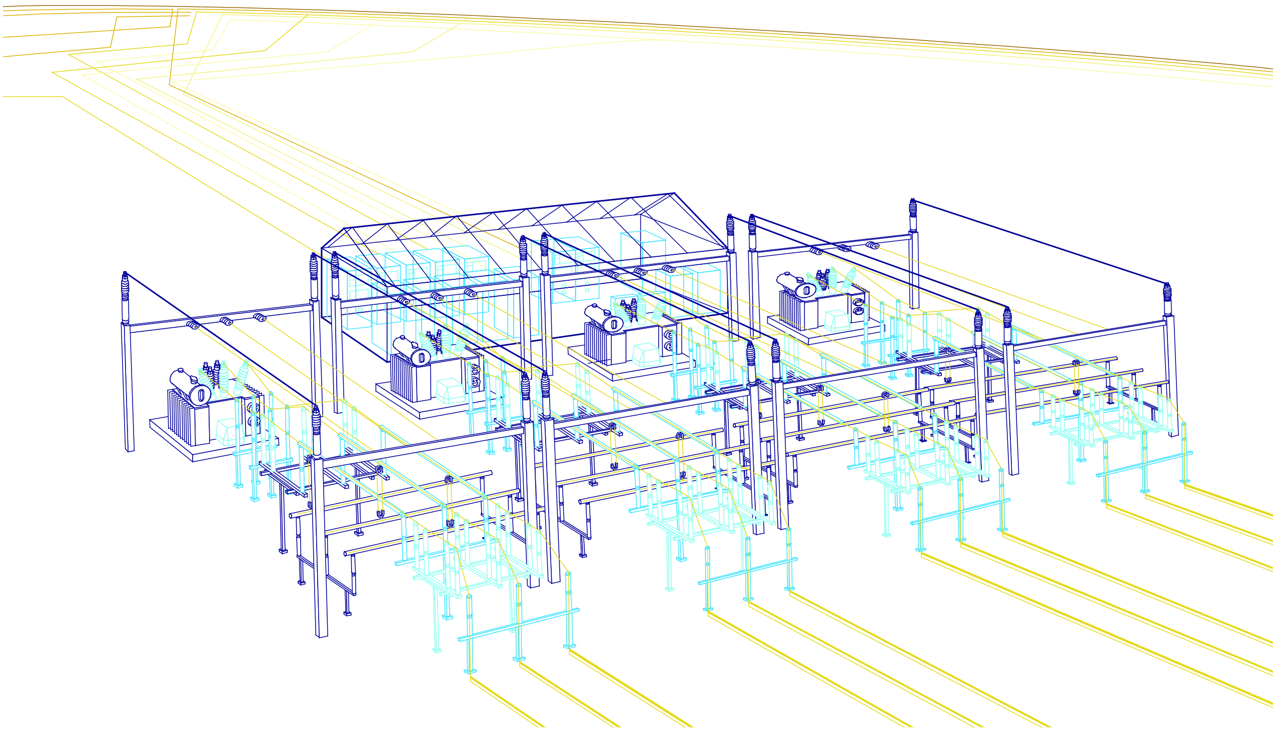
Distribution Automation Handbook

Section 8.7 Protection of HV Transformers



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8.7 Protection of HV Transformers

The transformer substations are important parts of a power system. Many utilities design their power systems so that they withstand the loss of a single transformer. In case of an internal transformer fault, the repair time is long. The outage of an EHV autotransformer will cause a substantial increase of network losses. The outage of a generator step-up transformer will force the owner to use more expensive power-generating units to buy replacement power. Short fault clearing times contribute to the reduction of damage and repair time.

Transformer protection is designed to limit the damage and system disturbance caused by faults that occur in power transformers. Very often the transformer protection system must provide backup protection for busbars connected to the transformer. Sometimes the transformer protection system is the main protection for busbars connected to the transformer. In many cases, the transformer protection system provides backup protection for power lines connected to these busbars.

Transformer protection systems can be designed in many ways. Generator step-up transformers and EHV autotransformers usually have a sophisticated protection system. Usually small distribution transformers have only fuses.

8.7.1 Faults and Abnormal Conditions

The transformer protection has to detect and determine if it shall operate on abnormal conditions and external faults. In case of internal faults, the transformer protection has to detect faults and initiate the tripping of the associated circuit breakers. In such cases, the disconnected transformer should not be re-energized without manual inspection.

8.7.1.1 Abnormal Conditions

The transformer protection has to limit damage to the transformer at overload and at low frequency. The protection has to disconnect the consumers if the voltage becomes too high.

8.7.1.1.1 Overvoltage

Transient overvoltages, switching overvoltages and temporary overvoltages are the most important overvoltages that may damage components in the power system. Transient overvoltages arise from lightning disturbances. Such overvoltages may cause turn-to-turn faults. Surge arresters connected close to the bushings of the transformer may reduce overvoltages. Power-frequency overvoltages and resonance conditions cause temporary overvoltages. They can cause an increase in dielectric stress on the insulation and an increase in the working flux density.

8.7.1.1.2 Overload

Overload causes increased copper losses and a consequent temperature rise. Power transformers can be temporarily overloaded. The length of the acceptable overload period depends on the initial temperature and the cooling conditions.

The thermal time constant of an ONAN (oil natural, air natural) transformer is of the order of 2-5 hours. Force-cooled transformers have shorter time constants.

8.7.1.1.3 Overexcitation

The transformer core becomes overexcited when the applied voltage is too high or the applied frequency is too low. Overexcitation causes an increase in the iron loss and a substantial increase in the magnetizing current. In addition, flux is diverted from the laminated core. It is forced through surrounding steel parts such as the metal of the tank and other non-laminated parts of the transformer. In particular, the core bolts, which normally carry little flux, may be subjected to a large component of flux. Under such conditions, the bolts may be rapidly heated to a temperature that destroys their own insulation and will damage the coil insulation if the condition continues. It follows that a transformer can operate with some degree of overvoltage with a corresponding increase in frequency. Operation must not continue if the applied voltage is high and frequency is low.

8.7.1.2 External Faults

The transformer protection will sometimes serve as the main protection for the busbar fed from the power transformer. The transformer protection will often serve as a station local backup protection for the busbar and the outgoing power lines fed from the power transformer.

8.7.1.2.1 Shunt Faults

System short circuits may produce a relatively intense rate of heating of the feeding transformers. The copper losses increase in proportion to the square of the per unit fault current. Table 8.7.1 shows typical duration of external short circuits that a transformer can withstand without damage if the current is limited only by the reactance of the transformer.

Table 8.7.1: Fault-withstand levels

Transformer reactances	Fault current	Permitted fault duration
%	multiple of rated current	seconds
4	25	2
5	20	3
6	16.6	4
7	14.2	5

Large fault currents produce severe mechanical stresses in transformers. The maximum stress occurs during the first cycle of asymmetric fault currents. Automatic tripping of circuit breakers cannot reduce such stresses. The control of such stresses is therefore a matter of transformer design. Fuses may, however, reduce mechanical stresses.

8.7.1.3 Internal Faults

A breakdown of the insulation results in an earth fault or a short circuit. Such faults may cause severe damage to the windings and to the transformer core. Furthermore, a fault with high fault currents may cause a high gas pressure. If the pressure becomes too high, it will damage the transformer tank.

Following factors may cause breakdown of the insulation between windings or between the windings and the core:

- ageing of insulation due to overtemperature
- contaminated oil
- partial discharges in the insulation
- transient overvoltages
- current forces on the windings

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

A flashover between the high-voltage winding and the low-voltage winding usually results in a breakdown of the insulation between the low-voltage winding and earth. Transformer failures are seldom transient.

8.7.1.3.1 Earth Faults

A direct metallic contact or flashover between a winding and an earthed part such as the core or the tank causes an earth-fault.

