CHAPTER 2

AN ELECTROMECHANICAL INVERSE TIME-LAG RELAY WITH DEFINITE MINIMUM TIME LAG

2.1 Application in a power system

Inverse time-lag relays are normally used for subtransmission and distribution line protections. They are also used for transformer overload protections. In case there is a power source at each end of the line, directional inverse time-lag relays are used.

As shown in Fig.2.1-1 is a single line diagram of a transmission line with a power source at one end. If a fault occurs between the line section B-C, the breaker at substation B should open only to clear the fault. Breaker A should not open. The selectivity of the breaker at substation A and substation B can be accomplished by using definite time-lag relays whose time-distance characteristics are shown in Fig.2.1-2. The disadvantage of this type of protectioniis that the heaviest fault is cleared slowest. In order to eliminate this disadvantage the inverse time graded protection whose time-distance characteristics as shown in Fig.2.1-3 is applied. The relays used in this type of protection make use of the fact that the fault current for a fault at the far end of the protected line is less than the fault current for a fault at the near end of the line. Consider a three-phase short circuit for the line section A-B. The equivalent circuit is shown in Fig.2.1-4. For a fault at bus A, the fault current is

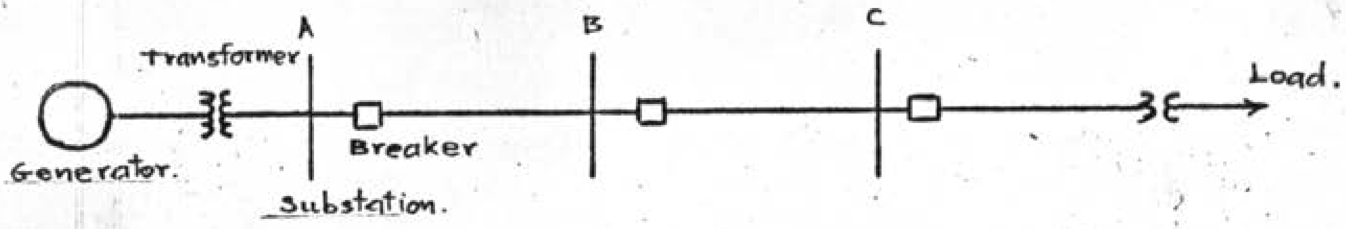

Fig.2.1-1. Single line diagram of a Transmission Line.

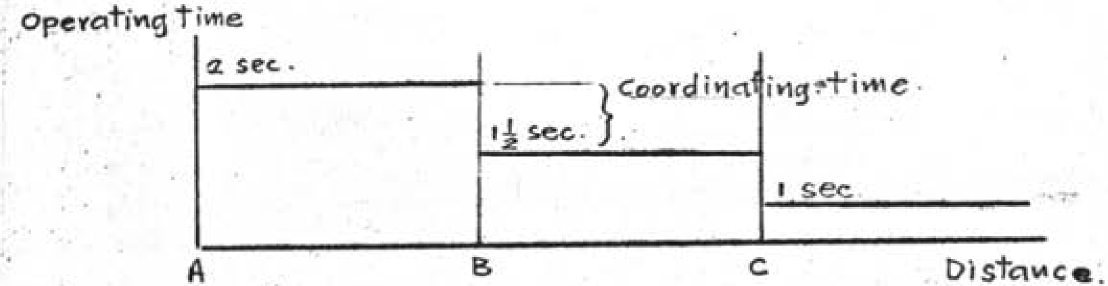

Fig.2.1-2 Definite-time grading on Radial Circuit.

