• 16 • *Transformer and Transformer-feeder Protection*

· 16 · Transformer and Transformer-Feeder Protection

16.1 INTRODUCTION

The development of modern power systems has been reflected in the advances in transformer design. This has resulted in a wide range of transformers with sizes ranging from a few kVA to several hundred MVA being available for use in a wide variety of applications.

The considerations for a transformer protection package vary with the application and importance of the transformer. To reduce the effects of thermal stress and electrodynamic forces, it is advisable to ensure that the protection package used minimises the time for disconnection in the event of a fault occurring within the transformer. Small distribution transformers can be protected satisfactorily, from both technical and economic considerations, by the use of fuses or overcurrent relays. This results in time-delayed protection due to downstream co-ordination requirements. However, time-delayed fault clearance is unacceptable on larger power transformers used in distribution, transmission and generator applications, due to system operation/stability and cost of repair/length of outage considerations.

Transformer faults are generally classified into six categories:

- **a.** winding and terminal faults
- **b.** core faults
- **c.** tank and transformer accessory faults
- **d.** on–load tap changer faults
- **e.** abnormal operating conditions
- **f.** sustained or uncleared external faults

For faults originating in the transformer itself, the approximate proportion of faults due to each of the causes listed above is shown in Figure 16.1.

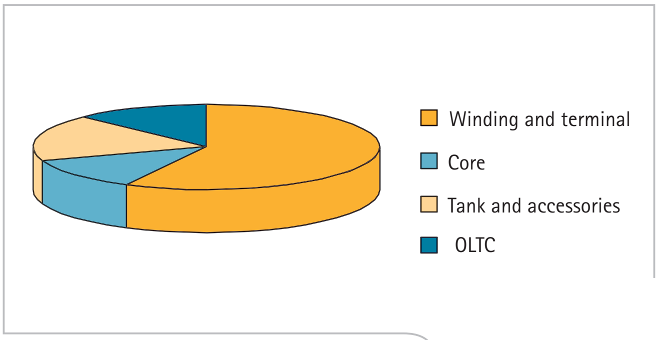


Figure 16.1: Transformer fault statistics

16.2 WINDING FAULTS

A fault on a transformer winding is controlled in magnitude by the following factors:

i. source impedance

ii. neutral earthing impedance

iii. transformer leakage reactance

iv. fault voltage

v. winding connection

Several distinct cases arise and are examined below.

16.2.1 Star-Connected Winding with Neutral Point Earthed through an Impedance

The winding earth fault current depends on the earthing impedance value and is also proportional to the distance of the fault from the neutral point, since the fault voltage will be directly proportional to this distance.

For a fault on a transformer secondary winding, the corresponding primary current will depend on the transformation ratio between the primary winding and the short-circuited secondary turns. This also varies with the position of the fault, so that the fault current in the transformer primary winding is proportional to the square of the fraction of the winding that is short-circuited. The effect is shown in Figure 16.2. Faults in the lower third of the winding produce very little current in the primary winding, making fault detection by primary current measurement difficult.

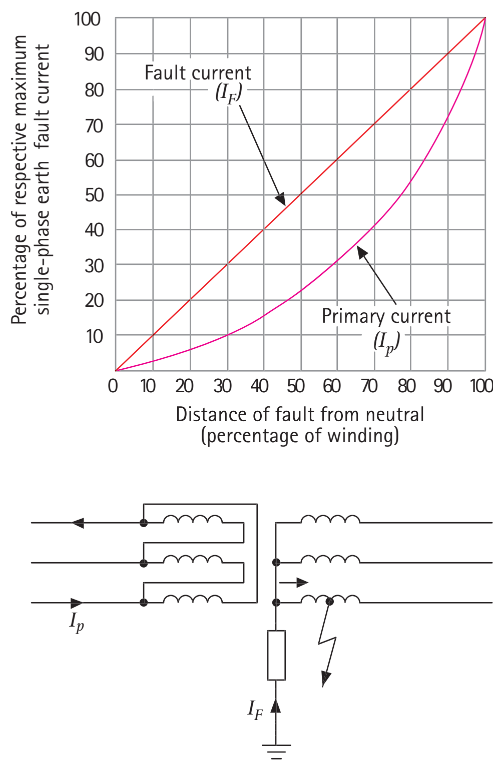


Figure 16.2 Earth fault current in resistance-earthed star winding

16.2.2 Star-connected winding with Neutral Point Solidly Earthed

The fault current is controlled mainly by the leakage reactance of the winding, which varies in a complex manner with the position of the fault. The variable fault point voltage is also an important factor, as in the case of impedance earthing. For faults close to the neutral end of the winding, the reactance is very low, and results in the highest fault currents. The variation of current with fault position is shown in Figure 16.3.

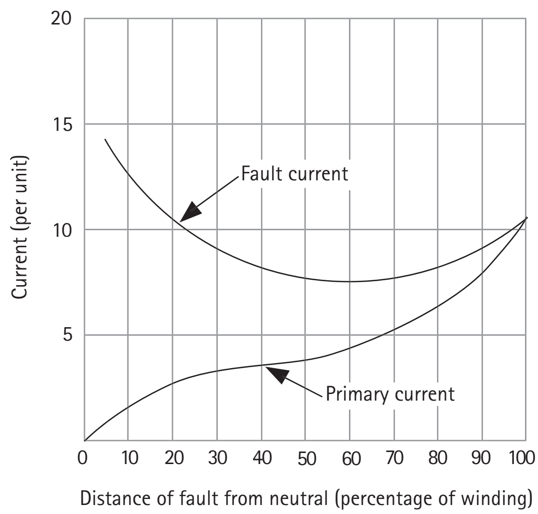


Figure 16.3 Earth fault current in solidly earthed star winding

For secondary winding faults, the primary winding fault current is determined by the variable transformation ratio; as the secondary fault current magnitude stays high throughout the winding, the primary fault current is large for most points along the winding.

16.2.3 Delta-connected Winding

No part of a delta-connected winding operates with a voltage to earth of less than 50% of the phase voltage. The range of fault current magnitude is therefore less than for a star winding. The actual value of fault current will still depend on the method of system earthing; it should also be remembered that the impedance of a delta winding is particularly high to fault currents flowing to a centrally placed fault on one leg. The impedance can be expected to be between 25% and 50%, based on the transformer rating, regardless of the normal balanced through-current impedance. As the prefault voltage to earth at this point is half the normal phase voltage, the earth fault current may be no more than the rated current, or even less than this value if the source or system earthing impedance is appreciable. The current will flow to the fault from each side through the two half windings, and will be divided between two phases of the system. The individual phase currents may therefore be relatively low, resulting in difficulties in providing protection.

16.2.4 Phase to Phase Faults

Faults between phases within a transformer are relatively rare; if such a fault does occur it will give rise to a substantial current comparable to the earth fault currents discussed in Section 16.2.2.

16.2.5 Interturn Faults

In low voltage transformers, interturn insulation breakdown is unlikely to occur unless the mechanical force on the winding due to external short circuits has caused insulation degradation, or insulating oil (if used) has become contaminated by moisture.

A high voltage transformer connected to an overhead transmission system will be subjected to steep fronted impulse voltages, arising from lightning strikes, faults and switching operations. A line surge, which may be of several times the rated system voltage, will concentrate on the end turns of the winding because of the high equivalent frequency of the surge front. Part-winding resonance, involving voltages up to 20 times rated voltage may occur. The interturn insulation of the end turns is reinforced, but cannot be increased in proportion to the insulation to earth, which is relatively great. Partial winding flashover is therefore more likely. The subsequent progress of the fault, if not detected in the earliest stage, may well destroy the evidence of the true cause.

A short circuit of a few turns of the winding will give rise to a heavy fault current in the short-circuited loop, but the terminal currents will be very small, because of the high ratio of transformation between the whole winding and the short-circuited turns.

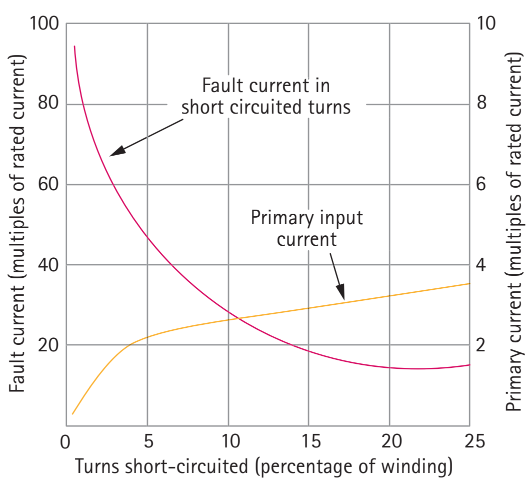


Figure 16.4 Interturn fault current/number of turns short-circuited

The graph in Figure 16.4 shows the corresponding data for a typical transformer of 3.25% impedance with the short-circuited turns symmetrically located in the centre of the winding.

16.2.6 Core Faults

A conducting bridge across the laminated structures of the core can permit sufficient eddy-current to flow to 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 loss, although causing severe local heating, will not produce a noticeable change in input current and could not be detected by the normal electrical protection; it is nevertheless highly desirable that the condition should be detected before a major fault has been created. In an oil-immersed transformer, core heating sufficient to cause winding insulation damage will also cause breakdown of some of the oil with an accompanying evolution of gas. This gas will escape to the conservator, and is used to operate a mechanical relay; see Section 16.15.3.

16.2.7 Tank Faults

Loss of oil through tank leaks will ultimately produce a dangerous condition, either because of a reduction in winding insulation or because of overheating on load due to the loss of cooling.

Overheating may also occur due to prolonged overloading, blocked cooling ducts due to oil sludging or failure of the forced cooling system, if fitted.

16.2.8 Externally Applied Conditions

Sources of abnormal stress in a transformer are:

a. overload

b. system faults

c. overvoltage

d. reduced system frequency

16.2.8.1 Overload

Overload causes increased 'copper loss' and a consequent temperature rise. Overloads can be carried for limited periods and recommendations for oil-immersed transformers are given in IEC 60354.

The thermal time constant of naturally cooled transformers lies between 2.5-5 hours. Shorter time constants apply in the case of force-cooled transformers.

16.2.8.2 System faults

System short circuits produce a relatively intense rate of heating of the feeding transformers, the copper loss increasing in proportion to the square of the per unit fault current. The typical duration of external short circuits that a transformer can sustain without damage if the current is limited only by the self-reactance is shown in Table 16.1. IEC 60076 provides further guidance on short-circuit withstand levels.

Transformer reactance (%)	Fault current (Multiple of rating)	Permitted fault duration (seconds)
4	25	2
5	20	2
6	16.6	2
7	14.2	2

Table 16.1: Fault withstand levels

Maximum mechanical stress on windings occurs during the first cycle of the fault. Avoidance of damage is a matter of transformer design.

16.2.8.3 Overvoltages

Overvoltage conditions are of two kinds:

i. transient surge voltages

ii. power frequency overvoltage

Transient overvoltages arise from faults, switching, and lightning disturbances and are liable to cause interturn faults, as described in Section 16.2.5. These overvoltages are usually limited by shunting the high voltage terminals to earth either with a plain rod gap or by surge diverters, which comprise a stack of short gaps in series with a non-linear resistor. The surge diverter, in contrast to the rod gap, has the advantage of extinguishing the flow of power current after discharging a surge, in this way avoiding subsequent isolation of the transformer.

Power frequency overvoltage causes both an increase in stress on the insulation and a proportionate increase in the working flux. The latter effect causes an increase in the iron loss and a disproportionately large increase in magnetising current. In addition, flux is diverted from the laminated core into structural steel parts. The core bolts, which normally carry little flux, may be subjected to a large flux diverted from the highly saturated region of core alongside. This leads to a rapid temperature rise in the bolts, destroying their insulation and damaging coil insulation if the condition continues.

16.2.8.4 Reduced system frequency

Reduction of system frequency has an effect with regard to flux density, similar to that of overvoltage.

It follows that a transformer can operate with some degree of overvoltage with a corresponding increase in frequency, but operation must not be continued with a high voltage input at a low frequency. Operation cannot be sustained when the ratio of voltage to frequency, with these quantities given values in per unit of their rated values, exceeds unity by more than a small amount, for instance if V/f >1.1. If a substantial rise in system voltage has been catered for in the design, the base of 'unit voltage' should be taken as the highest voltage for which the transformer is designed.

16.3 MAGNETISING INRUSH

The phenomenon of magnetising inrush is a transient condition that occurs primarily when a transformer is energised. It is not a fault condition, and therefore transformer protection must remain stable during the inrush transient.

