ABB Relays

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Power Transformer Protection

Application Guide

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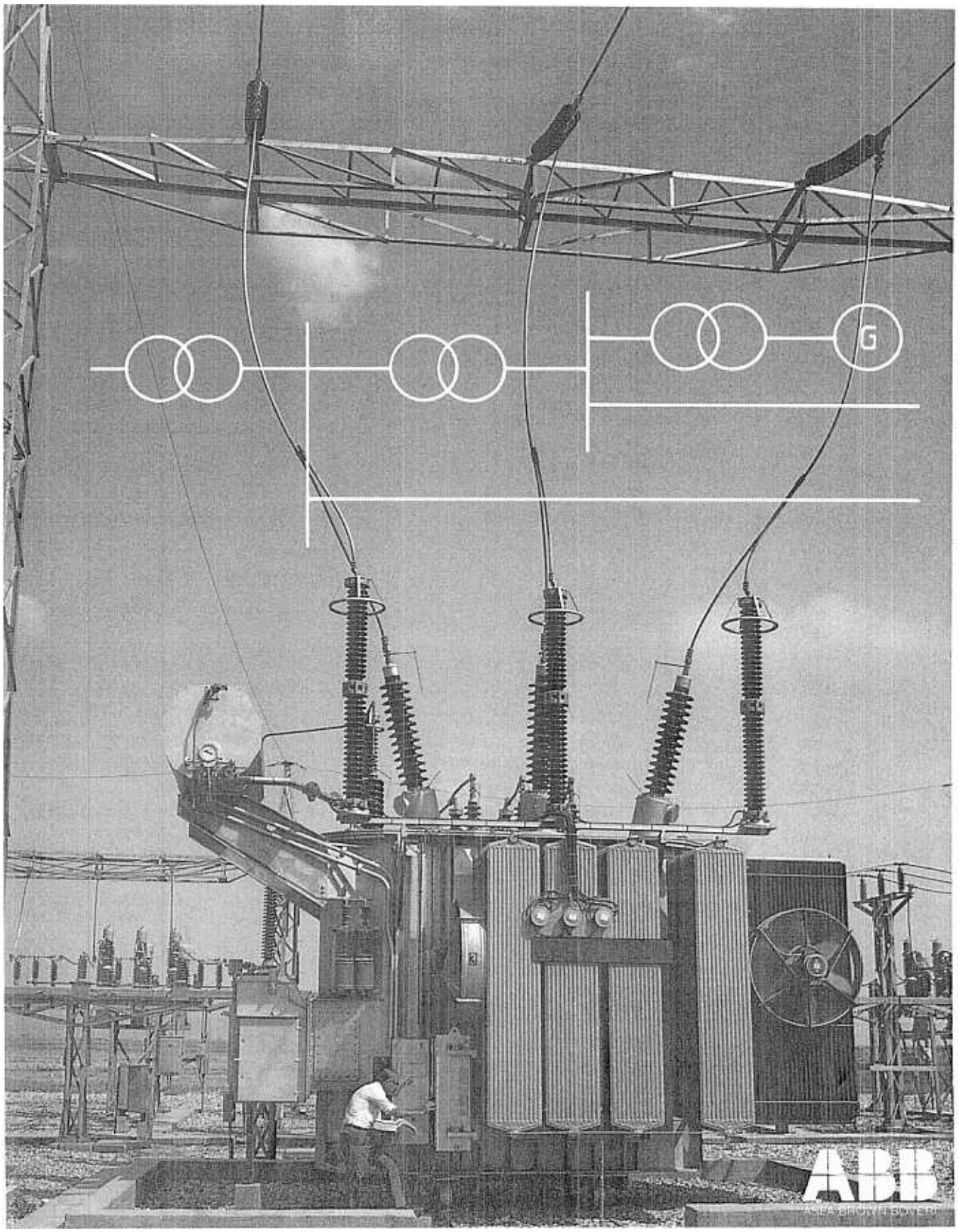

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1. INTRODUCTION

A power transformer is a very valuable and vital link in a power transmission system. High reliability of the transformer is therefore essential to avoid disturbances in transmission of power.

A high quality transformer properly designed and supplied with suitable protective relays and monitors is very reliable. Less than one fault in 100 transformer years can be expected.

When a fault occurs in a transformer, the damage is normally severe. The transformer has to be transported to a workshop and repaired, which takes considerable time. To operate a power transmission system with a transformer out of service is always difficult. Frequently, the impact of a transformer fault is more serious than a transmission line outage.

The operation and maintenance of a transformer can be a contributory cause of a fault. If a transformer is operated at too high temperature, too high voltage, or exposed to an excessive number of high current external faults etc, the insulation can weaken to the point of breakdown.

On-load tap-changers should be checked and maintained according to the operating instructions to prevent any faults. A fault in a tap-changer with a separate housing can cause too high a pressure in the housing. A pressure relay can be used to trip the circuit breakers at a certain set pressure, see point 5.4

To prevent faults and to minimize the damage in case of a fault, transformers are equipped with both protective relays and monitors. The choice of protective equipment varies depending on transformer size, voltage level, etc.

ASEA RELAYS is the largest manufacturer of protective relays in the world, leading the development of relays with microprocessors. The relays are built up in a modularized plug-in system called COMBIFLEX®, a system characterized by great flexibility and reliability. The relays in the COMBIFLEX system have been optimized with respect to their quality, dimension and cost.

All COMBIFLEX relays can be tested by a test system called COMBITEST by plugging a test-handle into a built-in test switch. By this it is possible to carry out a safe and easy injection test of a relay. The load current through a relay in service can be measured by an ammeter connected to a current measuring plug with a built-in overvoltage protection. If the ammeter circuit is open by mistake the plug will be short-circuited by the overvoltage protection. By this the current in a CT-circuit can be measured without any risk of getting an open CT-circuit. A very important safety feature.

2. CONDITIONS LEADING TO FAULTS

2.1 Insulation breakdown

A breakdown of the insulation results in short circuits or ground faults, frequently causing severe damage to the windings and the transformer core. Furthermore, a high gas pressure may develop, damaging the transformer tank.

Breakdown of the insulation between windings or between windings and the core can be caused by:

- aging of insulation due to overtemperature during long time.
- contaminated oil
- corona discharges in the insulation
- transient overvoltages due to thunderstorms or switching in the network
- current forces on the windings due to external faults with high current.

A flash-over between the primary and secondary windings usually results in a breakdown of the insulation between the secondary winding and ground.

2.2 Aging of insulation

Aging or deterioration of insulation is a function of time and temperature. The part of the winding which is operated at the highest temperature (hot-spot) will ordinarily undergo the greatest deterioration and gets the shortest length of life. However, it is not possible to accurately predict the length of life as a function of temperature and time under constant controlled conditions, much less under widely varying service conditions.

In case a transformer gets too hot, improve the cooling if possible or reduce the load in order to avoid accelerated aging of the insulation. A temporary moderate overtemperature can be allowed as it takes a considerable time to age the insulation.

2.3

Overheating due to overexcitation

According to IEC 76-1 guidelines, transformers shall be capable of delivering rated currents at an applied voltage equal to 105% of the rated voltage. Transformers may be specified for operation at a voltage up to 110% of rated voltage.

When a transformer is operated at too high voltage or at too low frequency, the transformer core gets overexcited. The flux is then forced through surrounding steel parts such as the sheet metal of the tank and other unlaminated parts of the transformer. These parts are heated up in an unacceptable way and the transformer can be damaged. As a transformer loaded with rated current can withstand only 105% of rated voltage continuously, the transformer has to be disconnected if the voltage is too high or the frequency too low. According to IEEE general guide for permissible short-time overexcitation of power transformers, see fig 1, transformers can only withstand overexcitation a short time.

Especially turbo-generator transformer units can be exposed to overvoltage and underfrequency conditions. They should be provided with an overexcitation relay operating when the ratio between voltage and frequency (V/Hz) gets too high.

To get a correct representation of the flux, the overexcitation relays must be connected to a potential transformer, measuring the voltage of an untapped transformer winding.

2.4

Oil contamination and leakage

The oil in a transformer constitutes an electrically insulating medium and also a cooling medium. The service reliability of an oil-immersed transformer therefore depends to a great extent on the quality of the oil. The oil should fulfill the requirements of IEC 296.

