

ANSI
C37.91-1972

IEEE
Std 273-1967

IEEE STANDARDS
ARCHIVES
DO NOT REMOVE

An American National Standard

**IEEE Guide for
Protective Relay Applications
to Power Transformers**

SH01628



PUBLISHED BY
THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, Inc.
345 EAST 47 STREET, NEW YORK, N. Y. 10017



Documents

Document Sharing Hub

Authorized licensed use limited to: Tsinghua University. Downloaded on March 06, 2026 at 21:45:24 UTC from IEEE Xplore. Restrictions apply.

An American National Standard

**IEEE Guide for
Protective Relay Applications
to Power Transformers**

Approved January 28, 1972
American National Standards Institute

© Copyright 1967 by

The Institute of Electrical and Electronics Engineers, Inc.

*No part of this publication may be reproduced in any form,
in an electronic retrieval system or otherwise,
without the prior written permission of the publisher.*

Foreword

(This foreword is not a part of American National Standard Guide for Protective Relay Applications to Power Transformers, ANSI C37.91-1972, IEEE Std 273-1967.)

This standard was developed by the Transformer Protection Subcommittee of the Power Systems Relaying Committee of the IEEE Power Engineering Society. Membership of this subcommittee was:

A. J. Bartlett
H. A. Buhl
C. J. Cregar
J. M. Fleissner
H. H. Gnuse, Jr
H. L. Goodridge

C. L. Headley
R. W. Hirtler
R. C. Hitchcock
A. J. McConnell
R. H. Meyer

V. A. Nosko
L. H. Perry
B. J. Schaefer
P. J. Vinett
W. A. Wolfe
R. W. World

The American National Standards Committee on Power Switchgear, C37, which reviewed and approved this standard, had the following personnel at the time of approval:

V. L. Cox, *Chairman*

W. R. Wilson, *Vice-Chairman*

J. G. Werner, *Secretary*

Organization Represented

Name of Representative

Association of American Railroads

W. O. Muller

Association of Iron and Steel Engineers

T. S. Novak

Electric Light and Power Group

H. W. Grissler

R. R. Wagstaff

J. E. Beehler

H. G. Frus

J. P. Markey (*Alt*)

F. R. Solis (*Alt*)

Institute of Electrical and Electronics Engineers

J. E. Conner

H. L. Lowe

J. B. Owens

H. O. Simmons, Jr

G. W. Walsh

H. C. Barnes (*Alt*)

W. A. Carter (*Alt*)

R. E. Friedrich (*Alt*)

W. A. Hall (*Alt*)

National Electrical Manufacturers Association

W. R. Wilson

R. W. Dunham

A. P. Colaiaco

C. E. Gryctko

W. J. Smith

B. K. Sturgis

J. G. Werner (*Alt*)

O. S. C. Hammer

Tennessee Valley Authority

W. K. Cave

U.S. Department of the Army

Norman Mawdsley

U.S. Department of the Navy

L. W. Johnson (*Alt*)

U.S. Department of the Interior, Bureau of Reclamation

E. M. Tomsic

U.S. Department of Defense, Defense Communications Agency

C. D. Friday



Documents

Document Sharing Hub

CONTENTS

1. INTRODUCTION	2
2. PHILOSOPHY AND ECONOMIC CONSIDERATIONS	2
3. TYPES OF FAULTS	5
3.1 Winding Failures	6
3.2 Tap-Changer Failures	6
3.3 Bushing Failures	6
3.4 Terminal-Board Failures	6
3.5 Core Failures	6
3.6 Miscellaneous Failures	6
3.7 Table of Types of Transformer Faults	6
4. RELAY CURRENTS	8
4.1 Minimum Internal Faults	8
4.2 Maximum Internal Faults	8
4.3 Through Faults	8
4.4 Phase-Shifting Transformers	8
4.5 Performance of Current Transformers During Faults	8
4.5.1 Internal Faults	8
4.5.2 External Faults	8
4.6 Nonfault Relay Current	9
4.6.1 Unbalance Caused by Current-Transformer Ratios	9
4.6.2 Magnetizing Current Inrush	9
4.6.3 Magnetizing Current During Overvoltage	9
4.6.4 Differential Current During Load Conditions	10
5. ELECTRICAL DETECTION OF FAULTS	10
5.1 Fuse Protection	10
5.2 Differential Protection	10
5.2.1 Differential Connection Using Time Overcurrent Relays	10
5.2.2 Differential Connection Using Percentage Differential Relays	10
5.2.3 Differential Connection Using Percentage Differential Relays with Harmonic Restraint	11
5.2.4 Unit Generator—Transformer Sets	11
5.2.5 Station Service	11
5.2.6 Multiple-Winding Transformer Differential	11
5.3 Overcurrent Protection	12
5.4 Ground-Fault Protection	13
5.4.1 Faults in Delta-Connected Transformer Windings	13
5.4.2 Faults in Grounded-Wye-Connected Transformers	13
5.4.3 Case Ground	13
5.4.4 High-Impedance-Grounded Systems	13
5.4.5 Detection of Ground Faults	14
5.5 Fault Detection for Special-Purpose Transformers	14
5.5.1 Regulating Transformers	14
5.5.1.1 In-Phase Type	14
5.5.1.2 Phase Shifting or Combined Phase-Shifting and In-Phase Regulating Transformers	14
5.5.2 Combined Power and Regulating Transformers	15
5.5.3 Grounding Transformers	15

5.6	Back-Up Protection	15
5.6.1	Overcurrent Relays	16
5.6.2	Voltage Relays	16
5.6.3	Temperature Relays	17
5.6.4	Miscellaneous Relays	17
6.	MECHANICAL DETECTION OF FAULTS	17
6.1	Gas Accumulator Relay	17
6.2	Gas Detector Relay	17
6.3	Static Pressure Relay	18
6.4	Sudden-Gas-Pressure Relay	18
6.5	Sudden Oil Pressure	18
7.	THERMAL PROTECTION	18
7.1	Thermal Relays for Winding Temperature	18
7.2	Thermal Relays for Tank Temperature	18
7.3	Other Means of Thermal Protection	19
7.4	Testing Thermal Relays	19
7.5	Overheating of Generator Step-Up Transformers Due to Overexcitation	19
8.	FAULT CLEARING	19
9.	RE-ENERGIZING POLICY	20
10.	GAS ANALYSIS	21
11.	SPECIAL PROTECTIVE SCHEMES	21
11.1	Over-all Unit Generator Differential	21
11.2	Unit Transformer of Three-Legged Core-Form Type	22
11.3	Grounding Transformer Inside Main Transformer Differential Zone	23
11.4	Protection of Wye-Connected Three-Legged Core-Type Transformers	23
12.	BIBLIOGRAPHY	23
13.	APPENDIX	26

Guide for **PROTECTIVE RELAY APPLICATIONS TO POWER TRANSFORMERS**

1. INTRODUCTION

This Guide has been prepared to aid in the effective application of relays and other devices for the protection of power transformers. It supplements information that was previously published in a Committee Report titled "Protection of Power Transformers, 1962 Relays Committee Survey of Practices." (Reference 2.1.2)

This Guide reviews the general philosophy and economic considerations involved in transformer protection, describes the types of faults that have been experienced, and discusses technical problems with such protection, including current transformer behavior under fault conditions. The various types of electric, mechanical, and thermal protective devices are described. Associated problems such as fault clearing and re-energizing considerations are also discussed. Emphasis in the Guide is placed on practical applications rather than basic theory which may be obtained from several good references in the Bibliography.

2. PHILOSOPHY AND ECONOMIC CONSIDERATIONS

Protective relaying is applied to components of a power system for two reasons: (1) To separate a faulted member from the remainder of the system so that the system can continue to function. (2) To limit damage to the faulted equipment and minimize the possibility of fire. In protecting some components, particularly high-voltage transmission lines, the limiting of damage becomes a byproduct of the system protection function of the relays. However, since the cost of repairing faulty transformers may be large and since high-speed, highly sensitive protective devices can reduce damage and therefore repair cost, the equipment protective aspects of relays must 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, indicating a need for high sensitivity as well as high speed to obtain good protection.