8.7.1.3.2 Short Circuits

A short circuit between the phases will cause a substantial fault current. The magnitude of the fault current depends mainly on the source impedance and the leakage impedance of the transformer.

8.7.1.3.3 Turn-to-turn Faults

A direct metallic contact or flashover between conductors within the same physical winding causes a turn-to-turn (an interturn) fault.

Fault currents will flow through a transformer when an external shunt fault occurs. The mechanical forces caused by high fault currents may damage the insulation. Severe damages to the insulation may cause turn-to-turn faults. This is a risk for relatively small and aged transformers connected to networks with high short-circuit power.

Line surges will concentrate on the end turns of the winding because of the high equivalent frequency of the surge front. The turn-to-turn insulation of the end turns is reinforced but cannot be increased in proportion to the insulation to earth, which must withstand high phase-to-earth voltages.

The risk of partial winding flashover is therefore higher than the risk of breakdown to earth. There are claims that 70 to 80% of all transformer failures arise from faults between turns. The subsequent progress of the fault may well destroy the evidence of the true cause.

The heat generated by the fault current will cause decomposition of oil and release of gas. A Buchholz protection can, therefore, detect turn-to-turn faults. A rate-of-rise pressure protection may also detect turn-to-turn faults. Turn-to-turn faults are very difficult to detect by protection equipment using electrical input quantities only.

A turn-to-turn fault may cause substantial damage not only at the fault location. The heat generated by the fault current will melt part of the winding. The molten copper from the fault location will solidify to small copper particles. The circulating oil in the transformer may transport these copper particles from the fault location. It is often necessary to transport the damaged transformer to a repair shop. It is necessary to clean the transformer thoroughly to remove all copper particles and soot. The outage time will be long.

8.7.1.3.4 Core Faults

A conducting bridge across the laminated structure of the core permits eddy currents to flow. They may cause serious overheating. The bolts that clamp the core together are always insulated, to avoid this trouble. If any portion of the core insulation becomes defective, the resultant heating may reach a magnitude sufficient to damage the winding.

The additional core losses, although causing severe local heating, will not produce a noticeable change in the input current. Protection equipment with electrical input quantities cannot detect core faults. It is nevertheless highly desirable that the protection system detects the condition before a major fault occurs. Fortunately, if in an oil-immersed transformer the heating of any part of the core is sufficient to be liable to cause damage to the winding insulation, it will also cause breakdown of some of the oil with an accompanying evolution of gas.

8.7.1.3.5 Tank Faults

The oil in a transformer constitutes an electrically insulating medium. It also constitutes a cooling medium. The service reliability of an oil-immersed transformer therefore depends to a large extent on the quality of the oil. The dielectric strength of the oil is the most important property of the oil. A breakdown of the insulation can occur if water and impurities have reduced the dielectric strength of the oil.

Loss of oil through tank leaks will ultimately produce a dangerous condition. Reduction in winding insulation is one such condition. Overheating on load due to the loss of effective cooling is another such condition. The oil level should be monitored. Oil immersed transformers with an oil conservator should therefore be provided with an oil level monitor.

8.7.1.3.6 Reduced Cooling

Oil sludge can block cooling ducts and pipes. This may result in overheating when the transformer is loaded. The failure of a forced cooling system can also cause overheating. It is necessary to supervise forced cooling systems. An alarm should be given if the cooling system stops. The oil temperature can be monitored and appropriate action taken before the transformer becomes overheated.

8.7.2 Consequences of Transformer Faults

The increase of rated voltage and rated capacity of transformers has been accompanied by various troubles [8.7.1]. Figure 8.7.1 shows results of a survey made in the USA by the Edison Electric Institute (EEI) concerning transformer troubles [8.7.7].

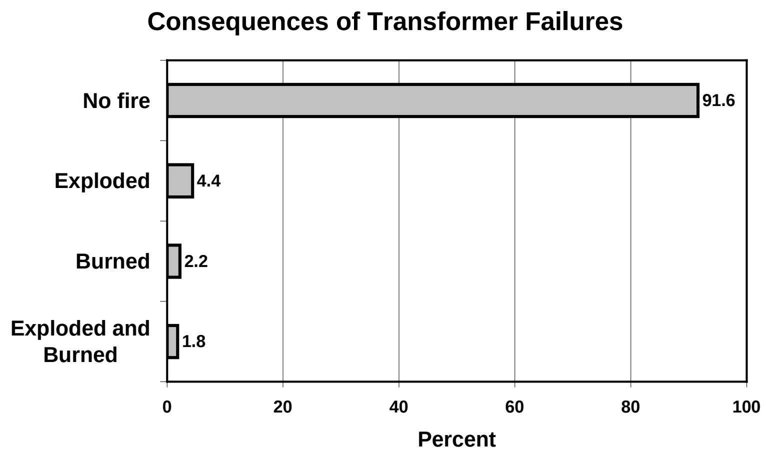

Figure 8.7.1: Consequences of transformer failures

The good news is that there was no fire in more than 90% of the cases. The bad news is that the transformer exploded or the transformer started to burn or both in more than 8% of the cases.

Figure 8.7.2 shows the various stages of a transformer fire in Kangasala, Finland.

Figure 8.7.2: Transformer fire in Kangasala

8.7.3 Fault Statistics

This section contains a compilation of failure rates for internal transformer faults. The rate of external faults and system abnormalities depends on the network.

8.7.3.1 CIGRE Survey

In 1975, CIGRE Study Committee 12 established WG12.05 "Transformer Reliability," which was assigned the task of studying problems connected with the reliability of large power transformers in service. A second task was to determine realistic values of the failure rate for power transformers. The survey involved power transformers and shunt reactors with a rated voltage not less than 72 kV and not older than 20 years. The analysis comprises more than 1 000 failures that occurred from 1968 to 1978. At the end of 1978 the population comprised more than 7 000 power transformers and represented more than 47 000 transformer years. The working group published [8.7.3] the results of the international questionnaire on failure rates for power transformers in 1983. The material is divided into generator step-up transformers, substation transformers and autotransformers. Figure 8.7.3, Figure 8.7.4 and Figure 8.7.5 show the failure rate for generator step-up transformers, substation transformers and autotransformers.

