Graded time lag and grade current overcurrent protection is used for single radial feeders where time lag can be permitted.

Distance relaying is based on measurement of impedance between relay location and fault point. It has three types namely impedance type, reactance type, mho type. The relay operates if the impedance is below the set value. Distance relay is used where time lag cannot be permitted. Differential protection is of unit type. It gives fast relaying. Pilot wire differential relaying used for lines upto 40 km of length.

QUESTIONS

1. Describe with the help of neat sketches the graded time lag protection of a radial feeder. What are the disadvantages of such a protection in case of the following?
   (*a*) Parallel feeders (*b*) Interconnected lines (*c*) Fast relaying.
2. Explain the principle of distance relaying applied to protection of radial transmission line Distinguish between reactance, impedance and mho relays as regards their applications to distance protection.
3. In what way is distance relaying superior to overcurrent relaying in case of feeder protection.
4. Distinguish between unit protection and non-unit protection. What are the various methods of protecting a transmission line by unit protection and by non-unit protection?
5. Explain with the help of neat sketches the set-up of carrier current relaying employed in transmission line protection.
6. Explain the principle of
   (*a*) Line trap unit (*b*) Coupling unit.
7. Explain the phase comparison method of carrier current protection.
8. Explain the directional comparison method of carrier current protection. Why should it be used in impedance or other type of non-unit protection?
9. What are the merits of carrier current relaying ? Where is it used ? Compare pilot wire relaying with carrier current protection.
10. Explain why carrier current protection in suitable for important interconnected lines.
11. Explain the schemes of pilot wire relaying employed
    (*a*) Circulating current method (*b*) Voltage balance method.
    What are the difficulties in circulating current protection of feeder.
12. State the applications of power line carrier signals.
13. Select suitable relaying method under the following conditions. Give reasons for your selection.
    Case (*a*) Protection of radial feeder from a power station to receiving station. Length of the feeder about 500 km. There are two stations in between. Time lag cannot be permitted.
    (*b*) An interconnecting line between two power station 16 km apart.
    (*c*) A feeder in case (*a*), but for following conditions.
    The line is fed from both the ends and fast relaying is desired for internal faults.
    (*d*) Distance protection of a feeder of
    (*i*) Medium length (*ii*) Short length (*iii*) Very long feeder
    State what type of distance protection will be suitable.
14. Discuss the various methods of protection of a transmission line with reference to advantages and disadvantages of each method.
15. Explain the principle of any one of the following :
    1. Carrier transfer 2. Carrier blocking (Directional comparison)
    3. Carrier acceleration
16. Explain the 3-steep characteristic of distance relay.
17. Explain the difference between 'switch' and 'non-switch' distance schemes.
18. Explain the functions of starting element, measuring element and time in distance protection.
19. Explain how power-swing affects distance relays.

31

Protection of Induction Motors

Introduction — Abnormal conditions — Under voltage protection — Contactors — Circuit Breaker — Motor protection — Single phasing protection — Short Circuit protection — Grounding — Protection of motors in general — Summary.

31.1. INTRODUCTION

The type of protection used for a particular motor depends on the switchgear used for its control (starting, stopping, speed variation, etc.) In general two basic protections are provided for every motor which are :

1. Thermal overload protection 2. Short circuit protection.

The switchgear used for motor control falls in two distinct classes:

(*i*) Contactor starters with H.R.C. Fuse and thermal over current relays.

(*ii*) Circuit-breakers and associated protective relays.

Contactors and fuses are used for motors upto approximately 150 kw. For larger motors, circuit-breakers are used.

Contractors are available for a wide range of a.c and d.c. duties (Ref. Sec. 15.10).

In general contactors can be used where current to be interrupted is limited to about six times rated current. The rated current is a little higher than the full load current of the motor (Ref. sec. 15.13).

Direct acting overload trip devices such as thermal overload relay can be incorporated with the contactor starter. The protection against short circuits is provided by HRC Fuses. The fuse selection depends upon starting current. The fuse should blow at currents more than those which can be interrupted by the contactor.

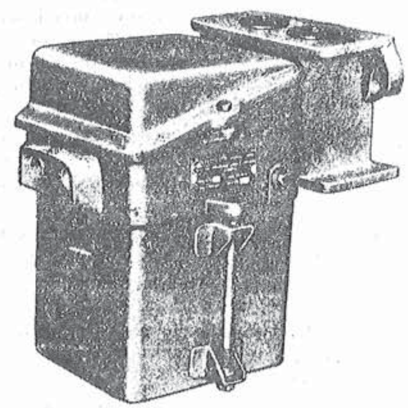


Fig. 31.1. Oil immersed direct on line starter.
(*Courtesy* : Jyoti Ltd., India.)

In case of voltage loss the coil is de-energised and the contactor opens. The motor has to be started again. Hence the contactor starter provides no volt release. Generally start, stop, reverse buttons are provided along with the starter. Large motors are provided with various relaying schemes and a circuit-breaker. The circuit breaker is air-break type or vacuum or SF_6. Air-break type circuit-breakers are more popular. The closing mechanisms are manually operated or solenoid operated or spring closing type. Solenoid closing is suitable for remote controlled motors and larger motors. Generally overload trip devices operating direct on the tripping mechanisms form and integral part of the circuit-breaker.

Motors rated upto 1000V are usually protected by HRC Fuses. Motors rated between 660 V and 2200 V are protected by direct acting overcurrent trip device associated with circuit-breaker. Differential protection is applied to motors rated above 3.3 kV, 1500 kW.