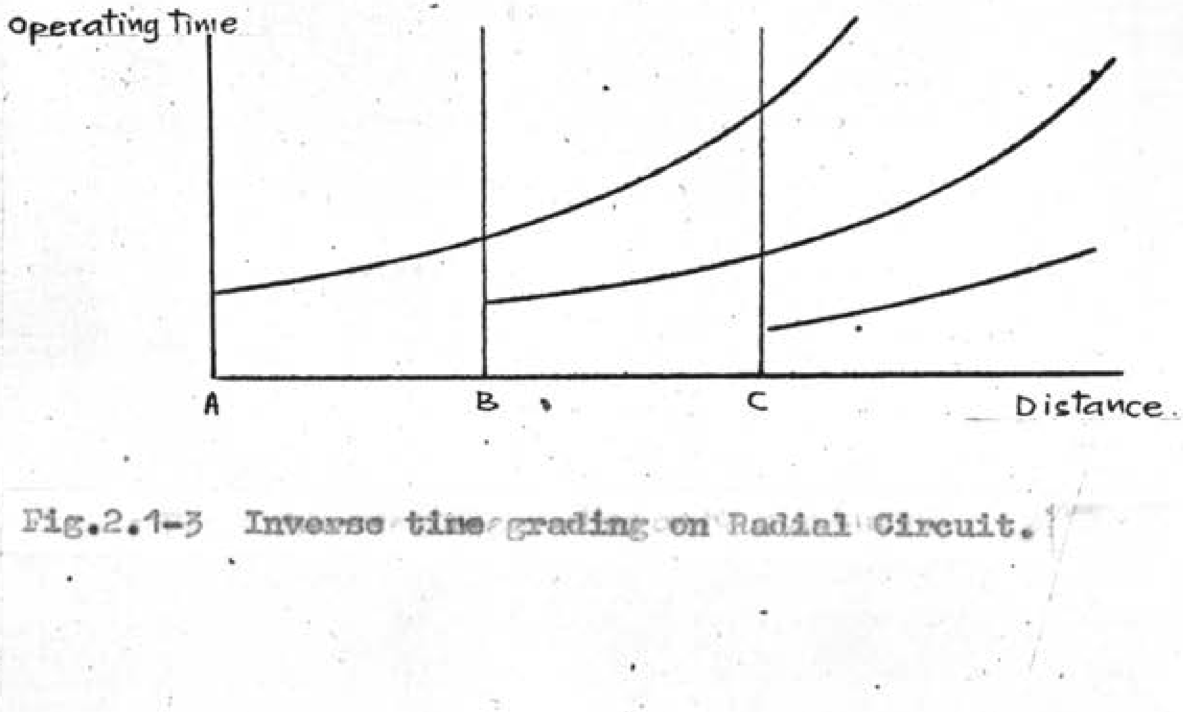

Fig.2.1-3 Inverse time grading on Radial Circuit.

$$I_A \quad = \quad V/Z_S \qquad (2.1\text{-}1)$$

where I_A = fault current

V = source voltage

Z_S = equivalent source impedance

For a fault at bus B, the fault current is

$$I_B \quad = \quad V/(Z_S + Z_L) \qquad (2.1\text{-}2)$$

where I_B = fault current

Z_L = the protected line impedance

In this case a relay whose characteristic is defined by Eq.(2.1-3) would trip faster for a fault at the end of the section nearer to the power source.

$$I.T \quad = \quad K \qquad (2.1\text{-}3)$$

where I = fault current

T = operating time

K = a constant

The ratio of the tripping time at the near end to the time at the far end is $Z_S/(Z_S + Z_L)$. There are two conditions however which reduce the advantage of the inverse time characteristics. First, Z_S can be so high on impedance graded system that the ratio $Z_S/(Z_S + Z_L)$ is not sufficiently lower than unity to give any appreciable reduction in tripping times. Secondly, Z_S will vary if the generating capacity is varied. Z_S increases as the generating capacity decreases and Z_S will not interfere with selectivity because the inverse curve increases the time discrimination at low current, but it does increase the tripping time and hence defeats its purpose of reducing them. In order to reduce the tripping time at the near end, the instantaneous or definite minimum time-lag relays are used. The time-distance characteristics are shown in Fig.2.1-5. This type of relays is not intended to delay but one can not eliminate the delay operating time. These relays are used as primary protection for a fault within the protected line. Setting these relays must be carefully performed so that tripping for a fault within the adjacent line should not occur. The combination of time-distance characteristics of the inverse time-lag relay and definite minimum time-lag relay are shown in Fig.2.1-6.

2.2 Principle of Operation of a Definite Minimum Time-Lag or Instantaneous Overcurrent Relay

The instantaneous overcurrent relays are of a solenoid, balance beam or clapper types. They are shown in Fig.2.2-1, Fig.2.2-2 and Fig.2.2-3 respectively. The operating characteristic is described mathematically as

$$F = K_1 . I^2 - K_2 \qquad (2.2\text{-}1)$$[1]

where F = net force

K_1 = a force-conversion constant

I = the r.m.s. magnitude of the current in the actuating coil

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[1] Mason, C. Russel. 1962. The Art and Science of Protective Relaying. New York: John Wiley and Sons, Inc. Chapter 2 Page 22.