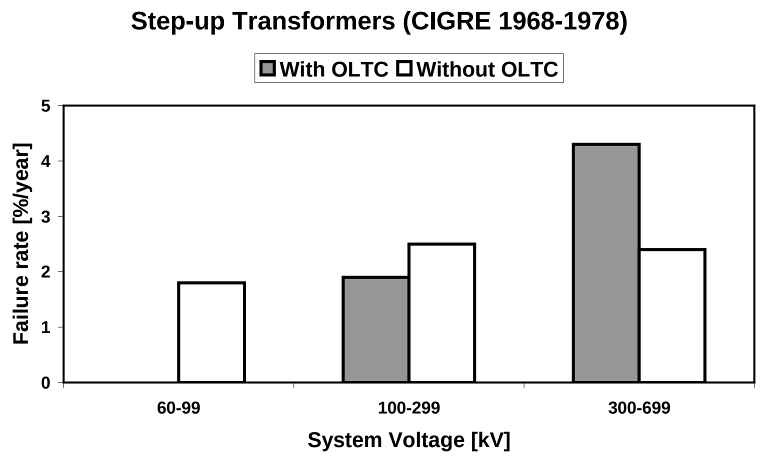

Figure 8.7.3: Generator step-up transformer failure rate

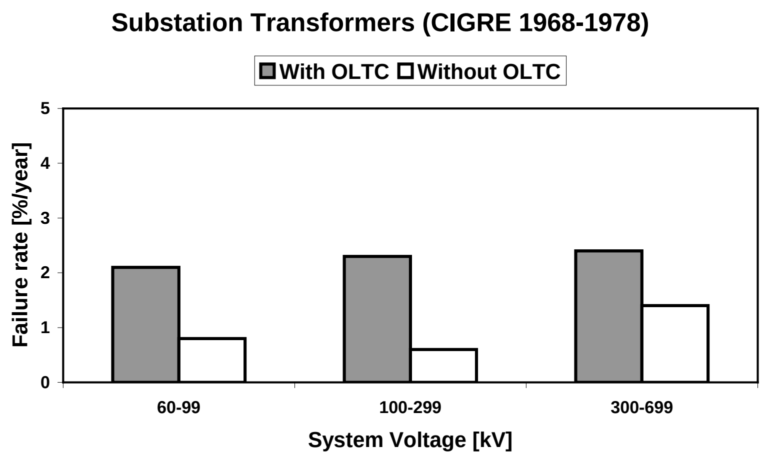

Figure 8.7.4: Substation transformer failure rate

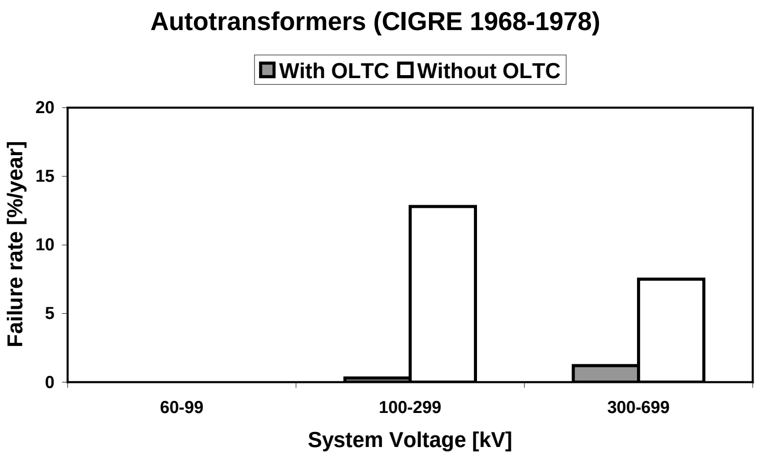

Figure 8.7.5: Autotransformer failure rate

The bars in Figure 8.7.3 represent the failure rate in percent per year or failures per 100 transformers and year. Figure 8.7.3 shows that the failure rate increases with increasing rated voltage. It can be estimated that 2-3% of the step-up transformers with a rated voltage of 220 or 400 kV suffer a fault every year. For a given step-up transformer, the mean time between failures can be estimated to be at 30 to 50 years. This corresponds roughly to one fault during the lifetime of the plant.

Figure 8.7.6 illustrates the faulty transformer component.

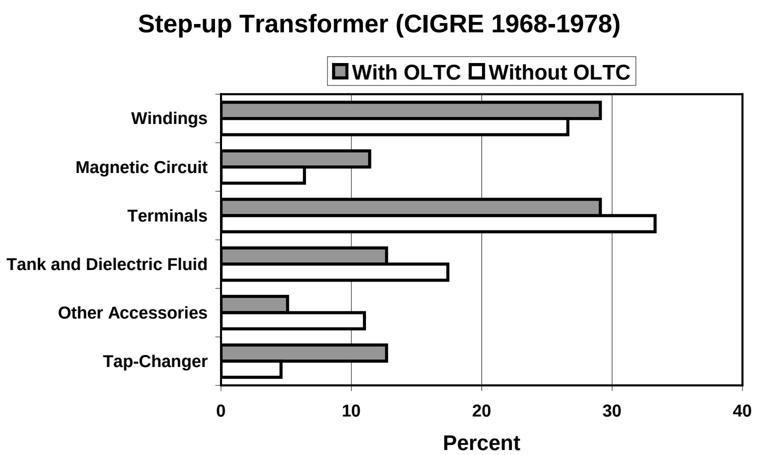

Figure 8.7.6: Faulty component in transformers

Figure 8.7.6 shows that the terminals are most prone to failure. The terminals and the windings represent more the 50% of all failures.

Figure 8.7.7 shows the percentage of failure origin.

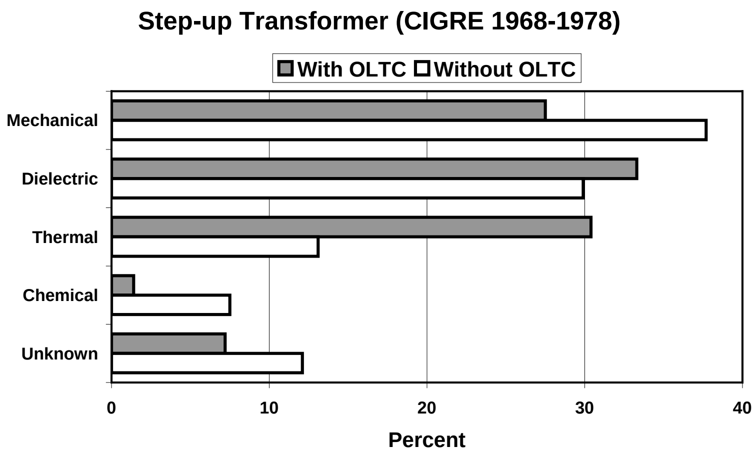

Figure 8.7.7: Origin of faults in transformers

Figure 8.7.7 shows that most failures have mechanical origin. They represent more than 1/3 of the transformer failures.

Figure 8.7.8 shows the percentage of failure causes.

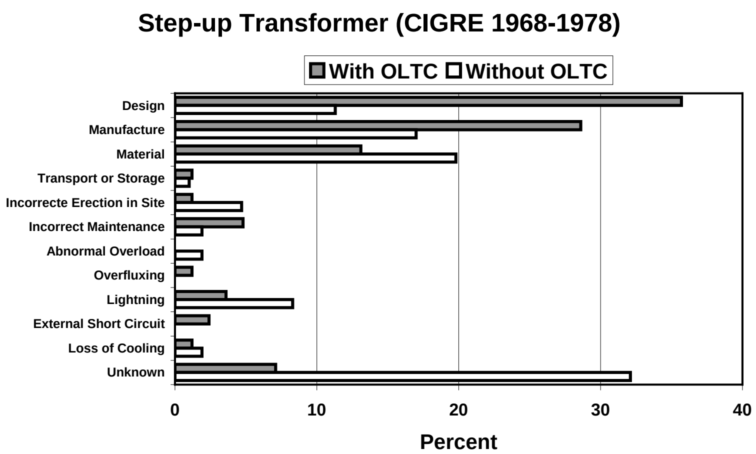

Figure 8.7.8: Cause of failure in transformers

From Figure 8.7.8 we can see most generator step-up transformer failures are associated with activities before the commissioning of the transformer. A variety of failure causes is included in the large number of unknown failure causes.

8.7.3.2 IEEE Guide

The IEEE Guide for Protective Relay Applications to Power Transformers [8.7.5] and [8.7.4] has grouped transformer failures into six major categories:

- Winding failures
- Tap-changer failures
- Bushing failures
- Terminal board failures
- Core failures
- Miscellaneous failures

Figure 8.7.9 shows summaries of failures in those categories reported by groups of utilities in USA.

Winding failures, tap-changer failures and bushing failures represent more than 85% of the transformer failures. The winding failures still represent the majority of transformer failures, with tap-changers being a distant second. Two transformer characteristics causing problems for protection schemes are the low-magnitude turn-to-turn faults and the high-magnitude magnetizing inrush current during energizing. Minimum internal faults can result in less than 10% of a transformer rated current. On the other hand, maximum fault current can flow for a high-side transformer bushing failure.