The dielectric strength of the oil is the most important property of the oil. If the dielectric strength of the oil is reduced by water and impurities etc, a breakdown of the insulation can occur. Testing of the dielectric strength of the oil is normally conducted on site to get a quick check of the purity of the oil.

The oil level must be monitored, a breakdown of the insulation occurs if the oil level gets to low.

Oil immersed transformers with an oil conservator should therefore be provided with both a silica gel breather and an oil level monitor.

2.5

Reduced cooling

Forced cooling systems must be supervised, and an alarm shall be given if the cooling system stops. The oil temperature can then be watched and appropriate action taken before the transformer becomes overheated.

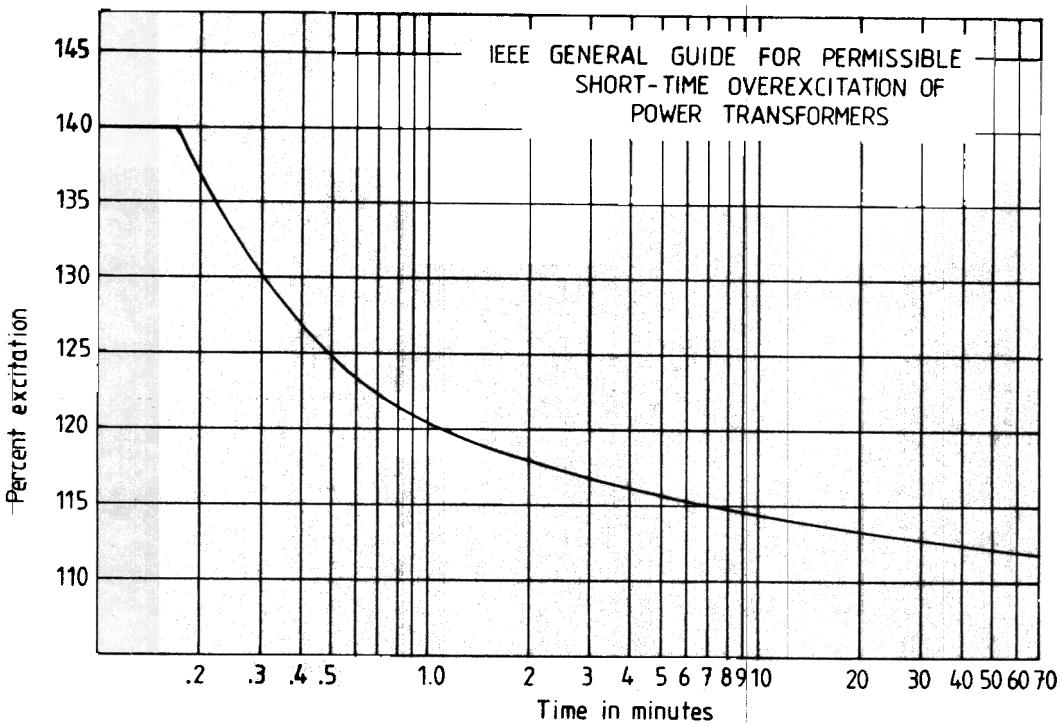


Fig. 1 Permissible short-time overexitation

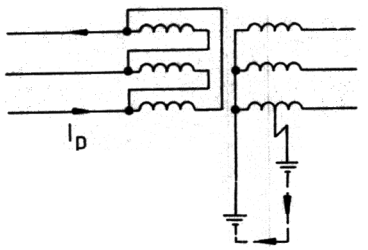
3. FAULT CURRENTS

3.1 Ground faults in a solidly grounded star-connected secondary winding

The magnitude of fault current is mainly controlled by the reactance and the voltage between the point of the fault and ground. The reactance decreases rapidly for faults approaching the neutral. The fault current can therefore be higher for a fault close to the neutral than for a fault at the middle of the winding.

Fig. 2 is valid for one type of transformer design. For this transformer the fault current is higher for a fault close to the neutral than for a fault between 10 - 60 % from the neutral.

It can also be seen that the primary current for a ground fault between 0 - 40% from the neutral is below 1,5 × I_n. Therefore in this case an overcurrent relay on the primary side can not detect ground faults located 0 - 40% from the neutral point as it has to be set about 1.5 × I_n due to the load current.



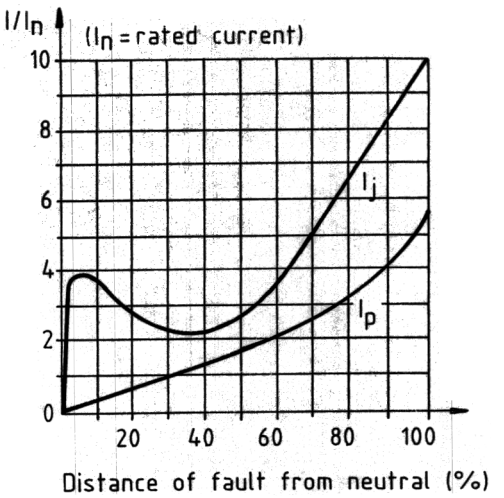
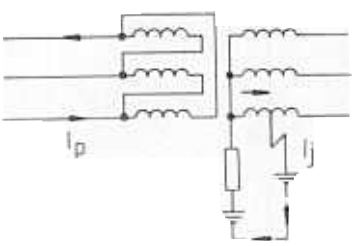


Fig. 2 Ground fault current in a solidly grounded star-connected winding

3.2 Ground faults in a high impedance grounded star-connected secondary winding

The fault current is controlled by the grounding impedance and the position of the fault. The primary current is approximately proportional to the square of the shortcircuited fraction of the winding. See fig 3.



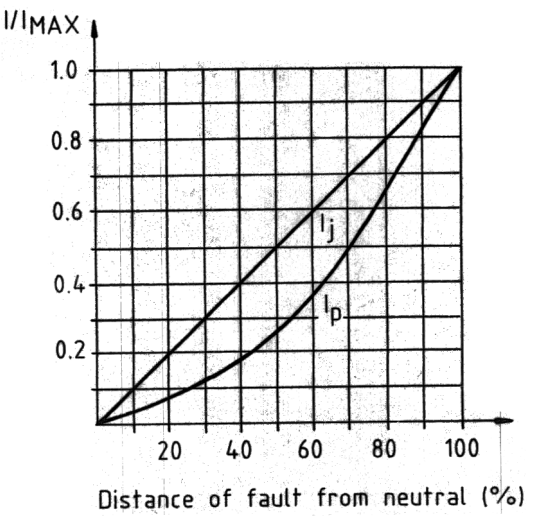


Fig. 3 Ground fault current in high a impedance grounded star-connected winding

3.3

Ground faults in a delta-connected winding

The magnitude of the ground-fault current depends on the grounding of the power system.

The fault impedance of a delta-connected winding is highest for faults at the midpoint of the winding and can be expected to be 25-50%, based on the transformer rating.

The fault current is equally divided between two phases for a fault at the midpoint. The fault currents in the phases may therefore be equal to or less than the rated current when the source impedance is appreciable. These relatively low phase currents must be considered when evaluating the performance of a protection scheme.

For faults close to one end of the winding the fault current approaches the fault current for a phase-to-ground fault.

3.4

Turn-to-turn faults

A direct metallic contact or flashover between conductors within the same physical winding is called a turn-to-turn fault. The current forces caused by high fault currents through a transformer during system faults, can crush or shave off the insulation and develop a turn-to-turn fault. This is particularly a risk for relatively small and aged transformers in powerful systems.

A turn-to-turn fault can also be caused by steep fronted surge voltages or corona discharges.

A turn-to-turn fault short-circuits a small part of the winding. This part behaves as an autoconnected winding of its own with very large turns ratio to the remaining part of the winding. An extremely high fault current is therefore transformed into the short-circuited loop. The resulting unbalanced current forces can rip apart or crush the loop.

If a turn-to-turn fault develops, the damaged area has sometimes lost a burned-away volume of copper as large as a fist. The whole winding is sprayed with copper beads and soot. The repair of the transformer will therefore be extensive.

Turn-to-turn faults between a few turns are difficult to detect by current measuring relays as the terminal current increases very little. The fault current at the terminals increases when the fault spreads and more turns are short-circuited. The fault current is equal to the rated current when 2-4% of the turns are short-circuited.

The current in the short-circuited turns may be 50-100 times the rated current. That means local overheating, arcing, decomposition of oil and release of gas. A gas detector relay therefore detects a turn-to-turn fault. A rate-of-rise pressure relay may also detect the fault.

