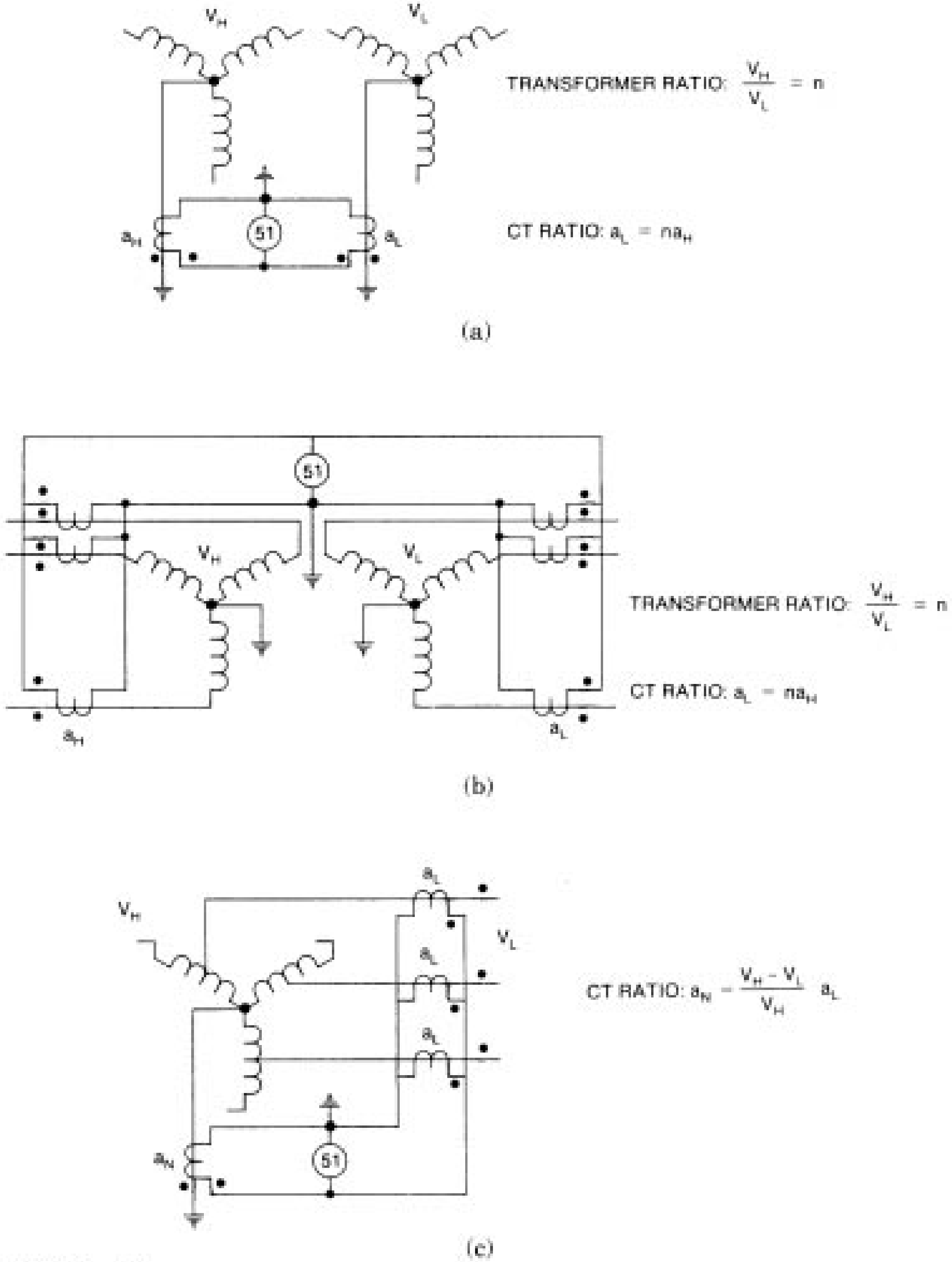
11.4.5 Alternative Solution

See 7.2.3

11.5 Differential Protection of Single Phase Transformers Connected in Three Phase Banks

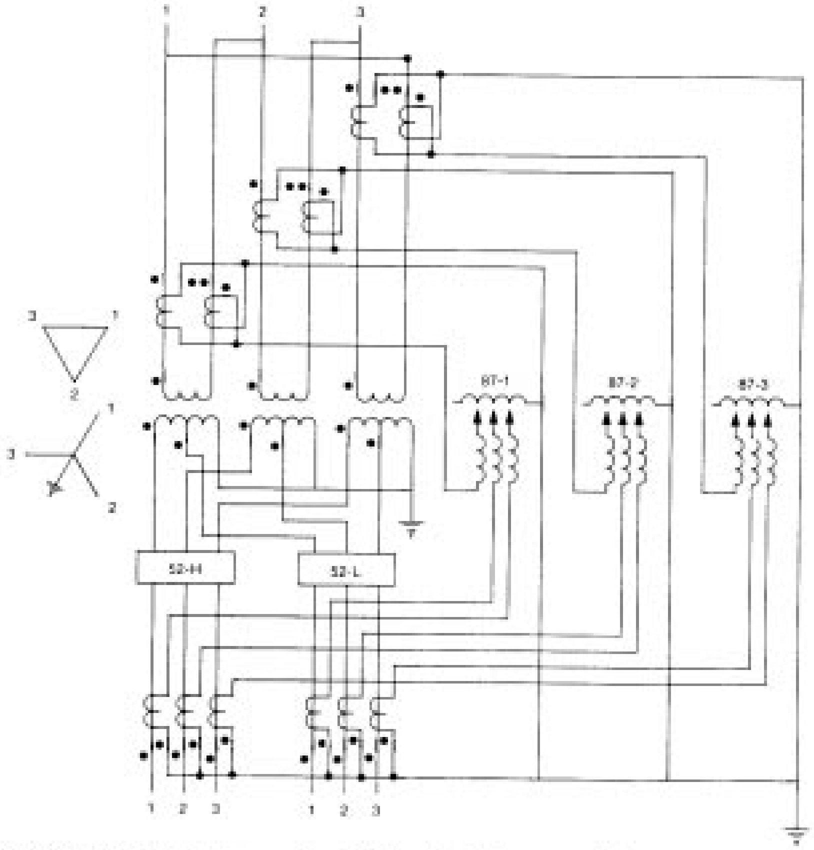
When single-phase transformers are connected in three-phase banks, care should be taken to ensure that a differential relay will operate for all internal transformer faults, particularly when the transformer has a Δ–connected winding. If current transformers for the Δ tertiary are located in a breaker, the differential may be connected, as it normally is for a three-phase transformer. But if the current transformers shall be located in the transformer, some special connections should be considered.

Complete protection for internal faults requires current transformers on both bushings of a winding if that winding is in a three-phase Δ connection. Without current transformers on both bushings an internal bushing flashover can go undetected by a differential relay if the connected system is grounded.



NOTE: See 11.4

Figure 16—Protection of Wye Connected Core Type Transformers with no Delta for Unbalanced Voltage Conditions

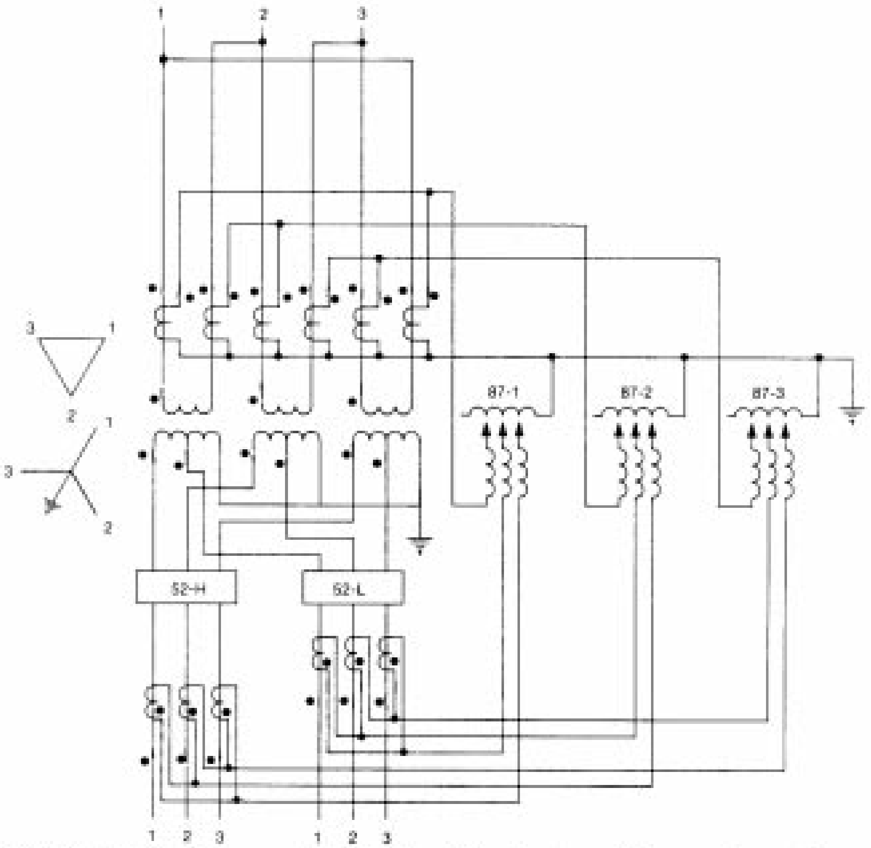


NOTES: (1) This scheme requires additional relaying to provide protection on the tertiary make-up bus.
(2) See 11.5

Figure 17—Differential Protection of Single Phase Transformers Connected in Three Phase Banks

Figures 17 and 18 show two differential relay connections to provide complete winding protection for the Δ winding on an autotransformer with a Δ tertiary. Note that the current transformer ratios and taps used shall take into account that the current transformers in the Δ supply the relay with two times winding rent.