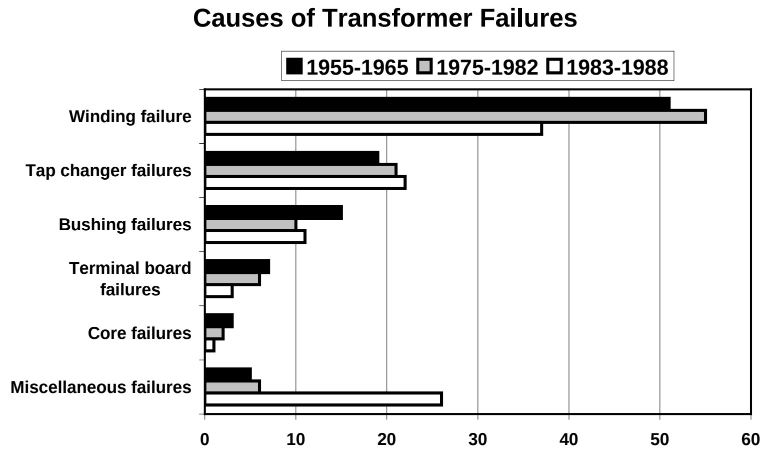

Figure 8.7.9: IEEE fault statistics

8.7.3.3 Nordel Fault Statistics

Nordel regularly presents aggregated fault statistics from Denmark, Finland, Iceland, Norway and Sweden. Below is presented material from reference [8.7.6]. The fault statistics comprise power transformers with system voltages from 110 to 400 kV as shown in Table 8.7.2.

Table 8.7.2: Power transformers in the Nordel statistics 1990-1999

Voltage	**110-150 kV**	**220-300 kV**	**400 kV**	**All**
Earthing	P or E	E	E	P or E
Denmark	523	2	18	543
Finland	7	24	42	73
Norway	726	269	61	1056
Sweden	591	207	132	930
Iceland	45	25	0	70
Nordel	1892	527	253	2672

Here

P Designates Petersen coil-earthed systems (resonant earthed systems)

E Designates effectively earthed systems

At the end of 1999, the total number of the power transformers covered by the fault statistics is 2 672. The expansion rate of the power system has been low during the last decade. It has been estimated that the fault statistics for 1990-99 comprise more than 25 000 transformer-years.

Figure 8.7.10 shows the power transformer failure rate as given in [8.7.6].

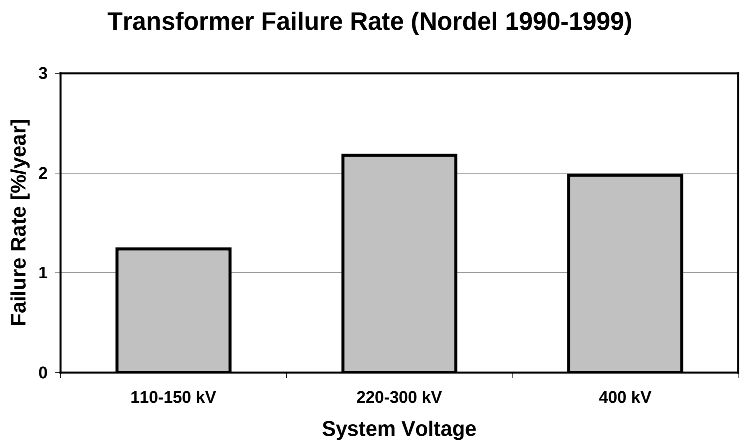

Figure 8.7.10: Failure rate for power transformers

Figure 8.7.11 shows causes of failure of power transformers in the Nordel system during the period from 1990 to 1999,

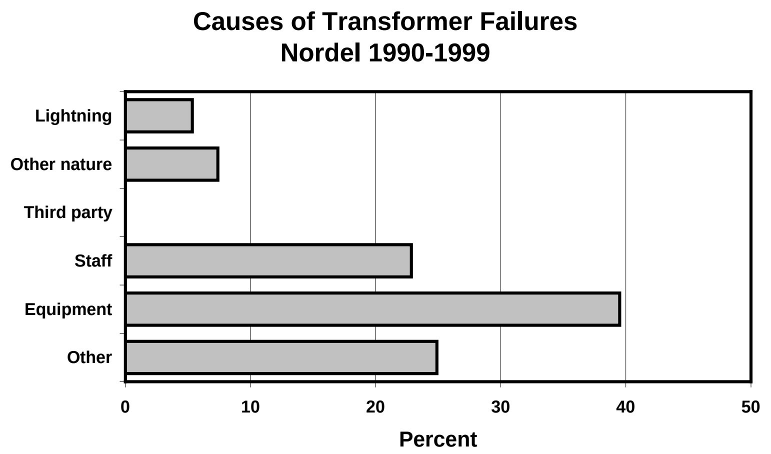

Figure 8.7.11: Breakdown of causes of transformer failures

8.7.3.4 Concluding Remarks

The probability is low that an individual transformer will suffer a fault during the next year. The failure rate for a power transformer can be related to the failure rate of an overhead line. The average failure rate for 400 kV overhead lines in Sweden is about 0.4 faults per 100 kilometers and year. It is reasonable to expect that the failure rate of a 400 kV transformer is 4 faults per 100 transformers and year. This means that the probability that a fault will hit a 400 kV transformer is of the same order of magnitude as the probability that a fault will hit a 10-kilometer-long 400 kV overhead line. If the power line has two main protections, it is reasonable to require that the transformer shall have a similar backup protection.

8.7.4 Fault Currents

The magnitude of the fault current depends on:

- the short-circuit power of the power networks
- the system earthing of the connected networks
- the leakage reactance of the transformer
- the position of the fault along the winding

8.7.4.1 An effectively earthed Y-connected winding

The leakage reactance is the most important parameter that controls the earth-fault current in this case. The leakage reactance varies in a complex manner with the position of the fault. The voltage at the variable fault location is also an important factor.

In Figure 8.7.12 a D/Y-connected transformer is depicted. In the example, a generator or a strong source energizes the D-connected winding, and the Y-connected winding is open-circuited.

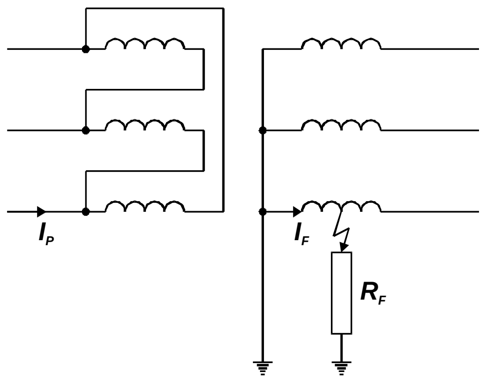

Figure 8.7.12: Internal fault on a Y-connected winding

Here, a single phase-to-earth fault occurs at a relative distance α from the neutral. The fault resistance is independent of the location of the fault and consists of arc resistance and local substation resistance.

Figure 8.7.13 shows a simplified Thévenin equivalent of the faulted power transformer. The no-load voltage is equal to $\alpha \times U_{sn}$, where U_{sn} is the rated value of the secondary phase-to-earth voltage.

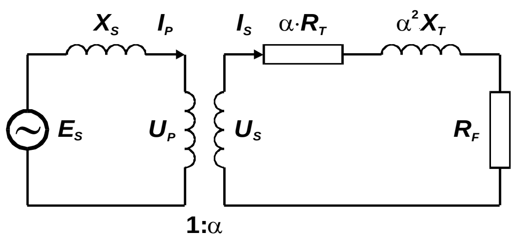

Figure 8.7.13: Fault on a Y-connected effectively earthed winding

Here, the short circuit reactance varies with the square of the number of turns from the neutral to the fault location. This is a crude approximation, but the internal reactance is assumed to be equal to $\alpha^2 \times X_T$, where X_T is the short circuit reactance of the power transformer. The short circuit resistance varies linearly with the number of turns and is equal to $\alpha \times R_T$, where R_T is the short circuit resistance of the power transformer. Figure 8.7.14 shows the estimated fault current as a function of the distance from the neutral.