31.2. ABNORMAL OPERATING CONDITIONS AND CAUSES OF FAILURES IN INDUCTION MOTORS

Three phase induction motors are very widely used for industrial use. The abnormal conditions can be classified follows :

1. *Mechanical overloads*

— sustained overloads — prolonged starting or locked rotor

— stalling

2. *Abnormal supply conditions*

— loss of supply voltage — unbalanced supply voltage

— phase sequence reversal of supply voltage

— overvoltage — undervoltage

— under frequency.

3. *Faults in starting supply/circuit*

— interruptions in phases — blowing of fuse/single phasing

— short circuit in supply cable.

4. *Internal Faults in Motor itself*

(Caused by 1, 2, 3 above)

— phase to phase faults — phase to earth faults

— failure to phase (open circuit) — mechanical failure.

The abnormal conditions are summarised below.

— *Prolonged overloading.* It is caused by mechanical loading, short time cyclic overloading. Overloading results in temperature rise of winding and deterioration of insulation resulting in winding fault. Hence motor should be provided with overload protection.

— *Single phasing.* One of the supply lines gets disconnected due to blowing of a fuse or open circuit in one of the three supply connections. In such cases the motor continues to run on a single phase supply. If the motor is loaded to its rated full load, it will draw excessive currents on single phasing. The winding get overheated and damage is caused. The single phasing causes unbalanced load resulting in excessive heating of rotor due to negative sequence component of unbalanced current. Static single phasing relays are becoming very popular.

— *Stalling.* If the motor does not start due to excessive load, it draws heavy current. It should be immediately disconnected from supply.

— *Stator earth faults.* Faults in motor winding are mainly caused by failure of insulation due to temperature rise.

— *Phase to phase faults.* These are relatively rare due to enough insulation between phases. Earth faults are relatively more likely.

— *Inter-turn faults.* These grow into earth faults. No separate protection is generally provided against inter-turn faults.

— *Rotor faults.* These are likely to occur in wound rotor motors, due to insulation failure.

— *Failure of bearing.* This causes locking up of rotor. The motor should be disconnected. Bearing should be replaced.

— *Unbalanced supply voltage.* This causes heating up of rotor due to negative sequence currents in stator winding.

— *Supply undervoltage.* The undervoltage supply cause increase in motor current for the same load.

— *Fault in starter or associated circuit.* The choice of protection for a motor is depends upon the size of the motor, its importance in the plant, nature of load. Table 31.1 gives an idea about the motor protection practice.

31.3. PROTECTION REQUIREMENTS

Motor protection should be simple and economical. Cost of protective system should be within about 5% of motor cost. The motor protection should not operate during starting and permissible overloads. The choice of motor-protection scheme depends upon the following :

— Size of motor, rated voltage, kW.

— Type : squirrel-cage or wound rotor.

— Type of starter, switchgear and control gear.

— Cost of motor and driven equipment.

— Importance of process, whether essential service motor or not ?

— Type of load, starting currents, possible abnormal conditions, etc.

31.4. PROTECTION OF LOW VOLTAGE INDUCTION MOTOR. (BELOW 1000V AC)

31.4.1. Scheme of Starting Circuit

These are most widely used industrial motors. [Ref. Fig. 31.1 (*b*)].

The motor (8) is connected to three phase supply *via* the main circuit (shown dark) comprising (1) Fuse ; (2) Isolating switch ; (3) thermal relay ; (4) Contactor. The auxiliary control circuit (shown thin) (which carries only control current) comprises (5) control coil (6) ON push button usually green normally off (7) OFF push button usually red and normally closed.

Table 31.1. Protection Chart for Induction Motors

Abnormal condition	*Alternate forms of protection from which choice is made*	*Remarks*
Overloads	— Over load release — Thermal overload relays — Inverse overcurrent relays — Miniature circuit-breaker with built in trip coils	— Overload protection given for almost all motors — Should not trip during starting currents
Phase faults and earth faults	— HRC fuses — High-set instantaneous over-current relays — Differential protection	— Differential protection becomes economical for motors above about 1000 kW. Below this high set instantaneous protection is preferred
Undervoltage	— Under voltage release — Under voltage relays	— Under voltage release incorporated with every starter — Under voltage relay used in certain applications
Unbalanced voltage	— Negative phase sequence relays	— Only in special applications
Reverse phase sequence	— Phase reversal protection	— Generally at supply point — Prevents reversal of running.
Single phasing	— Usual thermal overload relays — Special single phase preventer	— Recently developed static single phasing devices becoming popular. — Unbalance protection
Stalling	— Thermal relays — Instantaneous O.C. Relays	— Instantaneous — trip
Rotor faults	— Instantaneous overcurrent relays	— Only for wound rotor motors
Switching surges	— RC surge suppressor	— 100 ohm, 0.1 μF connected between phase and ground

The operation is as follows :

When push button (6) is pressed by the operator control coil (5) gets voltage from supply.

The coil current flows through contact of (6) and (7). The energized coil lifts contactor (4) and closes Main contact (RYB) and auxiliary contacts (C). The ON push button (6) is then shunted by auxiliary contact (C). Motor starts.

If motor is to be stopped, OFF button (7) is pressed. The control coil is de-energized. The contactor opens by spring action and gravity. Motor stops.

If supply voltage fails, control coil is de-energized and contactor opens.

During overloads, the thermal relay (3) operates and thereby control circuit is internally disconnected. HRC fuses (1) provide very rapid short-circuit protection*. Current is cut-off by HRC fuse even before it reaches prospective peak. (Ref. Ch. 14).