3.5

Phase-to-phase faults

Short-circuits between the phases will give rise to substantial fault currents only limited by the source impedance and the leakage impedance of the transformer.

4. PROTECTIVE RELAYS

4.1 General

When a fault occurs in a transformer, the damage is proportional to the fault time. The transformer should therefore be disconnected as fast as possible from the network. Fast reliable protective relays are therefore used for detection of faults.

Monitors can also detect faults and they can sense abnormal conditions which may develop into a fault, see section 5.

The size of the transformer and the voltage level have an influence on the extent and choice of protective equipment. Monitors prevent faults and protective relays limit the damage in case of a fault. The cost for the protective equipment is marginal compared to the total cost and the cost involved in case of a transformer fault.

There are often different opinions about the extent of transformer protection. However, it is more or less normal that transformers with an oil conservator are furnished with the following equipment:

Transformers larger than 5 MVA

- Gas detector relay (Buchholz relay)
- Overload protection (thermal relays or temperature monitoring systems)
- Overcurrent protection
- Ground fault protection
- Differential protection
- Pressure relay for tap-changer compartment
- Oil level monitor

Transformers smaller than 5 MVA

- Gas detector relay (Buchholz relay)
- Overload protection
- Overcurrent protection
- Ground fault protection

Transformers which may be exposed to overvoltage:

- Overexcitation protection should also be included.

In addition to the protective relays and monitors, trip units and alarm systems are required.

4.2 Differential relays

4.2. 1 General

A transformer differential relay compares the current fed to the transformer with the current leaving the transformer. Auxiliary transformers for correction of phase shift in the power transformer and for ratio corrections are needed. For transformers with a tap-changer, the ratio of the auxiliary current transformers should be calculated for balanced currents when the tap-changer is in the middle position.

The protective zone of a differential relay includes faults in the transformer and faults on the buses or cables between the current transformer and the power transformer. A differential relay has therefore a larger protective zone than a gas detector relay. When bushing CTs are used for the differential relay, the protective zones can be considered to be equal.

Fast operation of the relay is obtained when the differential current through the relay is larger than the setting of the relay.

A transformer differential relay must be able to cope with the following conditions:

Magnetizing inrush current

The inrush currents develop when a transformer is switched on to a power system. Similar inrush currents can occur when the voltage is returning to normal after a line fault.

The shape, magnitude and duration of the inrush current depend on the following characteristic factors:

- The size of the power transformer
- The source impedance
- The magnetic properties of the core material
- The remanence of the core
- The moment when the transformer is switched in

The inrush current can appear in all three phases and in a grounded neutral. The magnitude of the current is always different in all three phases as well as in the neutral. In power transformers with oriented core steel, the magnitude can be 5-10 times the rated current when switching is done on the outer winding (usually the high-voltage side) of the transformer and 10-20 times the rated current when switching the inner winding (usually the low-voltage side).

The magnetizing inrush current can get the magnitude and shape shown in fig 4. The maximum inrush current develops if the moment of switching occurs at the zero crossing of the voltage and when the new flux from the inrush current gets the same direction as the already present magnetic flux in the core. The two fluxes are added and the saturation limit of the core can be exceeded. The magnetizing inrush current then increases to a value permitted by the impedance of the power system and the residual impedance of the transformer. The probability that the maxi-mum inrush current should occur is low, but a considerable inrush current is obtained, say, one time out of 5-6 times of switching.

When the new flux at switch-in of the transformer gets the opposite direction of the already present flux, there will be no saturation of the core and the magnetizing inrush current will be small.

The magnitude of the inrush current is therefore dependent on the moment when the transformer is switched in.

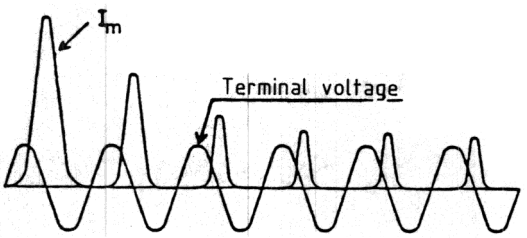


Fig. 4 Theoretical inrush current I_m

The inrush current has a large dc component and is also rich in harmonics. The fundamental frequency and the second harmonic are the basic frequencies. The current is more or less present in all three phases and also in the neutral, see fig 5. The inrush current in the neutral is spread out in the other grounded neutrals of the power system according to the distribution of the zero-sequence impedances.

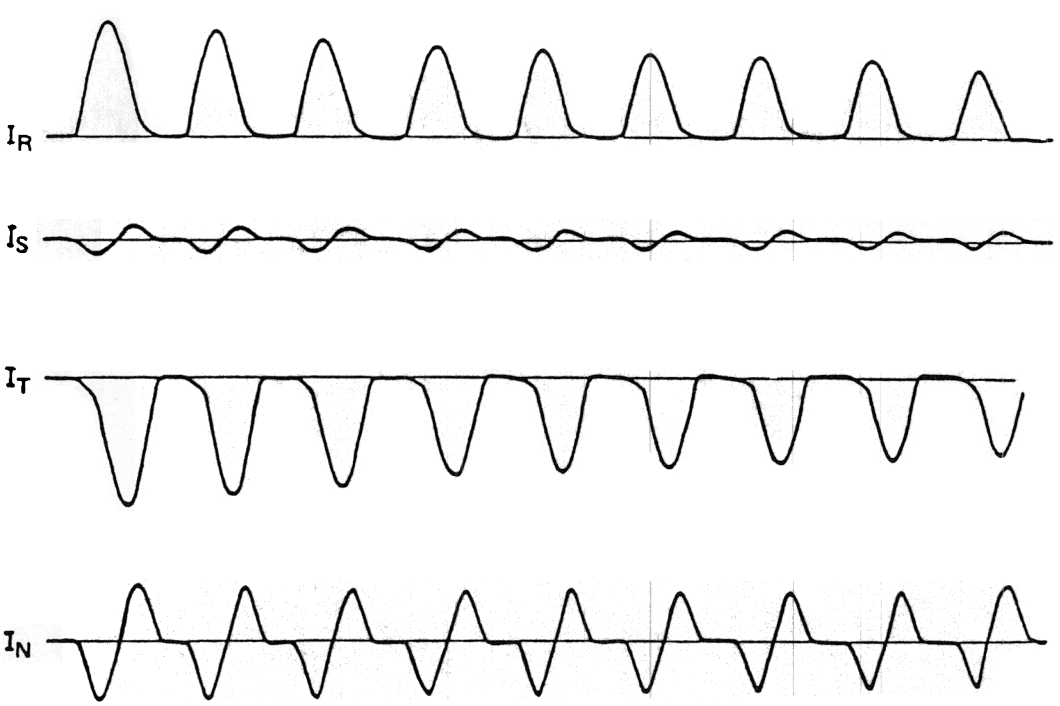


Fig. 5 Recorded inrush current for a 60 MVA transformer 140/40/6,6 kV, connected Y Nyd.

The damping of the inrush current depends on the total resistance of the source network. The duration in a powerful system is usually a few seconds.

In cases when a transformer is switched in parallel with another energized transformer, a corresponding inrush current can develop in the energized transformer when the direct current from the switched-in transformer is saturating its core. The inrush current in the parallel transformer is shifted 180 degrees. The damping of the combined inrush current will then be less than normal and the inrush current may be traced as long as several minutes.

The shape of the inrush current for a delta-connected transformer will not be the same as for a Y-connected transformer. The reason is that the phase current in a delta connected transformer is developed by currents from windings on two limbs.

The differential relay type RADSB is provided with a MAGNETIZING INRUSH RESTRAINT based on the 2nd harmonic content of the inrush current. Any unwanted operation of the relay due to the inrush current is thereby prevented.

Normal service

During normal service a small differential current flows through the differential relay. The current is due to the excitation current of the power transformer, ratio errors in the current transformers and the position of the tap-changer, if provided.

A power transformer with a tap-changer in the end position gives a differential current of 10-20% of load current depending on the regulating range of the tap-changer. Therefore, the mismatch due to the tap-changer in an end position determines the setting of the differential relay. A setting 15% higher than the mismatch is usual.

Internal faults

For faults inside the protective zone of the relay, a current proportional to the fault current occurs in the differential circuit and the relay operates.

