When $\phi = \alpha$ at the current flows through the resistor in the same direction the whole time and the average value of the voltage across the resistor, which is proportional to $I \cos(\phi - \alpha)$, thus provides maximum sensitivity, *i.e.* the relay operates for a current of the same value as the set value I_s.

The larger the difference between ϕ and α the smaller the average value of the voltage through the resistance will be at a constant current I. For a 0° difference, the average value will be zero irrespective of the value of the current.

The voltage over the resistor is smoothed fed to a transistorized level detector provided with an amplifier. By increasing the time constant in the smoothing circuit, it is possible to obtain a delayed operation with an inverse characteristic. The auxiliary voltage for the level detector and thus the operating value of the relay set by means of a potentiometer at the front of the relay. When operating, the amplifier feeds a voltage to the output relay which pick up, the indicating flag then becomes visible.

Summary

Static overcurrent relays have less burden compared electromagnet relays. They are compact and can give wide range of characteristics.

Basic static overcurrent relay has following functional blocks :

Input, Rectifier, Level detector, Amplifier, Output (Tripping).

In case of time lag overcurrent relay, an additional Time Delay Block is necessary.

Directional overcurrent relay, is basically double actuating quantity relay. It receives current input from CT and voltage input from VT. The rectified inputs are supplied to comparator. The comparator output is given to integrator or time delay circuit. The directional overcurrent relay can be instantaneous type of integrating type.

Static overcurrent relay circuit comprises the required functional blocks.

QUESTIONS

1. With the help of neat block diagram, explain the functioning of a static overcurrent relay without time delay. Explain function of each block.
2. Describe the circuit of a Directional Overcurrent Relay. Explain with the help of waveforms and block diagrams the use of integrating type coincidence phase comparator for directional overcurrent relay.
3. (*a*) Explain the principle of *RC* time delay circuit.

   Describe the use of such time delay circuit in a overcurrent time delay relay with the help of block diagram.

   (*b*) Explain the terms Inverse IDMT, Instantaneous overcurrent characteristics.
4. In a static relay, when the level detector operates, a voltage of 100 V DC applied across *RC* circuit having $R = 12\ \text{k}\Omega$, $C = 1\ \mu\text{F}$. Calculate time taken for the voltage across capacitor to reach threshold value of 60 V after operation of the level-detector.

   (**Hint.** Ref. Eqn. 39.5)
5. With the help of neat block diagram, explain the functioning of static overcurrent directional time delay relay.
6. Write short notes on any three :
   — Time delay circuits in static relay — Directional overcurrent relay
   — Time characteristics of static relays — Instantaneous overcurrent relay.
7. Write short note on merits of static overcurrent relay compared with electromagnetic overcurrent relay.

41

Static Differential Protection of Power Transformers

Introduction — Merits — Differential Protection of two winding Transformers — Three Winding Transformer — Inrush Proof Quantities — Technical Data — Summary

41.1. INTRODUCTION

The principle of differential protection was described in Ch. 28. Their application to protection of power transformer generator and station bus was covered in Ch. 32, 33 and 34. We will recall that the *differential protection responds to vector difference between two or more similar electrical quantities.* In differential protection, current transformer secondaries are connected in such a way that under internal fault condition, the out of balance secondary current flows through the operating coil of the relay. 'Bias'or 'Restraint' is provided to prevent maloperation during external faults and inrush currents. *This principle is applicable even for static differential relays. In static differential relays the two (or more) similar input quantities are compared in static comparators, usually the rectifier bridge comparators.* This gives wider flexibility in relay design regarding characteristic and range.

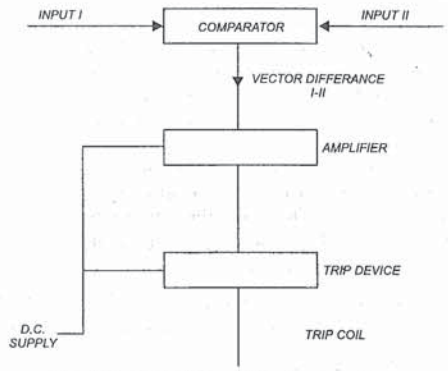


Fig. 41.1. Static differential relays principle. (Simplified block diagram)

This differential relay measures the vector difference between two similar electrical quantities say voltage/voltage or current/current.