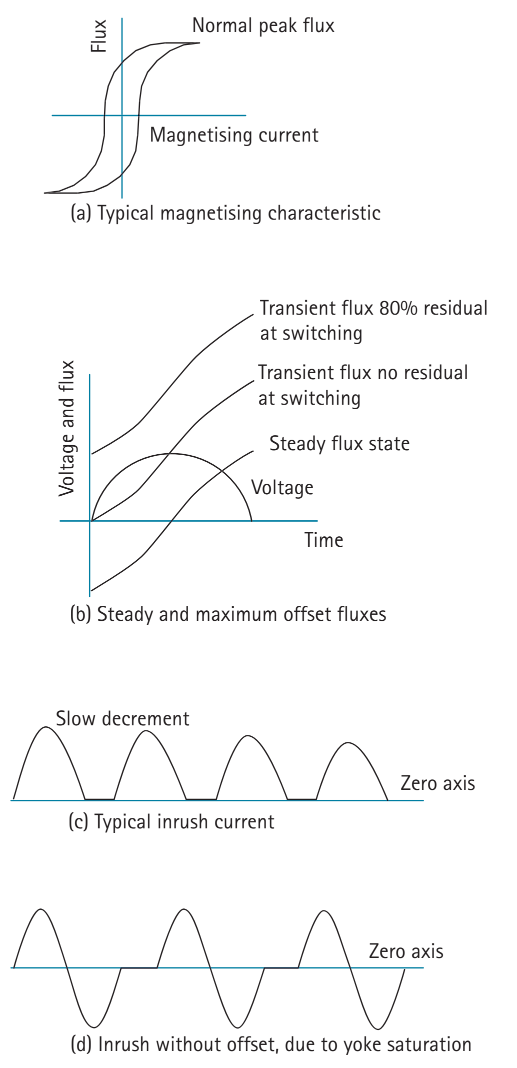


Figure 16.5: Transformer magnetising inrush

Figure 16.5(a) shows a transformer magnetising characteristic. To minimise material costs, weight and size, transformers are generally operated near to the 'knee point' of the magnetising characteristic.

Consequently, only a small increase in core flux above normal operating levels will result in a high magnetising current.

Under normal steady-state conditions, the magnetising current associated with the operating flux level is relatively small (Figure 16.5(b)). However, if a transformer winding is energised at a voltage zero, with no remanent flux, the flux level during the first voltage cycle (2 x normal flux) will result in core saturation and a high non-sinusoidal magnetising current waveform – see Figure 16.5(c). This current is referred to as magnetising inrush current and may persist for several cycles.

A number of factors affect the magnitude and duration of the magnetising current inrush:

a. residual flux – worst-case conditions result in the flux peak value attaining 280% of normal value

b. point on wave switching

c. number of banked transformers

d. transformer design and rating

e. system fault level

The very high flux densities quoted above are so far beyond the normal working range that the incremental relative permeability of the core approximates to unity and the inductance of the winding falls to a value near that of the 'air-cored' inductance. The current wave, starting from zero, increases slowly at first, the flux having a value just above the residual value and the permeability of the core being moderately high. As the flux passes the normal working value and enters the highly saturated portion of the magnetising characteristic, the inductance falls and the current rises rapidly to a peak that may be 500% of the steady state magnetising current. When the peak is passed at the next voltage zero, the following negative half cycle of the voltage wave reduces the flux to the starting value, the current falling symmetrically to zero. The current wave is therefore fully offset and is only restored to the steady state condition by the circuit losses. The time constant of the transient has a range between 0.1 second (for a 100kVA transformer) to 1.0 second (for a large unit). As the magnetising characteristic is non-linear, the envelope of the transient current is not strictly of exponential form; the magnetising current can be observed to be still changing up to 30 minutes after switching on.

Although correct choice of the point on the wave for a single–phase transformer will result in no transient inrush, mutual effects ensure that a transient inrush occurs in all phases for three-phase transformers.

16.3.1 Harmonic Content of Inrush Waveform

The waveform of transformer magnetising current contains a proportion of harmonics that increases as the peak flux density is raised to the saturating condition. The magnetising current of a transformer contains a third harmonic and progressively smaller amounts of fifth and higher harmonics. If the degree of saturation is progressively increased, not only will the harmonic content increase as a whole, but the relative proportion of fifth harmonic will increase and eventually exceed the third harmonic. At a still higher level the seventh would overtake the fifth harmonic but this involves a degree of saturation that will not be experienced with power transformers.

The energising conditions that result in an offset inrush current produce a waveform that is asymmetrical. Such a wave typically contains both even and odd harmonics. Typical inrush currents contain substantial amounts of second and third harmonics and diminishing amounts of higher orders. As with the steady state wave, the proportion of harmonics varies with the degree of saturation, so that as a severe inrush transient decays, the harmonic makeup of the current passes through a range of conditions.

16.4 TRANSFORMER OVERHEATING

The rating of a 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 sustained overload can be safely applied. Short-term overloads are also permissible to an extent dependent on the previous loading conditions. IEC 60354 provides guidance in this respect.

The only certain statement is that the winding must not overheat; a temperature of about 95°C is considered to be the normal maximum working value beyond which a further rise of 8°C-10°C, if sustained, will halve the insulation life of the unit.

Protection against overload is therefore based on winding temperature, which is usually measured by a thermal image technique. Protection is arranged to trip the transformer if excessive temperature is reached. The trip signal is usually routed via a digital input of a protection relay on one side of the transformer, with both alarm and trip facilities made available through programmable logic in the relay. Intertripping between the relays on the two sides of the transformer is usually applied to ensure total disconnection of the transformer.

Winding temperature protection may be included as a part of a complete monitoring package – see Section 16.18 for more details.

16.5 TRANSFORMER PROTECTION – OVERVIEW

The problems relating to transformers described in Sections 16.2-4 above require some means of protection. Table 16.2 summarises the problems and the possible forms of protection that may be used. The following sections provide more detail on the individual protection methods. It is normal for a modern relay to provide all of the required protection functions in a single package, in contrast to electromechanical types that would require several relays complete with interconnections and higher overall CT burdens.

Fault Type	Protection Used
Primary winding Phase-phase fault	Differential; Overcurrent
Primary winding Phase-earth fault	Differential; Overcurrent
Secondary winding Phase-phase fault	Differential
Secondary winding Phase-earth fault	Differential; Restricted Earth Fault
Interturn Fault	Differential, Buchholz
Core Fault	Differential, Buchholz
Tank Fault	Differential, Buchholz; Tank-Earth
Overfluxing	Overfluxing
Overheating	Thermal

Table 16.2: Transformer faults/protection

16.6 TRANSFORMER OVERCURRENT PROTECTION

Fuses may adequately protect small transformers, but larger ones require overcurrent protection using a relay and CB, as fuses do not have the required fault breaking capacity.

16.6.1 Fuses

Fuses commonly protect small distribution transformers typically up to ratings of 1MVA at distribution voltages. In many cases no circuit breaker is provided, making fuse protection the only available means of automatic isolation. The fuse must have a rating well above the maximum transformer load current in order to withstand the short duration overloads that may occur. Also, the fuses must withstand the magnetising inrush currents drawn when power transformers are energised. High Rupturing Capacity (HRC) fuses, although very fast in operation with large fault currents, are extremely slow with currents of less than three times their rated value. It follows that such fuses will do little to protect the transformer, serving only to protect the system by disconnecting a faulty transformer after the fault has reached an advanced stage.

Table 16.3 shows typical ratings of fuses for use with 11kV transformers.

Transformer rating		Fuse	
kVA	Full load current (A)	Rated current (A)	Operating time at 3 x rating(s)
100	5.25	16	3.0
200	10.5	25	3.0
315	15.8	36	10.0
500	26.2	50	20.0
1000	52.5	90	30.0

Table 16.3: Typical fuse ratings

This table should be taken only as a typical example; considerable differences exist in the time characteristic of different types of HRC fuses. Furthermore grading with protection on the secondary side has not been considered.

16.6.2 Overcurrent relays

With the advent of ring main units incorporating SF6 circuit breakers and isolators, protection of distribution transformers can now be provided by overcurrent trips (e.g. tripping controlled by time limit fuses connected across the secondary windings of in-built current transformers) or by relays connected to current transformers located on the transformer primary side. Overcurrent relays are also used on larger transformers provided with standard circuit breaker control. Improvement in protection is obtained in two ways; the excessive delays of the HRC fuse for lower fault currents are avoided and an earth-fault tripping element is provided in addition to the overcurrent feature.

The time delay characteristic should be chosen to discriminate with circuit protection on the secondary side.

A high-set instantaneous relay element is often provided, the current setting being chosen to avoid operation for a secondary short circuit. This enables high-speed clearance of primary terminal short circuits.

16.7 RESTRICTED EARTH FAULT PROTECTION

Conventional earth fault protection using overcurrent elements fails to provide adequate protection for transformer windings. This is particularly the case for a star-connected winding with an impedance-earthed neutral, as considered in Section 16.2.1.

The degree of protection is very much improved by the application of restricted earth fault protection (or REF protection). This is a unit protection scheme for one winding of the transformer. It can be of the high impedance type as shown in Figure 16.6, or of the biased low-impedance type. For the high-impedance type, the residual current of three line current transformers is balanced against the output of a current transformer in the

neutral conductor. In the biased low-impedance version, the three phase currents and the neutral current become the bias inputs to a differential element.
The system is operative for faults within the region between current transformers, that is, for faults on the star winding in question. The system will remain stable for all faults outside this zone.

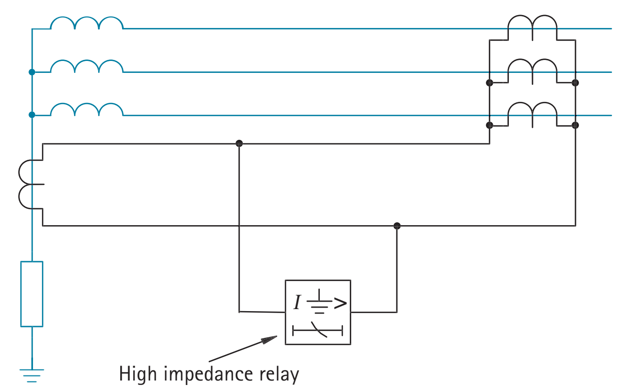


Figure 16.6: Restricted earth fault protection for a star winding

The gain in protection performance comes not only from using an instantaneous relay with a low setting, but also because the whole fault current is measured, not merely the transformed component in the HV primary winding (if the star winding is a secondary winding). Hence, although the prospective current level decreases as fault positions progressively nearer the neutral end of the winding are considered, the square law which controls the primary line current is not applicable, and with a low effective setting, a large percentage of the winding can be covered.
Restricted earth fault protection is often applied even when the neutral is solidly earthed. Since fault current then remains at a high value even to the last turn of the winding (Figure 16.2), virtually complete cover for earth faults is obtained. This is an improvement compared with the performance of systems that do not measure the neutral conductor current.
Earth fault protection applied to a delta-connected or unearthed star winding is inherently restricted, since no zero sequence components can be transmitted through the transformer to the other windings.
Both windings of a transformer can be protected separately with restricted earth fault protection, thereby providing high-speed protection against earth faults for the whole transformer with relatively simple equipment. A high impedance relay is used, giving fast operation and phase fault stability.

16.8 DIFFERENTIAL PROTECTION

The restricted earth fault schemes described above in Section 16.7 depend entirely on the Kirchhoff principle that the sum of the currents flowing into a conducting network is zero. A differential system can be arranged to cover the complete transformer; this is possible because of the high efficiency of transformer operation, and the close equivalence of ampere-turns developed on the primary and secondary windings. Figure 16.7 illustrates the principle. Current transformers on the primary and secondary sides are connected to form a circulating current system.

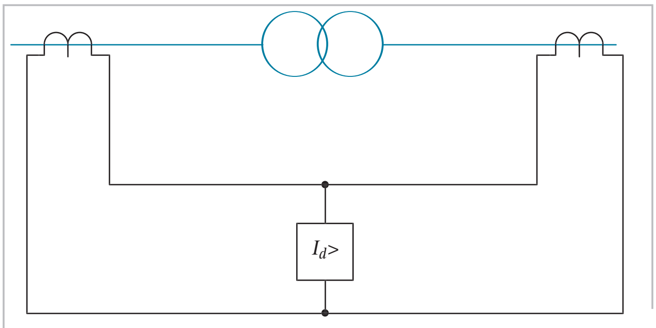


Figure 16.7: Principle of transformer differential protection

16.8.1 Basic Considerations for Transformer Differential Protection

In applying the principles of differential protection to transformers, a variety of considerations have to be taken into account. These include:

a. correction for possible phase shift across the transformer windings (phase correction)

b. the effects of the variety of earthing and winding arrangements (filtering of zero sequence currents)

c. correction for possible unbalance of signals from current transformers on either side of the windings (ratio correction)

d. the effect of magnetising inrush during initial energisation

e. the possible occurrence of overfluxing

In traditional transformer differential schemes, the requirements for phase and ratio correction were met by the application of external interposing current transformers (ICT's), as a secondary replica of the main winding connections, or by a delta connection of the main CT's to provide phase correction only. Digital/numerical relays implement ratio and phase correction in the relay software instead, thus enabling most combinations of transformer winding arrangements to be catered for, irrespective of the winding connections of the primary CT's. This avoids the additional space and cost requirements of hardware interposing CT's.

16.8.2 Line Current Transformer Primary Ratings

Line current transformers have primary ratings selected to be approximately equal to the rated currents of the transformer windings to which they are applied. Primary ratings will usually be limited to those of available standard ratio CT's.

16.8.3 Phase Correction

Correct operation of transformer differential protection requires that the transformer primary and secondary currents, as measured by the relay, are in phase. If the transformer is connected delta/star, as shown in Figure 16.8, balanced three-phase through current suffers a phase change of 30°. If left uncorrected, this phase difference would lead to the relay seeing through current as an unbalanced fault current, and result in relay operation. Phase correction must be implemented.