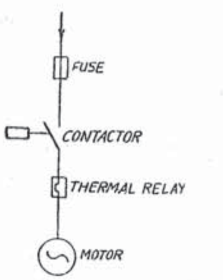
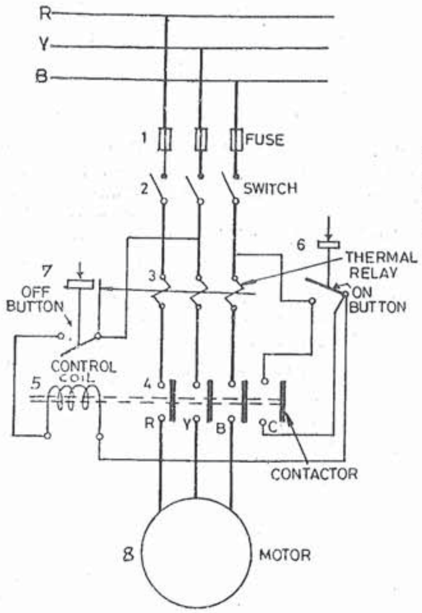


Fig. 31.1 (*a*). The fuse provided S.C. protection*, thermal relay provides overload protection.



1. Supply side Fuse
2. Switch
3. Thermal Relay
4. Generactor
5. Coil of Contactor

Fig. 31.1 (*b*) Circuit of magnetic contactor starter, for low voltage induction motor.

The selection of thermal relay (3) is such that for normal starting conditions, the relay does not operate. A setting range is provided for adjustment for different variations in load conditions. It is wrong to go on increasing the setting if the motor trips during starting. The starter should be selected properly. (Ref. Tables 31.2 and 31.3).

31.4.2. Bimetal Overload Devices**

These are very popular. In case of 3-phase motors triple pole bimetal relays are generally employed. Bending of one or more bimetal strips causes movement of a common lever which in

* Ref. Ch. 14 for applications of HRC fuses for motor protection.

** Courtesy : "Over-load Protection of Motors" Mr. V.S. Bhatia, Siemens India Ltd.

turn operates the trip contact in case of overloads. The bimetal strips are either heated directly by current flowing through them or by special heater coil through which motor current flows. In case of bigger motors, they are connected in the secondary circuit of CT's. Bimetal relays can usually be set in a certain range. Most of them are provided with additional bimetal strip to enable ambient temperature compensation. Further, bimetal strips can be self-setting type or hand resetting type. In the latter, the trip mechanism locks itself in operated condition until reset mechanically.

While selecting the bimetal-overload devices for motor protection, the following aspects should be considered.

— Characteristic of relay, characteristic of motor
— Nature of loading
— Type of starting, starting current
— Protection against overloads
— Protection against single phasing.

31.4.3. Short Circuit Protection by HRC Fuses (Ref. Ch. 14)

Short circuit protection of motor, connecting feeder and starter requires careful study. The overload protective device (OLPD) and short circuit protective devices (SCPD) employed for motor protection shall be well coordinated. The range of current between 1.5 to 10 times rated current is generally termed as overload range. The motor switching device for AC-3 duty can successfully make and break over-load currents in this range. Fault currents exceeding 10 times the rated current can be considered as short circuit currents and these should be covered by short circuit protecting devices (SCPD). The SCPD may be in one of the following forms :

— HRC Fuse
— Short circuit release opening the circuit-breaker
— Instantaneous high set overcurrent relay which trips the circuit-breaker.

By proper selection of short circuit protective devices, it is possible to prevent undue damage to the motor, starter in the event of a short circuit. The back-up protection of circuit-breakers through HRC fuses is now an accepted practice. It enables the use of economical circuit breakers of low breaking capacity.

Table 31.2. Relay Selection Chart
Direct-on-line Motor Starters

3 ph 50 c/s 400/440 V motors		*Full load line current in Amp.*	*Relay range Amp.*	*Back-up fuse rating in Amp. HRC fuses*	
HP	*kW*			*Max.*	*min.*
10	7.5	13.6	13—20	50	25
12.5	9.4	17	13—20	50	25
15	11	20	20—30	80	35
20	15	28	20—30	80	60
25	18	35	30—45	100	60
30	22	40	30—45	100	60
35	26	47	45—63	125	80
40	30	55	45—63	125	80

Table 31.3. Relay Selection Chart

Automatic Star Delta Starters

3 ph 50 c/s 400/440 V motors H.P.	3 ph 50 c/s 400/440 V motors kW	Full load line current Amp. I_n	$\frac{I_n}{\sqrt{3}}$	Relay range Amp.	Back-up fuse rating Amp. HRC fuses Max.	Back-up fuse rating Amp. HRC fuses Min
20	15	28	16	13—20	60	60
25	18	35	21	20—30	100	60
30	22	40	24	20—30	100	60
35	26	47	28	20—30	100	80
40	30	55	33	30—35	125	80
50	37.5	66	40	30—45	125	100
60	44	80	48	45—63	160	100
75	55	95	57	45—63	160	125

(*Courtesy* : Larson & Toubro Ltd., Bombay)

31.5. PROTECTION OF LARGE MOTORS (Ref. Sec. 43.7)

Large motors need protection against various abnormal conditions.

Several types of protective relays are developed to suit various applications. These relays sense the abnormal condition and trip the trip circuit of motor circuit breaker. The protection provided for large 3-phase motors takes into accounts overloads, short circuits and in some specially developed relays for motor protection, protection against unbalanced load is also incorporated. Large motors are provided with protection against following :

— Faults in windings and associated circuits

— Reduction of loss of supply voltage — Excessive overloads

— Phase unbalance, and single phasing — Phase reversal.