There are advantages for both connections. The connection shown in Fig 17 provides greater relay sensitivity because of the method of connecting the current transformers in the Δ tertiary. Additionally, 3rd harmonic current in the Δ flows in the differential relay restraint circuit. The connection shown in Fig 18 will permit more than one relay to detect an internal fault with Δ-connected current transformers on the high side and the connection is more like that normally used on the three-phase transformer. Also, note that the high-side current transformer shown in connections of Fig 17 shall not be used without the current transformers in the tertiary. If connected in Y, the differential could operate for an external ground fault without the tertiary current transformers to balance it. While other relays, such as fault pressure, would probably detect these internal faults, then most likely the differential relay should be connected so as to operate for all faults internal to the protected transformer.



NOTES: (1) This scheme requires additional relaying to provide protection on the tertiary make-up bus.
(2) See 11.5

Figure 18—Differential Protection of Single Phase Transformers Connected in Three Phase Banks

11.6 Differential Protection of Single Phase Transformers in a Three Phase Bank with a Spare Transformer

With the increase in usage of single phase transformers in three-phase banks with spare transformers, the question frequently arises of how to best include the spare in a transformer differential scheme. Differential relay connections are dependent to some extent on transformer connections, location of current transformers, and whether or not the spare power transformer will be energized all the time.

If the differential zone extends to circuit breakers on both sides of a transformer, then changing the current transformer secondary circuits is not required to place the spare transformer in service. However, if the spare transformer is to remain energized all the time, consideration shall be given how to protect the spare when not in use. When the transformer bank differential is used to protect the spare transformer the result is not always as sensitive to protection of the spare as of the transformers in service.

If bushing current transformers are used on both sides of the transformer bank, a separate relay for the spare could be used to facilitate rapidly placing the spare transformer in service. This is true whether or not it will remain energized. It will provide an energized spare with adequate protection. To connect a differential relay for three-phase and single-phase transformers, see 11.5.

The most difficult situation to handle is that where current transformers on one side of transformer bank are located in a circuit breaker and the other in the transformer. Unfortunately, this is a common occurrence. In this case, current transformer secondary circuits have to be switched or rewired to place the spare power transformer in service.

With any of the above combinations of transformer connections, it is possible to switch or rewire the current transformer secondaries. However, switching current transformer secondary circuits is not recommended as a good practice without a thorough analysis of the switching device and the risks of an open current transformer connection during the switching, or the result of a defective switching contact.

12. Device Numbers

Device numbers are used in this guide as outlined in ANSI/IEEE C37.2-1979 [1], Section 3

26	Thermal device
49	Thermal relay
50N	Instantaneous neutral overcurrent relay
51	Alternating-current time overcurrent relay
151N	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
59	Overvoltage relay
63	Pressure switch or relay
67	Alternating-current directional overcurrent relay
67N	Alternating-current directional overcurrent relay, neutral
87	Differential relay

13. Bibliography

13.1 General Information

[B1] ANSI C2-1984, National Electrical Safety Code.

[B2] ANSI/IEEE C57.12.01-1979, IEEE Standard, General Requirements for Dry-Type Distribution and Power Transformers.

[B3] ANSI/IEEE C57.12.90-1980, IEEE Standard, Test Code for Distribution, Power and Regulating Transformers.

[B4] ANSI/IEEE C57.12.91-1979, IEEE Standard for Dry-Type Distribution and Power Transformers.

[B5] ANSI/IEEE Std 142-1982, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems.

[B6] IEEE Std 242-1975, IEEE Recommended Practice for Protection. and Coordination of Industrial and Commercial Power Systems (IEEE Buff Book).

[B7] BEAN, R.L., CHACKAN, N., MOORE, H.R., and WENTZ, E.C. Transformers, New York: McGraw-Hill, 1959.

[B8] BLUME, L.F., BOYAJIAN, A., CAMILLI, G., MONTSINGER, V.M., LENNOX, T.C., and MINNECI, S. Transformer Engineering. New York: John Wiley, 1951.

[B9] DUTTON, J.C. and McNUTT, W.J. Transformer Standards—Status and Trends. *IEEE Transactions on Industry Applications*, vol IA-16, no 1, Jan/Feb, 1980, pp. 17–19.

[B10] GRIFFIN, C.H. Relay Protection of Generator Station Service Transformers. *IEEE Transactions on Power Apparatus and Systems* vol 101, no 8, Aug, 1982, pp 2780–2789.

[B11] LAZAR, I. Transformer Protection and Relaying in Industrial Power Plants. *Power Engineering*, vol 83, No 5, May, 1979, pp 56–61.

[B12] McCAULEY, T.M. Through-Fault Capability Requirements for Unit Auxiliary Transformers. *IEEE Transactions on Power Apparatus and Systems*, vol 96-5, Sept/Oct 1977, pp 1639–47.

[B13] McNUTT, W.M., McMILLEN, C.J., NELSON, P.Q., and DIND, J.E. Transformer Short-Circuit Strength and Standards (A state-of-the-art paper) *IEEE Transactions on Power Apparatus and Systems*, vol 94-2, Mar/Apr 1975, pp 432–43.

[B14] McNUTT, W.J. Short-Circuit Characteristics of Transformers. *IEEE Course Text* 76 CH1159-3-PWR, 1976.

[B15] STIGNANT, S.A., and FRANKLIN, A.C. J and P Transformer Book. New York: Wiley, 1973.

[B16] Transformer Standards—Status and Trends. *IEEE Transactions on Industry Applications*, vol IA-16, Jan/Feb, 1980, pp 17–29.

[B17] WENTZ, E.C., and ALLEN, D.W., Help for the Relay Engineer in Dealing with Transient Currents. IEEE *Transactions on Power Apparatus and Systems*, vol 101, no 3, Mar, 1982 pp 519–524.

13.2 Fault Detection

13.2.1 General

[B18] BAUMAN, H.A., BEATTIE, W.C., and DRISCOLL, J.M. Automatic Trip Protection for Boiler-Turbine-Generator-Transformer Unit Installations. Paper no 312, CIGRE, June 1960.

[B19] BRUBAKER, J.F. Fault Protection and Indication on Substation Transformers. *IEEE Transactions on Power Apparatus and Systems*, vol IA-13-3, May/June 1977, pp 199–207.

[B20] KLINGSHIRN, E.A., MOORS, H.R., and WENTZ, E.C. Detection of Faults in Power Transformers. *AIEE Transactions*, vol 76, pt III, Apr 1957, pp 87–98.

[B21] LABRIE, R.J. Protects Autotransformer Tertiary. *Electrical World*, vol 150 no 2, July 14, 1958, p 60.

[B22] MARTIN, J.P., WENDLING, J., and TOURNIER, Y. Specifics of the Short-Circuit Behavior of Concentrically-Wound Transformers and Autotransformers. *IEEE Transactions on Power Apparatus and Systems*, vol 99, no 6, Nov/Dec 1980, pp 2069–2078.

[B23] PERRY, E.R., and FREY, A.M. Transformer Protection with High-Speed Fault Initiating Switches. *Allis Chalmers Review*, vol 30, no 4, 1965, pp 4–8.

[B24] RICKLEY, A.L. SR, CLARK, R.E., and POVEY, E.H. Field Measurements of Transformer Excitation Current as a Diagnostic Tool. IEEE *Transactions on Power Apparatus and Systems*, vol 100, no 4, Apr, 1981, pp 1985–1988.

[B25] RIZK, F.A.M. and VINCENT, C. Testing for Low Breakdown Probability with Special Reference to Liquid Insulation. IEEE *Transactions on Power Apparatus and Systems*, vol 96, no 8, Nov/Dec, 1977, pp 1892–1899.

[B26] STAATS, G.W., and EBERT, J.A. Overvoltages in Medium Power Transformers. IEEE *Transactions on Power Apparatus and Systems*, vol 101, no 4, Apr, 1982, pp 877–885.

13.2.2 Electrical

[B27] Central Station Engineers Transmission and Distribution Reference Book, Westinghouse Electric Co, East Pittsburgh, PA, 1950, pp 126–188.

[B28] DOLAN, E.J., GILLES, D.A., and KIMBARK, E.W. Ferroresonance in a Transformer Switched with an EHV Line. IEEE *Transactions on Power Apparatus and Systems*, vol 91, no 3, May/Jun, 1972, pp 1273–1280.

[B29] EINVAL, C.H. and LINDERS, J.R., A Three-Phase Differential Relay for Transformer Protection, IEEE *Transactions on Power Apparatus and Systems*, vol 94-6, Nov/Dec 1975, pp 1971–1980.

[B30] GLASSBURN, W.E. and SHARP, R.L., A Transformer Differential Relay with Second Harmonic Restraint. *AIEE Transactions*, vol 77, pt III, Dec 1958, pp 913–918. <

[B31] GOODMAN, E.A. A New Approach to Distribution Trans. former Protection. *Proceedings of the American Power Conference*, vol 34, 1972, pp 984–992.

[B32] MATHEWS, C.A. An Improved Transformer Differential Relay. *Electrical Engineering*, pt III-A June 1954, pp 645–649.

[B33] MCKENNA, G.W. Theory and Application of Transformer Differential Protection. *AIEE Transactions*, no 69, pt 2, 1950, pp 1197–1202.

[B34] POVH, D., and SHULTZ, W. Analysis of Overvoltages Caused by Transformer Magnetizing Inrush Current. *IEEE Transactions on Power Apparatus Systems*, vol 97, no 4, Jul/Aug, 1978, pp 1355–1365.

[B35] SHAH, V.B. Power Transformer Protection. Checking Connections of Ratio Differential and Circulating Current Relays. *Electrical Review*. London no 149, 1951, pp. 937–940.

[B36] SMITH, R.L. Practical Low-Voltage Equipment Ground.Fault Protection for Solidly-Grounded Systems with Wye-Connected Source Transformers. *IEEE Transactions on Industry Applications*, vol 13, no 2, Mar/Apr, 1982, pp 93–103.

[B37] SPIESS, H. A New Surge Restrained Differential Relay for Transformer Protection. *Bulletin Oerlikon*, no 306, Oct 1954, pp 77–90.