The operating time of transformer differential relay type RADSB is shown in fig 6. For a fault current 5 times the operating current, the restrained operation time is 27 ms.

The relay is also provided with an unrestrained operation circuit to speed up the operation for a high fault current. Three settings are available: 8, 13 and 20 times rated current. The current setting for unrestrained operation has to be set above the max inrush current when the transformer is energized. At a fault current 10 times the set operating current, the relay operates in 8 ms.

Recommended setting for unrestrained operation:

Power transformer connection 1)	Rated power	Recommended setting x I_n when energizing from the High voltage side	Low-voltage side
	< 10 MVA	20x	20x
Yy	10-100 MVA	13x	13x
Yy	> 100 MVA	8x	8x
Yd	–	13x	13x
Dy	< 100 MVA	13x	20x
Dy	> 100 MVA	8x	13x

1) The transformers are assumed to be step-down transformers with power flow from the high voltage system to the low voltage system.

A setting of 20 x I_n is required when very large through-fault currents can saturate the CTs and cause a large differential current. This can, for example, be the case when the bus is included in the protective zone of the differential relay or when one and a half breaker arrangement is used.

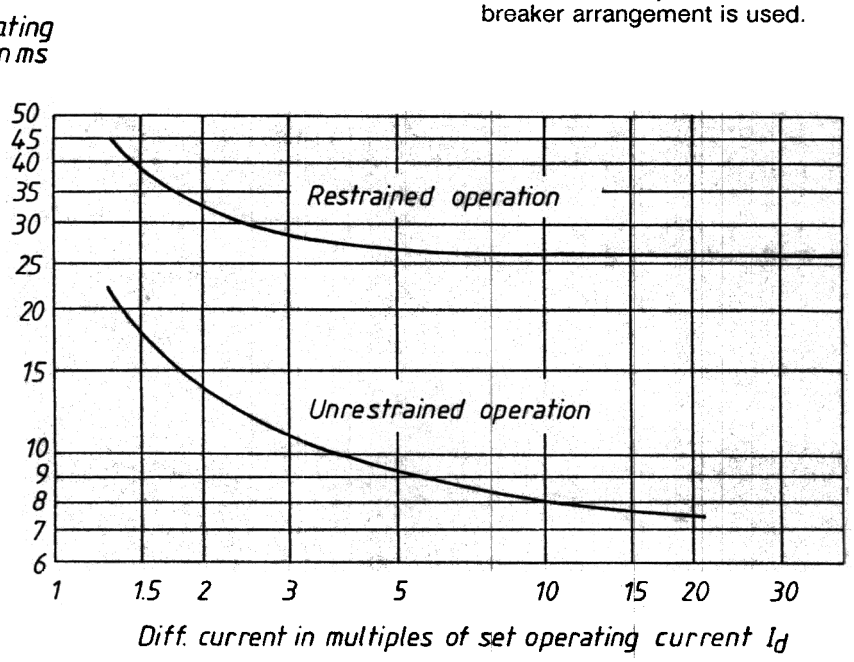


Fig. 6 Operating time

External faults

For faults outside the protective zone of the relay a relatively large differential current can occur due to the position of the tap-changer and differences between the CTs. With the tap-changer in an end position, the voltage could be 20% off from the voltage at the middle position. If then a short-circuit current 10 times the rated current occurs, a differential current of twice the rated current is obtained.

The differential relay should not operate for this differential current. The relay type RADSB is therefore provided with a through-fault restraint circuit which makes the relay operate for a certain percentage differential current related to the current through the transformer. The differential relay is therefore also called a PERCENTAGE RESTRAINT differential relay.

The through-fault restraint of RADSB is shown in fig 7. The curves show that for a through current 10 times the rated current I_n, the relay operates for a differential current ≥ 6 times I_n.

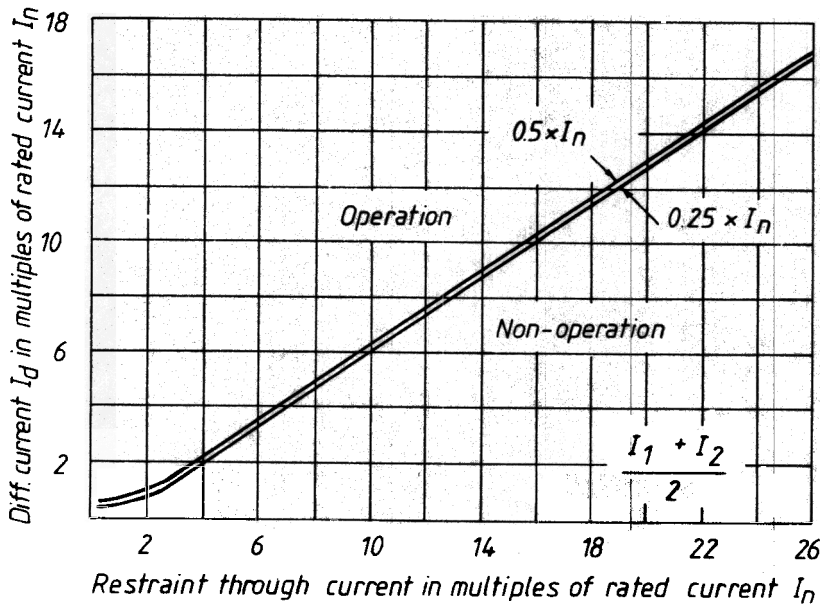


Fig. 7 Through fault restraint

Overexcitation

When a transformer gets overexcited, the excitation current increases dramatically and the transformer may get damaged if this condition is sustained, see section 2.3. For an overvoltage of 20%, the excitation current can increase about 10 times normal excitation current. For a higher overvoltage, the excitation current can increase above the pick-up level of a differential relay unrestrained for excitation current.

An overexcited transformer is not a transformer fault. It is an abnormal network condition for which a differential relay should not operate. Operation of a differential relay indicates a transformer fault. Investigation of a transformer shall therefore always be done after operation of a differential relay. If the relay has operated during an overexcitation condition of the transformer, valuable time for investigation of the transformer would then be lost before the transformer can be put back in operation again.

An analysis of the current during an overexcitation condition shows a pronounced 5th harmonic component. A typical example for a modern transformer is shown in fig 8. This can be utilized to identify an overmagnetizing condition. The differential relay type RADSB is therefore provided with a 5th HARMONIC RESTRAINT to prevent the relay from operation during an overexcitation condition of a transformer due to overvoltage.

Transformers likely to be exposed to overvoltage or underfrequency conditions should be provided with a V/Hz relay, see section 4.5.

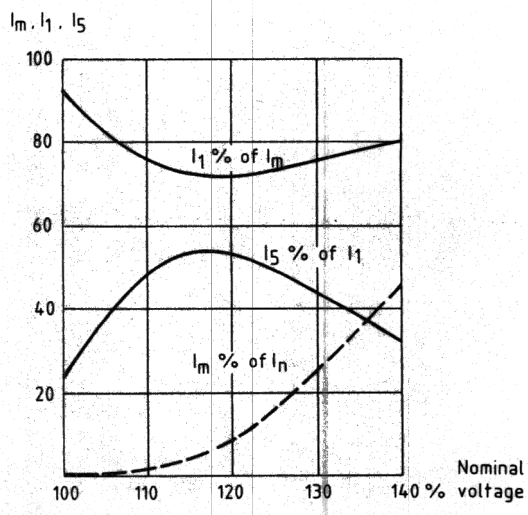


Fig. 8 Magnetizing current at overexitation
I_1 fundamental frequency current
I_5 fifth harmonic current
I_m total magnetizing current
I_n nominal current

4.2.2

Differential relays for fully insulated transformers

When applying a differential relay to a Yy connected power transformer, it may sometimes be possible to choose the main CTs on both the high and low voltage side of the transformer with ratios making the secondary currents equal at both sides. However, to prevent any operation for external ground faults, one set of auxiliary CTs with a delta connected tertiary winding or two sets of auxiliary CTs connected Yd are required.

When the power transformer is connected Yd, auxiliary CTs are always required at least on one side of the transformer for balancing of the currents and for correction of the phase angle between the currents.

With auxiliary CTs on only one side of a power transformer, a differential current occurs if the auxiliary CTs saturate during a heavy through fault. It is therefore recommended to use auxiliary CTs on all windings of the power transformer in order to get the same time to saturation on all inputs to the differential relay.