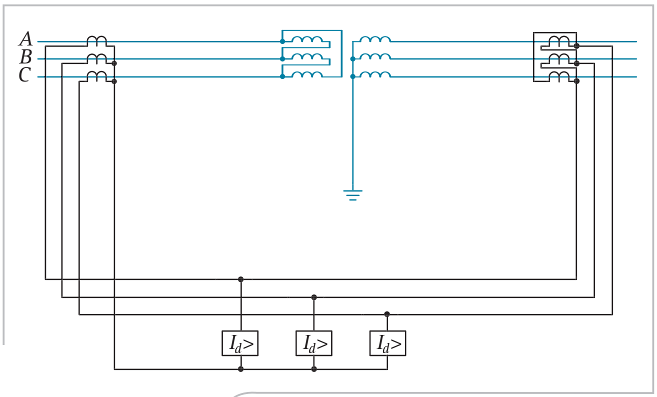


Figure 16.8: Differential protection for two-winding delta/star transformer

Electromechanical and static relays use appropriate CT/ICT connections to ensure that the primary and secondary currents applied to the relay are in phase.

For digital and numerical relays, it is common to use star-connected line CT's on all windings of the transformer and compensate for the winding phase shift in software. Depending on relay design, the only data required in such circumstances may be the transformer vector group designation. Phase compensation is then performed automatically. Caution is required if such a relay is used to replace an existing electromechanical or static relay, as the primary and secondary line CT's may not have the same winding configuration. Phase compensation and associated relay data entry requires more detailed consideration in such circumstances. Rarely, the available phase compensation facilities cannot accommodate the transformer winding connection, and in such cases interposing CT's must be used.

16.8.4 Filtering of Zero Sequence Currents

As described in Chapter 10.8, it is essential to provide some form of zero sequence filtering where a transformer winding can pass zero sequence current to an external earth fault. This is to ensure that out-of-zone earth faults are not seen by the transformer protection as an in-zone fault. This is achieved by use of delta-connected line CT's or interposing CT's for older relays, and hence the winding connection of the line and/or interposing CT's must take this into account, in addition to any phase compensation necessary. For digital/numerical relays, the required filtering is applied in the relay software. Table 16.4 summarises the phase compensation and zero sequence filtering requirements. An example of an incorrect choice of ICT connection is given in Section 16.19.1.

16.8.5 Ratio Correction

Correct operation of the differential element requires that currents in the differential element balance under load and through fault conditions. As the primary and secondary line CT ratios may not exactly match the transformer rated winding currents, digital/numerical relays are provided with ratio correction factors for each of the CT inputs. The correction factors may be

Transformer connection		Transformer phase shift	Clock face vector	Phase compensation required	HV Zero sequence filtering	LV Zero sequence filtering
Yy0		0°	0	0°	Yes	Yes
Zd0					Yes	
Dz0						Yes
Dd0						
Yz1	*Zy1*	-30°	1	30°	Yes	Yes
Yd1					Yes	
Dy1						Yes
Yy6		-180°	6	180°	Yes	Yes
Zd6					Yes	
Dz6						Yes
Dd6						
Yz11	*Zy11*	30°	11	-30°	Yes	Yes
Yd11					Yes	
Dy11						Yes
YyH	*YzH*	(H / 12) x 360°	Hour 'H'	-(H / 12) x 360°	Yes	Yes
YdH	*ZdH*				Yes	
DzH	*DyH*					Yes
DdH						

'H': phase displacement 'clock number', according to IEC 60076-1

Table 16.4: Current transformer connections for power transformers of various vector groups

calculated automatically by the relay from knowledge of the line CT ratios and the transformer MVA rating. However, if interposing CT's are used, ratio correction may not be such an easy task and may need to take into account a factor of $\sqrt{3}$ if delta-connected CT's or ICT's are involved. If the transformer is fitted with a tap changer, line CT ratios and correction factors are normally chosen to achieve current balance at the mid tap of the transformer. It is necessary to ensure that current mismatch due to off-nominal tap operation will not cause spurious operation.

The example in Section 16.19.2 provides an illustration of how ratio correction factors are used, and that of Section 16.9.3 shows how to set the ratio correction factors for a transformer with an unsymmetrical tap range.

16.8.6 Bias Setting

Bias is applied to transformer differential protection for the same reasons as any unit protection scheme – to ensure stability for external faults while allowing sensitive settings to pick up internal faults. The situation is slightly complicated if a tap changer is present. With line CT/ICT ratios and correction factors set to achieve current balance at nominal tap, an off-nominal tap may be seen by the differential protection as an internal fault. By selecting the minimum bias to be greater than sum of the maximum tap of the transformer and possible CT errors, maloperation due to this cause is avoided. Some relays use a bias characteristic with three sections, as shown in Figure 16.9. The first section is set higher than the transformer magnetising current. The second section is set to allow for off-nominal tap settings, while the third has a larger bias slope beginning well above rated current to cater for heavy through-fault conditions.

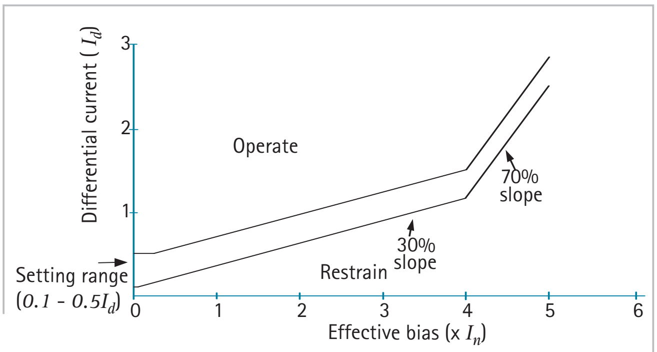


Figure 16.9: Typical bias characteristic

16.8.7 Transformers with Multiple Windings

The unit protection principle remains valid for a system having more than two connections, so a transformer with three or more windings can still be protected by the application of the above principles.

When the power transformer has only one of its three windings connected to a source of supply, with the other two windings feeding loads, a relay with only two sets of CT inputs can be used, connected as shown in Figure 16.10(a). The separate load currents are summated in the CT secondary circuits, and will balance with the infeed current on the supply side.

When more than one source of fault current infeed exists, there is a danger in the scheme of Figure 16.10(a) of current circulating between the two paralleled sets of current transformers without producing any bias. It is therefore important a relay is used with separate CT inputs for the two secondaries - Figure 16.10(b).

When the third winding consists of a delta-connected tertiary with no connections brought out, the transformer may be regarded as a two winding transformer for protection purposes and protected as shown in Figure 16.10(c).

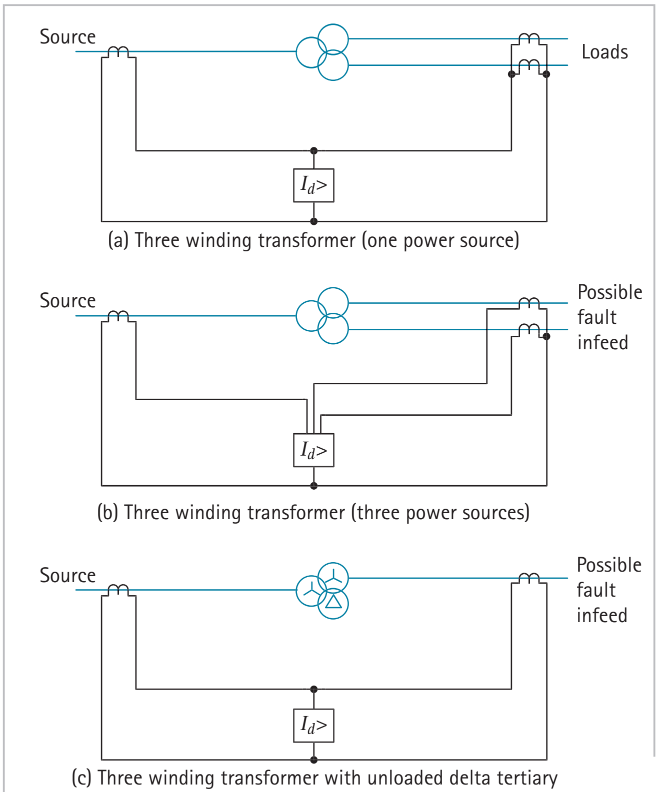


Figure 16.10 Differential protection arrangements for three-winding transformers (shown single phase for simplicity)

16.9 DIFFERENTIAL PROTECTION STABILISATION DURING MAGNETISING INRUSH CONDITIONS

The magnetising inrush phenomenon described in Section 16.3 produces current input to the energised winding which has no equivalent on the other windings. The whole of the inrush current appears, therefore, as unbalance and the differential protection is unable to distinguish it from current due to an internal fault. The bias setting is not effective and an increase in the protection setting to a value that would avoid operation would make the protection of little value. Methods of delaying, restraining or blocking of the differential element must therefore be used to prevent mal-operation of the protection.

16.9.1 Time Delay

Since the phenomenon is transient, stability can be maintained by providing a small time delay. However, because this time delay also delays operation of the relay in the event of a fault occurring at switch-on, the method is no longer used.

16.9.2 Harmonic Restraint

The inrush current, although generally resembling an in-zone fault current, differs greatly when the waveforms are compared. The difference in the waveforms can be used to distinguish between the conditions.

As stated before, the inrush current contains all harmonic orders, but these are not all equally suitable for providing bias. In practice, only the second harmonic is used.

This component is present in all inrush waveforms. It is typical of waveforms in which successive half period portions do not repeat with reversal of polarity but in which mirror-image symmetry can be found about certain ordinates.

The proportion of second harmonic varies somewhat with the degree of saturation of the core, but is always present as long as the uni-directional component of flux exists. The amount varies according to factors in the transformer design. Normal fault currents do not contain second or other even harmonics, nor do distorted currents flowing in saturated iron cored coils under steady state conditions.

The output current of a current transformer that is energised into steady state saturation will contain odd harmonics but not even harmonics. However, should the current transformer be saturated by the transient component of the fault current, the resulting saturation is not symmetrical and even harmonics are introduced into the output current. This can have the advantage of improving the through fault stability performance of a differential relay. faults.

The second harmonic is therefore an attractive basis for a stabilising bias against inrush effects, but care must be taken to ensure that the current transformers are sufficiently large so that the harmonics produced by transient saturation do not delay normal operation of the relay. The differential current is passed through a filter that extracts the second harmonic; this component is then applied to produce a restraining quantity sufficient to overcome the operating tendency due to the whole of the inrush current that flows in the operating circuit. By this means a sensitive and high-speed system can be obtained.

16.9.3 Inrush Detection Blocking – Gap Detection Technique

Another feature that characterizes an inrush current can be seen from Figure 16.5 where the two waveforms (c) and (d) have periods in the cycle where the current is zero. The minimum duration of this zero period is theoretically one quarter of the cycle and is easily detected by a simple timer t_1 that is set to $\frac{1}{4f}$ seconds. Figure 16.11 shows the circuit in block diagram form. Timer t_1 produces an output only if the current is zero for a time exceeding $\frac{1}{4f}$ seconds. It is reset when the instantaneous value of the differential current exceeds the setting reference.

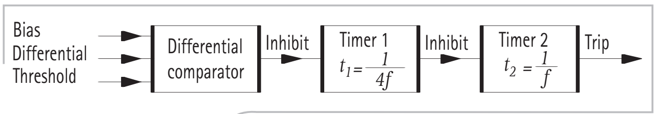


Figure 16.11: Block diagram to show waveform gap-detecting principle

As the zero in the inrush current occurs towards the end of the cycle, it is necessary to delay operation of the differential relay by $\frac{1}{f}$ seconds to ensure that the zero condition can be detected if present. This is achieved by using a second timer t_2 that is held reset by an output from timer t_1.

When no current is flowing for a time exceeding $\frac{1}{4f}$ seconds, timer t_2 is held reset and the differential relay that may be controlled by these timers is blocked. When a differential current exceeding the setting of the relay flows, timer t_1 is reset and timer t_2 times out to give a trip signal in $\frac{1}{f}$ seconds. If the differential current is characteristic of transformer inrush then timer t_2 will be reset on each cycle and the trip signal is blocked.

Some numerical relays may use a combination of the harmonic restraint and gap detection techniques for magnetising inrush detection.

16.10 COMBINED DIFFERENTIAL AND RESTRICTED EARTH FAULT SCHEMES

The advantages to be obtained by the use of restricted earth fault protection, discussed in Section 16.7, lead to the system being frequently used in conjunction with an overall differential system. The importance of this is shown in Figure 16.12 from which it will be seen that if the neutral of a star-connected winding is earthed through a resistance of one per unit, an overall differential system having an effective setting of 20% will detect faults in only 42% of the winding from the line end.