[B38] STURTON, A.B. A New Differential Stand-by Protection. *Electrical Engineering*, vol 82, Dec 1963, pp 745–746.

[B39] WALDRON, J.E., and ZOCHOLL, S.E. Design Considerations for a New Solid-State Transformer Differential Relay with Harmonic Restraint. *Western Protective Relay Conference*, Oct 15–18, 1978.

13.3 Fuse Protection

[B40] ANSI/IEEE C37.40-1981, IEEE Standard Service Conditions and Definitions for High-Voltage Fuses, Disconnecting Switches, and Accessories.

[B41] FITZGERALD, E.M. andSTEWARD, V.N., High Capacity Current Limiting Fuses Today. *AIEE Transactions*, 1959, vol 78, part III A, pp 937–947.

[B42] GRUESEN, K.R. LARNER, R.A., Fuse Protection of High-Voltage Power Transformers. *AIEE Transactions*, vol 78, pt III A, Oct 1959, pp 864–878.

[B43] HUBER, W.J. Selection and Coordination Criteria for Current Limiting Fuses, *IEEE Transactions on Industry Applications*, vol 13, no 6, Nov/Dec, 1977, pp 523–527.

13.4 Pressure and Gas Analysis

[B44] ANSI/IEEE C57.104-1978, IEEE Guide for the Detection and Determination of Generated Gases in Oil-Immersed Transformers and Their Relation to the Serviceability of the Equipment.

[B45] ANDERSON, R.N. A New Fault-Pressure Relay Provides Fast, Effective Power Transformer Protection. *Distribution*, vol 21, no 3, July, 1959, pp 8–9.

[B46] BEAN, R.L., COLE, H.L. A Sudden Gas-Pressure Relay for Transformer Protection. *AIEE Transactions*, vol 72, part III, 1953, pp 480–483.

[B47] Boyaris, E. and GUYOT, W.S. Experience with Fault-Pressure Relaying and Combustible Gas-Detection in Power Transformers. *Proceedings American Power Conference*, vol 33, 1971, pp 1116–1126.

[B48] CRAWFORD, C.I., and WILSON, A.F. Incipient Transformer Fault Detected by Combustible Gas Monitoring Program and Ultra-Sound Tests. *Power Apparatus and Systems Transactions*, Sept 1964, vol 83, no 9, p. 926.

[B49] HABERL, H.W., MADILL, J.T., and SMITH, R.K. Extensive Use of Gas Detector Relays in Canada. Paper no 120, CIGRE, June 1960, pp 1–15.

[B50] HARRISON, D. Transformer Gas Testing. *Ontario Hydro Research News*, vol 9, no 4, Dec 1957, pp. 11–15.

[B51] KELLY, J.J. Transformer Fault Diagnosis by Dissolved-Gas Analysis. IEEE Transactions on Industry Applications, vol 16, no 6, Nov/Dec, 1980, pp 777–782.

[B52] WEST, S.P. Maintenance and Tests Make Fault Pressure Relays Reliable. *Electrical World*, Jan 19, 1970, pp 45–46.

13.5 Overvoltage

[B53] ALEXANDER, G.W., CORBIN, S.L. and MCNUTT, W.J. Influence of Design and Operating Practices on Excitation of Generator Step-up Transformers. *IEEE Transactions on Power Apparatus and Systems*, vol 85, no 8, Aug 1966, pp 901–909.

[B54] ALEXANDER, G.W., McNUTT, W.J., TEMOSHOK, J., and WALKLEY, W.W. Generating Station Protection and Operating Practices to Avoid Equipment Overexcitation. *Proceedings of the American Power Conference*, 1967.

[B55] ARTHUR, J., LINDERS, J., and STRANNE, G. An Overexcitation Relay with Inverse Time Characteristics. *Western Protective Relay Converence*, Oct 26–28, 1982.

[B56] BARTHOLD, L.O., JOHNSON, I.B., and SCHULTZ, A.J. Overvoltages Following Secondary Switching of Transformers Connected to High-Voltage Lines. AIEE *Power Apparatus and Systems*, nos 58–1185, Feb 1959.

[B57] BELLASCHI, T.L. Overexcitation of Large Generator Transformers. *Transmission and Distribution*, Aug 1968.

[B58] CLARRIDGE, C.H. New Monitor System Guards Generator Transformers. *Electrical World*, May 2, 1966.

[B59] GOFF, L.E. A Volts Per Hertz Relay for the Protection of Transformers Against Overexcitation. *Georgia Institute of Technology Conference* May 4–5, 1967.

[B60] MCNUTT, W.J., Operation of Power Transformers During Major Power System Disturbances, *General Electrical GED-3237A*.

[B61] Overexcitation of Power Transformers. *General Electric GET-3364A*.

[B62] SEALEY, W.C. Overexcitation of Power Transformers. *Allis-Chalmers Engineering Review*, vol 30, no 4, 1965.

[B63] WAGNER, C.L., Overexcitation Problems and Protection of Generators and Transformers. *Georgia Institute of Technology*, May 4, 1967.

Annex A Application of the Transformer Through-Fault Current Duration Guide to the Protection of Power Transformers

(Informative)

(This Appendix is not a part of ANSI/IEEE C37.91-1985, IEEE Guide for Protective Relay Applications to Power Transformers)

Overcurrent protective devices such as relays and fuses have well-defined operating characteristics that relate fault-current magnitude to operating time. It is desirable that the characteristic curves for these devices be coordinated with comparable curves, applicable to transformers, (See ANSI/IEEE C57.109-1985 [15]), which reflect their through-fault withstand capability. Such curves for Category I, II, III, and IV transformers (as described in ANSI/IEEE C57.12.00 1985 [2]) are presented in this Appendix as through-fault protection curves.

It is widely recognized that damage to transformers from through faults is the result of thermal and mechanical effects. The latter have recently gained increased recognition as a major concern of transformer failure. Though the temperature rise associated with high magnitude through faults is typically quite acceptable, the mechanical effects are intolerable if such faults are permitted to occur with any regularity. This results from the cumulative nature of some of the mechanical effects, particularly insulation compression, insulation wear, and friction-induced displacement. The damage which occurs as a result of these cumulative effects is a function of not only the magnitude and duration of through faults, but also the total number of such faults.

The through-fault protection curves presented in this Appendix take into consideration that the transformer damage is cumulative, and the number of through faults to which a transformer can be exposed is inherently different for different transformer applications. For example, transformers with secondary-side conductors enclosed in conduit or isolated in some other fashion, such as those typically found in industrial, commercial, and institutional power systems, experience an extremely low incidence of through faults. In contrast, transformers with secondary-side overhead lines, such as those found in utility distribution substations, have a relatively high incidence of through faults, and the use of reclosers or automatic reclosing circuit breakers may subject the transformer to repeated current surges from each fault. For a given transformer in these two different applications, a different through-fault protection curve should apply, depending on the type of application. For applications in which faults occur infrequently, the through-fault protection curve should reflect primarily thermal damage considerations, since cumulative mechanical-damage effects of through faults will not be a problem. For applications in which faults occur frequently, the through-fault protection curve should reflect the fact that the transformer will be subjected to thermal and cumulative-mechanical-damage effects of through faults.

In using the through-fault protection curves to select the time-current characteristics of protective devices, the protection engineer should take into account not only the inherent level of through-fault incidence but also the location of each protective device and its role in providing transformer protection. Substation transformers with secondary-side overhead lines have a relatively high incidence of through faults. The secondary-side *feeder* protective equipment is the first line of defense against through faults and its time-current characteristics should be selected by reference to the frequent-fault-incidence protection curve. More specifically, the time-current characteristics of feeder protective devices should be below and to the left of the appropriate frequent-fault-incidence protection curve. Main *secondary-side* protective devices (if applicable) and *primary-side* protective devices typically operate to protect against through faults only in the rare event of a fault between the transformer and the feeder protective devices, or in the equally rare event that a feeder protective device fails to operate or operates too slowly due to an incorrect (higher) rating or setting.

The time-current characteristics of these devices should be selected by reference to the infrequent-fault-incidence protection curve. In addition, these time-current characteristics should be selected to achieve the desired coordination among the various protective devices.

In contrast, transformers with protected secondary conductors (for example, cable, bus duct, or switchgear), experience an extremely low incidence of through faults. Hence, the feeder protective devices may be selected by reference to the infrequent-fault-incidence protection curve. The main secondary-side protective device (if applicable) and the primary-side protective device should also be selected by reference to the infrequent-fault-incidence protection curve. Again, these time-current characteristics should also be selected to achieve the desired coordination among the various protective devices.

For Category I transformers (5 kVA to 500 kVA single-phase, 15 kVA to 500 kVA three-phase), a single through-fault protection curve applies. See Fig A.1. This curve may be used for selecting protective device time-current characteristics for all applications regardless of the anticipated level of fault incidence.

For Category II transformers (501 kVA to 1667 kVA single-phase, 501 kVA to 5000 kVA three-phase), two through-fault protection curves apply. Fig A.2.

1) The left-hand curve reflects both thermal and mechanical damage considerations and may be used for selecting feeder protective device time-current characteristics for frequent-fault-incidence applications. It is dependent upon the impedance of the transformer for fault current above 70% of maximum possible and is based on the I^2t of the worst-case mechanical duty (maximum fault current for 2 s).
2) The right-hand curve reflects primarily thermal damage considerations and may be used for selecting feeder protective device time-current characteristics for infrequent-fault-incidence applications. This curve may also be used for selecting main secondary-side protective device (if applicable) and primary-side protective device time-current characteristics for all applications—regardless of the anticipated level of fault incidence.

For Category III transformers (1668 kVA to 10 000 kVA single-phase, 5001 kVA to 30 000 kVA three-phase), two through-fault protection curves apply. See Fig A.3.