— Switching overvoltages — Surges (Ref. Sec. 18.12)

Types of relay available for motor protection.

— Thermal protection only

— Thermal protection, Instantaneous overcurrent protection

— Thermal Instantaneous Three Phase Overcurrent, Instantaneous Unbalance, Single phasing.

— Thermal, Instantaneous three phase overcurrent, Instantaneous Unbalance, Single phasing and Instantaneous Earth fault.

The characteristic of the relays are such that the time reduces with increase in current.

Protection against short circuits is provided by high set instantaneous overcurrent and earth fault relays. Attraction armature type relays are used in some cases. The typical settings of these relays are :

(*a*) 4 to 8 or 8 to 16 times full load current for instantaneous overcurrent element.

(*b*) 0.2 to 0.4 times full load current for instantaneous earth fault current.

31.6. OVERLOAD PROTECTION OF INDUCTION MOTORS

The overload protective devices can be grouped as :

— Those which respond to motor current, *e.g.* bimetal relays, Eutectic alloy relays, electromagnetic.relays, static relays. These relays opened the control circuit of the main contactor or close the trip of circuit-breaker.

— Those which respond to winding temperature, *e.g.*, resistor devices embedded in slots, thermostats, thermistors etc. Such devices are embedded in slots and serve to supervise the winding temperature and trip the switching device.

The current sensing overload protecting devices can sense the following abnormal conditions :

1. Overloads, undervoltage
2. Single phasing
3. Locked rotor, stalling
4. Heavy starting
5. Continuous overloads
6. Heavy breaking.

However, the following conditions can be sensed only by embedded thermal devices :

1. Temperature rise due to higher ambient temperature.
2. Temperature rise due to failure of cooling.
3. Temperature rise due to other causes.

The details about Thermal Overload protection are described below.

The purpose of thermal-overload protection is to protect the motor insulation from excessive thermal stresses. During full load, the temperature of motor winding reaches almost maximum permissible unit (dependent on insulation class). During abnormal condition, the temperature exceeds the safe limit and the life of insulation is reduced.

The temperature of stator winding rises exponentially with time under moderate overloads.

The rate of temperature rise is determined by losses and thermal time constant of the stator. The heat loss from motor to surrounding air depends upon ambient temperature, ventilation and design aspects.

The time taken to reach limit of temperature rise and the shape of current *versus* time curve depends on load on the machine. For any machine, the thermal withstand curves can be drawn for 'cold' condition and 'warm' condition. The 'replica' type thermal relay operates with a thermal facsimile of the motor, *i.e.* the characteristic of such relay is an approximate replica of motor heating curve.

The relay is compensated for ambient temperature variation so that it can protect the motor for both cold start and hot start conditions.

The characteristic of replica relay and motor heating curve is plotted on the same current versus time curve. The relay trips at point where the motor heating curve crosses the relay characteristic. (Ref. 31.3.)

In practice, motor heating curves are not readily available. The thermal time constant or the motor can vary widely (15 minutes to 1 hour). Hence the relay characteristic should be selected and set to suit the protection requirement of particular motor.

The operating conditions resulting in temperature rise should also be considered. If motor is required for frequent starting, its temperature rise more rapid.

Referring to Fig. 31.3 curve *A* indicates characteristic of motor heating to reach maximum permissible temperature in 15 minutes for moderate overload (1.3 times full load current). The relay will trip according to characteristic *B*. *e.g.* for overload of 200%, the relay will trip in less than 4 seconds. Motor can withstand 200% overload for 4 minutes.

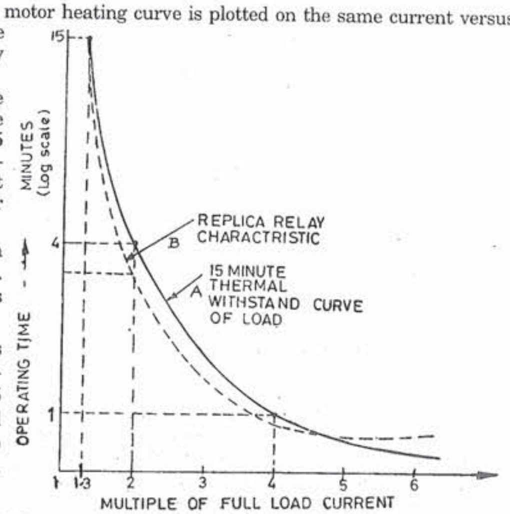


Fig. 31.3. Explaining Characteristic of Induction Motor Heating and Replica Relay.

31.7. PROTECTION AGAINST UNBALANCE

The voltage supplied to three phase induction motor can be unbalanced due to any of the following reasons :

— single phase loads on distribution service line
— blown out fuse in power factor correcting plant
— short circuit within or outside the motor
— phase failure by blown fuse. (single phasing)

The unbalanced voltage itself may not be harmful but the negative sequence currents caused by unbalanced voltage results in rotating magnetic field revolving in opposite direction. This field induces double frequency induced currents in the rotor body and conductors giving rise to heat due to copper losses (Ref. Table 31.4)

The rotor gets heated and the temperature of motor winding may reach above safe limit.

The unbalanced protection provided to a motor should prevent prolonged unbalanced condition, but should not disconnect the motor for permissible unbalance of short duration. The permissible loading depends upon the percentage unbalance and the ratio of positive sequence impedance to negative sequence impedance. (Ref. Table 31.5)

The unbalance protection is not provided, the motor should be derated to 40 to 60% of its rated full load capacity.