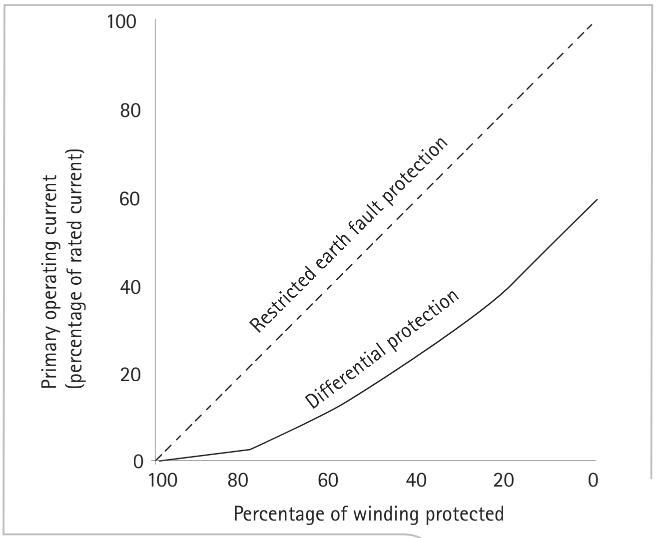


Figure 16.12: Amount of winding protected when transformer is resistance earthed and ratings of transformer and resistor are equal

Implementation of a combined differential/REF protection scheme is made easy if a numerical relay with software ratio/phase compensation is used. All compensation is made internally in the relay.

Where software ratio/phase correction is not available, either a summation transformer or auxiliary CT's can be used. The connections are shown in Figures 16.13 and 16.14 respectively.

Care must be taken in calculating the settings, but the only significant disadvantage of the Combined Differential/REF scheme is that the REF element is likely to operate for heavy internal faults as well as the differential elements, thus making subsequent fault analysis somewhat confusing. However, the saving in CT's outweighs this disadvantage.

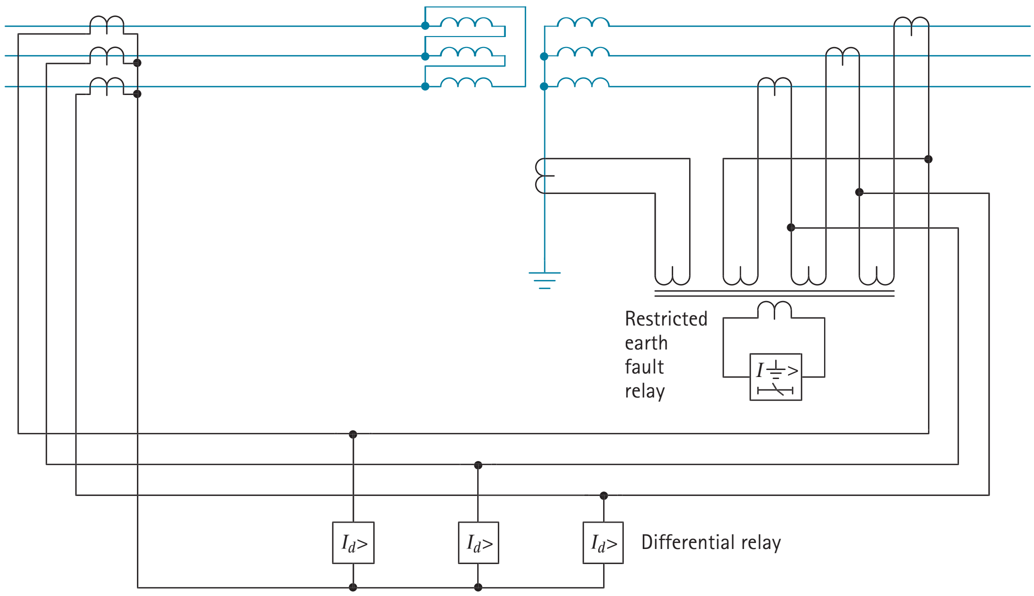


Figure 16.13 Combined differential and earth fault protection using summation current transformer

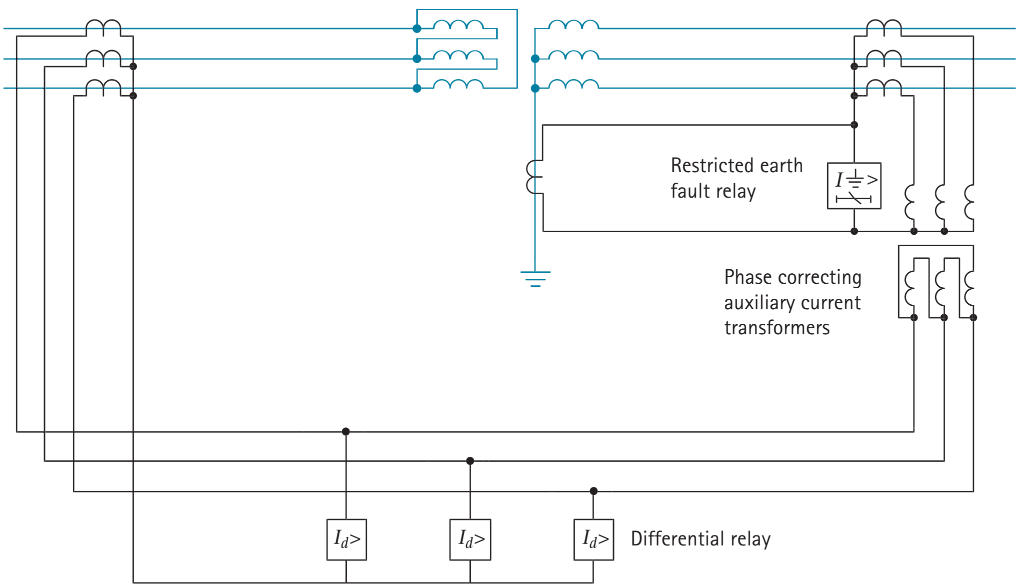


Figure 16.14: Combined differential and restricted earth fault protection using auxiliary CT's

16.10.1 Application when an Earthing Transformer is connected within the Protected Zone

A delta-connected winding cannot deliver any zero sequence current to an earth fault on the connected system, any current that does flow is in consequence of an earthed neutral elsewhere on the system and will have a 2-1-1 pattern of current distribution between phases. When the transformer in question represents a major power feed, the system may be earthed at that point by an earthing transformer or earthing reactor. They are frequently connected to the system, close to the main supply transformer and within the transformer protection zone. Zero sequence current that flows through the earthing transformer during system earth faults will flow through the line current transformers on this side, and, without an equivalent current in the balancing current transformers, will cause unwanted operation of the relays.

The problem can be overcome by subtracting the appropriate component of current from the main CT output. The earthing transformer neutral current is used for this purpose. As this represents three times the zero sequence current flowing, ratio correction is required. This can take the form of interposing CT's of ratio 1/0.333, arranged to subtract their output from that of the line current transformers in each phase, as shown in Figure 16.15. The zero sequence component is cancelled, restoring balance to the differential system.

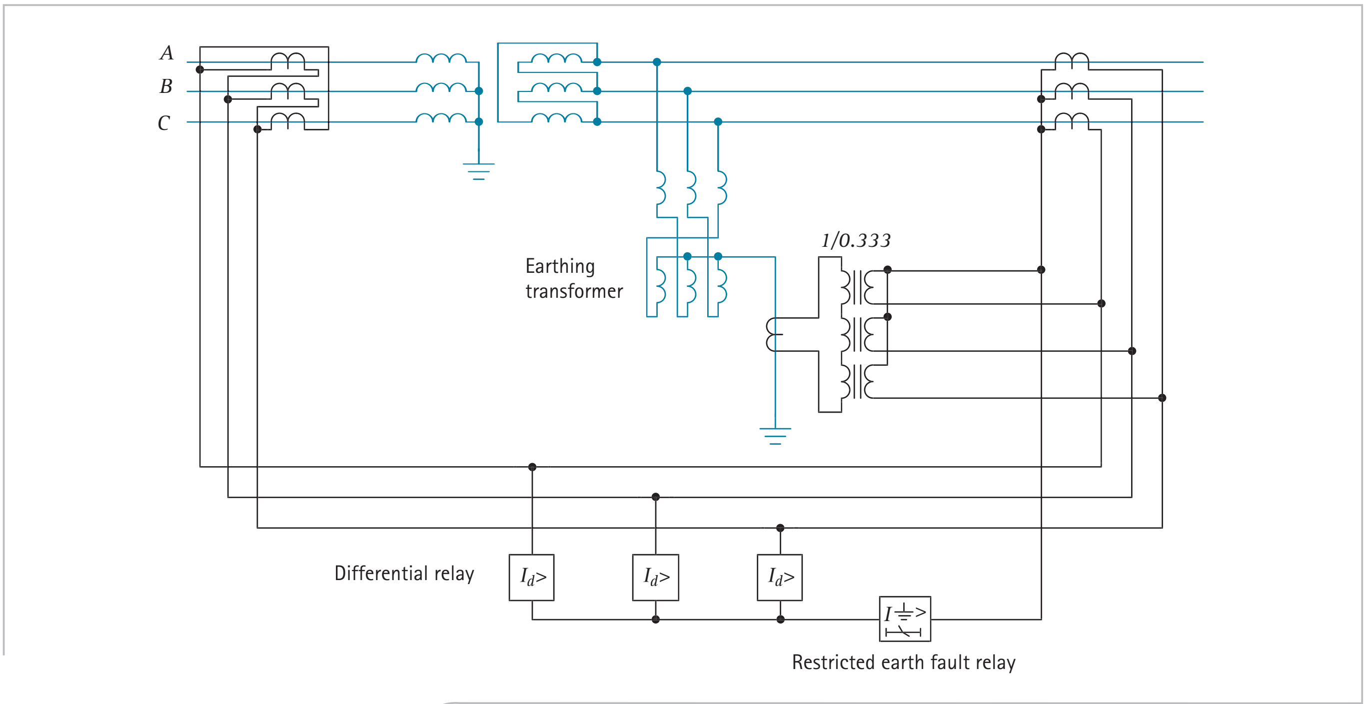


Figure 16.15: Differential protection with in-zone earthing transformer, with restricted earth fault relay

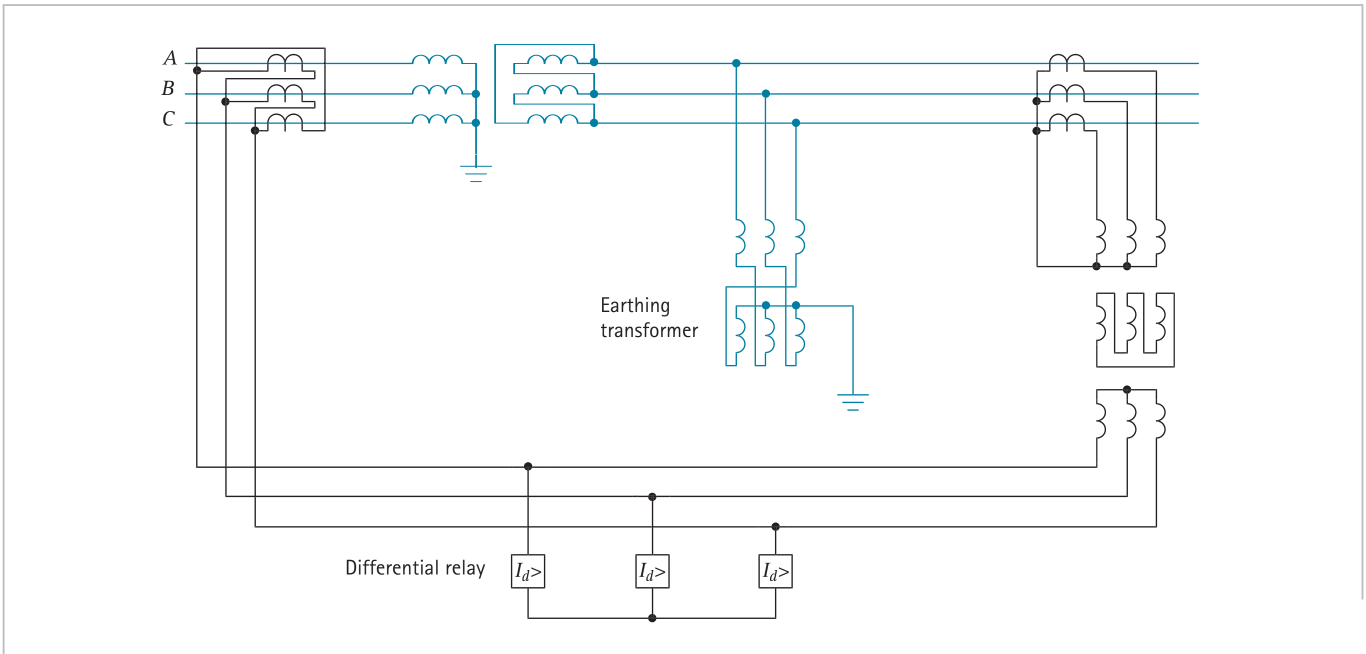


Figure 16.16: Differential protection with in-zone earthing transformer; no earth fault relay