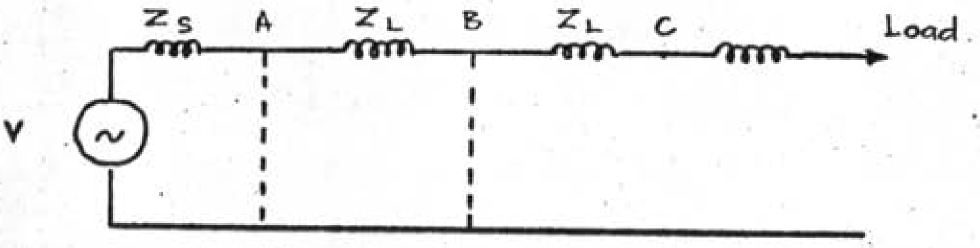

Fig.2.1-4 Equivalent circuit for fault calculation.

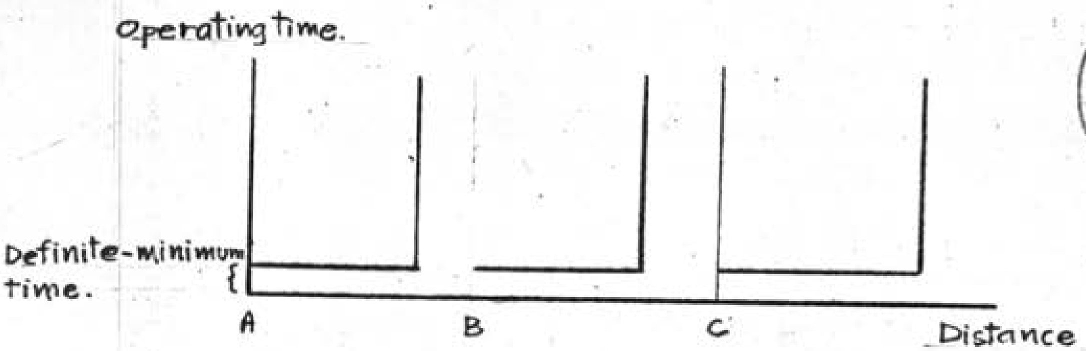

Fig.2.1-5 Time-distance characteristics of Instantaneous overcurrent relays.

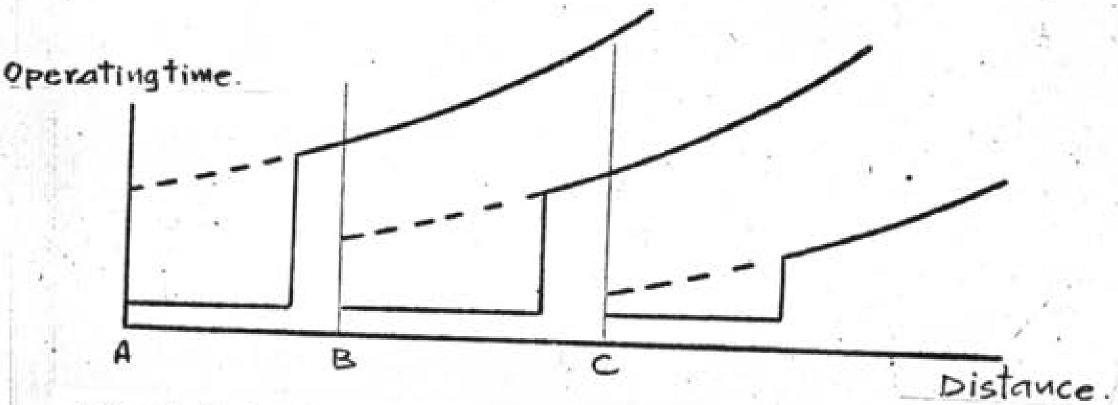

Fig.2.1-6 Combination time-distance characteristics of Inverse time-lag relays and Definite-minimum time lag relays or Instantaneous relays.