1) The left-hand curve reflects both thermal and mechanical damage considerations and may be used for selecting feeder protective device time-current characteristics for frequent-fault-incidence applications. It is dependent upon the impedance of the transformer for fault current above 50% of maximum possible and is keyed to the I^2t of the worst-case mechanical duty (maximum fault current for 2 s).
2) The right-hand curve reflects primarily thermal damage considerations and may be used for selecting feeder protective device time-current characteristics for infrequent-fault-incidence applications. This curve may also be used for selecting main secondary-side protective device (if applicable) and primary-side protective device time-current characteristics for all applications—regardless of the anticipated level of fault incidence.

For Category IV transformers (above 10 000 kVA single-phase, and above 30 000 kVA three-phase), a single through-fault protection curve applies. See Fig A.4. This curve reflects both thermal and mechanical damage considerations and may be used for selecting protective device time-current characteristics for all applications—regardless of the anticipated level of fault incidence. It is dependent upon the impedance of the transformer for fault current above 50% of maximum possible and is keyed to the I^2t of the worst-case mechanical duty (maximum fault current for two seconds).

The delineation of infrequent—versus frequent-fault-incidence applications for Category II and III transformers can be related to the zone or location of the fault. See Fig A.5.

For convenience, the through-fault protection curves for Category I, II, III, and IV transformers are summarized in Table A.1.

Fuse or overcurrent relay coordination with the through-fault protection curves, or both, are shown in Figs A.6 through A.7.

These should be self explanatory. A primary side fuse or overcurrent relay on a delta primary-wye grounded secondary transformer will *see* only 57.7% of the wye side phase-to-ground fault current. The applicable primary side curves are shifted to the right on the phase-to-ground fault figures to properly show coordination.

An example of the application of the new thermal/mechanical limit curves to a 3-winding autotransformer (wye-wye-delta) with overcurrent relays on the 30 MVA tertiary follows using Table A.2 nameplate data.

The coordination steps are as follows:

1) Select the category from the *minimum* nameplate rating of the *principal* winding (75000 kVA is category IV).
2) Select the impedance to use so as to plot the category IV curves (Z 132–13.2 = 7.94% at 30000 kVA).
3) Calculate “constant” $K = 1^2t = (100/7.94)^2 \cdot 2 = 317.24$ at 2 s.
4) Times normal base current at 2 s » 12.59
5) The 50% point is $(317.24)/(12.59/2)^2$ » 8 s.

The coordination of the overcurrent relays for this example is shown in Fig A.9.

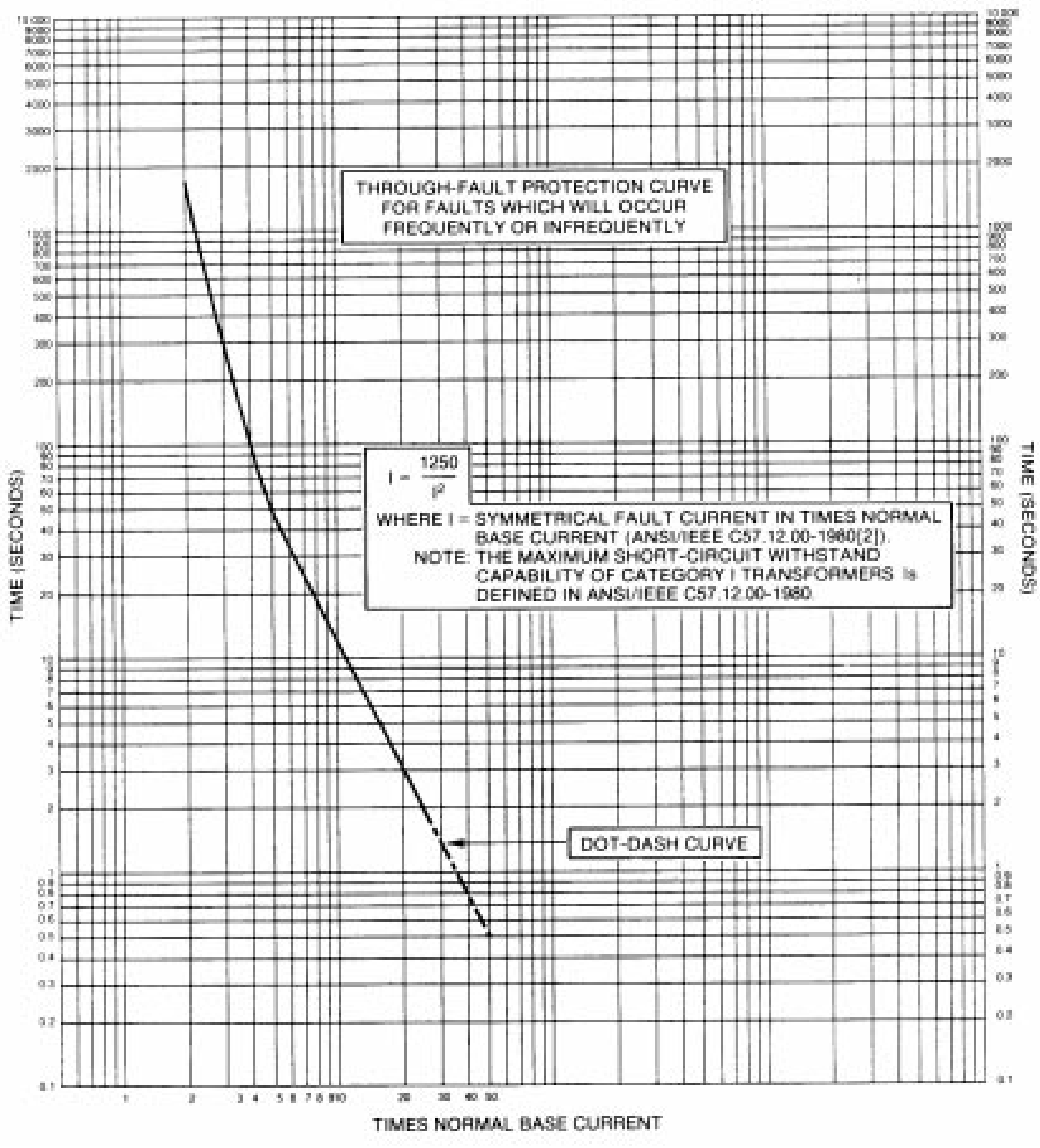


Figure A.1—Category I Transformers
5 to 500 kVA Single-Phase
15 to 500 kVA Three-Phase

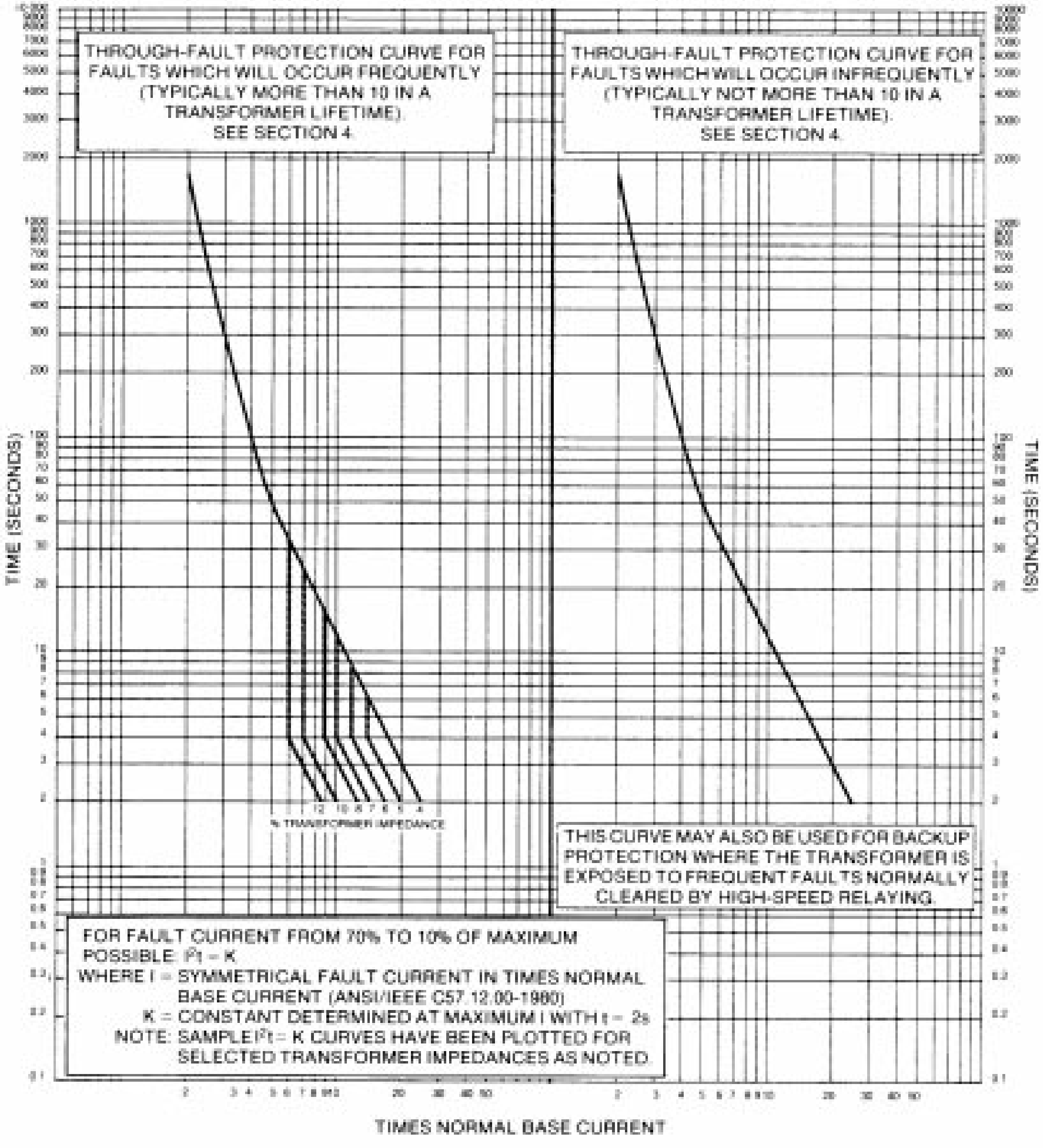


Figure A.2—Category II Transformers
501 to 1667 kVA Single-Phase
501 to 5000 kVA Three-Phase