The connection of the auxiliary CTs depends on the connection of the power transformer, see instruction RK 625-100E.

4.2.3

Differential protection for auto-transformers

An auto-transformer as well as a fully insulated transformer can be protected by the transformer differential relay type RADSB.The delta winding can be connected to the network as in fig. 9 or not connected.If not connected to the network, CTs are not needed for the connection of RADSB. In both cases, the delta winding is protected as well as the main winding. The sensitivity of RADSB can be set between 20-50% of rated current and an operating time as shown in fig. 6 is obtained.

By applying CTs in the neutral point of the main winding, a faster and more sensitive relay type RADHA or RADSG can be used to protect the main winding, see fig. 10. The relays operate for phase-to-phase faults and for phase-to-ground faults in the main winding. Faults in the delta-connected winding can not be detected by RADHA or RADSG. A transformer differntial relay protecting both winding is therefore also used.

RADHA is a high impedance differential relay. RADHA requires dedicated CT cores and all CTs must have the same ratio. No turns corrections can be allowed on any CT and no auxiliary CTs for ratio correction can be used. The saturation voltage of all CTs must be at least twice the selected operating voltage of RADHA.

A sensitivity of about 5% can normally be obtained. The operating time is 15-20 ms.

The ultra-high-speed relay type RADSG can be used instead of RADHA. Compared with RADHA, no dedicated CT cores are required and different ratios of the main CTs can be matched by using auxiliary CTs.

A sensitivity of about 4% and an operating time of 8-13 ms can be obtained.

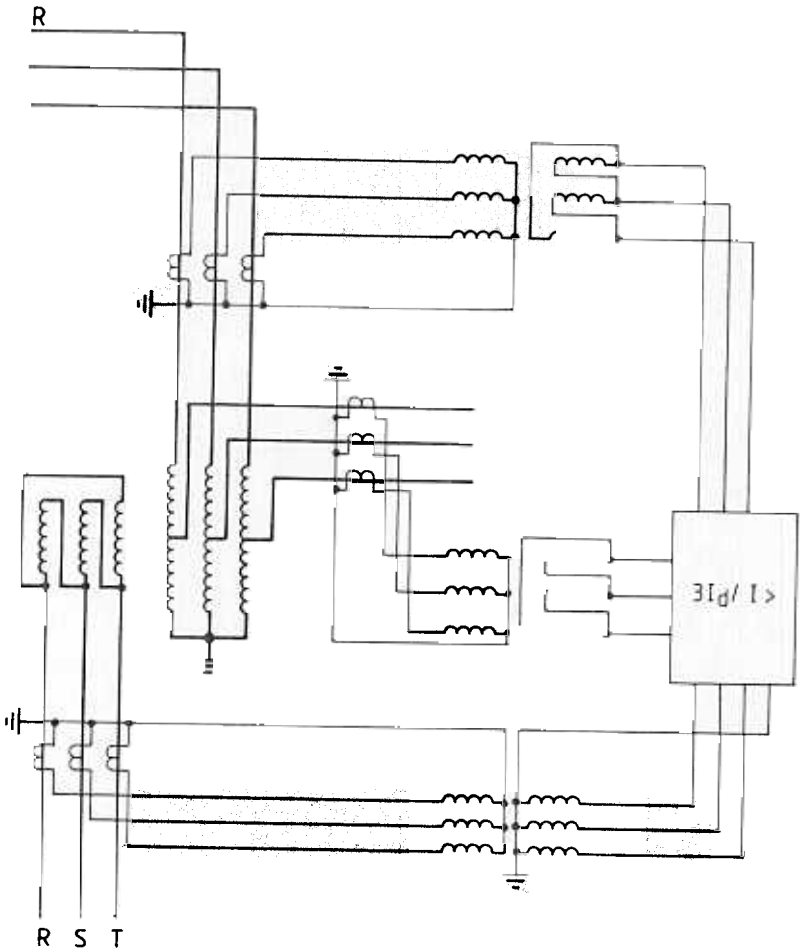


Fig.9 *Transformer differential relay for autotransformer*

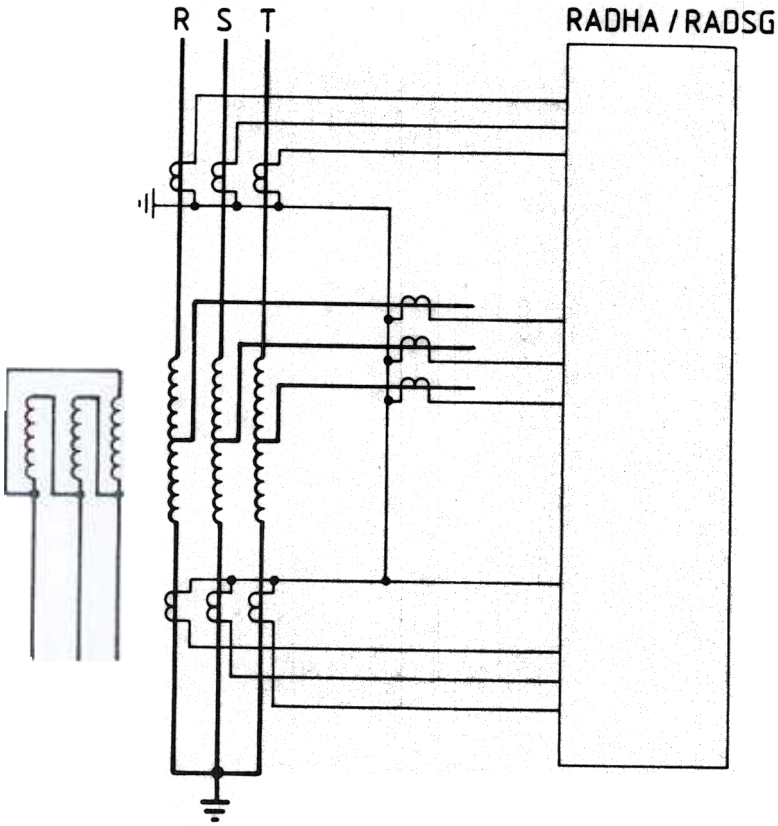


Fig. 10 *Differential relay RADHA or RADSG for autotransformer*

4.3

Overcurrent protection and impedance relays

4.3.1

Time-overcurrent relays

Time-overcurrent relays are used on all feeding circuits to a power transformer. Their function is to back up the differential protection and the protective relays on the load side of the transformer. The overcurrent relays perform as a primary short-circuit protection if no differential protection is used. Instead of overcurrent relays, underimpedance or distance relays are required when there is a large difference between the maximum and minimum short-circuit fault MVA.

Time-overcurrent relays with an instantaneous element for high-fault currents are normally used in each phase. The time-overcurrent relay is normally set for operation at about 150% of the rated current of the transformer. The time delay must be long enough to avoid tripping due to the magnetizing inrush current when the transformer is energized. Time selectivity must also be attained between the relays on the primary and secondary side of the transformer.

The instantaneous element has to be set about 25% above the maximum through-fault current and above the maximum inrush current. With this setting, instantaneous tripping is only obtained for severe faults on the feeding side of the transformer. There can, for example, be faults on the transformer winding close to the bushing, faults in the bushing or on the circuits between the CTs and the transformer.

The relay operates delayed for faults on the remaining parts of the windings and for faults on the load side of the transformer if the fault current and the duration exceed the setting of the relay.

4.3.2

Under-impedance relays

Overcurrent relays are not always suitable as back-up relays for system transformers connecting two networks or in networks with a large difference between maximum and minimum short-circuit fault MVA.

The back-up protection must be able to see a fault at any one of the voltage systems and it must also be able to operate for the minimum short-circuit MVA. In such cases, an under-impedance relay type RAKZB can be used. The reach is independent of the magnitude of the short-circuit current. The version of RAKZB measuring the current IR - IT, IS - IR and IT - IS should be used to get the same reach for two- and three-phase faults. The relay is not suitable for ground faults.

4.3.3

Distance relays

Distance relays are sometimes used instead of differential relays as the main transformer protection.

Distance relays instead of non-directional under-impedance relays are also used as a back-up for the transformer differential relay and at the same time they can act as a primary or back-up relay for the buses.