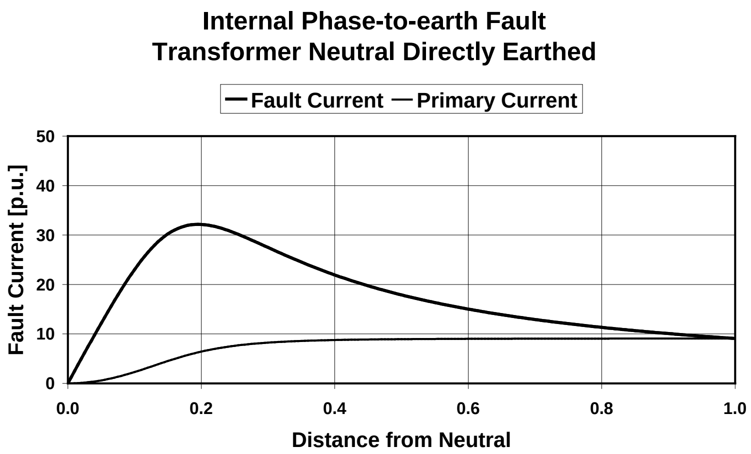

Figure 8.7.14: Fault current in a Y-connected winding with directly earthed neutral

The fault resistance has a significant influence on the magnitude of the fault current and the form of the curve.

8.7.4.2 A High-impedance Earthed Y-Connected Winding

An earth fault on such a winding will cause an earth-fault current that depends on the impedance of the neutral point equipment. The fault current also depends on the distance of the fault from the neutral point. The fault voltage is directly proportional to this distance. This means that the fault current is approximately proportional to the distance from the neutral.

The ratio of transformation between the primary winding and the short-circuited turns also varies with the position of the fault. This means that the current that flows into the transformer primary terminals will be in proportion to the square of the fraction of the short-circuited winding.

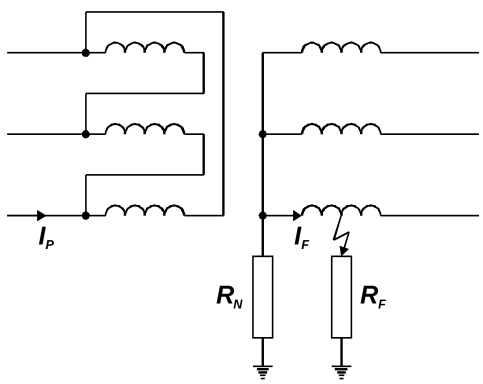

Figure 8.7.15: Fault on a Y-connected resistance earthed winding

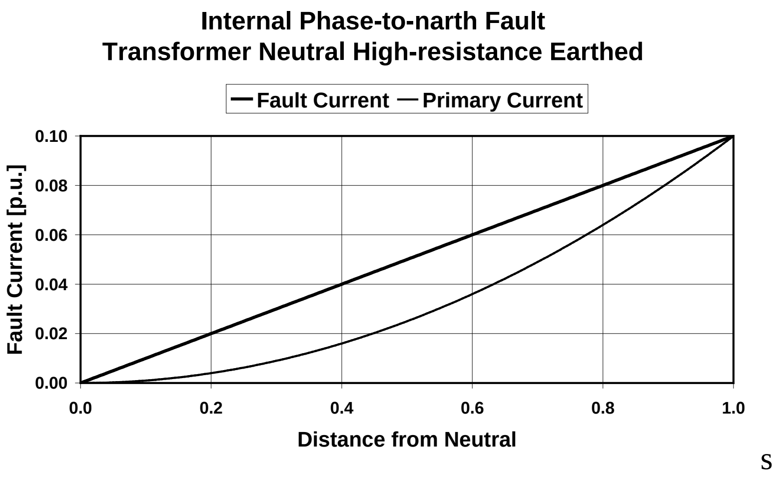

Figure 8.7.16: Fault current in a Y-connected winding with high-resistance earthed neutral

8.7.4.3 Earth Faults in a D-connected Winding

The conductor-to-earth voltage of a D-connected winding is always higher than 50% of the applied phase-to-earth voltage. The range of earth-fault current magnitude for such a winding is therefore less than for a Y-connected winding. The actual value of the earth-fault current will still depend on the way the system is earthed. The impedance of a D-connected winding is particularly high to fault currents flowing to a centrally placed fault on one leg. The impedance can be 25-50% based on the transformer rating, regardless of the normal balanced through-current impedance. As the pre-fault voltage to earth at this point is half the normal phase-to-neutral voltage, the earth-fault current may be no more than the rated current.

The earth-fault current is even less than this value if the impedance of the source is appreciable. The current will flow to the fault from each side through the two half windings, and will be divided between the two phases of the system. The individual phase-currents may therefore be relatively low, a fact that must be remembered when considering the performance of a protection scheme.

8.7.4.4 Turn-to-turn Faults

A turn-to-turn fault (an interturn fault) short-circuits a part of the winding. The faulty winding behaves like an autotransformer winding. The corresponding autotransformer has a very large turn ratio. The current in the short-circuited turns will become very high. The fault current from the network increases when the fault spreads and more turns are short-circuited. The fault current becomes equal to the rated current of the transformer when 2-4% of the turns of the winding are short-circuited. The current in the short-circuited turns may be 50-100 times the rated current of the winding. Such high fault currents will cause mechanical and thermal stresses at the fault location.

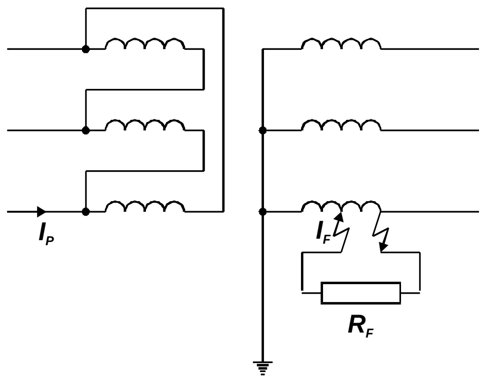

Figure 8.7.17: Turn-to-turn fault in a transformer

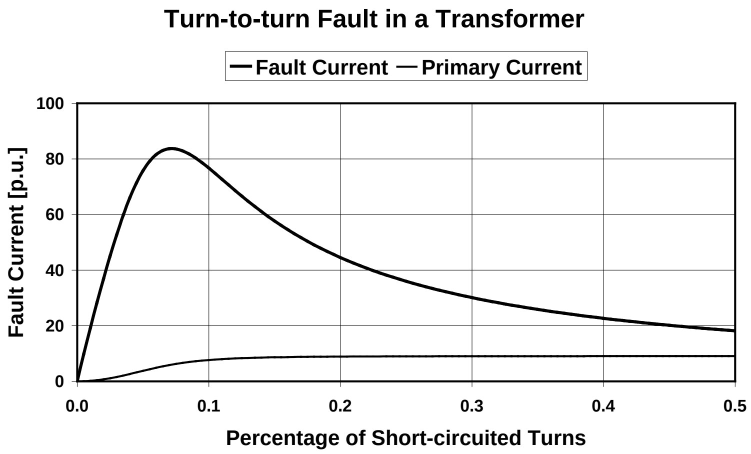

Figure 8.7.18: Fault current at a turn-to-turn fault

8.7.5 Differential Protection

A transformer differential protection compares the current flowing to the transformer with the current leaving the transformer. Auxiliary transformers for the correction of phase shift in the power transformer and for ratio corrections are needed. Differential protection is the most commonly used type of protection for large transformers. The differential protection is a unit protection.

The protective zone of a differential protection includes the transformer itself and the bus work or cables between the current transformer and the power transformer. When bushing current transformers are used for the differential relay, the protective zone does not include the bus work or cables between the circuit breaker and the power transformer. In some substations there is a current differential protection for the busbar. Such a busbar protection will include the bus work or cables between the circuit breaker and the power transformer

The differential protection is set to operate when the differential current exceeds 20 to 25% of the rated current. The operating value of the transformer differential protection must be high enough to avoid tripping on acceptable temporary overvoltages. According to Neugebauer [8.7.2], the operating value should be as low as possible but not lower than 30% of the rated current of the power transformer.