Rectifier bridge comparator can be used conveniently in static differential relay. Block diagram is such a relay is given in Fig. 41.1.

Merits of Static Differential Protection

(*Courtesy* : Brown Boveri, Switzerland)

— Three phase relay set with small dimensions.

— Absolute stability for heavy through faults, hence ideally preferred for large transformers, generators.

— High sensitivity for internal faults.

— Extremely short tripping times regardless of magnitude of auxiliary voltage (*e.g.* 20-50 ms).

— Accurate and absolutely stable tripping characteristic even for asymmetrical faults as each phase can have its own relay.

— Inrush-proof, even during high-starting currents, inrush currents.

— Low consumption (VA burden on CT's , VT's)
— Easy selection of auxiliary voltage.

Applications

— Protection of generators.
— Protection of generators-transformer units.
— Protection of two winding transformers.
— Protection of three winding transformers.

For

— Two and three phase faults.
— Earth faults in transformers with solidly grounded neutral or low resistance grounded neutral.
— Earth faults in generators with solidly grounded neutral or low resistance grounded neutral.
— Inter-turn faults.

41.2. DIFFERENTIAL PROTECTION OF TWO-WINDING TRANSFORMER

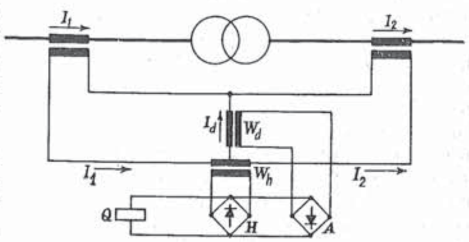
(Please Ref. Sec. 28.3, 32.5, 33.3)

Refer Fig. 41.2, which illustrates static differential protection of a two winding power transformer.

The differential relay is connected to the current transformers on either sides of the object (generator/transformer) to be protected. The incoming and outgoing currents are compared by the *differential circuit.*

When there is an internal fault in the protected zone, the differential current (I_d) increases. When the differential current (I_d) exceeds the picking level (usually 0.5 I_N) the relay operates.

The pick-up value depends on ratio of differential current (I_d) and through current $\left(\frac{I_1+I_2}{2}\right)$. The relay is thus biased or compensated to take care of through fault currents.



I_d = Operating (differential current)
$\left(\frac{I_1+I_2}{2}\right)$ = Restraining current
Q = Tripping Relay
W_d = Auxiliary CT for operating current I_d
W_h = Auxiliary CT for restraining current $(I_1+I_2)/2$.
A = Rectifier for forward (operating) current
H = Rectifier for restraining current.

Fig. 4.2. Differential protection of two winding transformer by static differential relay.

In static differential relay circuit, an auxiliary CT (W_d) is connected in operating current (I_d) circuit and another auxiliary CT (W_h) is connected in restraining (bias) circuit. (Ref. Fig. 41.2) The secondaries of these auxiliary CT's are connected to rectifier bridge comparator (Ref. Ch. 39)

The output of operating auxiliary CT W_d is given to rectifier bridge A, whose output gives forward current to the tripping device Q.

The output of restraining auxiliary CT is given to rectifier bridge H, whose output gives restraining current to the tripping device Q. The tripping device receives the forward current which is a difference of I_A and I_H.

$$I_o = I_A - I_H$$

where I_o = Operating current in forward direction in tripping device.
I_A = Output of rectifier A in the forward direction.
I_H = Output of rectifier B in reverse directional.

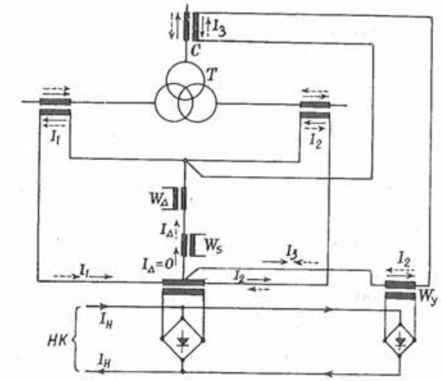
when I_o exceeds the pick-up value, the relay operates.