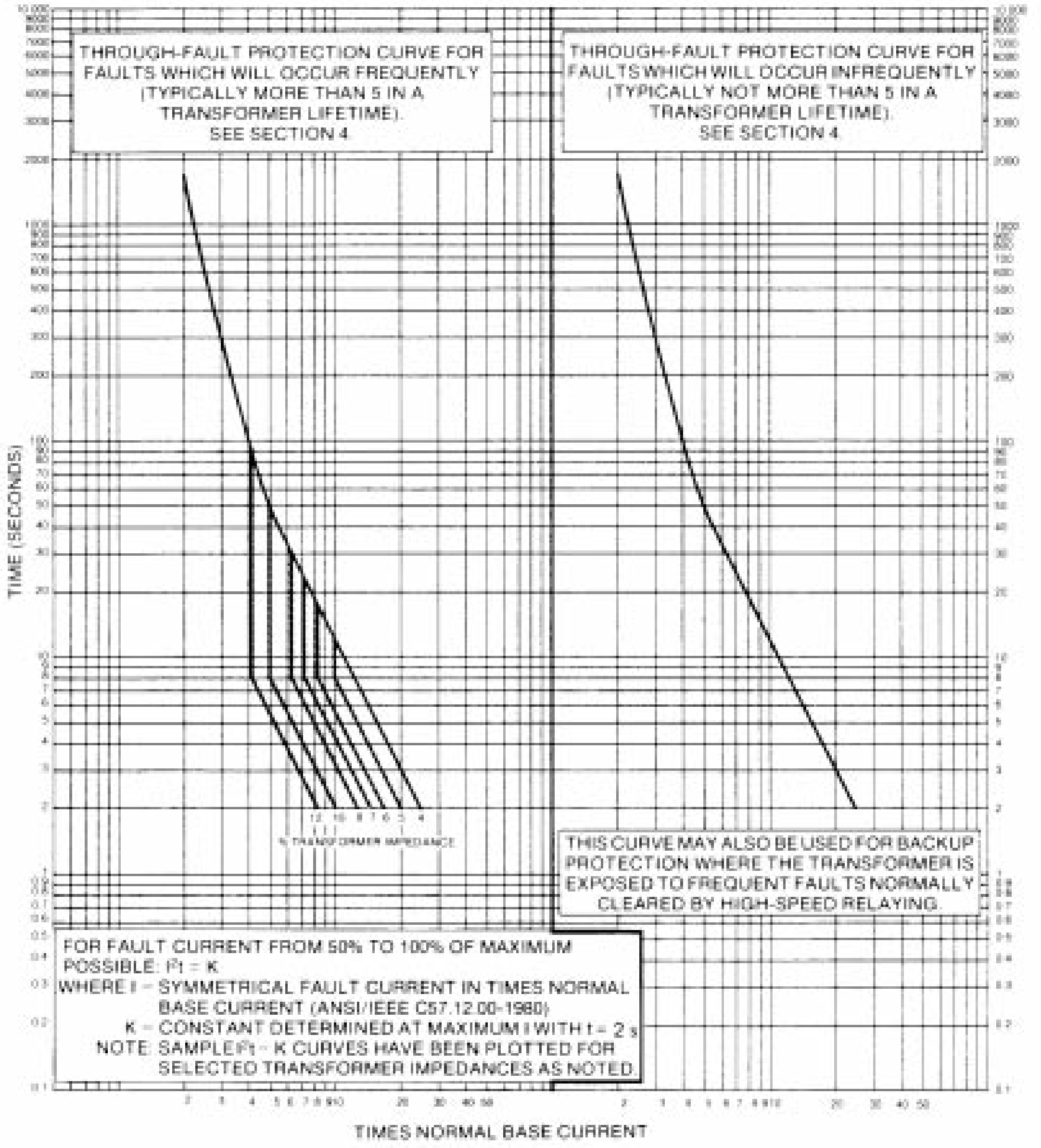


Figure A.3—Category III Transformers
1668 to 10000 kVA Single-Phase
5001 to 30000 kVA Three-Phase

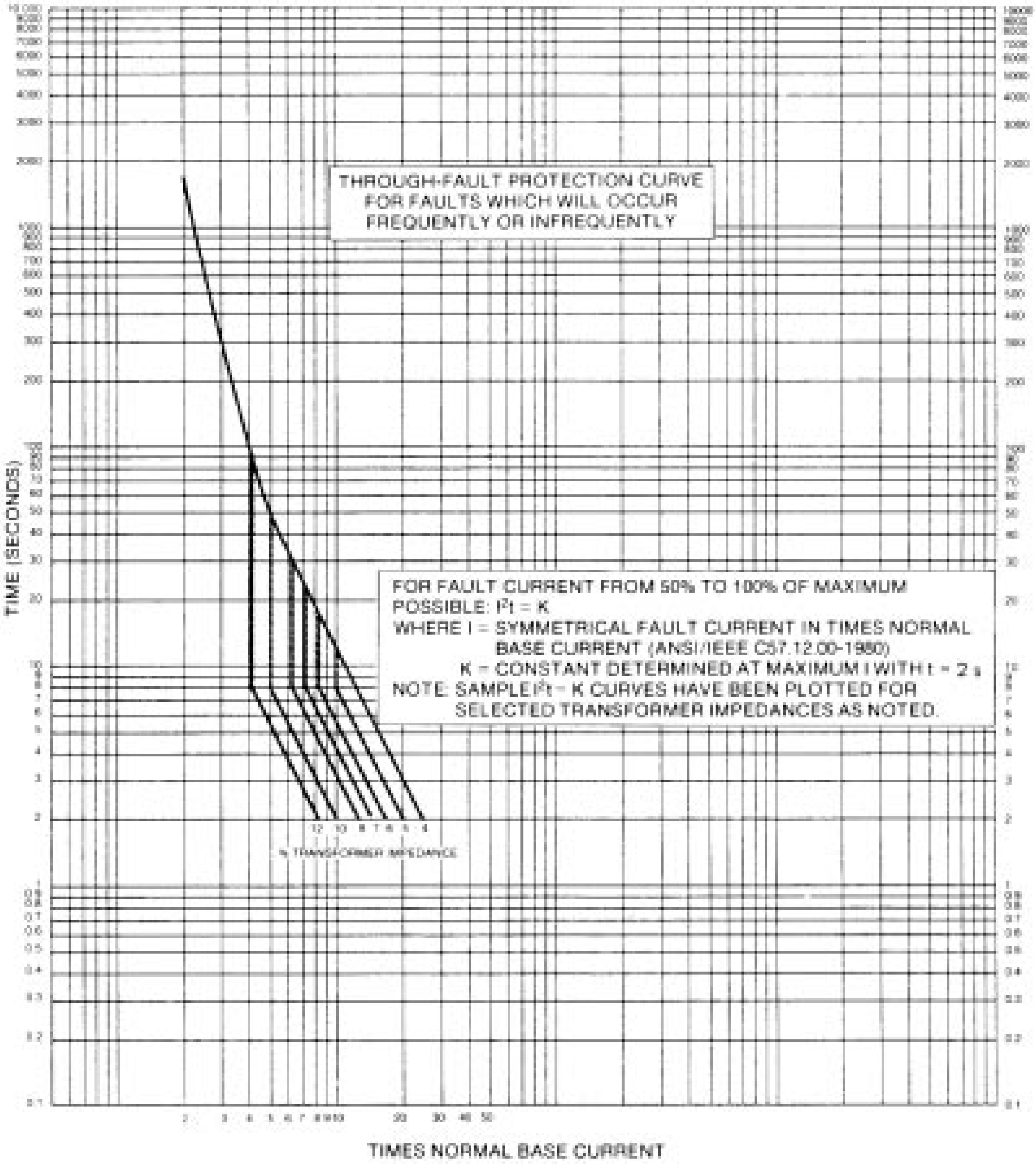
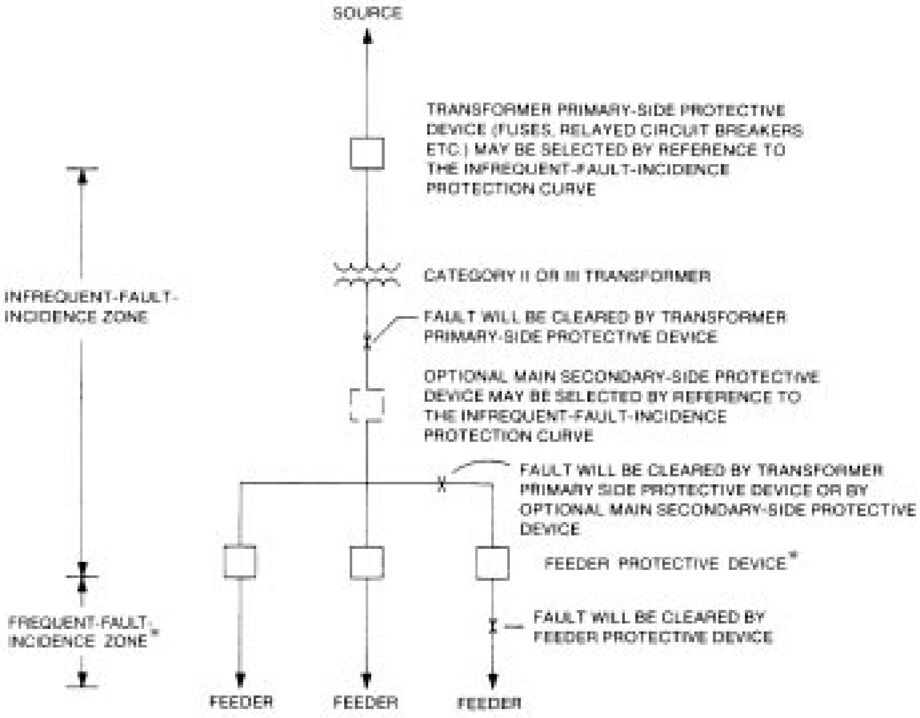