8.7.5.1 Connection of Current Transformers

A simple rule of thumb is that the current transformers on any Y-connected winding of the power transformer should be D-connected. The current transformers on any D-connected winding of the power transformer should be Y-connected.

For transformers with an on-load tap-changer, the ratio of the auxiliary current transformers should be calculated for balanced currents when the tap-changer is in the middle position.

8.7.5.2 The Differential Current

The magnetizing current appears as a differential current to the differential protection and it may operate incorrectly if no precautions are taken.. During normal service, the magnetizing current is very low in comparison with the operating value of the transformer differential protection. Magnetizing inrush currents flow when the transformer is energized. Similar inrush currents flow when the voltage returns to normal after the clearing of shunt faults. The steady-state magnetizing current and the magnetizing inrush current are both described in Chapter 3.

The magnetizing inrush current has a large DC-component and several significant harmonics. The fundamental frequency and the second harmonic (100 Hz in Europe and 120 Hz in USA) dominate. The current is present in all three phases and in the neutral too. The neutral inrush current flows to other earthed neutral points. The zero-sequence impedances determine the distribution of the neutral-point current.

A transformer with an on-line tap-changer in the end position gives a differential current of 10 to 20% of the load current. The differential current caused by the tap-changer determines the most sensitive setting of the differential protection. The operating value must be set at least 15% higher than the mismatch differential current caused by the on-load tap-changer.

8.7.5.3 Harmonic Restrained Differential Protections

Many transformer differential protections have harmonic restraint to avoid tripping due to magnetizing inrush current. The protection restrains if the second or fifth harmonic exceeds a preset fraction of the fundamental component or the total current.

Differential protection is the most commonly applied protection for transmission transformers. In a working group survey, all except for one of the companies were using at least one differential relay on all transmission transformers. Figure 8.7.19 shows the basic scheme.

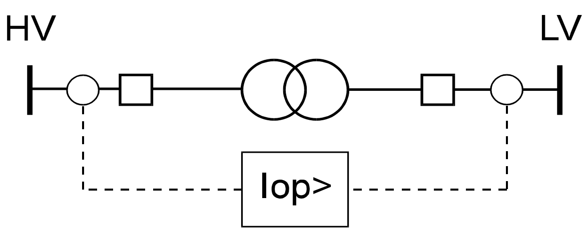

Figure 8.7.19: Transformer differential

Differential schemes include percentage differential, percentage differential with harmonic restraint, and for autotransformers high-impedance differentials. The differential relay simplicity of comparing currents to all terminals of the transformer gives it a very high reliability. Current transformers or auxiliary CTs in a delta connection have to be used at the earthed transformer windings to avoid false operation on external faults. The removed zero-sequence component, however, makes the transformer differential relay less sensitive.

8.7.5.4 Concluding Remarks

The differential relay protection does an excellent job of meeting a large number of the protective relaying requirements but must be combined with other protective devices to provide full transformer protection.

8.7.6 Impedance Protection

An impedance protection can provide backup protection for external short circuits. An impedance protection may replace a current differential protection as the main protection for internal short circuits. Two types of impedance protections are of general occurrence: underimpedance protections and distance protections.

8.7.6.1 Underimpedance protection

It is a common practice to install current differential protections as the main protection for busbars in transmission networks. Usually, there is no complete station local backup protection for the busbars. Few utilities install two complete sets of current differential protections for the busbar. Transmission lines, generator step-up transformers and EHV autotransformers may feed fault current to the busbar. Line protections in remote power stations and substations provide backup protection for the actual busbar. The protections initiate interruption of the fault current from transmission lines. Underimpedance protections in the power station or substation also provide backup protection for the busbar in the same station. A second underimpedance protection may provide remote backup protection for the busbars in adjacent stations.

8.7.6.2 Distance Protection

Some utilities use distance protections instead of differential protections as the main transformer protection. Many utilities use distance protections instead of non-directional underimpedance protections as backup protection for the transformer differential protection. At the same time, they can act as a main or backup protection for the busbars.

Distance relays can be used as the primary protection or as a backup protection for the transformer. They consist of a multi-zone impedance relay on the high side of the transformer looking into the transformer as shown in Figure 8.7.20.

The impedance relay has some benefits of providing overlapping protection with the bus protective zones but negative traits of having to coordinate with transmission line relaying, causing it to be slower than the differential relay. It must also be set not to operate for inrush currents during transformer energization.

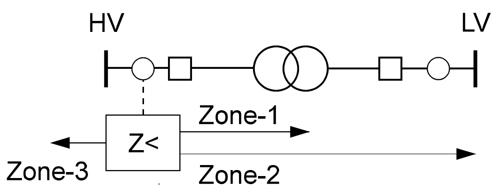

Figure 8.7.20: Distance relay protection

Some applications use two impedance relays. The first one is set as in Figure 8.7.20. A second, low-side impedance relay is set looking into the transformer from the low side. This provides backup protection for non-cleared HV- and LV-faults. In Germany, the distance relays are used in a directional comparison scheme for transformer backup protection.

8.7.6.3 Concluding Remarks

The main area that the distance relay includes is a backup protection for remote faults and protection for fault withstand. It has some severe problems because of coordination timer requirements with transmission line relays and the lack of any earth-fault protection.

8.7.7 Overcurrent Protection

Power transformers often have an overcurrent protection as the main protection. Overcurrent protections have inferior sensitivity to what differential protections have. Many large transformers have an overcurrent protection as a backup protection. It may provide main protection or backup protection of the associated busbars. Overcurrent protections may also provide backup protection of the outgoing power lines. At least two overcurrent phase relays should be provided on each side of the transformer that are connected to a source of short-circuit current.

8.7.7.1 Short-circuit Protection

If a short circuit occurs on the low-voltage side of a Y/D-connected power transformer, only one of the phases on the high-voltage side of the transformer carries full short-circuit current. The two other phases on the high-voltage side carry only 50% of the current in the third phase. The sensitivity of an overcurrent protection with two overcurrent relays on the high-voltage side may be only 50% of the sensitivity of an overcurrent with three overcurrent relays on the high-voltage side. The overcurrent protection on the high-voltage side should have three overcurrent relays except on the Y/Y-connected transformers.

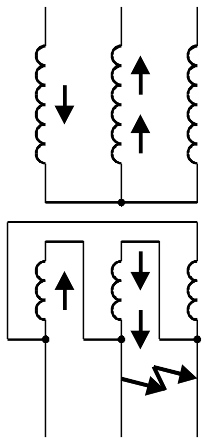

Figure 8.7.21: Phase-to-phase fault on a Y/D-connected transformer

The overcurrent relays should have an inverse-time element whose pickup can be adjusted to somewhat above maximum rated load current, say about 150% of maximum, and with a sufficient time delay to be selective with the protections of adjacent power system components during external transformer faults. The relays should also have an instantaneous element whose pickup can be slightly higher than either the maximum short-circuit current for an external fault or the magnetizing-current inrush.

When the transformer is connected to more than one source of short-circuit currents, it may be necessary for at least some of the overcurrent relays to be directional to obtain good protection as well as selectivity for external faults.

The phase overcurrent protection is an inexpensive, simple and reliable scheme for fault detection and is used for some transformer protection applications. It suffers from having to be set very high for transformer inrush and for coordination for down-line relays and to allow transformer overloads. Therefore, it is ineffective for low-magnitude internal transformer faults or phase-to-earth faults on the low-voltage side of the transformer.

The phase overcurrent protection provides for transformer fault withstand protection and for some limited overload protection. It can provide backup protection for the failure of the switching device but only with very long time delays. In some applications, directional overcurrent relays are located on both the HV- and LV-sides of the transformer. Both relays are set to see into the transformer. This allows better coordination with external overcurrent relays because of the need only to see part of the transformer windings.