The tripping relay is generally permanent magnet moving coil relay.

41.3. DIFFERENTIAL PROTECTION OF THREE WINDING TRANSFORMER

The principle of the differential protection of three winding transformer is the same as described for two-winding transformers.

To protect three-winding transformer additional components are needed. A reliable differential measurement is only guaranteed under all possible operating conditions when a separate restraint circuit is also provided for the third winding. The circuitry is illustrated in Fig. 41.3, and Fig. 41.4.

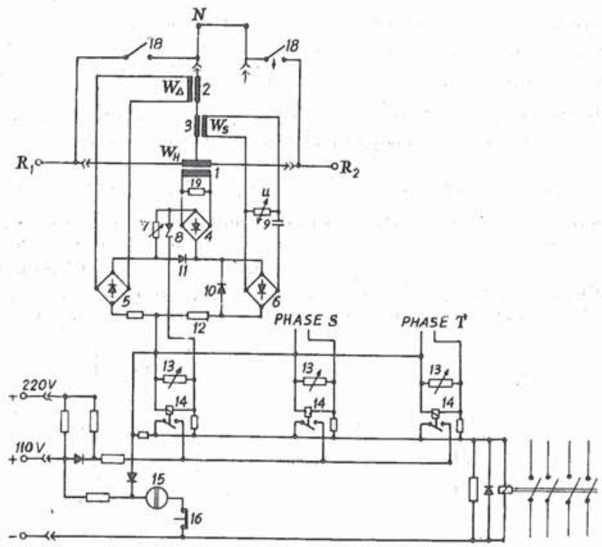


T	Transformer protected
W_H	Restraining current transformer (Ref. Fig. 41.2)
W_R	Additional restraining current transformer
W_S	Blocking transformer for stabilisation circuit
W_*	Differential current transformer
$\rightarrow I_1, I_2, I_3$	Currents during normal service.
$\rightarrow I_1, I_2, I_3$	Currents during fault inside the protected zone.
I_Δ	Differential current
I_H	Restraining current
HK	Restraining circuit.

Fig. 41.3. Principle of measurement of differential protection for a three winding transformer.

By connecting the two restraint circuits W_H and W_Y in parallel on the d.c. side, restraint is assured in the event of a through fault, even if it flows through the third transformer winding into the part of the system connected to it.

The restraining action of two circuits W_H and W_Y is equally strong when the through currents are equal ($I_1 = I_2 = I_3$), as the circuits are so designed that $I_H = \frac{1}{2}(I_1 + I_2)$ through W_H produces the same restraining effect in the relay as $I_Y = I_3$ through W_Y. When the currents are different ($I_1 \neq I_2 \neq I_3$), restraint in the relay is governed by the highest value, *i.e.* either $I_H = \frac{1}{2}(I_1 + I_2)$ or $I_Y = I_3$, depending on which is larger. The smaller is not taken into accounts.



1. Restraining current transformer W_H
2. Tripping current transformer W_H
3. Blocking transformer W_H (Air gap transformer)
4. Restraining current rectifier bridge.
5. Difference current rectifier bridge.
6. Blocking current rectifier bridge.
7. Resistance for bias setting.
8. 'Zener' diode
9. Non-linear resistance
10. Blocking current limiting diodes.
11. Diodes
12. Plug-in blocking element
13. Resistance for basic setting
14. Moving coil-relay
15. Annunciator
16. Reset button
17. Tripping contractor
18. Automatic shorting links
19. Restraining circuit resistance

R_1, R_2 Input terminals of the phase R

N Neutral of current transformer sets.