Figure A.4—Category IV Transformers
Above 10000 kVA Single-Phase
Above 30000 kVA Three-Phase



*Should be selected by reference to the frequent-fault-incidence protection curve or for transformers serving industrial, commercial, and institutional power systems with secondary-side conductors enclosed in conduit, bus duct, etc., the feeder protective device may be selected by reference to the infrequent-fault-incidence protection curve

Figure A.5—Infrequent-Frequent-Fault Incidence Zones for Category II and Category III Transformers

Table A.1—Summary of Through-Fault Protection Curves

Category	Minimum Nameplate kVA (Principal Winding)		Through-Fault Protection Curves*
	Single-Phase	Three-Phase	
I	5 to 500	15 to 500	Fig A.1
Il	501 to 1667	501 to 5000	Fig A.2
III	1668 to 10000	5001 to 30000	Fig A.3
IV	above 10000	above 30000	Fig A.4

*The times normal base current scale in Figs A.1 through A.4 relates to minimum nameplate kVA. Low values of 3.5 or less times normal base current may result from overloads rather than faults, and for such cases, loading guides may indicate allowable time durations different from those given in Figs A.1 through A.4. (See ANSI/IEEE C57.91-1981 [3] and ANSI/IEEE C57.921981 [4])

Table A.2—An Application Example of the Thermal/Mechanical Limit Curves for a Three-Winding Transformer

GUIDE: ART

60 Cycles, Class OA/FA/FOA, Three-Phase

Voltage Rating: 132000 GR Y/76200-66000 GR Y/38100-13200

H Winding	X Winding	Y Winding	
MVA rating 75 (output)	60	30	Continuous 55C Rise self-cooled
MVA rating 100 (output)	40	40	Continuous 55C Rise forced-air-cooled
MVA rating 125 (output)	100	50	Continuous 55C Rise forced-oil and forced-air-cooled
MVA rating 140 (output)	100	56	Continuous 65C Rise forced-oil and forced-air-cooled

Impedance volts 5.00% 132000 GR Wye-66000GR Wye Volts at 60 MVA

Impedance volts 7.94% 132000 GR Wye-13200 volts at 30 MVA

Impedance volts 11.43% 66000 GR Wye-13200 volts at 30 MVA

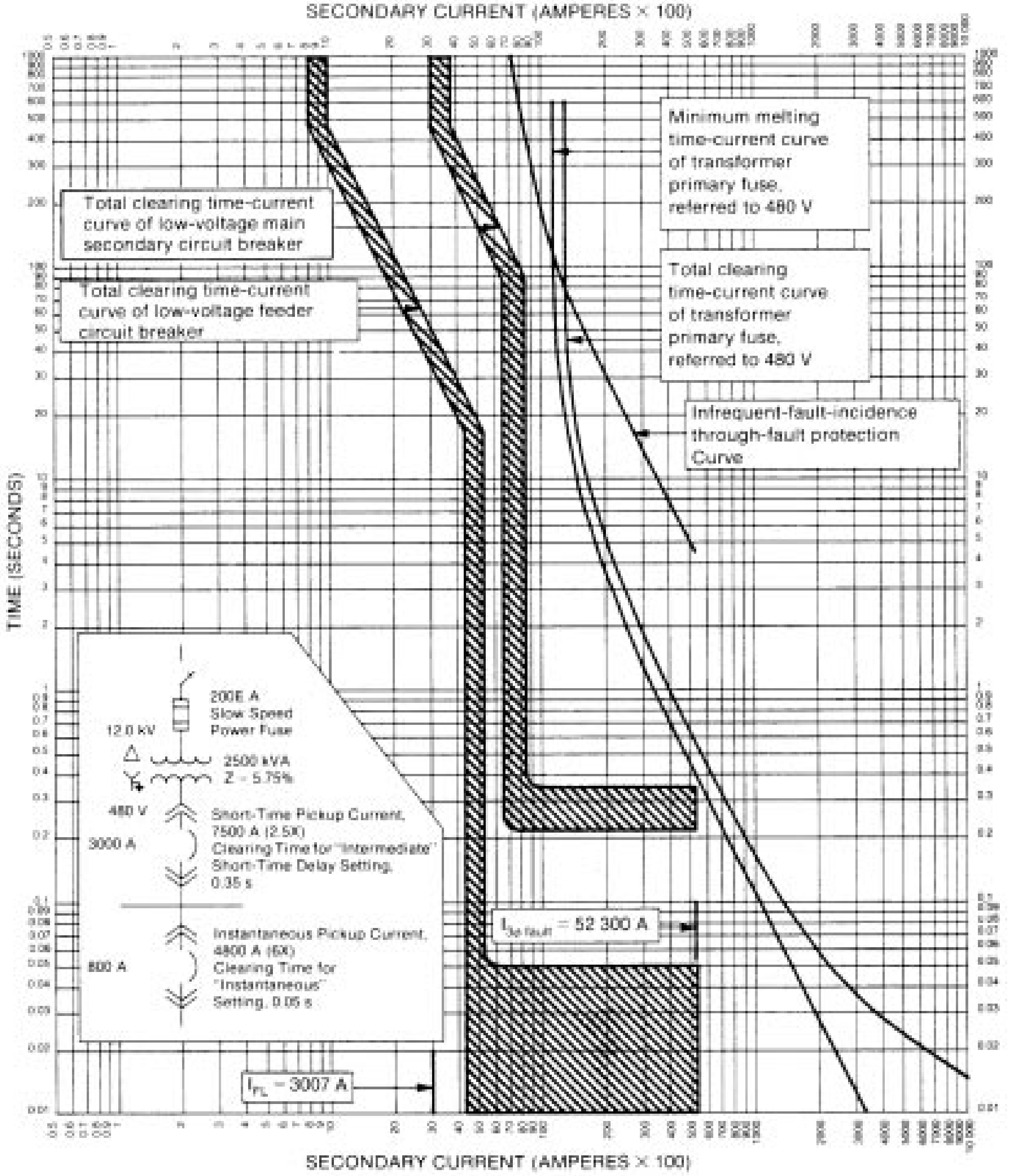


Figure A.6 (a)—Protection of a Category II Transformer Serving Protected Secondary-Side Conductors (for example, cable, bus duct, or switchgear) for Three-Phase Secondary-Side Fault

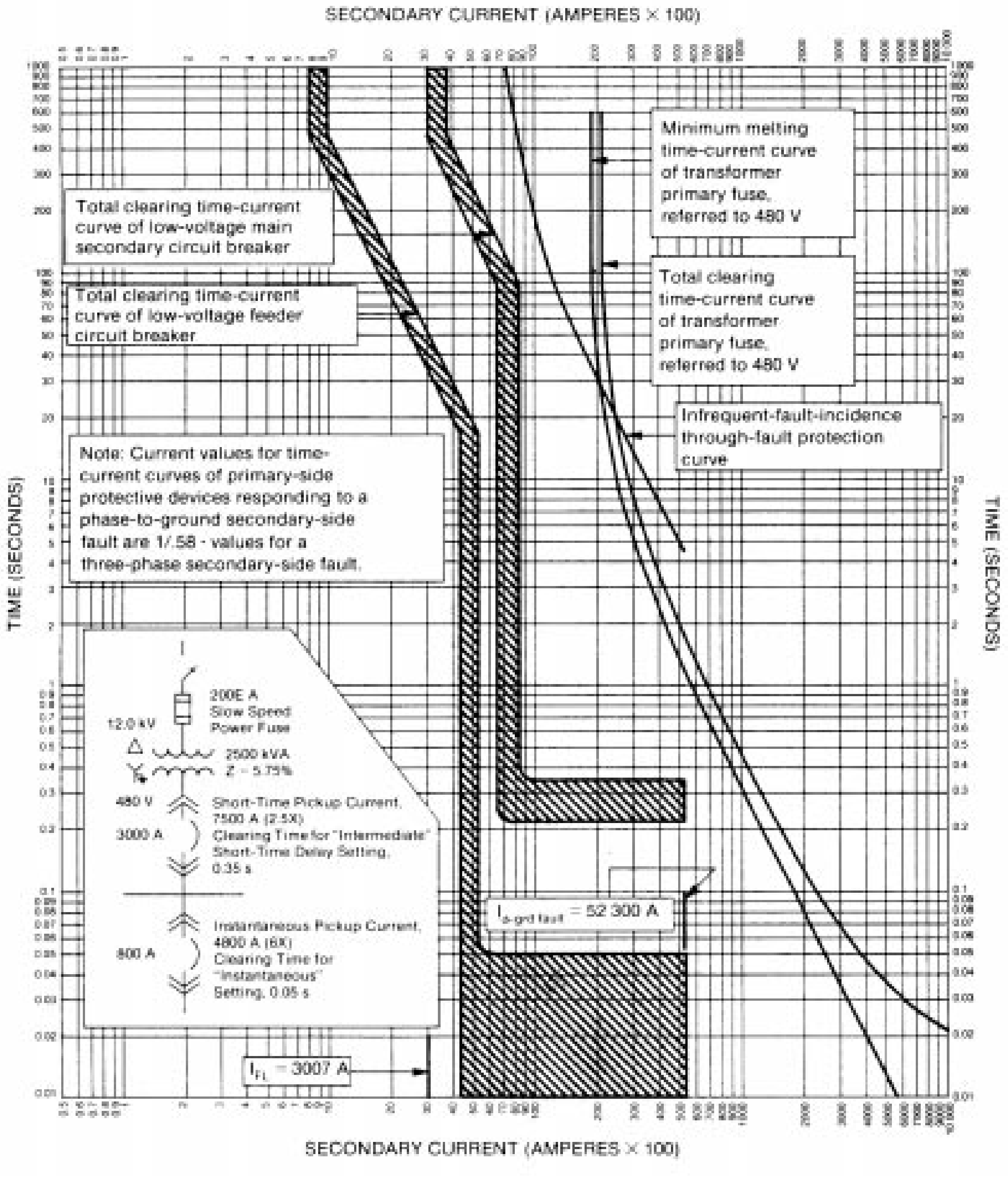


Figure A.6 (b)—Protection of a Category II Transformer Serving Protected Secondary-Side Conductors (for example, cable, bus duct, or switchgear) for Phase-to-Ground Secondary-Side Fault