Numerical overcurrent relays also provide upgraded performance for transformer backup protection. The digital filters now remove the DC component and harmonics from the inrush current. Numerical backup overcurrent relays can therefore be set much more sensitive than conventional types.

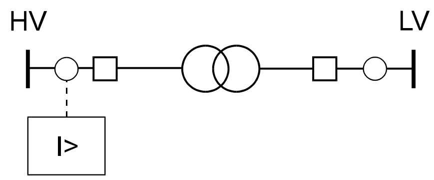

Figure 8.7.22: Phase overcurrent protection

8.7.7.2 Concluding Remarks

Generally, overcurrent phase protection relays provide some additional protection for through-fault withstand but do not provide adequate primary protection in many applications.

8.7.8 Earth-fault Protection

In effectively earthed networks, earth-fault currents and short-circuit currents have the same order of magnitude. In such networks, earth faults have to be cleared instantaneously. In non-effectively earthed networks, the earth-fault current is much smaller than the short-circuit current. The legal requirements on automatic clearing of earth faults in such networks vary from country to country. In Denmark, it is not necessary to clear earth faults automatically. In Sweden, it is necessary to clear earth faults automatically within five seconds. It is necessary to clear earth faults with a fault resistance of 5 000 ohms automatically. It is no surprise that the policy concerning the clearing of earth faults varies from utility to utility.

This type of protection is specific to transformers with at least one directly earthed or resistance earthed winding. The protection is specialized to protect for winding faults to earth as shown in Figure 8.7.23. The connections of the overcurrent units can be only in the neutral or only in the residual phase or a differential connection including all phases and the earth. These overcurrent units can be set much lower than the phase overcurrent units because of the cancellation of the load current. Harmonic restraint may be required if the non-differential connections are used. Generally, they will give a lower setting but only provide protection for the earthed winding.

8.7.8.1 Restricted Earth-fault Protection

A restricted earth-fault protection provides a sensitive and high-speed protection of a Y-connected winding. The residual current from three phase-current transformers balances the current from the neutral-point current transformer. The restricted protection can operate for earth faults within the region between current transformers. The protection zone is the Y-connected winding in question. The protection should remain stable for all faults outside this zone. This protection is a unit protection.

The restricted earth-fault protection is used in effectively earthed networks. It can also be used in non-effectively earthed networks with an earth-fault current higher that the operating value of the restricted earth-fault protection.

8.7.8.1.1 High-impedance Restricted Earth-fault Protection

The restricted earth-fault protection is usually a high-impedance protection. For an internal earth fault, the residual current from three phase-current transformers balances the current from the neutral-point current transformer. For an external fault, the current circulates between the current transformers. The current phase current transformers and the neutral-point current transformers must have exactly the same turn ratio. The saturation of the current transformers should be at least twice the operating voltage of the overvoltage relay. The protection is then stable for all external faults even if one of the current transformers should saturate.

A high-impedance restricted earth-fault protection is more sensitive than the transformer differential protection. However, it cannot replace the transformer differential protection. The latter protects both the high-voltage and low-voltage winding.

Each Y-connected winding of a power transformer can be protected with a separate restricted earth-fault protection. D-connected windings can also be protected and the earthing transformer can be located inside the protected zone.

8.7.8.1.2 Low-impedance Restricted Earth-fault Protection

It is sometimes possible to use a low-impedance current relay instead of a high-impedance voltage relay. The neutral point current transformer can then have a different turn ratio than the phase current transformers. An auxiliary current transformer can be used for ratio correction.

If a phase current transformer should saturate during an external short circuit, the protection must not operate. In such cases, a residual voltage relay must release the low-impedance restricted earth-fault protection.

8.7.8.2 Residual Overcurrent Protection

Residual overcurrent protections can detect earth faults on windings connected to effectively earthed systems. Generator step-up transformers and EHV autotransformers in Sweden have a residual overcurrent protection with two overcurrent relays. The first step has an independent time overcurrent relay. The main task of the first step is to provide backup protection for earth faults on the high-voltage busbar in the station. It can also provide backup protection for earth faults within the transformer itself. The second step has a dependent time overcurrent relay with harmonic restraint. The main task is to provide protection for series faults associated with the power transformer itself. It can also provide backup protection for remote earth faults. Some residual overcurrent protections have a third overcurrent relay. It has an operating value between the first step and the sensitive step described above. The sum of the currents from three phase-current transformers is the input to the residual overcurrent protection.

8.7.8.3 Neutral-point Overcurrent Protection

Neutral-point overcurrent protections can detect earth faults in effectively earthed networks. They provide backup protection for local and remote busbars. Generator step-up transformers and EHV autotransformers in Sweden have a neutral-point overcurrent protection. It has two overcurrent relays. The first step has an independent time overcurrent relay. The main task of the first step is to provide backup protection for earth faults on the local busbars. It can also provide backup protection for earth faults within the transformer itself. The second step has a dependent time overcurrent relay with harmonic restraint. The main task is to provide protection for series faults associated with the power transformer itself. It can also provide backup protection for remote earth-faults. Some neutral-point overcurrent protections have a third overcurrent relay. It has an operating value between the first step and the sensitive step described above.

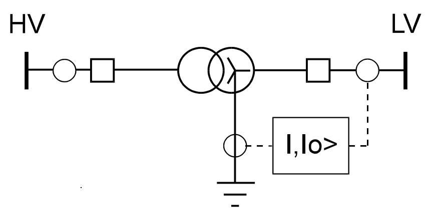

Figure 8.7.23: Neutral and differential protection

8.7.8.4 Tank Earth-fault Protection

This type of protection is specific to transformers with at least one earthed or resistance-earthed winding. The protection is specialized to protect for winding faults to earth as shown in Figure 8.7.24.

The tank earth-fault protection deserves special attention. It is a relay which is connected in series with the main tank earth. The tank is insulated from earth except for one path, which has a current transformer around it connected to the tank earth relay. The relay will see any current flowing from the tank to the earth such as bushing failures, winding-to-tank failures and core-to-winding failures. Since minimal current flows through this path during normal operation the relay can be set very sensitive. The problem with this protection is that it requires a single path to earth through 1.0 Ω resistance at maximum. This creates a high voltage to remote earth from the transformer tank during earth faults, which may cause safety problems. Inadvertent control or metallic paths to the transformer case can easily shorten the path. Also maloperation must be carefully prevented from transformer tank capacitance currents.

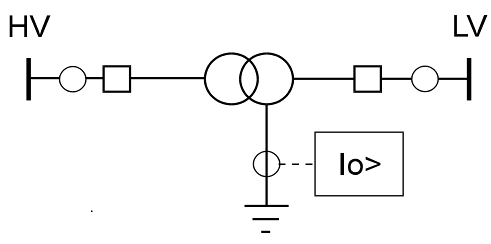

Figure 8.7.24: Tank earth-fault protection

In general, this protection is specialized to provide an earthed winding with a low-sensitivity earth-fault protection only. It does not provide other types of protection.

8.7.8.5 Neutral-point Displacement Protection

In this example, a transformer winding feeds a non-effectively earthed system. The winding is an unearthed Y-connected one or a D-connected one. A zero-sequence overvoltage protection can provide earth-fault protection of this winding. It will also provide earth-fault protection for the conductors between the transformer and the busbar. Finally, it will provide earth-fault protection for the connected busbar. The zero-sequence overvoltage protection can also provide backup earth-fault protection. Feeders connected to the busbar should have the main and backup earth-fault protection. The transformer protection provides station local backup protection for such feeders.

Traditionally, the operating value of the overvoltage relay has been 36%. The operating value is 40 V and full-rated phase-to-neutral voltage gives 110 V. Nowadays, the operating value is as low as 15 to 25 Volts. This trend is a consequence of the stringent requirement on clearing of high-resistive earth faults in Sweden. The zero-sequence overvoltage protection must have the longest delay among the earth-fault protections.