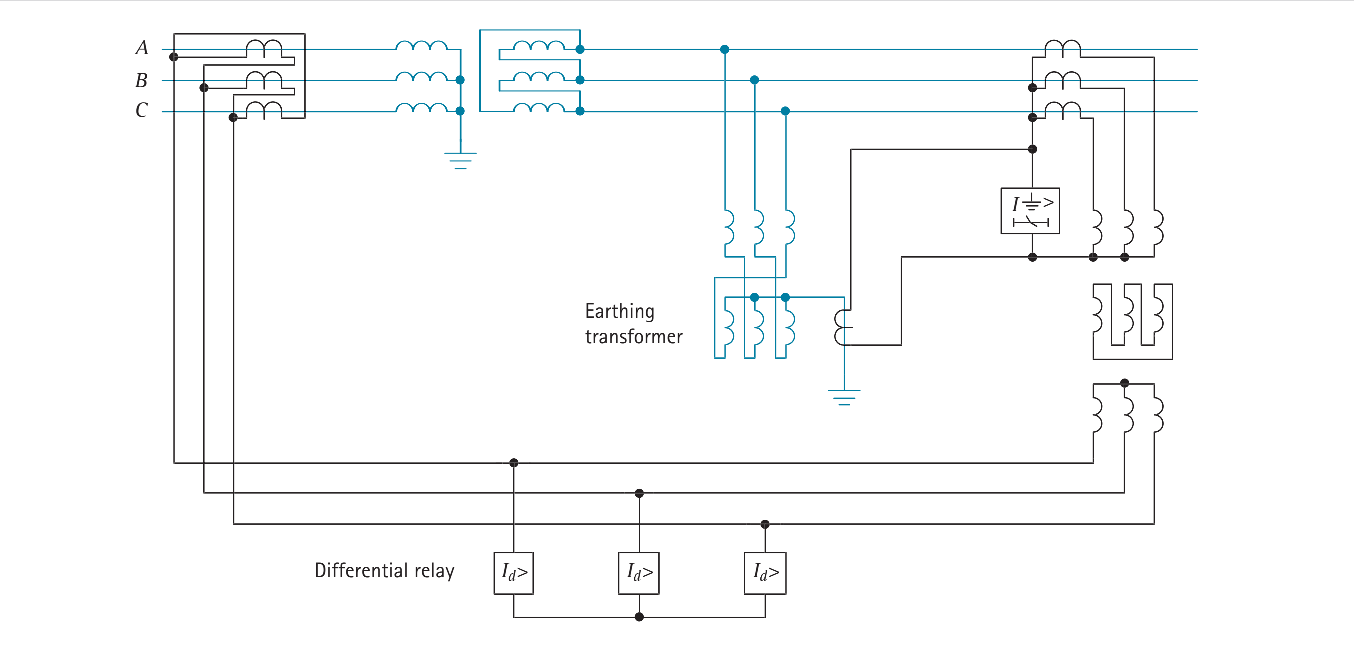


Figure 16.17: Differential protection with in-zone earthing transformer, with alternative arrangement of restricted earth fault relay

Alternatively, numerical relays may use software to perform the subtraction, having calculated the zero sequence component internally.

A high impedance relay element can be connected in the neutral lead between current transformers and differential relays to provide restricted earth fault protection to the winding.

As an alternative to the above scheme, the circulating current system can be completed via a three-phase group of interposing transformers that are provided with tertiary windings connected in delta. This winding effectively short-circuits the zero sequence component and thereby removes it from the balancing quantities in the relay circuit; see Figure 16.16.

Provided restricted earth fault protection is not required, the scheme shown in Figure 16.16 has the advantage of not requiring a current transformer, with its associated mounting and cabling requirements, in the neutral-earth conductor. The scheme can also be connected as shown in Figure 16.17 when restricted earth fault protection is needed.

16.11 EARTHING TRANSFORMER PROTECTION

Earthing transformers not protected by other means can use the scheme shown in Figure 16.18. The delta-connected current transformers are connected to an overcurrent relay having three phase-fault elements. The normal action of the earthing transformer is to pass zero sequence current. The transformer equivalent current circulates in the delta formed by the CT secondaries without energising the relay. The latter may therefore be set to give fast and sensitive protection against faults in the earthing transformer itself.

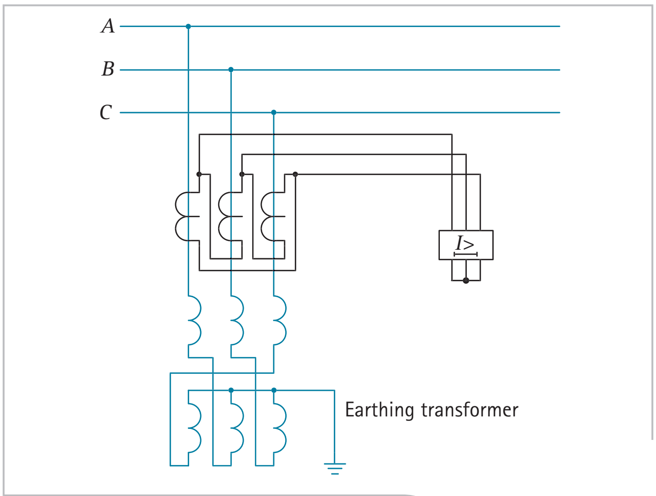


Figure 16.18: Earthing transformer protection

16.12 AUTOTRANSFORMER PROTECTION

Autotransformers are used to couple EHV power networks if the ratio of their voltages is moderate. An alternative to Differential Protection that can be applied to autotransformers is protection based on the application of Kirchhoff's law to a conducting network, namely that the sum of the currents flowing into all external connections to the network is zero.

A circulating current system is arranged between equal ratio current transformers in the two groups of line connections and the neutral end connections. If one neutral current transformer is used, this and all the line current transformers can be connected in parallel to a single element relay, thus providing a scheme responsive to earth faults only; see Figure 16.19(a).

If current transformers are fitted in each phase at the neutral end of the windings and a three-element relay is used, a differential system can be provided, giving full protection against phase and earth faults; see Figure 16.19(b). This provides high-speed sensitive protection. It is unaffected by ratio changes on the transformer due to tap-changing and is immune to the effects of magnetising inrush current.

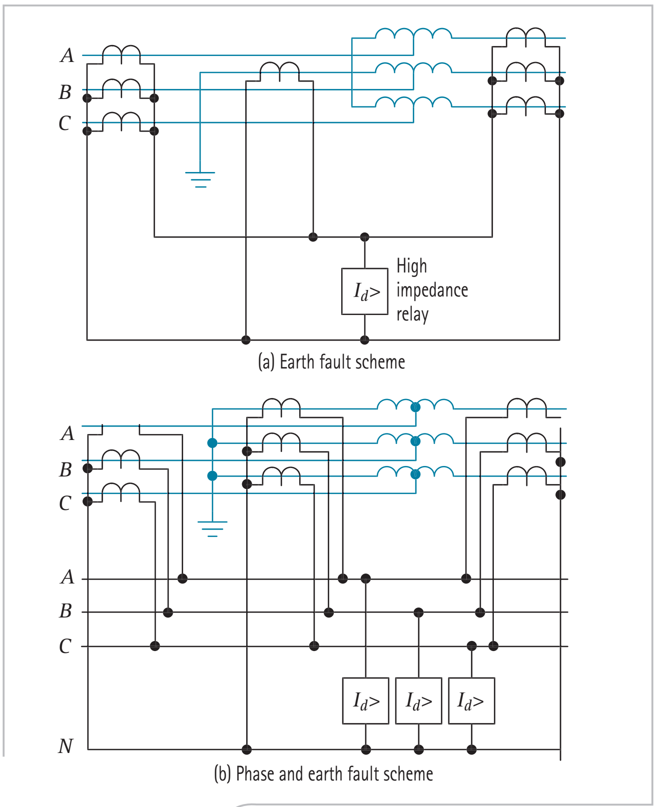


Figure 16.19: Protection of auto-transformer by high impedance differential relays

It does not respond to interturn faults, a deficiency that is serious in view of the high statistical risk quoted in Section 16.1. Such faults, unless otherwise cleared, will be left to develop into earth faults, by which time considerably more damage to the transformer will have occurred.

In addition, this scheme does not respond to any fault in a tertiary winding. Unloaded delta-connected tertiary windings are often not protected; alternatively, the delta winding can be earthed at one point through a current transformer that energises an instantaneous relay. This system should be separate from the main winding protection. If the tertiary winding earthing lead is connected to the main winding neutral above the neutral current transformer in an attempt to make a combined system, there may be 'blind spots' which the protection cannot cover.

16.13 OVERFLUXING PROTECTION

The effects of excessive flux density are described in Section 16.2.8. Overfluxing arises principally from the following system conditions:

a. high system voltage

b. low system frequency

c. geomagnetic disturbances

The latter results in low frequency earth currents circulating through a transmission system.

Since momentary system disturbances can cause transient overfluxing that is not dangerous, time delayed tripping is required. The normal protection is an IDMT or definite time characteristic, initiated if a defined V/f threshold is exceeded. Often separate alarm and trip elements are provided. The alarm function would be definite time-delayed and the trip function would be an IDMT characteristic. A typical characteristic is shown in Figure 16.20.

Geomagnetic disturbances may result in overfluxing without the V/f threshold being exceeded. Some relays provide a 5th harmonic detection feature, which can be used to detect such a condition, as levels of this harmonic rise under overfluxing conditions.

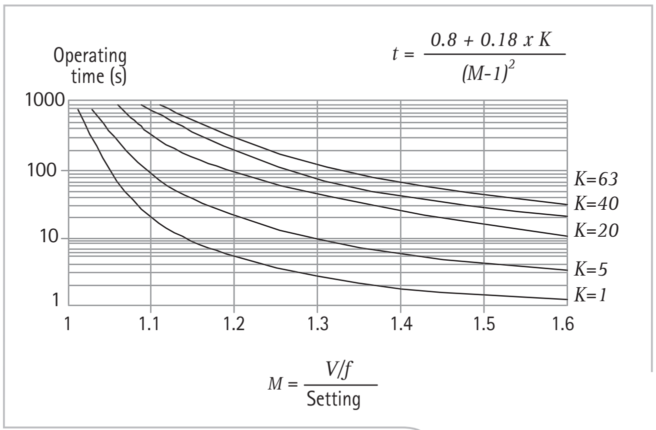


Figure 16.20: Typical IDMT characteristic for overfluxing protection

16.14 TANK-EARTH PROTECTION

This is also known as Howard protection. If the transformer tank is nominally insulated from earth (an insulation resistance of 10 ohms being sufficient) earth fault protection can be provided by connecting a relay to the secondary of a current transformer the primary of which is connected between the tank and earth. This scheme is similar to the frame-earth fault busbar protection described in Chapter 15.

16.15 OIL AND GAS DEVICES

All faults below oil in an oil-immersed transformer result in localised heating and breakdown of the oil; some degree of arcing will always take place in a winding fault and the resulting decomposition of the oil will release gases. When the fault is of a very minor type, such as a hot joint, gas is released slowly, but a major fault involving severe arcing causes a very rapid release of large volumes of gas as well as oil vapour. The action is so violent that the gas and vapour do not have time to escape but instead build up pressure and bodily displace the oil.

When such faults occur in transformers having oil conservators, the fault causes a blast of oil to pass up the relief pipe to the conservator. A Buchholz relay is used to protect against such conditions. Devices responding to abnormally high oil pressure or rate-of-rise of oil pressure are also available and may be used in conjunction with a Buchholz relay.

16.15.1 Oil Pressure Relief Devices

The simplest form of pressure relief device is the widely used 'frangible disc' that is normally located at the end of an oil relief pipe protruding from the top of the transformer tank.

The surge of oil caused by a serious fault bursts the disc, so allowing the oil to discharge rapidly. Relieving and limiting the pressure rise avoids explosive rupture of the tank and consequent fire risk. Outdoor oil-immersed transformers are usually mounted in a catchment pit to collect and contain spilt oil (from whatever cause), thereby minimising the possibility of pollution.

A drawback of the frangible disc is that the oil remaining in the tank is left exposed to the atmosphere after rupture. This is avoided in a more effective device, the sudden pressure relief valve, which opens to allow discharge of oil if the pressure exceeds a set level, but closes automatically as soon as the internal pressure falls below this level. If the abnormal pressure is relatively high, the valve can operate within a few milliseconds, and provide fast tripping when suitable contacts are fitted.

The device is commonly fitted to power transformers rated at 2MVA or higher, but may be applied to distribution transformers rated as low as 200kVA, particularly those in hazardous areas.

16.15.2 Rapid Pressure Rise Relay

This device detects rapid rise of pressure rather than absolute pressure and thereby can respond even quicker than the pressure relief valve to sudden abnormally high pressures. Sensitivities as low as 0.07bar/s are attainable, but when fitted to forced-cooled transformers the operating speed of the device may have to be slowed deliberately to avoid spurious tripping during circulation pump starts.

16.15.3 Buchholz Protection

Buchholz protection is normally provided on all transformers fitted with a conservator. The Buchholz relay is contained in a cast housing which is connected in the pipe to the conservator, as in Figure 16.21.

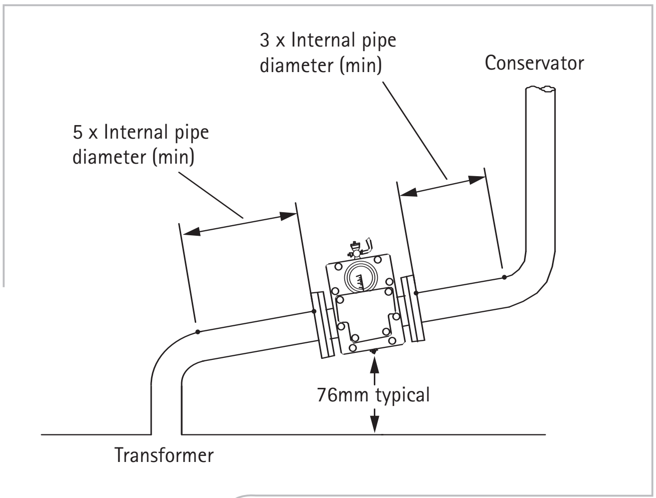


Figure 16.21: Buchholz relay mounting arrangement

A typical Buchholz relay will have two sets of contacts. One is arranged to operate for slow accumulations of gas, the other for bulk displacement of oil in the event of a heavy internal fault. An alarm is generated for the former, but the latter is usually direct-wired to the CB trip relay.