Present-day transformers with modern lightning protection are very reliable devices; however, as long as a possibility of failure exists, protection must 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 economical scheme. Usually more than one scheme is technically feasible and the alterna-

tives offer varying degrees of sensitivity, speed, and selectivity. The plan selected must balance the best combination of these factors against the over-all economics of the situation while holding to a minimum:

1. Cost of repairing damage.
2. Adverse effects on the balance of the system.
3. The spread of damage to adjacent equipment.
4. 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 non-clearing 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. A recent survey shows this to be true. (Reference 2.1.2). The major economic consideration is not ordinarily the fault-detection equipment but the protective gear (circuit breakers). Protective gear 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 and system design philosophy as to the protection of the transformer. Evaluation of the risks involved, the protection afforded, and the costs incurred is necessary to avoid going to extremes. Such considerations involve the Art rather than the Science of protective relaying. (References 2.1.9, 2.1.1, 1.3).

3. TYPES OF FAULTS

Transformer failures can be grouped into several major categories. For simplicity, failures reported in this summary are grouped into the following six categories:

1. Winding failures
2. Tap-changer failures
3. Bushing failures
4. Terminal-board failures
5. Core failures
6. Miscellaneous failures

The following summary is based on a ten-year period of transformer failures reported by a group of utilities. Some 262 transformer fail-

ures were analyzed and tabulated. Because of limited space allotted to this section in the Guide, the itemized list had to be grouped as shown. Specifics concerning the actual failures are not considered of primary concern. This summary may assist engineers in making an evaluation of just how much protection can be applied economically on specific transformer installations.

3.1 Winding Failures

By far the largest number of transformer faults involved winding failures. Shown in Table 1 is an analysis of these winding failures. As can be seen, the largest number of winding failures with reasons assigned involved: (1) turn-to-turn shorts from turn-insulation deterioration, (2) lightning and lightning surges, and (3) moisture. The turn-to-turn faults or layer-to-layer faults occurred in roughly 24 percent of all transformer-winding faults reported, i.e., the initial failure started as a turn-to-turn short or an open turn but the ultimate failure may have involved other categories. Lightning was the primary instrument causing roughly 13.5 percent of all transformer winding failures. Moisture was the direct cause of 12 percent of the total failures. For the most part, moisture was caused by water seepage into the oil through poor gaskets, etc.

3.2 Tap-Changer Failures

Faults and failures associated with the load tap changer unit made up the second largest major category of transformer failures. Mechanical failures due to malfunction and stress made up 30 percent of the transformer failures attributed to faults associated with the load tap changer and its auxiliaries. Twenty-six percent of the transformer faults attributed to the tap changer were caused by electric failures of the mechanism. Roughly 17 percent of the tap-changer failures were the direct result of contact trouble. As shown in Table 1, other types of faults were also present in tap-changer failures.

3.3 Bushing Failures

Bushing failures made up the third largest group in transformer outages. High within this category were failures due to aging, contamination, and cracking. This accounted for roughly 50 percent of bushing failures. Moisture, flash-overs, and animals each accounted for approximately 12 percent of bushing failures. Lightning and low oil in the bushings accounted for a total of about 15 percent. (The split here was about even.) See Table 1.

3.4 Terminal Board Failures

In the order of the number of failures, faults originating in the vicinity of the terminal boards ranked fourth. Approximately 37 percent of the failures associated with the terminal board were due to loose connections which resulted in leads pulling out, poor contact, and poor solder joints. Thirty-one percent of the terminal board faults occurred because of lead failures. The remaining faults occurring in the terminal boards were of various causes as listed in Table 1.

In summary, the majority of the failures in this category were of mechanical nature resulting from poor assembly or from constant vibration.

3.5 Core Failures

Faults occurring due to core failures were found to be few in number and generally speaking were from one cause, a breakdown in insulation. The insulation failure manifested itself in the form of shorted laminations, fiber-bolts failure, loose wedges, and insulation failures between clamp bolt and core. See Table 1.

3.6 Miscellaneous Failures

The largest single item failing in this category was bushing current transformers. This made up approximately 30 percent of the failures attributed to miscellaneous. The other failures listed in this category are itemized in Table 1.