The unbalance voltage protection can be based upon the following methods :

1. Bimetallic relays arranged to trip faster for unbalanced currents.
2. Single phase relays sensing overcurrent in heavily loaded phases.
3. Phase unbalance relays.

Table 31.4. Derating factors of Induction Motor Under Unbalanced Supply Voltage Condition

Voltage unbalance $V_2/V_1 \times 100$	*Derating factor for full load current*		
	$\frac{Z_1}{Z_2} = 4$	$\frac{Z_1}{Z_2} = 6$	$\frac{Z_1}{Z_2} = 8$
1	—	—	—
5	0.96	0.93	0.9
8	0.92	0.88	0.72
10	0.9	0.8	0.56
12	0.9	0.7	0.3
15	0.9	0.4	0

Note. 1. This factor is to be applied if unbalance protection is not given.
2. Z_1/Z_2 is approximately equal to the ratio of starting current to full load current.

Table 31.5. Relation between Voltage Unbalanced and Copper Losses in Motor

% Voltage unbalance	1	2	3	5
% Stator loss*	101	102	106	115
% Rotor loss*	105	112	130	175

*For full load as per cent of losses during balanced voltage condition.

For *smaller motors* the cost of separate phase unbalance relay, is not justified. The unbalance protection is given by (1) and (2) on page 700. Additional phase failure relay (single phasing preventer) is provided where essential. For larger motors, additional unbalanced current relays are provided. The secondary currents of CT's are fed to negative phase sequence filter. The output of the negative sequence filter is given to a overcurrent unit or static level detector. The setting is based on the Z_1/Z_2 ratio and permissible time for per cent unbalances (Also Ref. 33-11 for Negative Sequence Circuit).

31.8. PROTECTION AGAINST SINGLE-PHASING (PHASE FAILURE)

A 3-phase induction motor continuous to run even if one of the supply lines is disconnected. The whole power is then supplied through the two windings and they are likely to get overheated. The single phasing causes unbalanced stator currents. The negative sequence component of unbalanced current causes heating of rotor and temperature rise. For small motors, separate protection against single phasing is generally not necessary as the thermal relays sense the increased current in healthy phases due to single phasing and thereby offer adequate protection.

In case of large motors (say 50 kW and above) even a modest unbalance can cause damage of motor winding due to overheating. Further, if motor is stalled due to losses of one phase, severe damage to rotor is possible while starting. Therefore, a separate single phasing protection is desirable.

Single phasing is extreme unbalance condition for a three phase motor. Such a condition can be caused by blowing of fuse in the supply circuit or due to improper contact in a switch or a contactor.

During single phasing, the current in healthy phases increases by $\sqrt{3}$ times. This increases the heating in motor windings. The unbalanced stator currents have a negative sequence component. This component causes magnetic flux rotating in opposite direction to the main flux. Thereby double frequency currents are induced in rotor body and rotor conductors. Rotor heating caused by these currents is very high. This heating is not detected by replica type thermal relays protecting the stator winding. Hence single phasing causes major damage to motor rotor. The phase overcurrent relays act slowly. Hence it cannot give instantaneous protection against single phasing.

In some applications like elevator motors, where it is dangerous to eliminate plugging, inching and reversing, the motor should be disconnected instantaneously when single phasing occurs. The phase unbalance relays (Ref. Sec. 31.10) are provided for large motors. But they are with time lag depending upon magnitude of unbalance.

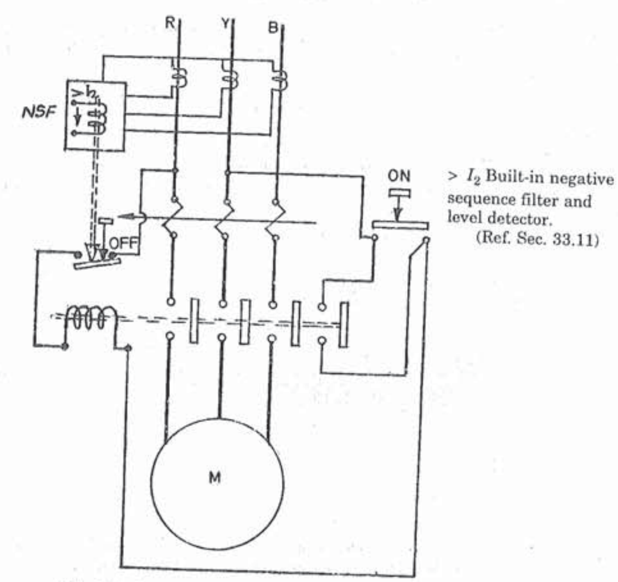


Fig. 31.4. Connections of single phasing preventer.

Single phasing preventers are used for small motors. These are connected to secondaries of line CT's. These contain a negative sequence filter. The output of the negative sequence filter is fed to a level detector (Ref. Fig. 31.4) which sends tripping command to the starter or circuit breaker when the negative sequence current exceeds a pre-set limit.

31.9. PHASE REVERSAL RELAY

The direction of rotation of an induction motor depends upon the phase sequence of the supply voltage. Phase reversal occurs when the supply connections are changed after repairs. Assuming after the repairs (at local load point or supply sub-station) the phase sequence of supply is reversed, the motor will run in wrong direction. In some applications, phase reversal is dangerous, *e.g.* elevators, cranes, hoists, trams etc. In such applications phase reversal relays should be provided. The phase reversal relay may be provided at main incoming substation of industrial works.