The static distance relay RAZOA is a suitable relay for this purpose. The direction of measurement of any one of the three impedance zones can be reversed. The reach and directions of the zones, see fig 11, can be set as follows: Zone 1 reaches 70-80% into the transformer, zone 2 is reversed and covers bus 2 and zone 3 reaches through the transformer and covers bus 1.

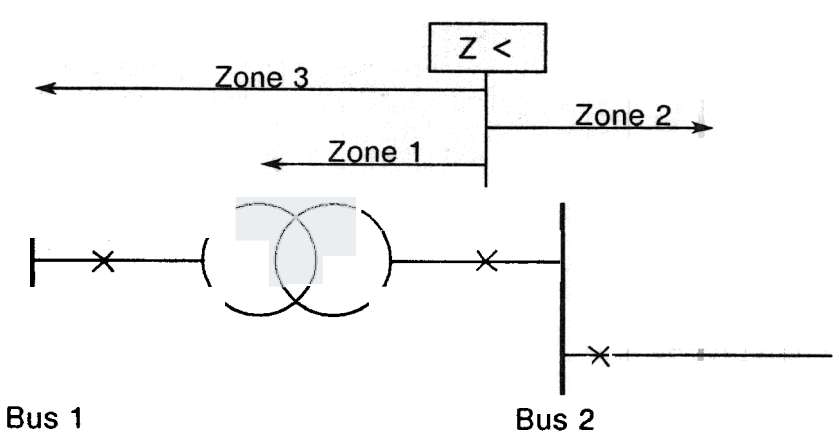


Fig. 11 Distance relay used as a transformer protection

4.4

Ground fault protection

4.4.1

General

Power transformers with impedance-grounded or solidly grounded neutral, can be equipped with different types of ground fault relays to protect the grounded winding.

Low-impedance residual overcurrent relays or **harmonic restraint** overcurrent relays can be connected according to A or B in fig 12.

When the transformer neutral in fig 12 is solidly or effectively grounded and the transformer is fed from either side H or side L, a fault at F1 or F2 is detected by a relay at point A. The relay at point B may also operate depending on the distribution of the zero-sequence impedance in the network. A fault at F3 is detected by the relays at point A and B.

Consider the transformer fed from either side H or side L and that the transformer neutral is impedance-grounded. With only one point in the network grounded, a fault at F1 or F2 is detected by a relay at point A. Fault F3 is detected by the relays at point A and B.

These types of overcurrent relays must therefore be delayed, or else they will operate for faults which should be taken care of by other ground fault relays in the network.

The relays also have a back up function regarding the ground fault protection of the lines. They are also a slow back up for transformer differential relays in solidly grounded networks.

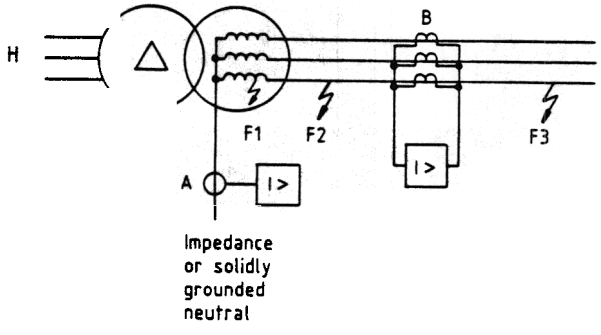


Fig. 12 Connection of ground fault overcurrent relays

A **restricted** ground fault relay of the **current differential type** can only operate for faults inside the protective zone, see fig 13 and 14.

The relay is sensitive and reliable and a high speed of operation is obtained.

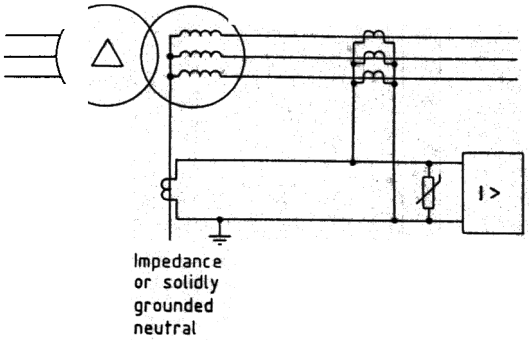


Fig. 13 Connection of a restricted ground fault relay for a Y-connected winding.

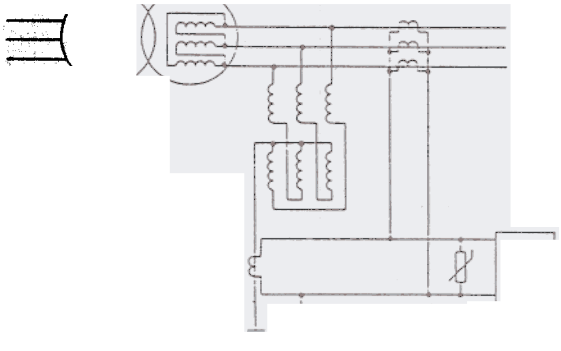


Fig. 14 Connection of a restricted ground fault relay for a D-connected winding and a grounding transformer.

4.4.2

Low-impedance residual overcurrent relay

This type of ground fault relay can be connected either to a current transformer in the neutral or to residually connected phase current transformers, see fig 12.

The relay should be released by a residual voltage relay to prevent operation due to saturation of any CT during a short-circuit or due to a magnetizing inrush current.

The relay can operate for ground faults in the network and also for magnetizing inrush current containing a zero sequence component. The relay must therefore be delayed longer than the duration of the inrush current or longer than the delay of other ground fault relays in the network.

4.4.3

Harmonic restraint overcurrent relay type RAISA

An overcurrent relay with a second-harmonic restraint is stable for the inrush current. The time setting of this relay is therefore independent of the duration of the inrush current. The delay can be chosen only with regard to other ground fault relays in the network.

The basic version can be delayed by an independent time-delay relay or an inverse time-delayed relay.

4.4.4

High-impedance restricted relay

A high-impedance restricted ground fault relay type RADHD (differential ground relay) will provide a sensitive and high speed restraint protection. The relay is used in solidly grounded networks. It can also be used in impedance grounded networks with a fault current above the sensitivity of the relay, see fig 13 and 14.

The current from residually connected line CTs is balanced against the current from a CT in the grounded neutral. For an **internal** fault, the currents from the CTs have opposite direction and a high voltage occurs across a high-impedance relay. The saturation voltage of the CTs should be at least twice the operation voltage U_s of the relay.

For an **external** fault, the current circulates between the current transformers. The relay is then stable for all external faults even if one of the CTs should be saturated.

The CTs in the phases and in the neutral shall, if possible, be dedicated for the relay and they must have exactly the same turns ratio. No turns correction can be accepted.

Relay type RADHD provides a more sensitive protection than the transformer differential relay but is not a back-up for a transformer differential relay which protects both the high and low voltage windings.

The relay may have to share the CT cores with the differential relay, see fig 15.

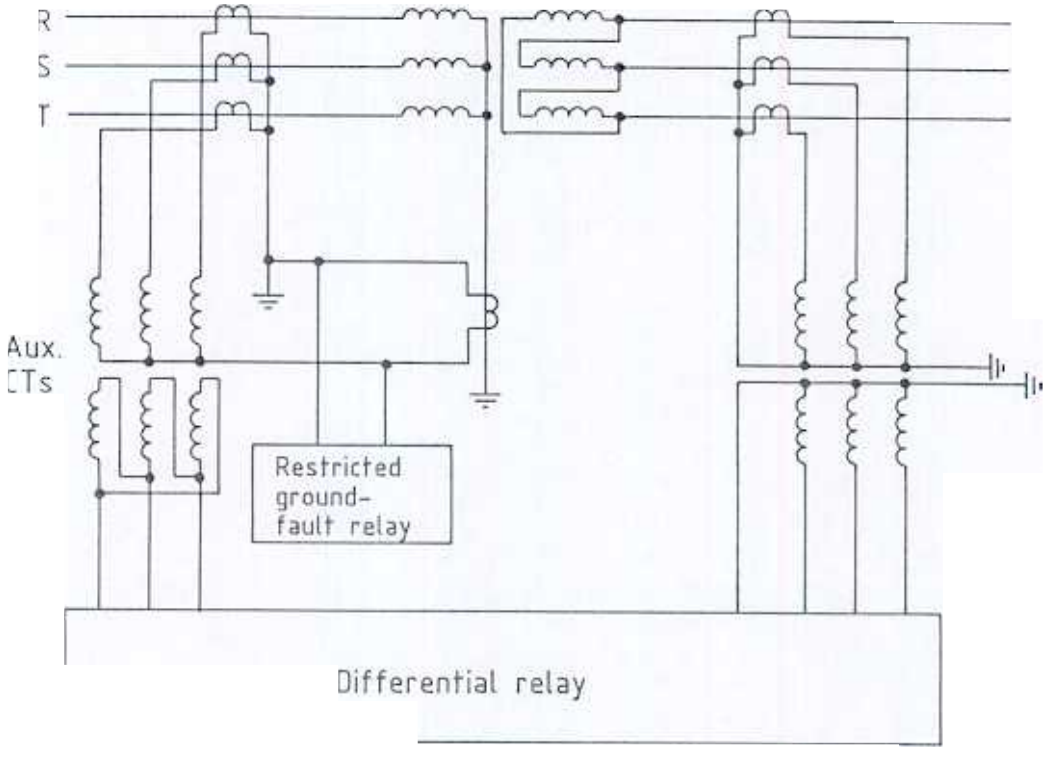


Fig. 15 Transformer differential and restricted ground fault relays on the same CT cores.