3.7 Table 1

Types of Transformer Faults

I. Transformer Outages Due to Winding Failures Causes and Occurrences

	Number	Percent of Subtotal	Percent of Total
1. Miscellaneous	36	27	
2. Turn-to-turn insulation failure	32	24	
3. Lightning	18	13	
4. Moisture	16	12	
5. External faults (producing insulation failure)	10	7	
6. Overheating	5	4	
7. Open winding	4	3	
8. Deterioration	4	3	
9. Improper blocking	3	2	
10. Grounds	3	2	
11. Phase-to-phase failures	2	2	
12. Mechanical weakness	1	1	
Total	134	100	51

	<i>Number</i>	<i>Percent of Subtotal</i>	<i>Percent of Total</i>
II. Transformer Outages Due to Tap-Changer Failures			
Causes and Occurrences			
1. Mechanical	15	31	
2. Electrical	13	27	
3. Contacts	8	16	
4. Leads	4	8	
5. Tracking	4	8	
6. Overheating	2	4	
7. Three-phase short	1	2	
8. Oil leak	1	2	
9. External fault	1	2	
Total	49	100	19
III. Transformer Outages Due to Bushing Failures			
Causes and Occurrences			
1. Aging, contamination, and cracking	20	49	
2. Animals	5	12	
3. Flashover	5	12	
4. Moisture	4	10	
5. Low oil	4	10	
6. Lightning	3	7	
Total	41	100	15
IV. Transformer Outages Due to Terminal-Board Failures			
Causes and Occurrences			
1. Loose connections	7	37	
2. Leads (opened)	6	33	
3. Links	2	10	
4. Moisture	1	5	
5. Insufficient insulation	1	5	
6. Tracking	1	5	
7. Short circuit	1	5	
Total	19	100	7
V. Transformer Outages Due to Core Failures			
Causes and Occurrences			
1. *Core insulation failure	6	86	
2. Ground strap burned away	1	14	
Total	7	100	3
VI. Transformer Outages Due to Miscellaneous Causes			
Causes and Occurrences			
1. Bushing current transformer failure	4	33	
2. Metal particles in oil	2	17	
3. Damage in shipment	2	17	
4. External shorts	2	17	
5. Bushing flange grounding	1	8	
6. Poor tank weld	1	8	
Total	12	100	5

* Consisted of: shorted laminations, loose clamps, fiber-bolts failure, loose wedges and bolts, clamp touching core, insulation between clamp bolt and core failure.

4. RELAY CURRENTS

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 currents, that flow in one set of terminals, may equal as much as ten times rated current. These, and other considerations, require special consideration to obtain relay characteristics best suited to the particular application.

4.1 Minimum Internal Faults

The most difficult transformer fault for which to provide protection is the fault that initially involves one turn. Even with a two-winding transformer, a turn-to-turn fault will result in a terminal current of less than rated full-load current. In fact, possibly 10 percent of the winding may have to be shorted to cause full-load terminal current to flow. If the transformer is an auto-transformer or a regulating transformer, it will be physically smaller than a two-winding transformer of the same rating, and 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 percent or even less of 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. Of importance here is that the relay must be capable of withstanding the secondary current on a short time basis, assuming no current transformer saturation. 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 of current protection of transformers is that fault current through a transformer is limited by the transformer. Thus, if all external faults relative to the protected zone involve currents through the transformer, reasonable currents relative to the transformer rating are involved.

The above favorable aspect disappears 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 currents 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 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 degrees, such as with the familiar wye-delta transformer, current transformer connections for proper differential relaying are easy to obtain. However, if the phase-angle shift is some other angle, say 15 degrees, orthodox connections of current transformers, either wye or delta, will not provide proper differential relaying. With either connection on either side of the transformer, proper balance cannot be obtained and an operating (differential) current will flow. If an external fault is an unbalanced fault, such a differential current can flow with practically no through current for restraining purposes. Therefore, even a percentage-differential relay could operate incorrectly.

If the 15-degree phase shift were fixed, it would be 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 to a given phase-shifting transformer.

4.5 Performance of Current Transformers During Faults

4.5.1 Internal Faults. In the event of an internal terminal fault, or a fault external to the transformer but in the protective zone, the current transformers can be expected to saturate, perhaps severely. This has no significance unless the relay can block itself because of the harmonic content of the secondary current.

On a transient basis, with a saturated current transformer, second and third 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, of course, on whether or not the current transformers saturate on a steady-state basis.