The device will therefore give an alarm for the following fault conditions, all of which are of a low order of urgency.

a. hot spots on the core due to short circuit of lamination insulation

b. core bolt insulation failure

c. faulty joints

d. interturn faults or other winding faults involving only lower power infeeds

e. loss of oil due to leakage

When a major winding fault occurs, this causes a surge of oil, which displaces the lower float and thus causes isolation of the transformer. This action will take place for:

i. all severe winding faults, either to earth or interphase

ii. loss of oil if allowed to continue to a dangerous degree

An inspection window is usually provided on either side of the gas collection space. Visible white or yellow gas indicates that insulation has been burnt, while black or grey gas indicates the presence of, dissociated oil. In these cases the gas will probably be inflammable, whereas released air will not. A vent valve is provided on the top of the housing for the gas to be released or collected for analysis. Transformers with forced oil circulation may experience oil flow to/from the conservator on starting/stopping of the pumps. The Buchholz relay must not operate in this circumstance.

Cleaning operations may cause aeration of the oil. Under such conditions, tripping of the transformer due to Buchholz operation should be inhibited for a suitable period.

Because of its universal response to faults within the transformer, some of which are difficult to detect by other means, the Buchholz relay is invaluable, whether regarded as a main protection or as a supplement to other protection schemes. Tests carried out by striking a high voltage arc in a transformer tank filled with oil, have shown that operation times of 0.05s-0.1s are possible. Electrical protection is generally used as well, either to obtain faster operation for heavy faults, or because Buchholz relays have to be prevented from tripping during oil maintenance periods. Conservators are fitted to oil-cooled transformers above 1000kVA rating, except those to North American design practice that use a different technique.

16.16 TRANSFORMER-FEEDER PROTECTION

A transformer-feeder comprises a transformer directly connected to a transmission circuit without the intervention of switchgear. Examples are shown in Figure 16.22.

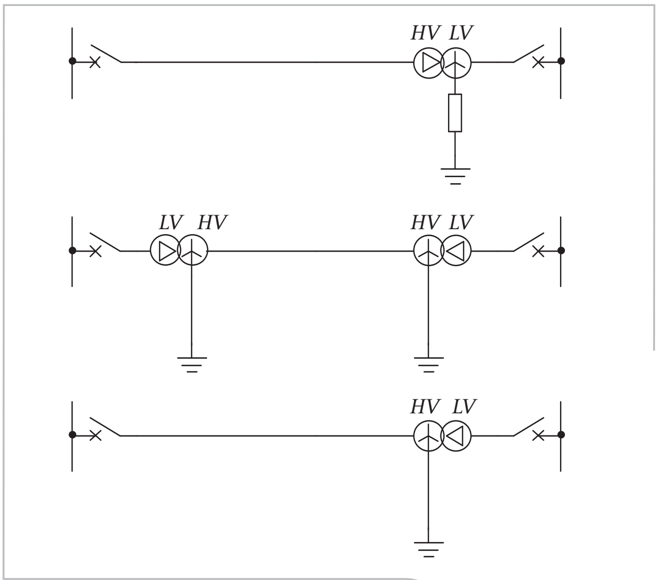


Figure 16.22: Typical transformer-feeder circuits.

The saving in switchgear so achieved is offset by increased complication in the necessary protection. The primary requirement is intertripping, since the feeder protection remote from the transformer will not respond to the low current fault conditions that can be detected by restricted earth fault and Buchholz protections.

Either unrestricted or restricted protection can be applied; moreover, the transformer-feeder can be protected as a single zone or be provided with separate protections for the feeder and the transformer. In the latter case, the separate protections can both be unit type systems. An adequate alternative is the combination of unit transformer protection with an unrestricted system of feeder protection, plus an intertripping feature.

16.16.1 Non-Unit Schemes

The following sections describe how non-unit schemes are applied to protect transformer-feeders against various types of fault.

16.16.1.1 Feeder phase and earth faults

High-speed protection against phase and earth faults can be provided by distance relays located at the end of the feeder remote from the transformer. The transformer constitutes an appreciable lumped impedance. It is therefore possible to set a distance relay zone to cover the whole feeder and reach part way into the transformer impedance. With a normal tolerance on setting thus allowed for, it is possible for fast Zone 1 protection to cover the whole of the feeder with certainty without risk of over-reaching to a fault on the low voltage side.

Although the distance zone is described as being set 'half way into the transformer', it must not be thought that half the transformer winding will be protected. The effects of auto-transformer action and variations in the effective impedance of the winding with fault position prevent this, making the amount of winding beyond the terminals which is protected very small. The value of the system is confined to the feeder, which, as stated above, receives high-speed protection throughout.

16.16.1.2 Feeder phase faults

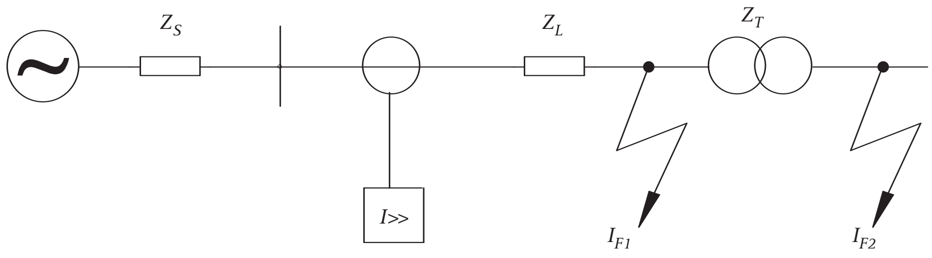
A distance scheme is not, for all practical purposes, affected by varying fault levels on the high voltage busbars and is therefore the best scheme to apply if the fault level may vary widely. In cases where the fault level is reasonably constant, similar protection can be obtained using high set instantaneous overcurrent relays. These should have a low transient over-reach, defined as:

$$\frac{I_S - I_F}{I_F} \times 100\%$$

where: I_S = *setting current*

I_F = *steady - state r.m.s. value of fault current which when fully offset just operates the relay*

The instantaneous overcurrent relays must be set without risk of them operating for faults on the remote side of the transformer.



Transient over-reach (%) ▶	Setting ratio $r = \frac{I_S}{I_{F2}}$: 5	25	50	100
$x = \frac{Z_T}{Z_S + Z_L}$ = 0.25	1.01	1.20	1.44	1.92
0.5	0.84	1.00	1.20	1.60
1.0	0.63	0.75	0.90	1.20
2.0	0.42	0.50	0.60	0.80
4.0	0.25	0.30	0.36	0.48
8.0	0.14	0.17	0.20	0.27

I_s = Relay setting = $1.2(1 + t)I_{F2}$
t = Transient over-reach (p.u.)

Figure 16.23: Over-reach considerations in the application of transformer-feeder protection

Referring to Figure 16.23, the required setting to ensure that the relay will not operate for a fully offset fault I_{F2} is given by:

$$I_S = 1.2\ (1 + t)\ I_{F2}$$

where I_{F2} is the fault current under maximum source conditions, that is, when Z_S is minimum, and the factor of 1.2 covers possible errors in the system impedance details used for calculation of I_{F2} , together with relay and CT errors.

As it is desirable for the instantaneous overcurrent protection to clear all phase faults anywhere within the feeder under varying system operating conditions, it is necessary to have a relay setting less than I_{F1} in order to ensure fast and reliable operation.

Let the setting ratio resulting from setting I_S be

$$r = \frac{I_S}{I_{F1}}$$

Therefore,

$$rI_{F1} = 1.2(1 + t)I_{F2}$$

Hence,

$$r = 1.2(1+t)\frac{Z_S + Z_L}{Z_S + Z_L + Z_T}$$

$$r = 1.2(1+t)\frac{Z_S + Z_L}{(1+x)(Z_S + Z_L)}$$

$$= \frac{1.2(1+t)}{1+x}$$

where:

$$x = \frac{Z_T}{Z_S + Z_L}$$

It can be seen that for a given transformer size, the most sensitive protection for the line will be obtained by using relays with the lowest transient overreach. It should be noted that where r is greater than 1, the protection will not cover the whole line. Also, any increase in source impedance above the minimum value will increase the effective setting ratios above those shown. The instantaneous protection is usually applied with a time delayed overcurrent element having a lower current setting. In this way, instantaneous protection is provided for the feeder, with the time-delayed element covering faults on the transformer.

When the power can flow in the transformer-feeder in either direction, overcurrent relays will be required at both ends. In the case of parallel transformer-feeders, it is essential that the overcurrent relays on the low voltage side be directional, operating only for fault current fed into the transformer-feeder, as described in Section 9.14.3.

16.16.1.3 Earth faults

Instantaneous restricted earth fault protection is normally provided. When the high voltage winding is delta connected, a relay in the residual circuit of the line current transformers gives earth fault protection which is fundamentally limited to the feeder and the associated delta-connected transformer winding. The latter is unable to transmit any zero sequence current to a through earth fault.

When the feeder is associated with an earthed star-connected winding, normal restricted earth fault protection as described in Section 16.7 is not applicable because of the remoteness of the transformer neutral.

Restricted protection can be applied using a directional earth fault relay. A simple sensitive and high-speed directional element can be used, but attention must be paid to the transient stability of the element. Alternatively, a directional IDMT relay may be used, the time multiplier being set low. The slight inverse time delay in operation will ensure that unwanted transient operation is avoided.

When the supply source is on the high voltage star side, an alternative scheme that does not require a voltage transformer can be used. The scheme is shown in Figure 16.24. For the circuit breaker to trip, both relays *A* and *B* must operate, which will occur for earth faults on the feeder or transformer winding.

External earth faults cause the transformer to deliver zero sequence current only, which will circulate in the closed delta connection of the secondary windings of the three auxiliary current transformers. No output is available to relay *B*. Through phase faults will operate relay *B*, but not the residual relay *A*. Relay *B* must have a setting above the maximum load. As the earthing of the neutral at a receiving point is likely to be solid and the earth fault current will therefore be comparable with the phase fault current, high settings are not a serious limitation.

Earth fault protection of the low voltage winding will be provided by a restricted earth fault system using either three or four current transformers, according to whether the winding is delta or star-connected, as described in Section 16.7.

16.16.1.4 In-zone capacitance

The feeder portion of the transformer-feeder will have an appreciable capacitance between each conductor and earth. During an external earth fault the neutral will be displaced, and the resulting zero sequence component of voltage will produce a corresponding component of zero sequence capacitance current. In the limiting case of full neutral displacement, this zero sequence current will be equal in value to the normal positive sequence current.

The resulting residual current is equal to three times the zero sequence current and hence to three times the normal line charging current. The value of this component of in-zone current should be considered when establishing the effective setting of earth fault relays.

16.16.2 Unit Schemes

The basic differences between the requirements of feeder

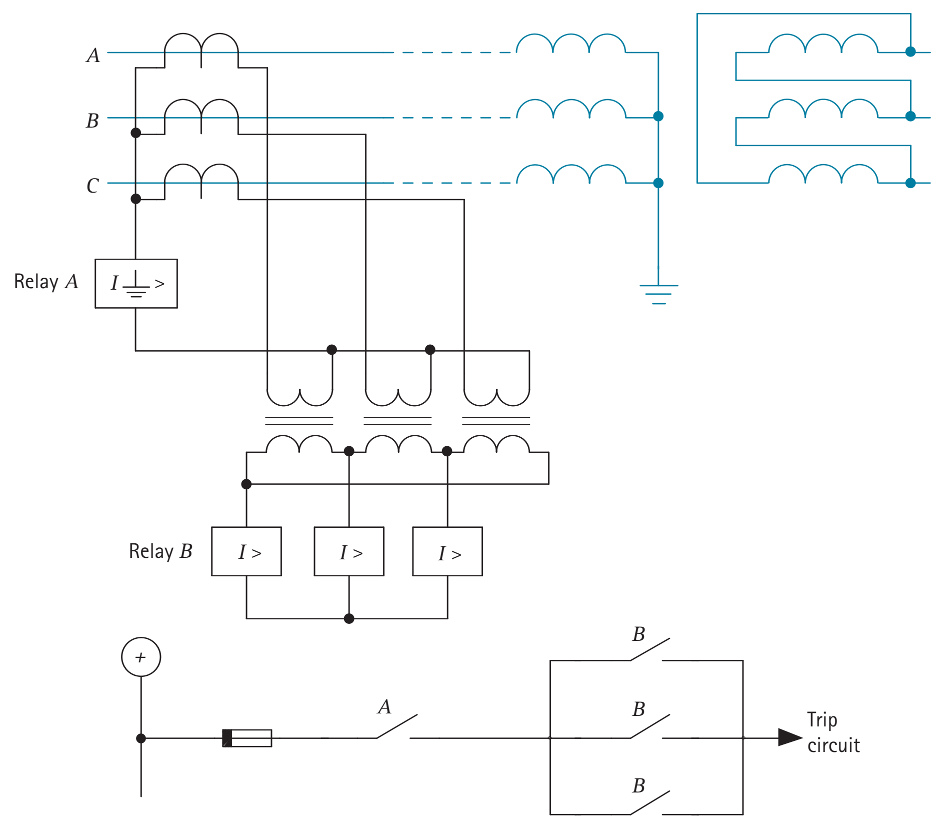


Figure 16.24: Instantaneous protection of transformer-feeder

and transformer protections lie in the limitation imposed on the transfer of earth fault current by the transformer and the need for high sensitivity in the transformer protection, suggesting that the two components of a transformer-feeder should be protected separately. This involves mounting current transformers adjacent to, or on, the high voltage terminals of the transformer. Separate current transformers are desirable for the feeder and transformer protections so that these can be arranged in two separate overlapping zones. The use of common current transformers is possible, but may involve the use of auxiliary current transformers, or special winding and connection arrangements of the relays. Intertripping of the remote circuit breaker from the transformer protection will be necessary, but this can be done using the communication facilities of the feeder protection relays.