Fig. 41.4. Circuit diagram of three-phase differential relay in Fig. 41.3 (*Courtesy* : Brown Boveri, Switzerland)

The circuit diagram of the R phase of three phase differential relay is illustrated in Fig. 41.4. The auxiliary tripping c.t. $W\,\Delta$, restraining *c.t.* W_H and blocking transformer W_s correspond to those shown in Fig. 41.3.

41.4. INRUSH-PROOF QUALITIES.

When a transformer is switched on, a current surge is produced which eventually reverts to the charging current of the transformer. It only occurs on the closed side and is therefore experienced by the relay as a difference current. Difference currents of similar shape but shorter duration can also be produced in the differential protection of generators by current surges resulting from momentary differences in the behaviour of the current transformers.

The oscillogram in Fig. 41.5 shows the inrush current with severely distorted waveforms produced when a transformer is switched on. Analysis of this curve indicates the presence of a large amount of the second harmonic. To make the relay inrush proof this 2nd harmonic component of the difference current is employed, in that this current, after resonance amplification is fed to the moving-coil relay in the blocking direction. The resonance amplification is performed by a filter in

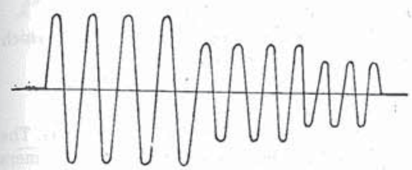


Fig. 41.5. Oscillogram on inrush current of transformer.

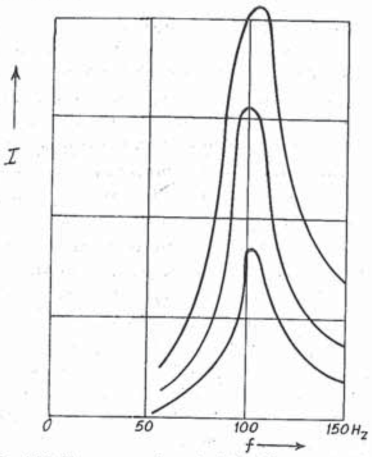


Fig. 41.6. Frequency characteristic of harmonic filter for three magnitudes of inrush current.

the secondary circuit of the blocking transformer W_s. (Ref. Fig. 41.3). The frequency characteristics of the filter are shown in Fig. 41.6 for three different currents.

Since this blocking action is only sensitive to the second harmonic which of course is characteristics for inrush surge of power transformers the relay is certain to distinguish between an inrush and a short circuit in the protected object.

Ref. Fig. 41.4. The blocking current is diverted through diode 11 so that it does not have to flow through the resistor 7 used for setting the bias or the rectifier bridge 4 for the restraining current. By this means the blocking properties are quite independent of the bias.

41.5. REQUIREMENTS TO BE FULFILLED BY THE MAIN CT

Although the relay, on account of the restraining action described is fairly insensitive to C.T. saturation, the main C.T. used should not reach the saturation point at the connected burden and at the maximum fault current experienced. It has proved advantageous in practice to allow for an overcurrent factor of at least 10. The corresponding C.T. class is 5P10, *i.e.* between 0.33 and 10 I_N the current error is less than 5% and the angular error less than 300. The C.T. load in this case consists of all connected loads, such as the leads, auxiliary C.T., the differential relay and any other elements connected, the consumption being referred to the rated current of the C.T. If the C.T. is loaded below its rated burden, the overcurrent factor rises in the ratio of the actual load plus C.T. consumption to the rated output plus C.T. consumption.

On account of the very short tripping time of the relay, allowance has to be made for dynamic phenomena in the transformation of the short circuit. It is therefore advisable to make the secondary time constants of the circuits on either side of the relay nearly equal as possible, *e.g.*, by using auxiliary transformers on either side of the relay. In the case of three-winding transformers or unit-connected generators and transformer with feeders to the units auxiliaries, C.T. ratios which relate to very different powers should be avoided. In other words, the ratios of the differential protection cores of all main C.T. should be based on the same power *i.e.* the highest.

41.6. AUXILIARY C.T.

These C.T. have to perform various duties, including :

1. Restoration of the phase shift between the currents on the primary and secondary sides of a power transformer, caused by the connection of the windings.