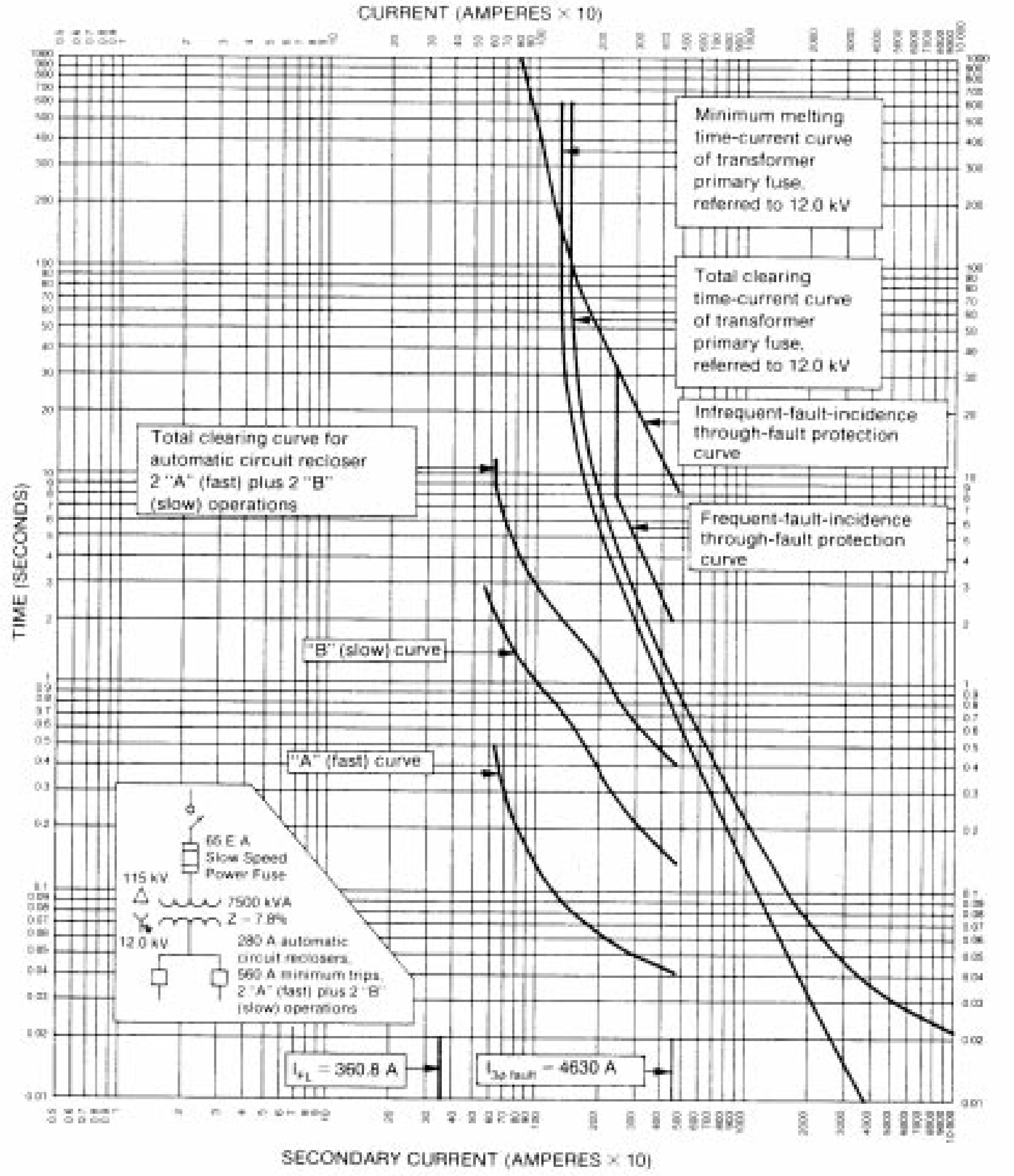


Figure A.7 (a)—Protection of a Category III Transformer Serving Secondary-Side Overhead Lines, for Three-Phase Secondary-Side Fault

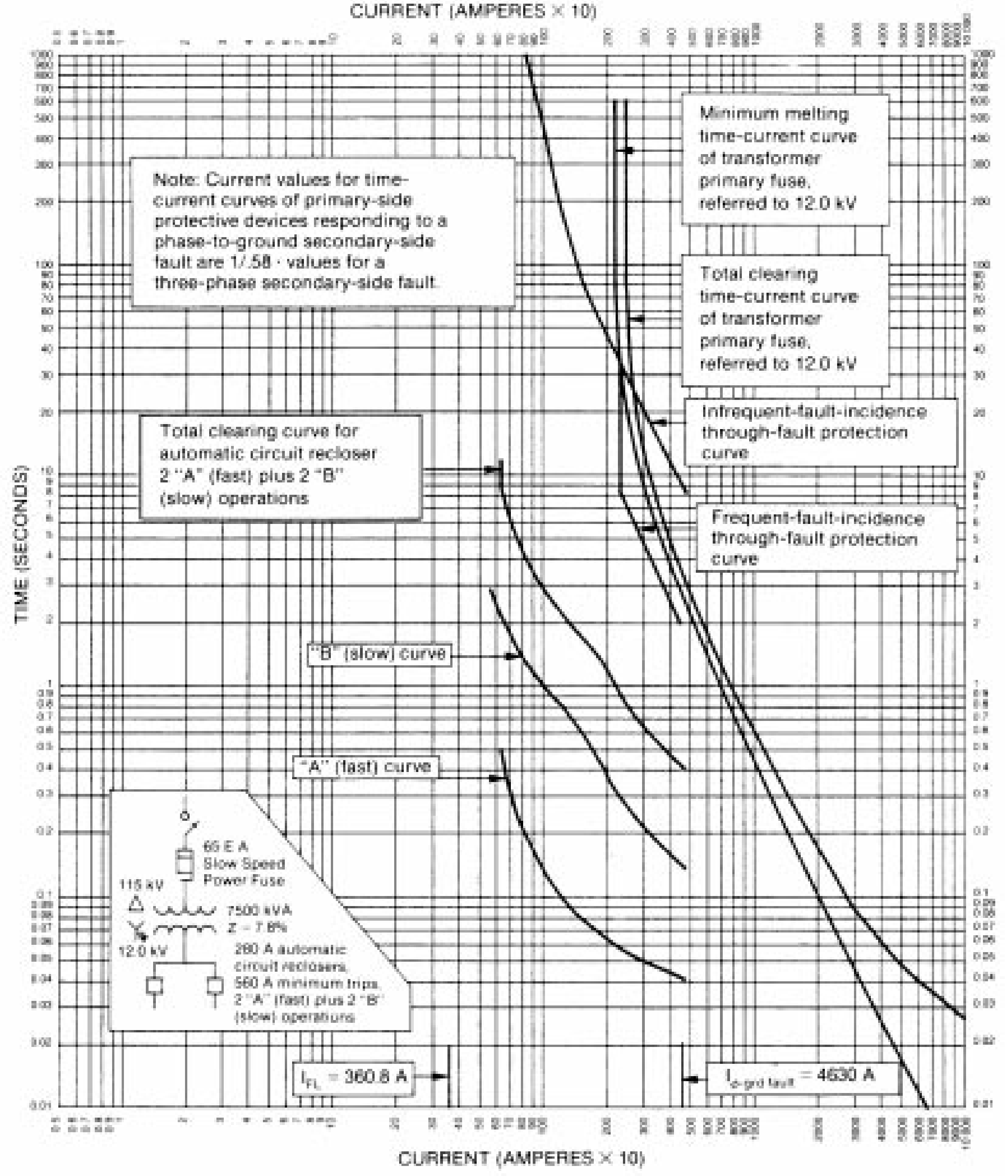


Figure A.7 (b)—Protection of a Category III Transformer Serving Secondary-Side Overhead Lines, for Phase-to-Ground Secondary-Side Fault