Although technically superior, the use of separate protection systems is seldom justifiable when compared with an overall system or a combination of non-unit feeder protection and a unit transformer system.

An overall unit system must take into account the fact that zero sequence current on one side of a transformer may not be reproduced in any form on the other side. This represents little difficulty to a modern numerical relay using software phase/zero sequence compensation and digital communications to transmit full information on the phase and earth currents from one relay to the other. However, it does represent a more difficult problem for relays using older technology. The line current transformers can be connected to a summation transformer with unequal taps, as shown in Figure 16.25(a). This arrangement produces an output for phase faults and also some response for A and B phase-earth faults. However, the resulting settings will be similar to those for phase faults and no protection will be given for C phase-earth faults.

An alternative technique is shown in Figure 16.25(b).

The B phase is taken through a separate winding on another transformer or relay electromagnet, to provide another balancing system. The two transformers are interconnected with their counterparts at the other end of the feeder-transformer by four pilot wires. Operation with three pilot cores is possible but four are preferable, involving little increase in pilot cost.

16.17 INTERTRIPPING

In order to ensure that both the high and low voltage circuit breakers operate for faults within the transformer and feeder, it is necessary to operate both circuit breakers from protection normally associated with one. The technique for doing this is known as intertripping.

The necessity for intertripping on transformer-feeders arises from the fact that certain types of fault produce insufficient current to operate the protection associated with one of the circuit breakers. These faults are:

a. faults in the transformer that operate the Buchholz relay and trip the local low voltage circuit breaker, while failing to produce enough fault current to operate the protection associated with the remote high voltage circuit breaker

b. earth faults on the star winding of the transformer, which, because of the position of the fault in the winding, again produce insufficient current for relay operation at the remote circuit breaker

c. earth faults on the feeder or high voltage delta-connected winding which trip the high voltage circuit breaker only, leaving the transformer energised form the low voltage side and with two high voltage phases at near line-to-line voltage above earth. Intermittent arcing may follow and there is a possibility of transient overvoltage occurring and causing a further breakdown of insulation

Several methods are available for intertripping; these are discussed in Chapter 8.

16.17.1 Neutral Displacement

An alternative to intertripping is to detect the condition by measuring the residual voltage on the feeder. An earth fault occurring on the feeder connected to an unearthed transformer winding should be cleared by the feeder circuit, but if there is also a source of supply on the secondary side of the transformer, the feeder may be still live. The feeder will then be a local unearthed system, and, if the earth fault continues in an arcing condition, dangerous overvoltages may occur.

A voltage relay is energised from the broken-delta connected secondary winding of a voltage transformer on the high voltage line, and receives an input proportional to the zero sequence voltage of the line, that is, to any displacement of the neutral point; see Figure 16.26.

The relay normally receives zero voltage, but, in the presence of an earth fault, the broken-delta voltage will rise to three times the phase voltage. Earth faults elsewhere in the system may also result in displacement of the neutral and hence discrimination is achieved using definite or inverse time characteristics.

16.18 CONDITION MONITORING OF TRANSFORMERS

It is possible to provide transformers with measuring devices to detect early signs of degradation in various

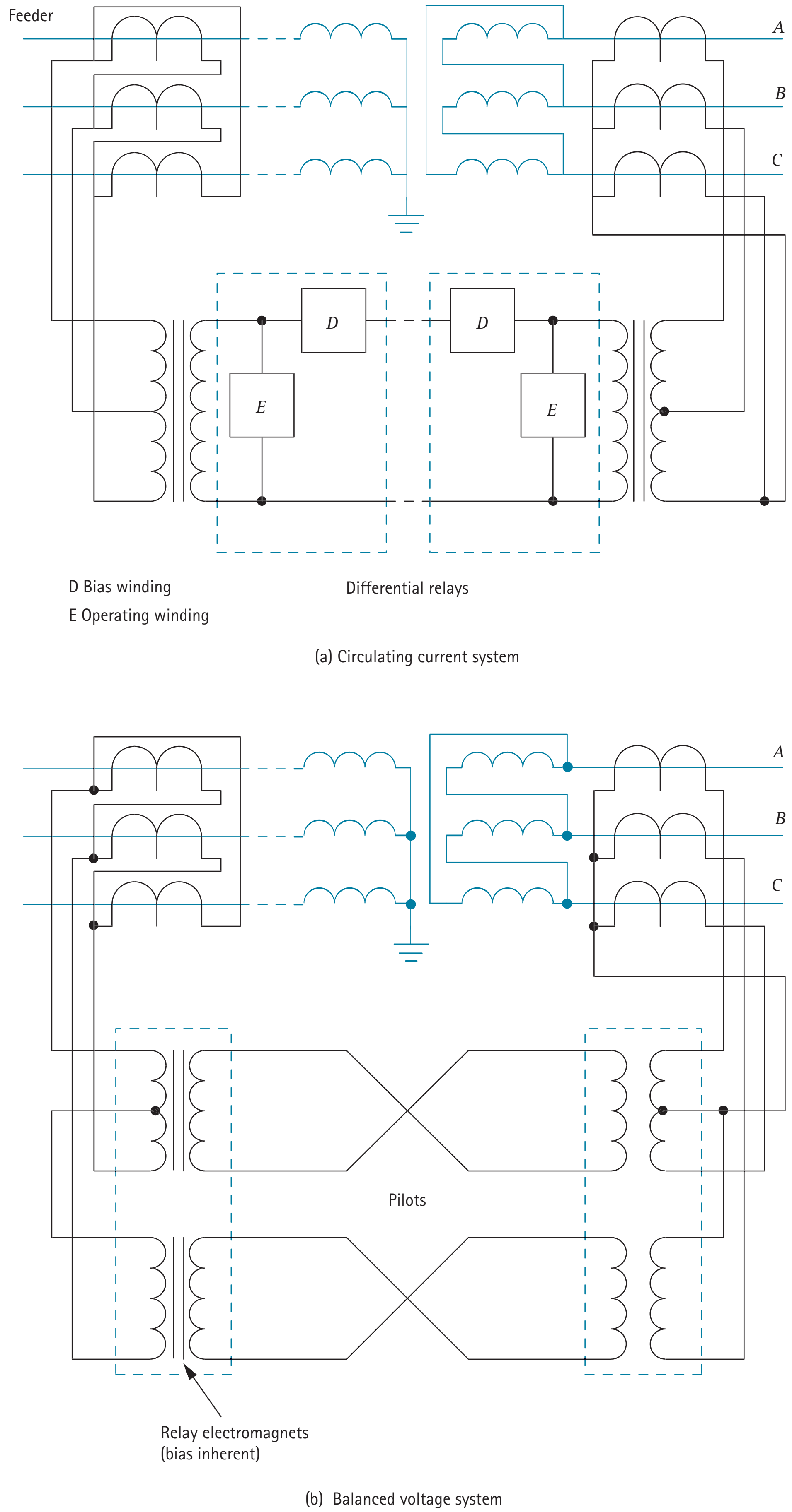


Figure 16.25: Methods of protection for transformer-feeders using electromechanical static technology

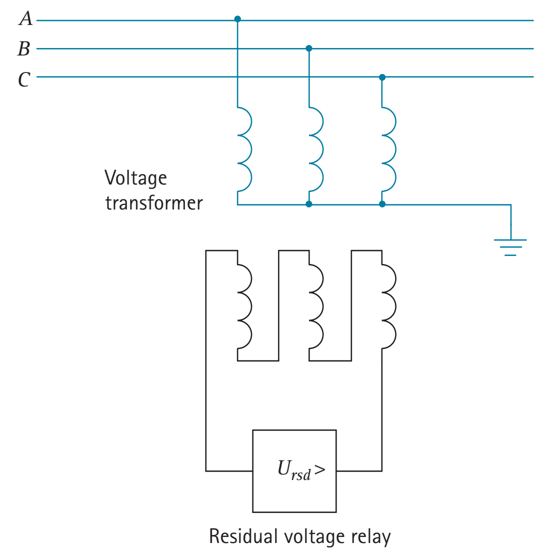


Figure 16.26: Neutral displacement detection using voltage transformer.

components and provide warning to the operator in order to avoid a lengthy and expensive outage due to failure. The technique, which can be applied to other plant as well as transformers, is called condition monitoring, as the intent is to provide the operator with regular information on the condition of the transformer. By reviewing the trends in the information provided, the operator can make a better judgement as to the frequency of maintenance, and detect early signs of deterioration that, if ignored, would lead to an internal fault occurring. Such techniques are an enhancement to, but are not a replacement for, the protection applied to a transformer.

The extent to which condition monitoring is applied to transformers on a system will depend on many factors, amongst which will be the policy of the asset owner, the suitability of the design (existing transformers may require modifications involving a period out of service – this may be costly and not justified), the importance of the asset to system operation, and the general record of reliability. Therefore, it should not be expected that all transformers would be, or need to be, so fitted.

A typical condition monitoring system for an oil-immersed transformer is capable of monitoring the condition of various transformer components as shown in Table 16.5. There can be some overlap with the measurements available from a digital/numerical relay. By the use of software to store and perform trend analysis of the measured data, the operator can be presented with information on the state of health of the transformer, and alarms raised when measured values exceed appropriate limits. This will normally provide the

Monitored Equipment	Measured Quantity	Health Information
Bushings	Voltage	Insulation quality
	Partial discharge measurement (wideband voltage)	
	Load current	Loading
		Permissible overload rating
		Hot-spot temperature
	Oil pressure	Insulation quality
Tank	Oil temperature	Hot-spot temperature
		Permissible overload rating
	Gas-in-oil content	Oil quality
		Winding insulation condition
	Buchholz gas content	Oil quality
	Moisture-in-oil content	Winding insulation condition
Tap changer	Position	Frequency of use of each tap position
	Drive power consumption	OLTC health
	Total switched load current	OLTC contact wear
	OLTC oil temperature	OLTC health
Coolers	Oil temperature difference	Cooler efficiency
	Cooling air temperature	
	Ambient temperature	
	Pump status	Cooling plant health
Conservator	Oil level	Tank integrity

Table 16.5: Condition monitoring for transformers

operator with early warning of degradation within one or more components of the transformer, enabling maintenance to be scheduled to correct the problem prior to failure occurring. The maintenance can obviously be planned to suit system conditions, provided the rate of degradation is not excessive.

As asset owners become more conscious of the costs of an unplanned outage, and electric supply networks are utilised closer to capacity for long periods of time, the usefulness of this technique can be expected to grow.

16.19 EXAMPLES OF TRANSFORMER PROTECTION

This section provides three examples of the application of modern relays to transformer protection. The latest MiCOM P630 series relay provides advanced software to simplify the calculations, so an earlier AREVA type KBCH relay is used to illustrate the complexity of the required calculations.

16.19.1 Provision of Zero-Sequence Filtering

Figure 16.27 shows a delta-star transformer to be protected using a unit protection scheme. With a main winding connection of Dyn11, suitable choices of primary and secondary CT winding arrangements, and software phase compensation are to be made. With the KBCH relay, phase compensation is selected by the user in the form of software-implemented ICT's.

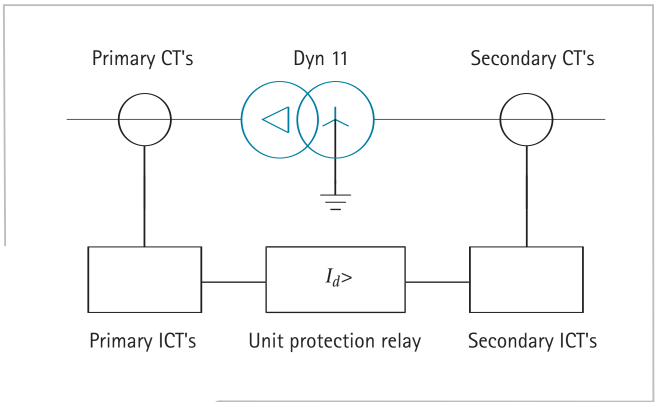


Figure 16.27: Transformer zero sequence filtering example

With the Dyn11 connection, the secondary voltages and currents are displaced by +30° from the primary. Therefore, the combination of primary, secondary and phase correction must provide a phase shift of –30° of the secondary quantities relative to the primary.