2. Ensuring that when the same power is being carried by the two transformer windings, the same flows to the relay from both sides and that, at the full power of the winding, the current flowing to the relay is at least 0.7 times the relay current.

3. Filtration of zero-sequence currents when the transformer neutral is earthed, or in auto-transformers. For this purpose the auxiliary C.T. shall be connected in star/delta on that side of the transformer which has its neutral earthed.

4. Auxiliary C.T. should never be employed on only one side. With an asymmetrical arrangement the different transient response of the two circuits in the event of through short circuits can give rise to considerable difference currents which could cause the extremely rapid relay to operate.

In order to keep the burden on the auxiliary C.T. as small as possible, they should be mounted as close to the relay as can be permitted.

Apart from individually matched auxiliary c.t., it is also possible to supply universal c.t. which are suitable for use in the majority of cases.

Summary

Static differential relays are preferred for protection of large generators and transformers. The principle is similar to that of conventional differential protection. Additional auxiliary transformers are used in secondary circuit of main CT's. The output of operating auxiliary CT and restraining auxiliary CT is supplied to rectifier bridge comparator. A permanent magnet moving coil relay is used as tripping device.

QUESTIONS

1. Describe the circuit of static differential relay for protection of two winding transformer.
2. Describe the circuit of a static differential relay for three winding transformer.
3. Write short notes on any two :
   — use of rectifier comparator in static differential protection of two winding transformers
   — advantages of static differential protection
   — inrush proofing in static differential protection of power transformers.
4. Describe the difficulties in conventional differential protection of power transformers. State the merits of static protection. Explain clearly the additional features in static protection schemes.
5. Describe the rectifier bridge comparator used in static differential protection of power transformer. Illustrate the provision of blocking during inrush currents.
6. Explain the requirements of main and auxiliary CT's (intermediate CT's) in static differential relays.

42

Static Distance Relays and Distance Protection of EHV Lines

Introduction — Static distance relays — Comparator combinations — Voltage comparator — Current comparator multi-input comparator Elliptical and quadrangular impedance characteristic — Errors in distance measurement — Performance under power swing conditions — Distance protection of lines with series capacitors — Parallel lines — Ted line — Distance protection as back-up — Compensation in distance relays — Setting of distance relays — Static distance relay.

42.1. INTRODUCTION

The principles of distance protection are discussed in Ch. 29 and distance protection of transmission lines is described in section 30-*B*. The principles of carrier aided distance protection have been briefly mentioned in sec. 30.14.

This chapter deals with *advanced topics in distance protection of HV and EHV lines with particular reference* to static distance relays.

The principle of measurement of impedance (distance) is the same in both electromagnetic relays and static relays (Ref. Sec. 29). However static distance relays offer several advantages.

Merits of Static Distance Relays.

— no moving parts in measuring circuit, hence no effect of vibrations, shocks, dust.

— faster operation 20 ms, 40 ms, 60 ms

— less burden *e.g.*, burden of CT : 0.9 VA to 4.2 VA during normal and short circuit conditions respectively. Burden on VT : 2.2 to 12 VA during normal and short-curcuit condition respectively. This results in more economical CT's, VT's and better accuracy.

— comparator with elliptical or quadrangular impedance characteristics on R -X plane can be used. Such characteristics are *not* possible by electromagnetic distance relays whose characteristics are limited to sectors of circles on R-X plane.

— greater adoptability due to large range of adjustments and characteristics.

— Versatile range of relays available for various specific applications.

— better stability under power swing conditions.

— suitable for long heavily loaded lines, cables, even distribution lines.

— cover all types of faults selectively, *e.g.*, single line to ground, line to line, three phase.

— can have distance time step characteristic with four *independently* adjustable time steps and impedance zones.

— lower impedance setting possible

— fast tripping of first step — selector switches for
  — under reach and over-reach
  — rapid auto-reclosure or delayed reclosure
  — programmed auto-reclosure

— provision of contacts for remote annunciation of kind of fault, step of operation, tripping

— possibility of temporary reversal of measurement direction of second or second and thrid zones.