K_2 = the restraining force (including friction)

The operating force of the solenoid and clapper type depends on the initial position of the moving armature. The restraining force of the balance beam type depends on the restraining spring. When the relay is on the verge of picking up, the net force is zero, and the operating characteristic is

$$K_1 . I^2 = K_2$$

or

$$I = (K_2/K_1)^{1/2} \qquad (2.2\text{-}2)$$

The pick-up current can be adjusted by taps on the actuating coil or the reluctance of the magnetic circuit or the spring tension. The relay needs time to close its contacts. The operating time depends on the net force exerted on the moving armature. The time-current characteristics are shown in Fig.2.2-1, Fig.2.2-2 and Fig.2.2-3.

2.3 Principle of Operation of an Inverse Time-Lag Relay

An inverse time-lag relay is genarally of an induction-disc, induction-cup or watthour-meter type. The most commonly used type is the induction-disc type, as shown in Fig.2.3-1. The relay consists of a control spring, an induction disc, a magnetic core, an actuating coil, a damping magnet, two stationary contacts and a moving contact. The induction disc is made of non-magnetic current-conducting material and held horizontally by two bearings and its rotating axis. One end of the control spring is fixed to the rotating axis and the other to the external structure. The torque produced by the control spring is

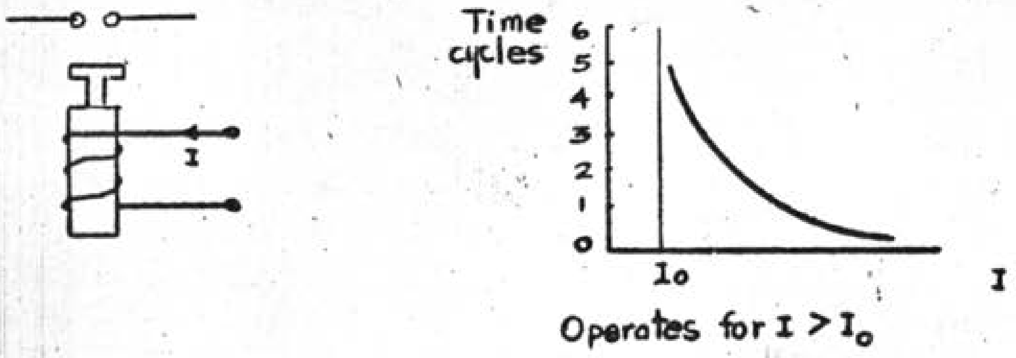

Fig.2.2-1 Solenoid type.

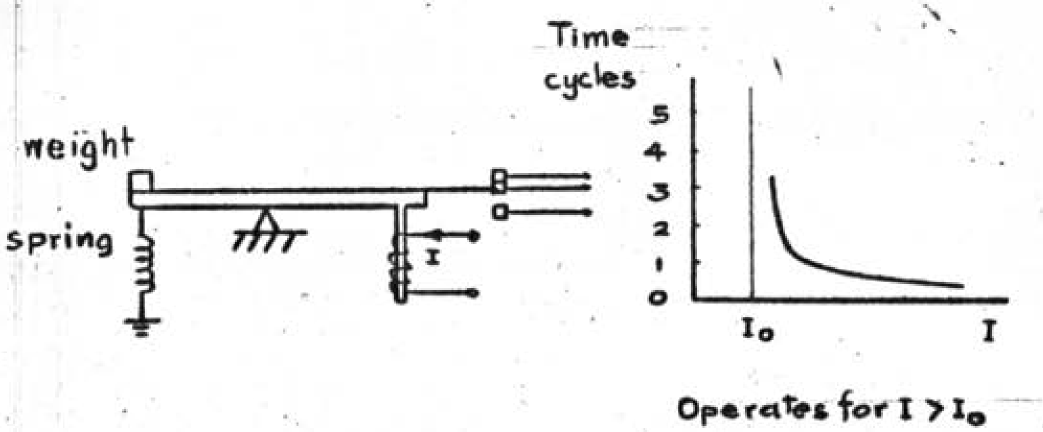

Fig.2.2-2 Balance beam type.