4.5.2 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. On the other hand, if current can flow through the differen-

tial zone at the same voltage (e.g., ring bus, or breaker-and-a-half applications), then the current is not so limited. In either case, any deficiency of current output (caused by saturation, References 1.7 and 2.2.27) of one current transformer that is not matched by a similar deficiency of another current transformer will cause the difference to appear in the operating circuit of a differential relay. Simple time-overcurrent relays, without restraint, can meet this problem only by having their tap and time-dial settings made sufficiently high, when direct-current saturation of the current transformers is the problem. Percentage differential relays offer the advantage of greater sensitivity and faster speeds, but they should be applied with a restraint element in each current transformer circuit. Also, the loading 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.

4.6 Nonfault Relay Current

The usual over-all differential protection of a transformer can be considered as only a partial differential since the transformer magnetizing branch is within the differential zone but is not compensated by the differential connection of the current transformers. The protection is based on change of impedance of the magnetizing branch in the event of a transformer fault. The normally high impedance of the magnetizing branch is radically reduced by even a turn-to-turn fault. This ideal situation is violated by the following several factors that the relay engineer cannot control:

4.6.1 Unbalance Caused by Current Transformer Ratios. Even if a transformer has a fixed ratio, it is usually difficult and inconvenient 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. When the transformer has taps, the possible mismatch is increased many times. During a through-fault condition, the differential current can be comparable at least with the current rating of the transformer.

4.6.2 Magnetizing Current Inrush. This is a phenomenon which causes the violation of the basic principle of differential relaying in that 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. The mechanism has

been adequately explained elsewhere (Reference 2.2.13) so will not be considered here.

Although usually considered only in conjunction with the energizing of a transformer, magnetizing current inrush can be caused by any transient that causes an abrupt change of voltage on the magnetizing branch of the transformer. Such transients include the occurrence of a fault, the removal of a fault, the change of character of a fault (e.g., the change from a single-phase-to-ground fault to a two-phase-to-ground fault) and a poor synchronizing attempt. 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. (Reference 2.2.13) One involves the energizing of a transformer at a station at which at least one other transformer is already energized. The inrush phenomenon (Reference 2.2.14) involves the already energized transformers as well as 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 be nearly a sine wave of fundamental frequency. This phenomenon makes necessary a separate harmonic suppression relay unit for each bank. Another inrush phenomenon involves the energizing of a transformer by means of an air switch. Arcing of the switch can result in successive half cycles of arc of the same polarity. Thus, if the first half cycle results in substantial residual magnetism in the 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.

4.6.3 Magnetizing Current During Overvoltage. In the event of the load rejection, it is possible for a transformer to be subjected to substantial overvoltage. If saturation requirements have not been specified, a transformer is likely to be able to withstand little overvoltage beyond the requirements of Standards. If saturation occurs, substantial exciting current will flow. The wave form will be distorted, but in this case there are principally only odd harmonics, particularly the third. (Because of the abrupt voltage change, there can also be a magnetizing-current inrush, but this will be of secondary importance.)

4.6.4 Differential Current During Load Conditions. Because of current transformer saturation, bushing current transformer ratios below 200/5 should not be used. Another reason, especially at 345 kV and higher, is that the error current, during load conditions (or during fault conditions resulting in currents up to about twice full-load current), might be sufficient to operate a sensitive relay. This is because current transformer exciting current increases with core circumference, which in turn increases with voltage. A further factor is that the relays are likely to be farther away from the transformer in an extra-high-voltage application than at lower voltages, and thus the lead burden may be high, with consequent increase in current transformer exciting current.

5. ELECTRICAL DETECTION OF FAULTS

5.1 Fuse Protection

Fuses are widely used to protect power transformers; and although the fuse has certain limitations, it has the merits of being economical, simple to maintain, and generally fail safe. This is true for any size transformer; however, transformers exceeding 10,000 kVA in rating are usually provided with more sensitive protection. Fuses can be reliably used to protect the transformer against external short-circuit current under most conditions, but cannot be relied upon to protect the transformer from internal faults or long-time overloads.