The combination of the relays on the same CT cores should be avoided when only the winding protected by the high impedance relay is supplied from the network. Due to the impedance of the restricted ground-fault relay, the differential relay might not get enough current for operation for a phase-to-ground fault.

A non-linear resistor should be connected in parallel with the high impedance relay close to the connection point of the CTs. The resistor reduces the high peak voltage which can be developed during an internal fault. The interconnected secondary circuits of the CTs have to be grounded at only one point.

Each Y-connected winding of a transformer can be protected with a separate high-impedance restricted ground fault relay, see fig 13. Delta-connected windings can also be protected and the grounding transformer can be located inside the protected zone, see figure 14.

With RADHD, a sensitivity of about 10% of rated current can normally be obtained. The operating time of the relay is approximately 20 ms.

During a fault, a relatively high transient voltage occurs across the relay circuit of a high-impedance relay. This voltage can be considerably reduced if the moderate high-impedance relay type RADSG is used instead of RADHD. The relay type RADSG requires no dedicated CT cores and auxiliary CTs can be used for matching the ratios of the CTs and for reducing the transient voltage.

With RADSG, a sensitivity of about 4% and an operating time of 8 - 13 ms can be obtained.

4.4.5

Low-impedance restricted relay

It is sometimes possible to use a low-impedance current relay as a ground differential relay instead of a high impedance relay. The current transformer in the neutral can then have a different ratio from the phase CTs since an auxiliary CT can be used for ratio correction.

If a phase CT gets saturated during a short-circuit, the relay may operate. The relay should therefore be released by a residual voltage relay.

4.4.6

Tank protection

The tank protection is a ground fault protection with a limited use in some countries. The transformer tank is insulated from the ground. About 10 ohm insulation resistance is sufficient. The tank is connected to ground through a current transformer. An instantaneous overcurrent relay is connected to the current transformer.

The relay operates for ground faults inside the tank and for flashovers on the bushings.

No path for the ground fault current except through the current transformer can be allowed. Therefore, the following must be taken care of:

- All cable sheaths must be insulated from the transformer tank.
- All pipes to heat-exchangers etc must be insulated.
- Fan motors and motors in a tap-changer must be insulated from the tank to prevent a ground fault in a motor from activating the tank protection.
- Instead of insulating cable sheaths and pipes, all cables and pipes can be brought through the cable current transformer located on the connection between tank and ground.
- Mistakes like leaving a metal bar etc leaning against the transformer tank can be made.
- Hazardous potentials to personnel working in the vicinity of the transformer can occur at a ground fault

The tank protection is seldom used due to these points.

4.4.7

Residual voltage relay

A residual voltage relay connected to potential transformers connected in broken delta measures the neutral displacement for any ground fault in the network. The relay is a back-up for other ground fault relays and must therefore have the longest delay among the ground fault relays.

Normal voltage setting of the relay in high impedance grounded networks is 10 - 40% of the phase voltage.

In solidly or effectively grounded networks, a residual voltage relay can be used as a back-up ground fault relay. The relay can be set to operate in case the grounding of the network is lost or reduced to such an extent that the residual current relays do not get enough current for operation.

4.5

Overexcitation protection

Overexcited transformers may become overheated and damaged, see point 2.3 and fig 1. A V/Hz overexcitation relay is therefore needed for transformers which may be operated at a too high voltage or at a too low frequency. Especially generator transformer units can be overexcited during acceleration or deceleration of the turbine. The actual ratio between generator voltage and frequency shall not be allowed to exceed 1.1 times the ratio of rated voltage and frequency of the transformer.

A V/Hz relay provides improved measurement of overexcitation as compared to only measuring the voltage. The inverse-time operation characteristic of RATUB corresponds closely to fig 1. This relay therefore ensures maximum usage of a transformer during system disturbances, causing an overvoltage or an underfrequency condition.

4.6

Flashover and ground fault protections for low voltage systems.

4.6.1

Systems without rectifiers or frequency converters.

If a fault between the primary and secondary winding in a transformer occurs, the voltage level of the secondary network can be exposed to the voltage level of the primary winding. This can cause extensive damage to the low voltage network.

A flashover protection consisting of an instantaneous voltage relay type RXEG 21 or RXEL 24 connected to a voltage transformer between the neutral point of the low voltage system and ground can be used to trip the circuit breakers. The voltage relay is normally set at 1.5-2 times the phase voltage and no delay of the relay is allowed.

No rectifiers or frequency converters are allowed to be connected to the low voltage system. The voltage transformer will get saturated by dc from the rectifiers or converters and damaged if a ground-fault occurs on the dc-system.

This type of flashover protection can only be used if the ground-fault current on the primary side of the power transformer is limited to about 25 A. The condition has to be fulfilled to be able to use a voltage-dependent resistor connected in parallel with the primary side of the voltage transformer in the grounded neutral. The resistor is used to limit the voltage across the relay to max 2 kV in order to protect the low voltage system and the relay against excessive overvoltage. See fig 16.

A delayed residual voltage relay with RXEG 21 or RXEL 24 can be connected in parallel with the flashover relay. The relay is normally set for operation at 20-40% of the phase voltage and gives an alarm in case of a ground fault.

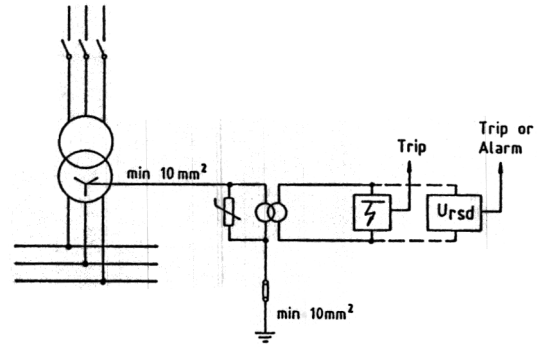


Fig. 16 Flashover relay.

4.6.2

Systems with rectifiers and frequency converters without pulse-width-modulation.

When rectifiers or static frequency converters are connected to a low voltage system, a voltage transformer in the neutral point can not be used. The voltage transformer can be saturated by dc and damaged.

In such cases the voltage transformer must be replaced with a neutral point equipment with a voltage dependent resistor, which limits the voltage in case of a flashover.

A ground fault in the relay circuit will not be detected during normal operation. It will be detected by a miniature circuit breaker (MCB) in the relay circuit if a ground fault occurs in the low voltage network. A resistor limits the current through the MCB. See fig. 17.

If the dc-link voltage of the static frequency converters is regulated and the maximum output frequency is 65 Hz, a relay of type RAEUB is recommended as a ground fault relay. See fig. 17.

The RAEUB relay can also be used in systems without any neutral point,
See B03-2712E.

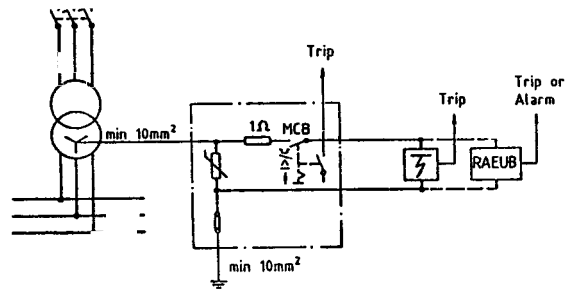


Fig. Ground fault relay

4.6.3

Systems with rectifiers and pulse-width-modulated frequency converters.