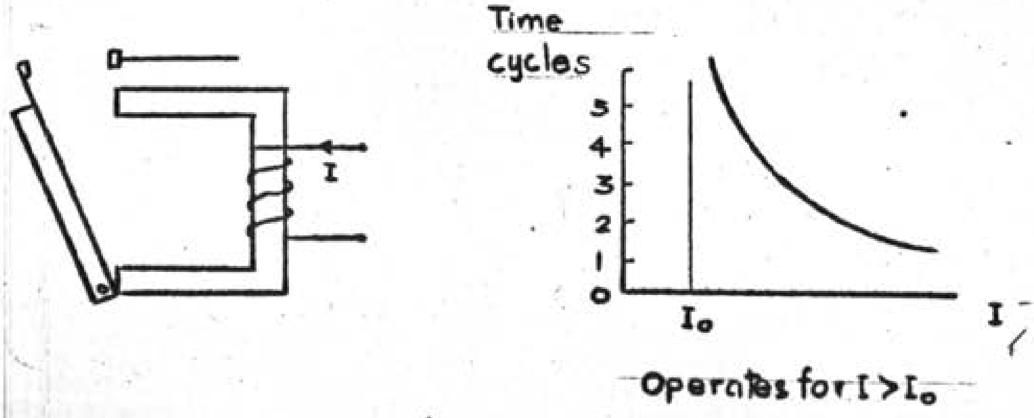

Fig.2.2-3 Clapper type.

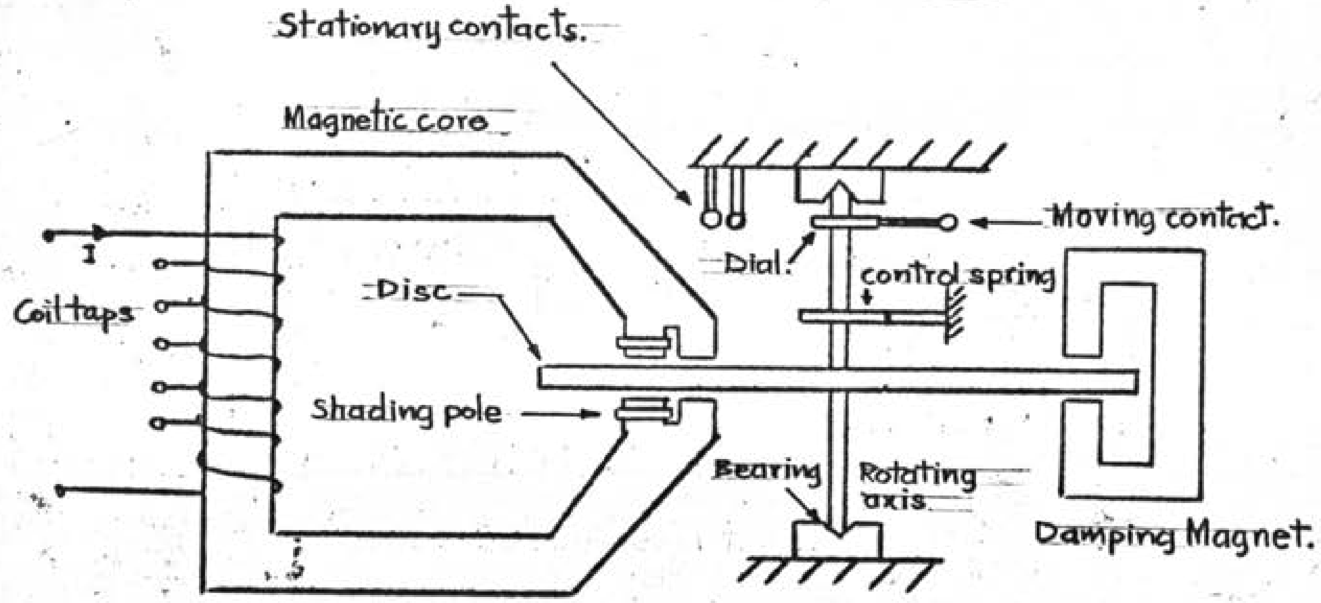

Fig.2.3-1 The main parts of an Induction-Disc Inverse Time-Lag Relay.

in such a direction that it restrains the operating torque produced by the actuating current. The actuating coil is wound around the magnetic core to set up flux proportional to the actuating ampere-turns. The flux is devided into two paths and returns through the outer leg. A shading coil causes the flux through the left leg to lag the main pole flux by approximately 90 degrees. Thus, the out of phase fluxes are produced in the air gap and cause a contact closing torque, exerting on the disc. The moving contact is mounted on the rotating axis and can be adjusted for the required travelling distance to the stationary contacts. Taps on the coil are provided so that pick-up current settings can be varied. The damping magnet provides a damping torque to keep the disc to rotate with a constant speed. The operation of the relay can be described mathematically as follows.