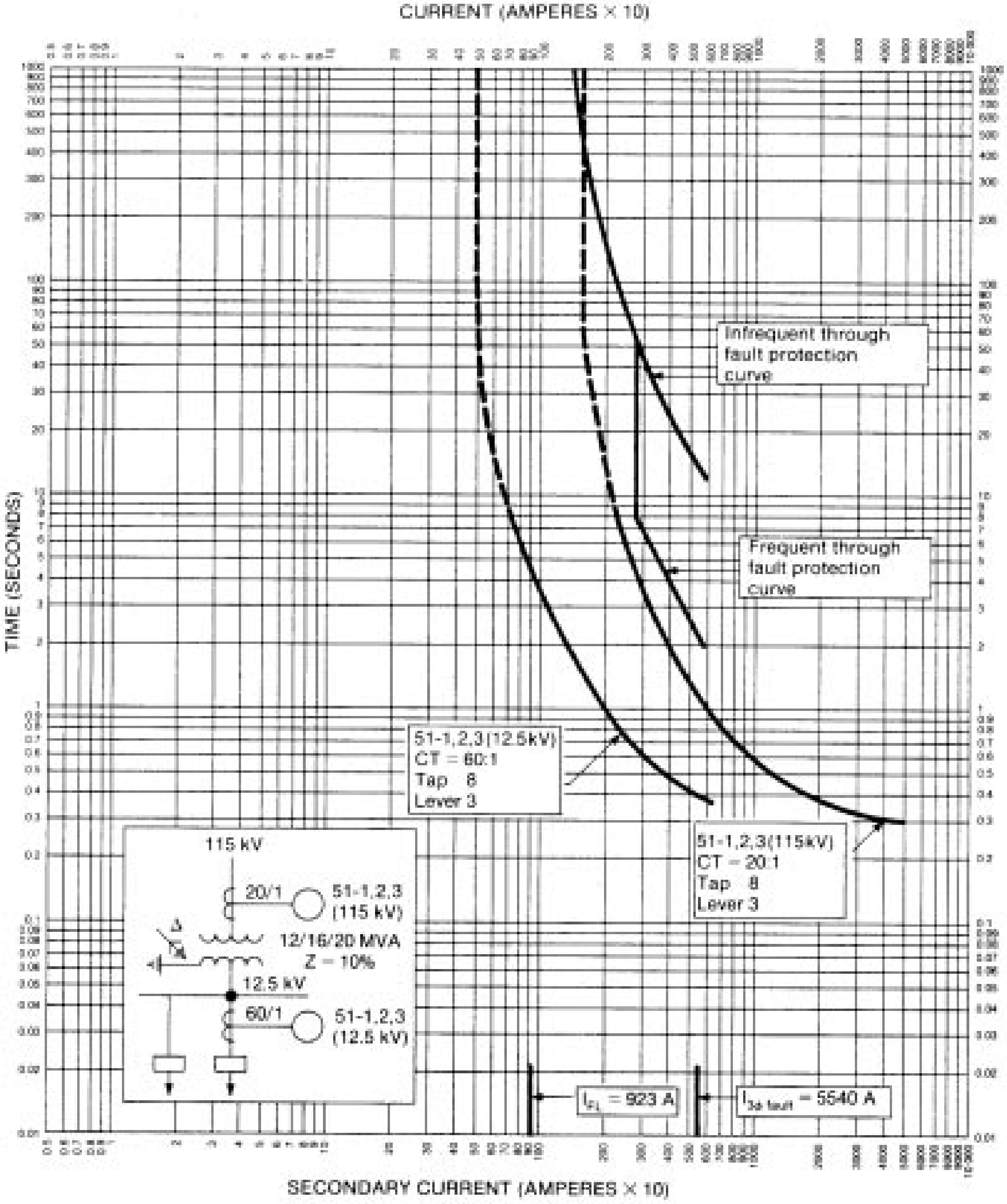
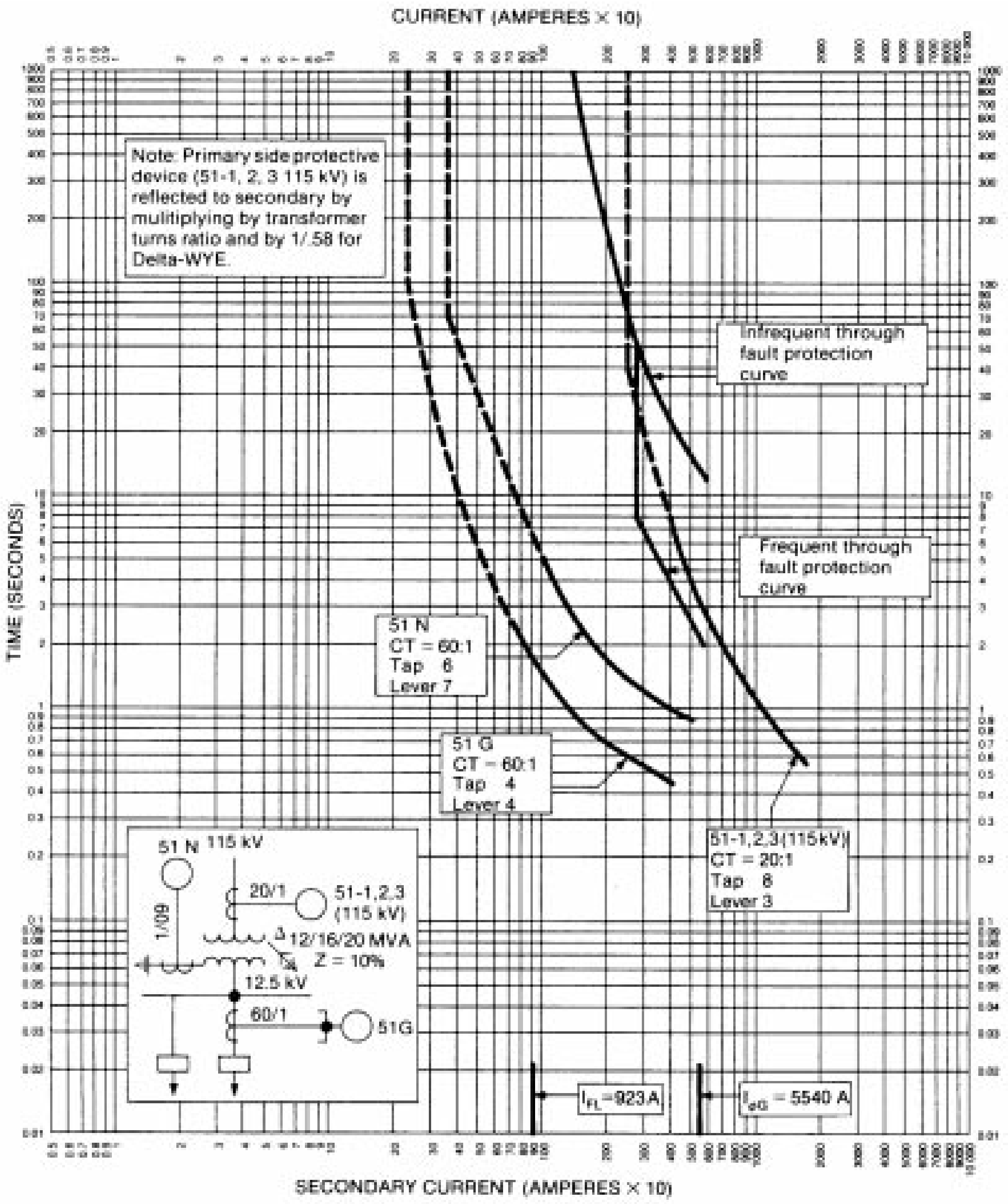


Figure A.8 (a)—Protection of Category III Transformer Three-Phase Secondary Fault



Note: Primary side protective device (51-1, 2, 3 115 kV) is reflected to secondary by mulitiplying by transformer turns ratio and by 1/.58 for Delta-WYE.

Figure A.8 (b)—Protection of Category III Transformer Phase-Ground Secondary Fault

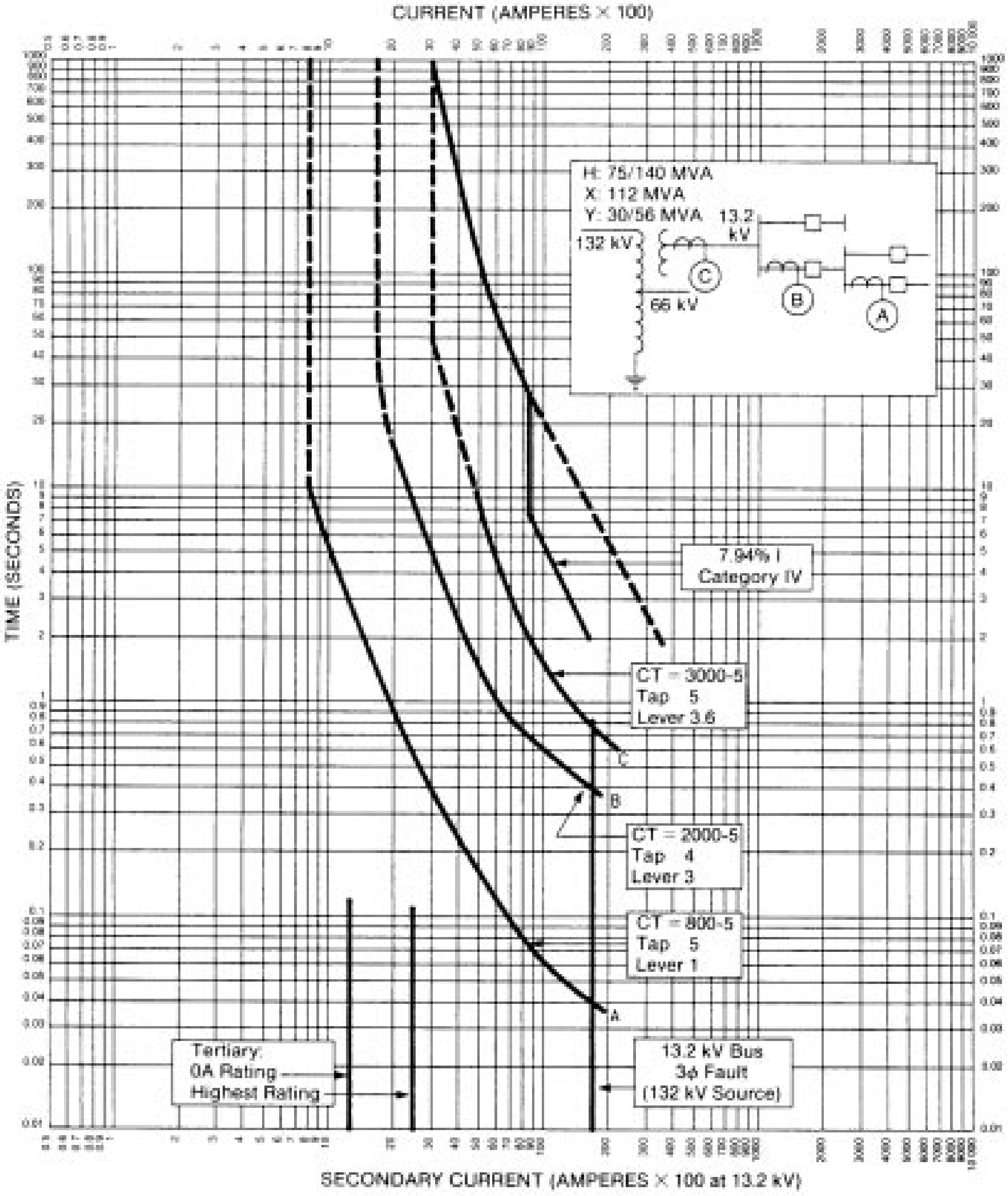


Figure A.9—Coordination of Tertiary Overcurrent Relays Large Auto Transformer