The phase reversal relay based on electromagnetic principle comprises a disc motor driven by magnetic system actuated by secondaries of two line CT's or VT's.

For correct phase sequence (*RYB*) the disc exerts torque in positive direction so as to keep the auxiliary contacts closed. When phase reversal takes place, the torque reverses and the disc rotates in opposite direction to open the contacts. Thereby the magnetic coild of starter can be de-energized or circuit breaker can be tripped. The *solid-state* phase reversal relays and phase failure relay senses the phase reversal or phase failure. Under abnormal condition it sends tripping command to output stage (which is a auxiliary relay or static device).

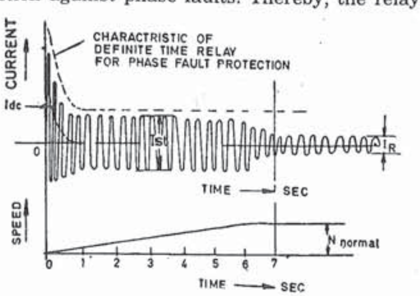
31.10. PHASE TO PHASE FAULT PROTECTION

The phase to phase fault short-circuit in stator winding causes burn-out of coils and stampings. Hence the motor should be disconnected from supply very quickly. Fast overcurrent relays are provided for phase to phase short-circuit protection.

The relays giving short-circuit protection to the motor should not act during starting currents. The setting of instantaneous overcurrent relays for phase faults should not be below the starting characteristic of the motor.

Therefore, the short-circuit protection characteristic is set just above the maximum starting current the motor.

While switching on the motor, staring current has d.c. transient and a.c. component (Ref. Sec. 3.4). The overcurrent relay set for short-circuit protection should not operate due to d.c. component. To avoid to high setting, it is a usual practice to provide a definite time lag of 2 to 4 cycles for overcurrent protection against phase faults. Thereby, the relay does not operate for initial high



N = Speed r.p.m
I_R = Normal full load current
I_{st} = Starting current

Fig. 31.5. Starting characteristic of squirrel cage induction motor co-ordinated with over-current relay for phase faults.

value of d.c. component. After three/four cycles, value of d.c. component in starting current reduces and the relay does not pick-up due to the same. (Fig. 31.5).

Limitations of Overcurrent Relays. With higher setting of overcurrent relays above starting characteristic, (say above 5 to 7 times full load current), the fault current may be less than the pick-up value of relay. This can happen for phase to phase faults near the neutral point of the star connected motor. Although the probability of such a fault is less, the fault can cause extensive damage as it will not be cleared instantaneously.

The most sensitive and quick protection for all phase faults in the motor is possible by *Circulating Current Differential Protection* (Ref. Ch. 28). The biased differential protection prevents mal-operation due to d.c. component and CT errors.

Slip Ring Induction Motors. The starting current of slipping induction motors is limited to about 1.25 times full load current by means of resistance in rotor circuit. Hence overcurrent relays set to about 1.4 to 1.6 times rotated full load current provide satisfactory protection against phase faults.

Overload and Phase Fault Protection of Large Motors*

The characteristics of IDMT relays (inverse definite minimum time) for motor protection should be matched with the motor heating curve (Fig. 31.6). Thermal protection usually given adequate protection at light and medium long time overloads but are usually not enough for very heavy overloads. High set instantaneous overload relay do not give adequate protection against overloads. Hence the schemes of overcurrent protection of large motors include various combinations of :

— thermal overcurrent relay
— inverse long time relay
— instantaneous overcurrent relays.

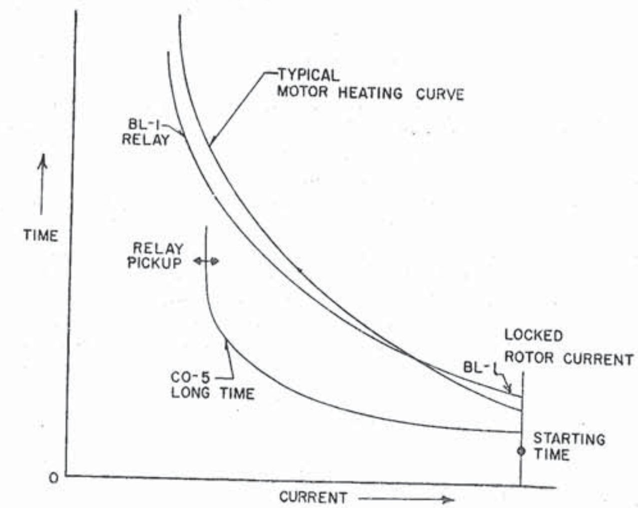


Fig. 31.6. Typical motor and relay characteristics.

Table 31.6. Overcurrent Protection for Motors*
(Earth-fault Relays Considered Separately)

Scheme	*Relays applied*	*Action (Note 4)*	*Typical Settings*	
1.	2 thermal over-current	Trip or alarm	100% I_R	(Note 1)
	1 long time ind. over-current	Trip or alarm	300—350% I_R	(Note 2)
	3 instantaneous over-current	Trip	above max start I	(Note 3)
2.	2 long time ind. over-current	Trip	300—125% I_R	(Note 2)
	1 long time ind. over-current	Alarm	115—125% I_R	
	2 instantaneous over-current	Trip	above max I_{st}	(Note 3)
3.	2 long time ind. over-current	Trip or alarm	125—150% I_R	(Note 2)
	2 instantaneous over-current	Trip	above max I_{st}	(Note 3)
4.	2 thermal over-current	Trip or alarm	100% I_R	(Note 1)
	2 instantaneous over-current	Trip	above max I_{st}	(Note 3)

I_R is rated (full load) motor current.
I_{st} is starting current.
Courtesy : Westinghouse Electric Corporation

***Notes.** 1. Replica type relay such as BL-I. Adjustment is change in contact setting. Normal setting provides operation in 60 minutes at 125% I_R. Can be set at 25 minutes at 125% current.