Each manufacturer publishes time-current curves of his various types of fuses. These curves should be corrected for ambient temperature and prefault load current according to predicted operating conditions and by the use of appropriate correction factors, also published by the manufacturers. Experience indicates that these time-current curves are accurate, within established tolerances, provided correction factors are properly applied. Some users are reluctant to operate fuses at loads greater than approximately 65 percent of the minimum current required to melt the fusible element. This load limit reduces operating temperature in the fuse, permits short-time emergency loading of transformers, and establishes some basis for the selection of prefault load-current correction factors. The maximum continuous load current should not exceed the continuous current rating of the complete fuse assembly.

Selection of the proper fuse link rating and speed should be based on the following factors:

1. Maximum permissible transformer load current and the transformer heating curve recommended by the transformer manu-

facturer, Appendix Figure 1 (Reference 1.4).

2. Transformer connections, as they affect primary current for three-phase, phase-to-phase, and phase-to-ground secondary faults.
3. Available primary system fault current and transformer impedance.
4. Coordination with low-side protection equipment.
5. Maximum allowable fault time on the low-side bus conductors.
6. Maximum degree of sensitivity for protection from high-impedance faults.

5.2 Differential Protection

Electrical differential is the most commonly used type of protection for transformers of approximately 10 MVA and above. (Reference 2.1.2).

The term is properly applied only to the connection of current transformers which are connected so that the net output to the relay is the difference between input and output current.

Relays of three general classes are used with this transformer connection. They are:

1. Time-overcurrent relay, usually with an instantaneous trip attachment 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. The percentage characteristic may be fixed or it may be variable. The restraint functions may be in two separate units, or combined in one.

Current-transformer connections must be such that the net current to the relay operating coil for any type or location of external fault is substantially zero. Various types of connections are shown in the Appendix (Figures 12, 13 and 14).

5.2.1 Differential Connection Using Time-Overcurrent Relays. Overcurrent relays without restraint are seldom used in present-day applications due to their susceptibility to false operation from the following causes: (1) In-rush magnetizing current when energizing transformer, (2) Saturation errors or mismatch of current transformers and (3) Excessive excitation current when transformer is overexcited.

5.2.2 Differential Connections Using Percentage-Differential Relays. To avoid undesired tripping due to a mismatch, restraint may be added for through (external) faults. This

permits a more sensitive setting, and somewhat faster operation 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.

The amount of restraint is stated (or defined) as a percent of the current required by the operating winding to overcome the restraint torque and is called the characteristic slope. The required slope may vary between 15 and 50 percent, depending on the range of taps on the power transformer. The percent slope will increase near pickup, as a fixed restraint of the restraint spring adds to the electrical restraint. Typical settings are 25 percent slope, 60 percent pickup and 0.1 second at 3 times pickup. Addition of instantaneous overcurrent (no restraint) set above inrush will shorten clearing time for heavy faults.

While this relay is more expensive than an overcurrent relay, the installed cost is usually no more. It is provided with taps which ordinarily make auxiliary balancing current transformer unnecessary. The overcurrent relay in many instances requires an auxiliary current transformer and additional wiring which increases its installed cost.

5.2.3 Differential Connections Using Percentage-Differential Relays with Harmonic Restraint. Various schemes have been used to increase the pickup or delay tripping during energizing, especially for large transformers located near large sources of generation. Harmonic restraint is the only one now in general use. Other schemes have not been very satisfactory for the following reasons:

1. Clearing of a fault which may occur on energizing will be delayed.
2. When an external fault clears, the inrush current may cause a tripout.
3. There is no protection against "outrush" when energizing another transformer.

Harmonic-restraint relays make use of harmonics present in the inrush current, particularly the second, to block tripping or to increase the pickup during inrush. Thus a lower normal pickup and a minimum time delay become possible without danger of false tripouts. A filter is also used in the operating coil circuit. Unfortunately there is still an imperfection in some makes of differential relays but it is easily overcome. At high internal fault currents, sufficient harmonics may appear to prevent operation. An instantaneous overcurrent element set above inrush is added

to solve this problem. This relay is also provided with balancing taps as well as taps for approximately 15 to 40 percent slope.

While the cost of harmonic restraint relays is higher, it can often be justified. Important points are:

1. Cost of investigating an inrush tripout when the harmonic restraint is not used.
2. Faster operating time (0.03 to 0.05 second versus 0.1 to 0.2 second for the percentage-restraint type).
3. Lower pickup (20 to 40 percent of transformers rating versus 40 to 100 percent for the percentage-restraint type).