The RAEUB relay or other neutral point voltage relays can not be used if the frequency converters are pulse-width-modulated (PWM). The PWM frequency converters generate harmonic voltages, which at certain frequencies may be higher than the fundamental harmonic voltage in the neutral point at a ground fault.

For a low voltage network with PWM frequency converters, a relay of type RAERA with both ground fault and flashover functions is used. See fig. 18.

The RAERA relay will cope with the conditions typically found on systems having PWM frequency converters. The relay is also applied on systems with ac/dc-converters and low frequency induction stirrers. For operation at a ground fault, RAERA injects a direct voltage into the system and measures the direct current which occurs during a ground fault.

The neutral point equipment has a voltage dependent resistor in series with a spark-gap, a resistor and a miniature circuit breaker (MCB) in the relay circuit. See fig. 18.

The RAERA relay can also be used in systems without any neutral point.
See B03-2711E.

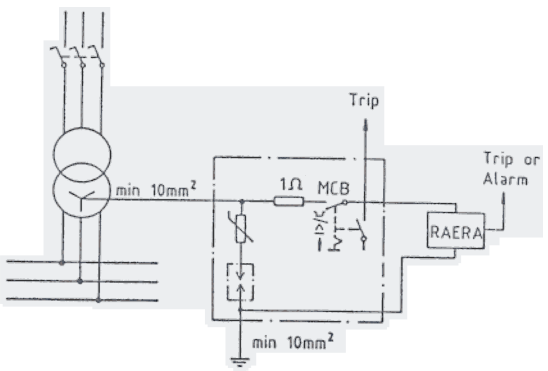


Fig. 18 Ground fault and flashover relay.

5 MONITORS

5.1 General

Monitors are very valuable. They can detect faults and abnormal service conditions which may develop into a fault.

For example, the gas released in the transformer oil can be monitored by a gas detector. Small amounts of gas from a slowly developing faults can be detected before any protective relay can detect the fault. In case of a serious fault the gas detector trips the circuit breakers. The gas detector is then a back-up for the protective relays.

The extent of monitors on a transformer depend mainly on the size of the transformer and the voltage level.

5.2 Gas detector relay

During a fault in an oil-immersed transformer, arcing will occur, releasing gas from decomposition of the oil. The gas passes through the oil pipe to the conservator and can therefore be detected by a gas detector relay.

Gas detector relays have an alarm and a trip device. Gas is collected in the alarm device, and when there is enough gas, an alarm contact is closed. The gas detector relay detects small amounts of gas developed over a long time. A slowly developing fault can therefore be detected before it becomes more serious.

The trip device responds to the high flow of oil which occurs when a serious fault suddenly occurs in the transformer. The device actuates a contact normally connected for tripping the circuit breakers for the transformer. The operating time of the trip contact depends on the size of the transformer, the magnitude and location of the fault. The operating time can therefore vary between 0,1-0,3 s.

If the gas detector has operated, the gas should be investigated. The following indications could be used for a preliminary evaluation of the cause of gas.

Character of the gas:	Indicating:
• Colorless and odorless	• Air
• Whitish, pungent, usually incombustible	• Overheated insulating material (pressboard, paper)
• Dense, yellowish	• Flashover on wood
• Grey or black, combustible	• Products of decomposition of the oil

Air collected in the gas detector usually originates from air bubbles trapped in the transformer when the transformer was filled with oil. In such cases, alarm signals caused by escaping air do not usually continue for any length of time.

5.3

Temperature monitoring

Overtemperature in a transformer may occur because of overloading or loss of cooling capacity (forced-cooling units).

The largest contribution to the heat capacity of an oil-filled transformer comes from the oil. The time constant with which the oil temperature responds to a change of loading is several hours, which means that during a daily load cycle, the temporary loading may well exceed rated power without the transformer reaching maximum allowable temperature. According to standards, short-time overloads up to 1.5 times the rated load can be allowed.

Therefore, overcurrent relays cannot be used for overload monitoring. They have to be set above predicted short time overload.

Temperature and overload monitoring of oil-filled transformers is carried out with indicating thermostats ("contact thermometers") which are standard accessories on a transformer. There are two conventional functions, called "oil thermometer", and "winding thermometer" (or winding temperature indicator).

The oil thermometer type TITG 54 has a liquid thermometer bulb in a pocket at the top of the transformer, connected through a capillary tube to an indicating, bellow-type instrument with a set of adjustable contacts. The instrument is compensated for changes in ambient temperature and essentially feels the top oil temperature in the transformer.

The winding thermometer type TITG 64 has a thermometer bulb measuring the top oil temperature and the instrument is provided with a heater element fed from the load current which introduces a bias to the reading. This bias is set by a rheostat according to the heat run test result so that it corresponds to the temperature difference of the winding above its surrounding oil. The indication is therefore closer to the winding hot spot temperature, and the bias function has a time constant similar to that of the winding-over-oil temperature difference (a couple of minutes). The measuring system is compensated for changes in ambient temperature.

Depending on the climate, a suitable early alarm is set for high oil temperature in a temperate or arctic zone typically at 75 °C. An emergency trip contact is set at 100-110 °C. Additional contacts may be used for thermostatic control of cooling pumps and fans as the loading and ambient temperature varies.

Winding thermometer signal and trip contacts are set correspondingly higher. The winding thermometer type TITG 64 provides for settings up to 160 °C.

Static thermal relay type RXVE 4 with built-in compensation for the temperature of the cooling media can be used. Only one temperature level can be set on one relay.

Bimetal relays are not suitable as overload protection as their time constant τ and the time constant of a transformer do not correspond.

5.4

Pressure relay for on-load tap changers

If a fault causing gas development occurs in a tap-changer compartment, a pressure relay can be used to trip the circuit breakers before excessive pressure occurs.

The pressure relay delivered by ASEA has a setting range of 30-150 kPa and an operating time of 10-15 ms. The relay is preset at a function-value valid for the type of tap changer used.

5.5

Pressure relief valve

A flashover or a short-circuit in an oil-filled transformer is usually accompanied by overpressure in the tank. By providing the transformer with a pressure relief valve, the overpressure can be limited to a magnitude harmless to the tank.

The valve delivered by ASEA opens for a pressure of 120 ± 12 kPA within approximately 2 ms. The valve closes automatically when the overpressure is released.

5.6

Oil level monitor

Monitoring of the oil level is specified for transformers with oil conservators. The indicator shows the oil level and also has two contacts for alarm of the max and min oil level.

5.7

Silica gel dehydrating breather

The silica type breather is used for drying the air drawn into the oil conservator when the drop in load and temperature causes the oil to contract. The silica gel in the breather is able to absorb moisture to the extent of 20% of its own weight. When the silica gel gets saturated with moisture, the color changes from blue to pale pink and it has to be replaced.

6 SUMMARY

The protective equipment discussed is engineered to limit the damage and system disturbance caused by faults which can occur in a transformer.

The choice of protective equipment depends on the size and the connection of a transformer, voltage level, power system grounding and the protective relays of the power network. The power companies also have different opinions about the extent and choice of protective equipment for a transformer. No general recommendations can therefore be made.

7 REFERENCES

COMBIFLEX	Mounting and connection hardware	B03-9302 E
COMBITEST	Test system COMBITEST	B03-9510 E
RADHA	High-impedance three-phase differential relay	B03-6011 E
RADHD	High-impedance, single phase, restricted ground-fault relay	B03-5013 E
RADSB	Transformer differential relay	B03-5012 E
RADSG	Ultrahigh-speed generator differential relay	B03-4011 E
RAISA	Harmonically restrained overcurrent or ground-fault relay	B03-2311 E
RAKZB	Three-phase impedance relay	B03-3213 E
RATUB	V/Hz overexcitation relay for transformers	B03-5011 E
RAZOA	Three-zone, phase and ground distance relay for transmission lines	B03-7012 E
RXEG 21	Instantaneous ac over- and undervoltage relays	B03-2534 E
RXEL 24	Electromechanical instantaneous ac and dc overvoltage relays	B03-2513 E
RXVE 4	Thermal overcurrent relay assemblies (RXVE 41, 42, 43, 45)	B03-2270 E
RAERA	Ground fault and flashover relay	B03-2711 E
RAEUB	Neutral point voltage relay for systems with current converters	B03-2712 E

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