For simplicity, the CT's on the primary and secondary windings of the transformer are connected in star. The required phase shift can be achieved either by use of ICT connections on the primary side having a phase shift of +30° or on the secondary side having a phase shift of –30°. There is a wide combination of primary and secondary ICT winding arrangements that can provide this, such as Y_{d10} (+60°) on the primary and Y_{d3} (-90°) on the secondary. Another possibility is Y_{d11} (+30°) on the primary and Y_{y0} (0°) on the secondary. It is usual to choose the simplest arrangements possible, and therefore the latter of the above two possibilities might be selected.

However, the distribution of current in the primary and secondary windings of the transformer due to an external earth fault on the secondary side of the transformer must now be considered. The transformer has an earth connection on the secondary winding, so it can deliver zero sequence current to the fault. Use of star connected main CT's and Y_{y0} connected ICT's provides a path for the zero sequence current to reach the protection relay. On the primary side of the transformer, the delta connected main primary winding causes zero-sequence current to circulate round the delta and hence will not be seen by the primary side main CT's. The protection relay will therefore not see any zero-sequence current on the primary side, and hence detects the secondary side zero sequence current incorrectly as an in-zone fault.

The solution is to provide the ICT's on the secondary side of the transformer with a delta winding, so that the zero-sequence current circulates round the delta and is not seen by the relay. Therefore, a rule can be developed that a transformer winding with a connection to earth must have a delta-connected main or ICT for unit protection to operate correctly.

Selection of Y_{y0} connection for the primary side ICT's and Y_{d1} (–30°o) for the secondary side ICT's provides the

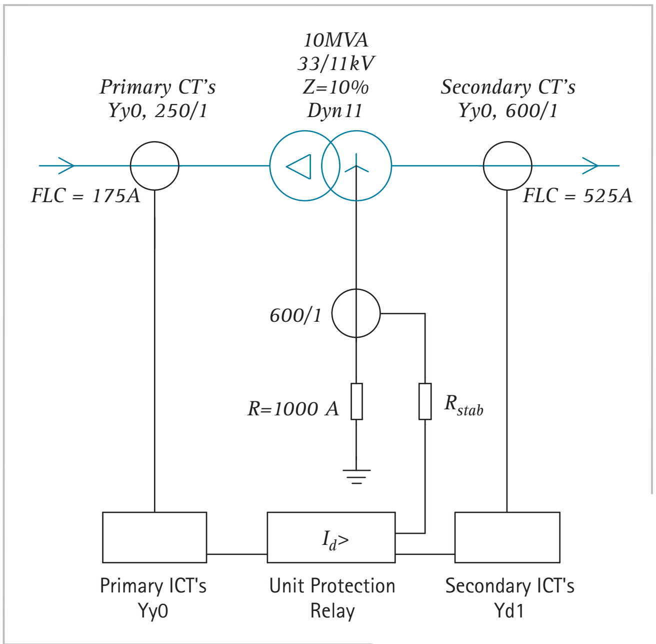


Figure 16.28: Transformer unit protection example

required phase shift and the zero-sequence trap on the secondary side.

16.19.2 Unit Protection of a Delta-Star Transformer

Figure 16.28 shows a delta-star transformer to which unit protection is to be applied, including restricted earth fault protection to the star winding.

Referring to the figure, the ICT's have already been correctly selected, and are conveniently applied in software. It therefore remains to calculate suitable ratio compensation (it is assumed that the transformer has no taps), transformer differential protection settings and restricted earth fault settings.

16.19.2.1 Ratio compensation

Transformer HV full load current on secondary of main CT's is:

175/250 = *0.7*
Ratio compensation = *1/0.7*
= *1.428*
Select nearest value = *1.43*
LV secondary current = *525/600*
= *0.875*
Ratio compensation = *1/0.875*
= *1.14*

16.9.2.2 Transformer unit protection settings

A current setting of 20% of the rated relay current is recommended. This equates to 35A primary current. The KBCH relay has a dual slope bias characteristic with fixed bias slope settings of 20% up to rated current and 80% above that level. The corresponding characteristic is shown in Figure 16.29.

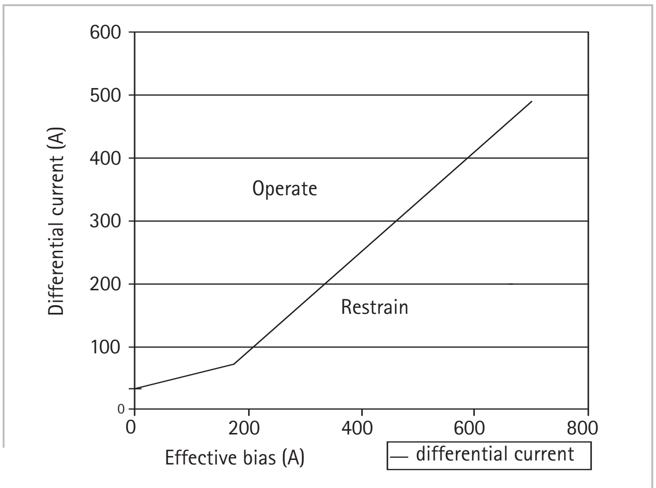


Figure 16.29: Transformer unit protection characteristic

16.9.2.3 Restricted earth fault protection

The KBCH relay implements high-impedance Restricted Earth Fault (REF) protection. Operation is required for a primary earth fault current of 25% rated earth fault current (i.e. 250A). The prime task in calculating settings is to calculate the value of the stabilising resistor R_{stab} and stability factor K.

A stabilising resistor is required to ensure through fault stability when one of the secondary CT's saturates while the others do not. The requirements can be expressed as:

$$V_S = I_S R_{stab} \text{ and}$$

$$V_S > K I_f (R_{ct} + 2R_l + R_B)$$

where:

V_S = stability voltage setting

V_K = CT knee point voltage

K = relay stability factor

I_S = relay current setting

R_{ct} = CT winding resistance

R_l = CT secondary lead resistance

R_B = resistance of any other components in the relay circuit

R_{stab} = stabilising resistor

For this example:

V_K = 97V

R_{ct} = 3.7Ω

R_l = 0.057Ω

For the relay used, the various factors are related by the graph of Figure 16.30.

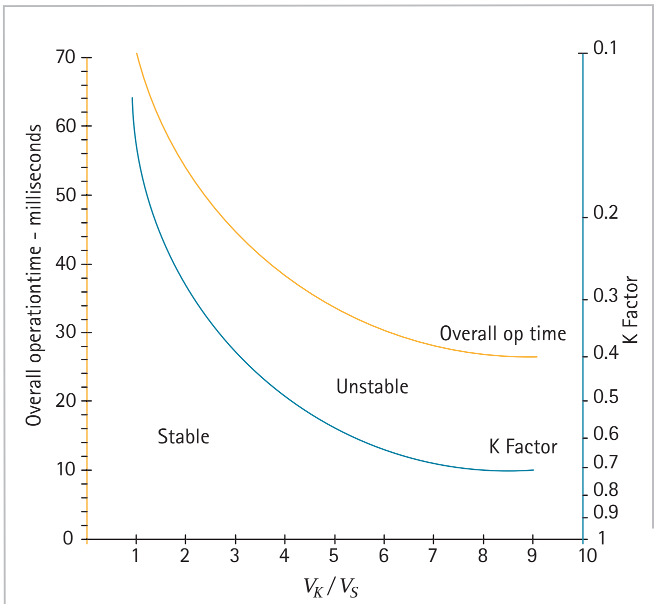


Figure 16.30: REF operating characteristic for KBCH relay

Starting with the desired operating time, the V_K/V_S ratio and K factor can be found.

An operating of 40ms (2 cycles at 50Hz) is usually acceptable, and hence, from Figure 16.30,

$V_K/V_S = 4$

$K = 0.5$

The maximum earth fault current is limited by the earthing resistor to 1000A (primary). The maximum phase fault current can be estimated by assuming the source impedance to be zero, so it is limited only by transformer impedance to 5250A, or 10A secondary after taking account of the ratio compensation. Hence the stability voltage can be calculated as

$$V_S = 0.5 \times 10(3.7 + 2 \times 0.057) = 19.07V$$

Hence,

$$Calculated\ V_K = 4 \times 19.07 = 76.28V$$

However,

Actual $V_K = 91V$ and

$V_K/V_S = 4.77$

Thus from Figure 16.30, with $K = 0.5$, the protection is unstable.

By adopting an iterative procedure for values of V_K/V_S and K, a final acceptable result of $V_K/V_S = 4.55$, $K = 0.6$, is obtained. This results in an operating time of 40ms.

The required earth fault setting current I_{op} is 250A. The chosen E/F CT has an exciting current I_e of 1%, and hence using the equation:

$$I_{op} = CT\ ratio \times (I_S + nI_e)$$

where:

n = no of CT's in parallel (=4)

I_S = 0.377, use 0.38 nearest settable value.

The stabilising resistance R_{stab} can be calculated as 60.21Ω.

The relay can only withstand a maximum of 3kV peak under fault conditions. A check is required to see if this voltage is exceeded – if it is, a non-linear resistor, known as a Metrosil, must be connected across the relay and stabilising resistor. The peak voltage is estimated using the formula:

$$V_P = 2\sqrt{2V_K\left(V_F - V_K\right)}$$

where:

$$V_F = I_f\left(R_{ct} + 2R_l + R_{stab}\right)$$

and

I_f = fault current in secondary of CT circuit

and substituting values, $V_P = 544V$. Thus a Metrosil is not required.

16.9.3 Unit Protection for On-Load Tap Changing Transformer

The previous example deals with a transformer having no taps. In practice, most transformers have a range of taps to cater for different loading conditions. While most transformers have an off-load tap-changer, transformers used for voltage control in a network are fitted with an on-load tap-changer. The protection settings must then take the variation of tap-change position into account to avoid the possibility of spurious trips at extreme tap positions. For this example, the same transformer as in Section 16.19.2 will be used, but with an on-load tapping range of +5% to -15%. The tap-changer is located on the primary winding, while the tap-step usually does not matter.

The stages involved in the calculation are as follows:

a. determine ratio correction at mid-tap and resulting secondary currents

b. determine HV currents at tap extremities with ratio correction

c. determine the differential current at the tap extremities

d. determine bias current at tap extremities

e. check for sufficient margin between differential and operating currents

16.19.3.1 Ratio correction

In accordance with Section 16.8.4, the mid-tap position is used to calculate the ratio correction factors. The mid tap position is –5%, and at this tap position:

Primary voltage to give rated secondary voltage:

$$= 33 \times 0.95 = 31.35kV$$

and

$$Rated\ Primary\ Current = 184A$$

Transformer HV full load current on secondary of main CT's is:

$184/250$	$= 0.737$
Ratio compensation	$= 1/0.737$
	$= 1.357$
Select nearest value	$= 1.36$
LV secondary current	$= 525/600$
	$= 0.875$
Ratio compensation	$= 1/0.875$
	$= 1.14$

Both of the above values can be set in the relay.

16.19.3.2 HV currents at tap extremities

At the +5% tap, the HV full-load current will be:

$$\frac{10}{33 \times 1.05 \times \sqrt{3}}$$

$$= 166.6A \text{ primary}$$

Hence, the secondary current with ratio correction:

$$= \frac{166.6 \times 1.36}{250}$$

$$= 0.906A$$

At the -15% tap, the HV full-load current on the primary of the CT's:

$$= \frac{10}{33 \times 0.85 \times \sqrt{3}}$$

$$= 205.8\ A$$

Hence, the secondary current with ratio correction:

$$= \frac{205.8 \times 1.36}{250}$$

$$= 1.12\ A$$

16.19.3.3 Determine differential current at tap extremities

The full load current seen by the relay, after ratio correction is $0.875 \times 1.14 = 0.998A$.

At the +5% tap, the differential current

$$I_{difft2} = 0.998 - 0.906 = 0.092A$$

At the −15% tap,

$$I_{difft2} = 1.12 - 0.998 = 0.122A$$

16.19.3.4 Determine bias currents at tap extremities

The bias current is given by the formula:

$$I_{bias} = \frac{(I_{RHV} + I_{RLV})}{2}$$

where:

I_{RHV} = relay HV current

I_{RLV} = relay LV current

Hence,

$$I_{biast1} = \frac{(0.998 + 0.906)}{2}$$

$$= 0.952A$$

and

$$I_{biast2} = \frac{(0.998 + 1.12)}{2}$$

$$= 1.059A$$

16.19.3.5 Margin between differential and operating currents

The operating current of the relay is given by the formula

$$I_{op} = I_S + 0.2 I_{bias}$$

Hence, at the +5% tap, with $I_S = 0.2$

$$I_{opt1} = 0.2 + (0.2 \times 0.952)$$

$$= 0.3904A$$

At the −15% tap,

$$I_{op} = I_S + 0.2 + (I_{bias} - 1) \times 0.8$$

(since the bias >1.0)

$$I_{opt2} = 0.2 + 0.2 + (1.059 - 1) \times 0.8$$

$$= 0.4472A$$

For satisfactory operation of the relay, the operating current should be no greater than 90% of the differential current at the tap extremities.

For the +5% tap, the differential current is 24% of the operating current, and at the −15% tap, the differential current is 27% of the operating current. Therefore, a setting of I_S is satisfactory.