Three phase-to-earth connected transformers can provide the energizing quantity to the overvoltage relay. The voltage transformer measures the phase-to-earth voltage. The secondary windings have an open D-connection. In a first step, the protection should trip the circuit breaker associated with the protected winding. The first step should have a time delay. This time delay must be longer than the time delay of any earth-fault protection for the objects connected to the busbar. The worst case is the clearing of a cross-country fault. In a second step, the protection should trip the other circuit breaker(s) associated with the transformer. The second step has a longer time delay that the first step.

A single phase-to-earth connected transformer can also provide the energizing quantity to the overvoltage relay. The voltage transformer measures the neutral-point voltage. The protection will not operate at an earth fault if there is an interruption in the primary or secondary circuit. It is very difficult to detect such a condition during normal operation. This is a drawback of using a voltage transformer connected to the neutral point.

In some networks, some of the transformer neutral points are not earthed to limit the earth-fault current. In this case, it may happen that a transformer winding may be left connected to an unearthed system. Zero-sequence voltage detection relays are therefore applied here as earth-fault protection.

8.7.9 Flashover Protection

Many power transformers have bushing current transformers. In such cases, it is not necessary to install freestanding current transformers in the open-air switchyard. Bushing current transformers are seldom used on transformer windings connected to in-door switchgear. Transformer differential protections, fed from bushing current transformers, cannot detect flashover faults on the surface of the bushings. They are outside the protection zone of the transformer differential protection.

The fault statistics in section 8.7.3 show that terminal failures and bushing failures occur frequently. Several old transformers have a flashover protection. It consists of a metallic ring around the root of each bushing. The rings are insulated from the transformer tank and connected to each other. There is a conductor from the rings to the earthing mat in the substation. A flashover on the surface of the bushing should terminate on the flashover ring. In such cases, a current starts to flow in the earthing conductor. The current is fed through a current transformer and an instantaneous overcurrent protection on the secondary side. The overcurrent protection will detect many flashover faults on the surface of the bushings.

A current differential protection for the busbar connected to the transformer will also detect such flashover faults. There is very little need for a special flashover protection when there is a busbar protection.

8.7.10 Overload Protection

The rating of a power transformer is based on the temperature rise above an assumed maximum ambient temperature. Under this condition, no sustained overload is usually permissible. At a lower ambient temperature, some degree of overload can be safely accepted. Short overloads are also permissible to an extent, depending on the previous loading conditions.

It is difficult to formulate rules for short overloads. The only safe statement is that the winding must not overheat. International standards do not give identical and unambiguous limits for the hotspot temperature.

Thermal electrical protections can be used to protect power transformers against overload. Such protections are of the thermal replica model. The protection characteristic is defined by the heating time constant.

A power transformer can carry a substantial overload for an hour or two. Many utilities want to utilize this capability temporarily. An overcurrent protection may also provide overload protection of a power transformer. Such an overload protection must have a longer time constant than a conventional overcurrent protection has. However, the on-line tap-changer can limit the overload capability. Its thermal time constant may be shorter than the thermal time constant of the main transformer unit. Most overload protections sound an alarm but some trip the associated circuit breakers.

Because of the heating and cooling requirements of a transmission transformer, some specialized temperature protection is required to provide protection over the full range of operating limits of the transformer. The transformer is temperature-limited by the ambient temperature, the cooling system condition, the excitation voltage and the transformer load. The top-oil temperature has a maximum acceptable value of 100 to 105°C. A top-oil temperature sensor usually provides temperature protection.

To simulate the winding temperature, a resistor sized to approximate the heating in the transformer winding at full load is supplied by a current transformer from one of the phase currents. The resistor heating is added to the top oil temperature by circulating the top oil into a well with the resistor. This combined heating temperature is used to simulate the winding temperature. The winding temperature is usually limited to 140-180°C. These two relays do not meet any of the other requirements but are again the only relays which meet the overload temperature limit requirements.

8.7.11 Overexcitation Protection

A transformer loaded with rated current can withstand only 105% of rated voltage continuously. Overexcitation is an abnormal condition that may damage the transformer. Equation (8.7.1) gives the RMS value E_i [V] of the induced EMF in a transformer.

$$4.44 \cdot f \cdot N \cdot A \cdot B_{\max} \qquad \textbf{(8.7.1)}$$

Here

f	is the system frequency [Hz]
N	is the number of turns on the core leg [1]
A	is the area of the core leg [m^2]
$B_{\max}$	is the peak value of the flux density [T]

Equation (8.7.2) gives a good measure of the excitation.

$$\left(\frac{B_{\max}}{B_n}\right) = \frac{V/f}{V_n/f_n} \qquad \textbf{(8.7.2)}$$

Here

B_n	is the rated peak value of the flux density [T]
V	is the RMS value of the terminal voltage [V]
V_n	is the rated RMS value of the terminal voltage [V]
f_n	is the rated system frequency [Hz]

Equation (8.7.2) motivates the name volt per hertz protection. The transformer has to be disconnected if the ratio between terminal voltage and system frequency becomes too high. The ratio must not exceed the value 1.1 continuously. The ratio may assume values up to 1.4 for 10 seconds.

Transformers prone to overvoltage, underfrequency or both should have an overexcitation protection. Especially unit-connected generator step-up transformers can be exposed to overvoltage and underfrequency conditions. During startup and shutdown the transformer operates with a reduced frequency. The flux density will become very high if the generator is attempted to be magnetized when the turbine-generator speed is too low. There is a risk that the staff leaves the automatic voltage regulator (AVR) in operation during the shutdown procedure. This has happened many times and caused overexcitation incidents.

It is important that the overexcitation gets correct representation of the flux density in the core. The protection has to be connected to a voltage transformer, measuring the voltage of an untapped winding.

This is another type of specialized protective relaying application where only one protective level is covered. No other relay provides adequate overexcitation protection of the transformer core. Damage to the core laminations can occur if an excitation larger than the Volts/Hertz rating of the transformer is reached. This type of protection does not cover any other requirements except this one.

8.7.12 Mechanical Fault Detectors

Protection equipment that monitors currents or voltages can operate and trip the appropriate circuit breakers when certain operating conditions exist. Some transformer faults are, unfortunately, not detected when using protection relays using electrical inputs only. Such electrical relays can seldom detect incipient faults and turn-to-turn faults. A turn-to-turn fault can cause a considerable current to flow in the shorted turn while the current in the remaining winding stays relatively unchanged. The transformer may be seriously damaged before the electrical relays detect such faults. The slow clearing of internal faults may require expensive repairs. It is clearly desirable to use other methods to detect internal faults which may not be detected by electrical relays.

The sudden pressure protection, the Buchholz protection and the oil level monitor complement the electrical relays and improve the dependability of the transformer protections. They are called mechanical fault detectors, because they use other input quantities than electrical ones. The mechanical fault detectors are all designed to provide specialized protection for internal faults and abnormal conditions. Such mechanical fault detectors are described in Chapter 3.

References

[8.7.1] Kawashima, K.; Fukuda, T.; Kashima, Y. & Maruyama, K.: "Improvement of Reliability for 500 kV Transformers," Hitachi Review, vol. 24, no. 11, pp. 421-427, November 1975.

[8.7.2] Neugebauer, H.: "Selektivschutz," Springer-Verlag, Berlin, 1955.

[8.7.3] "An international survey on failures in large power transformers in service," Electra, no. 88, pp. 21-48, May, 1983.

[8.7.4] "Guide for Protective Relay Applications to Power Transformers," IEEE Standard C37.91-2000, The Institute of Electrical and Electronics Engineers, October 2000.

[8.7.5] "IEEE Guide for Protective Relay Applications to Power Transformers," ANSI/IEEE C37.91-1985, IEEE, New York, 1985.

[8.7.6] "Nordel – Driftstörningsstatistik (Fault Statistics)," Nordel, 1999.

[8.7.7] "Report on Power Transformer Troubles," Edison Electric Institute, 1971.

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