2. Time selected so that operation occurs on locked rotor current but not on motor starting when starting time is less than locked rotor time. Where data are not available, this setting can be obtained by successive motor starts and advancing the time setting until relay operation does not occur, then add around 1-5 sec to the relay operating time. Typical setting might be 10 sec. on locked rotor current magnitude. If the relay are used for alarm only settings are reduced to 115% except where service factors or short time overload rating exist.

3. It is difficult to determine as d.c. offset currents may occur particularly when starting large motors. Setting is best obtained by successive starts to determine the no operation setting and then increasing pick-up approximately 10%. Typical settings might be 160 to 170% of locked rotor current although settings as 250% may be required. This may be 12 to 15 times rated motor current.

4. Decision to trip or alarm depends on emphasis placed on service continuity and motor protection. For essential motors of power house auxiliaries (where failure would cause shut-down of generating capacity) alarms are frequently used so that operator can take corrective measures to avoid shunt-down or transfer generation before shut-down.

5. Replica type relay attempts to duplicate on a small scale within the relay operating unit, the heating characteristic of the motor. The current from CT secondary passes through relay and its characteristic approximately parallel that of the machine as illustrated in Fig. 31.6. The BL-1 relay has two spiral-wound bimetallic springs. One is actuated by the heat preduced by the applied current while the other, by the ambient temperature surrounding the relay. This provides ambient temperature compensation so that relay operates on the same time current curve approximately independent on the temperature of the air surrounding the relay.

The BL-1 relay is available with one or two thermal overload units with instantaneous trip attachments for applications.

31.11. STATOR EARTH-FAULT PROTECTION

Earth-fault protection is set to disconnect the motor from supply as early as possible so that the damage to winding and laminations is minimum.

Zero Sequence Current Transformer (ZSCT) or core balance type protection (Ref. Sec. 27.9) is very convenient method of protection of motors from earth-faults (Ref. 31.7). This method is especially suitable for system neutral earthed through resistance. In such systems, earth-fault currents are so low (due to resistance earthing) that phase overcurrent relays cannot be set to pick-up for earth faults. (Ref. Fig. 27.11 (*b*)—Core Balance CT)

Where the supply source is earthed, an inverse, very inverse, or instantaneous induction type relay is connected in the current transformer neutral. These sources usually have neutral impedance to limit the ground current so that sensitive ground relay settings are required. Typical settings are 1/5 of the minimum fault current for a solid fault at the machine terminals. Time dial setting around 1 are used which give operations of 4–5 cycles at 500% pick-up.

Occasionally the high in-rush current of direct on-line starting of large motors will cause the grounded relays to operate. This results from unequal saturation of the current transformers which causes a false residual current in the secondary or relay circuits. Two instead of three phase relays or different settings among the three phase relays tend to increase the effect.

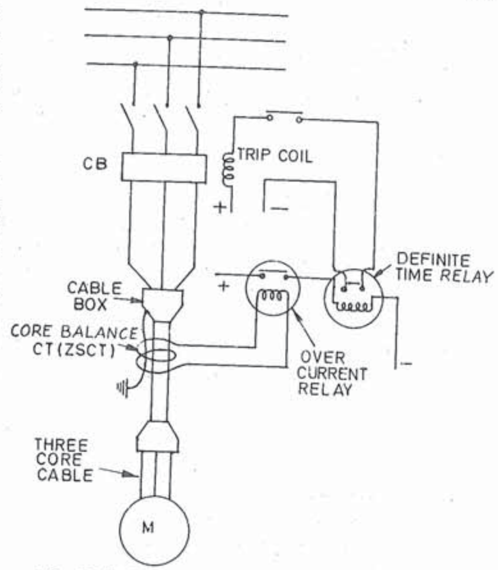


Fig. 31.7. Connections of core balance CT (Zero Sequence CT) for earth-fault protection of motor

As a thumb-rule, no trouble should occur is the phase burdens are limited so that the voltage developed by the current transformer during starting is less than 75% of the 10 P accuracy rating of the current transformer. A practical solution to prevent relay operation, should trouble develop, is to increase the ground relay burden by using a lower tap. This forces all three transformers to saturate more nearly together and effectively reduce the false residual current. An alternate solution is to connect a resistor or reactor in series with the ground relay (earth faults relay).

The trend in 3.3 to 11 KV sub-stations and industrial power systems is towards higher neutral impedance and appreciably less ground fault current. This increases the problem of obtaining a very sensitive relay setting that will not operate on the false residual current of the starting inrush. This is the best solved by using a window type current transformer which has a single secondary winding surrounding all three phase conductors (Fig. 31.7). This eliminates the false residual and permits applying a very sensitive instantaneous earth-fault relay. An alternative is to use a directional overcurrent relay with the current of voltage polarizing coil connected in the ground source neutral or across the neutral resistor.

31.12. FAULTS IN ROTOR WINDING

In slip-ring induction motor, rotor faults are possible. The increase in rotor current is reflected on stator current and the stator over-current protection can thereby act. The setting of stator over-current relay is generally of the order of 1.6 times full load current. This is enough to detect the rotor faults.