5.2.4 Unit Generator-Transformer Sets. On cross-compound units, field is usually applied while the set is on turning gear. Application of field to such machines normally excites the generator step-up transformer as well as the generator so that protection is required for all of the unit system. The filter circuit of some harmonic-restraint relays may cause failure to operate 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 Station Service. Where a startup transformer is used 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 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 attachment 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.

5.2.6 Multiple-Winding Transformer Differential. Differential relays for three-winding transformers are available in both the percentage-differential and harmonic-restraint relay types. These relay types are also made as specials to accommodate four or five 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 and the other two windings each rated at 50 MVA. Care must be taken in

selecting current transformer ratios or 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 being considered. This is clarified, if through fault current involving only the high side and one winding is studied. Proper selection will result if each pair of windings is treated in this manner.

5.3 Overcurrent Protection

A fault on a power system external to a transformer can result in a failure of the transformer if the fault is not cleared promptly since the fault results in overloading the transformer. Overcurrent relays (or fuses, Section 5.1) may be used to clear the transformer from the faulted line or feeder before the transformer is damaged. On 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, discussed elsewhere in this report, may also be used to protect transformers against overload.

Overcurrent relays can provide an inexpensive, simple, and reliable protective scheme for transformers. However, since sensitive settings and fast operation are not usually possible with overcurrent relays, they will provide limited protection for internal transformer faults and should be used for primary protection only on small unimportant installations. Insensitive settings result since the pickup value of phase-overcurrent relays must be high enough to take advantage of the overload capabilities of the transformer. Fast operation is not possible since the transformer relays must coordinate with relays on lines or feeders terminating on the high- and low-voltage buses. Faster clearing for heavy internal faults may be obtained through the use of instantaneous tripping attachments in the overcurrent relays on the primary side of the transformer. The relays may be set to pick up at a value above the maximum through-fault current and will thus provide instantaneous tripping for heavy internal faults. Where overcurrent relays are used for primary transformer protection, extensive damage to the transformer from an internal fault must be expected.

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 percent of the self-cooled current rating of the transformer is common, although higher values are sometimes used.

The time setting is usually chosen for coordination with relays on adjacent equipment. However, an upper limit to the overcurrent-relay time setting exists in the time-current characteristic of the transformer windings. For proper backup protection, the relays may operate for an external fault before the windings are damaged by the heavy currents. Many such transformer "heat-curves" are available, but as all seem based on USA Standard C57, (Reference 1.4) one may use the curve in Appendix Figure 1.

The easiest method of determining the relay time setting is to draw the time-current curves of the adjacent line or feeder relays and the transformer "heat-curve." The expected values of fault current for adjacent and remote bus faults should also be plotted. The necessary relay time setting can then be determined and plotted on this sheet. Obviously, for the best coordination, the curve of the transformer-overcurrent relays should have the same general shape as the adjacent relays. See Appendix Figure 2.

Instantaneous-trip attachment, if usable, should be set to pick up at a value higher than the maximum through-fault value—usually the fault current through the transformer for a low-side three-phase fault. A pickup of 125 percent of the calculated maximum symmetrical short-circuit current or eight times full-load bank current should provide sufficient margin to avoid false tripping for the bus fault, and still provide a maximum of protection to the transformer for heavy internal faults. In many cases, instantaneous-trip attachments cannot be used because the necessary settings are greater than the fault currents or the maximum tap available on the relay.

When the transformer is part of the transmission system, setting time-overcurrent relays becomes difficult because the possible infeeds cause large variations in fault currents and hence the relay operating times may be quite variable for the same fault. One simple solution is to set the transformer relays for a fixed time of 0.5 to 1.0 second for the adjacent bus faults. Two sets of relays, one high-voltage set and one low-voltage set, may be needed. Another simple solution is to consider the overcurrent relays last-resort protection and provide a time setting only slightly faster than the transformer time-current heating curve. An advantage to this solution is that no fault data is required, only the transformer full-load current and the relay pickup setting need to be known. An inverse-curve relay usually provides the best coordination. Relays set in this manner will operate only for very unusual conditions, probably because of the failure of the other equipment to operate for a fault, yet the transformer is about as well protected from external faults as if the relay were extremely fast.