Inter-turn Faults. Inter-turn faults are difficult to be, detected. The method adopted for generator stator winding inter-turn faults can be adopted for motors. But it is too complex and is not practicable.

Grounding or Earthing (Ref. Ch. 18)

In low voltage circuits the neutral point of supply should be earthed. In ungrounded systems a single line to ground fault on one line causes increase in voltage of healthy lines with respect of neutral by $\sqrt{3}$ times. This can damage motor insulation.

To avoid this, the neutral point of supply, should be earthed at every voltage level. Cascade failure of motors can occur if supply neutral is not earthed (Ref. Sec. 18.6.2.)

Summary (Refer Table 31.1)

The protection of motor is normally provided along with stator or switchgear.

Contactor starters or circuit-breakers are used for motor switching.

Thermal relays provided overload protection, single phasing protection. This circuit protection is provided by fuses or instantaneous relays. Protection against unbalanced supply voltage is provided by negative phase sequence relays.

H.R.C. fuses are used for short circuit protection of motor. They should be co-ordinated with overload relays.

Abnormal condition is motors include : faults, under voltage, single phasing, unbalanced voltages, overloads etc.

QUESTIONS

1. Describe contactors starter of a three phase induction motor. State what protective measures are provided along with the starter ?
2. Describe the principle of operation of thermal relay used for motor protection.
3. State the various abnormal conditions in a 1200 h.p. Induction motor and protection provided against each.
4. Distinguish between overload protection, short circuit protection and earth fault protection of motor.
5. Explain how to select a fuse for motor. How to co-ordinate it with circuit breaker or contactor?
6. Explain the various methods of short circuit and earth fault protection of motors.
7. Which protections are provided for essential service motors?
8. Discuss the causes of motor failure of both electrical and mechanical origin.
9. In a factory, a 15 kW motor is to be provided with a starter. However a starter for 35 kW motor is readily available in the store. Can this starter be used ? Give technical considerations.
10. It was found that the thermal relays tripped while starting the motor was started without load the thermal relay did not trip. What can be the various causes of tripping during starting?
11. Explain the term "Single Phasing ". In what form the protection is provided in case of
    (*a*) Fractional horse power motor (*b*) Large motor above 150 h.p.
12. State whether correction or wrong. Write corrected statements if necessary.
    — Squirrel-cage motors can fail by rotor insulation failure.
    — In motor protection, thermal relay provide short circuit protection.
    — Phase sequence of supply determines the direction of rotation of motor.
    — Differential protection if provided for 100 h.p. motor.
    — Differential protection does not sense overloading of motors.
    — Undervoltage of supply reduce starting current of motor.

Ref. Sec. 43.7 and 43.8 for static protection scheme for motors.

1. Ref. Sec. 18.12. Protection against switching overvoltages. Vacuum circuit-breakers tend to chop the current giving switching voltage surges. RC surge suppressors are connected with such switchgear to protect motor insulation.

2. Thyristor-control of induction motors gives harmonic contents in the supply wave form. Harmonics cause addition heating in the magnetic circuit. The harmonic content in supply would be within certain limits. The voltage waveform should be sinusoidal with permissible deviation less than 3 per cent suitable harmonic filters should be provided on supply side.

32

Protection of Transformers

General — Protection Chart — Buchholz Relay — Sudden Pressure Relay — Biased Differential or Merz Price Protection — Problems arising in Merz Price System — Harmonic Restraint — Overcurrent Relays — Interlock protection — Restricted earth fault protection — Overfluxing protection — Protection of Arc-furnace transformers — Safety devices.

32.1. PROTECTION REQUIREMENTS

Protective equipment for transformer protection includes gas relays which give an alarm on incipient faults, differential system of protection which gives protection on phase to phase faults plus phase to ground faults, other protective relays, and surge arresters which give protection to the insulation from high voltage surges (Ref. Table 32.1)

A *Through Fault* in one which is beyond the protected zone of the transformer, but fed through the transformer. The unit protection of the transformer (usually differential current protection) should not operate for through faults. The overload relaying may be provided to operate with a time lag to provide back-up protection. Internal faults are those in the protected zone of the transformer. These faults can be between phase-to-phase and phase-to-ground. Generally they result from failure of insulation due to temperature rise or deterioration of transformer oil. Incipient faults are initially minor faults causing gradual damage. These faults grow into serious faults. Incipient fault include loose connections in conducting path, sparking, small arcing, etc.

The faults occurring in power transformers are earth-faults phase-to-phase faults, inter-turns faults and overheating from overloading or from some internal cause such as core-heating. Of these the most common are earth-faults ; inter-turns faults ; but the latter develop rapidly into earth-faults and, therefore, only earth-fault protection is generally provided.

The choice of protection for any given power-transformer depends upon a number of factors, such as its size, importance, and whether it has no-load or off-load tap changer.

The following information is necessary while selecting the protection scheme for a power transformer.

1. Particulars of transformer
   (*a*) kVA (*b*) Voltage ratio
   (*c*) Connections of windings (*d*) Percentage reactance
   (*e*) Neutral point earthing, value of resistance
   (*f*) Value of system earthing resistance
   (*g*) Whether indoor or outdoor, dry or oil filled
   (*h*) With or without conservator.
2. Length and cross-section of connecting leads between CT's and relay panel.
3. Fault level at power transformer terminals.
4. Network diagram showing position of transformer, load characteristics.

The general practice of protection of power transformer is given in Table 32.1.

The faults in transformer can be caused by failure of insulating materials due to dust, moisture, voids weakening of winding due to external short-circuits.