When the actuating current produces a torque greater than the restraining torque of the control spring, the disc begins to rotate.

$$T = K.I^2 \qquad (2.3\text{-}1)^1$$

where T = the torque produced by the actuating current

K = a torque-conversion constant

I = the actuating current in r.m.s magnetude

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[1] Mason, C. Russel. 1962. <u>The Art and Science of Protective Relaying</u>. New York: John Wiley and Sons, Inc. Chapter2 Page 27.

The differential equation describing the motion of the disc is

$$T = M.d^2A/dt^2 + K_d.dA/dt + K_s.A \qquad (2.3\text{-}2)$$

where M = the moment inertia of the disc

K_d = a torque-conversion constant of the damping magnet

K_s = a torque-conversion constant of the control spring

A = the angular displacement of the moving contact measured from its initial position

t = time

K_s is practically small as compared to M and K_d, and negligible for simplicity. The above equation reduces to

$$T = M.dW/dt + K_d.W \qquad (2.3\text{-}3)$$

where $W = dA/dt$ = angular velocity

The solution of Eq.(2.3-3) subjected to the initial condition that $W(0) = 0$ and the steady state condition that $W(\infty) = T/K_d$ is

$$W(t) = \frac{T}{K_d}.\left\{ 1 - \text{Exp.}(-K_d.t/M) \right\} \qquad (2.3\text{-}4)$$

The time function of the angular displacement is obtained by integrating Eq.(2.3-4), subjected to the initial condition that $A(0) = 0$.

$$A(t) = T.t/K_d - \frac{T.M}{K_d^2}.\left\{ 1\text{-Exp.}(-K_d.t/M)\right\} \qquad (2.3\text{-}5)$$

If the time constant M/K_d is small as compared to relay operating times, the time function of the angular displacement is approximate as

$$A(t) = T.t/K_d \qquad (2.3\text{-}6)$$

Substitute Eq.(2.3-1) into Eq.(2.3-6), the result is

$$A(t) = K.I^2.t/K_d$$

Let A_o = the angular displacement from the initial position of the moving contact to the stationary contacts

T_o = the corresponding travelling time of the moving contact

Substitute A_o and T_o into the above equation and rearrange:

$$T_o = K_d.A_o/(K.I^2) \qquad (2.3\text{-}7)$$

Fig.2.3-2, Fig.2.3-3 and Fig.2.3-4 show the graphical representations of Eq.(2.3-4), Eq.(2.3-5) and Eq.(2.3-7) respectively.

Equation (2.3-7) is an ideal operating characteristic of the relay. In practice Eq.(2.3-1) may not satisfy the actual behaviour of the torque-current relation. This is due to the magnetic saturation or other magnetic circuits which are intentionally made up in order to produce operating characteristics to satisfy each application. Fig.2.3-5 shows a family of the operating characteristics of a typical inverse time-lag relay.[1]

The setting of the pick-up current is accomplished by coil taps and the operating characteristic of each tap is the same for the same dial setting. The dial setting is provided in order that one can choose a desired operating characteristic. This corresponds to choose the angular displacement A_o in Eq.(2.3-7).

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[1] Westinghouse I.L. 41-101H. 1962. <u>Type CO Overcurrent Relay</u>. Page 11.

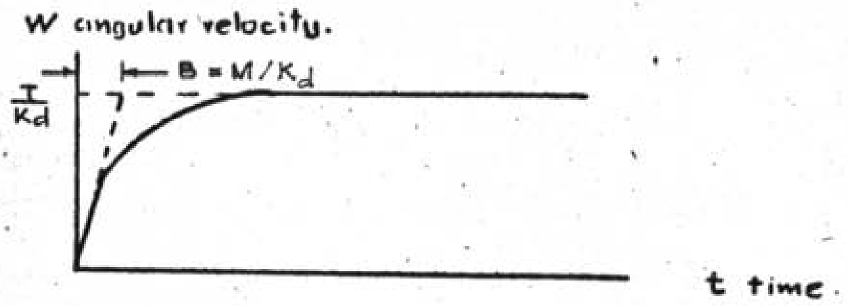

Fig.2.3-2 Angular Velocity vs. Time.

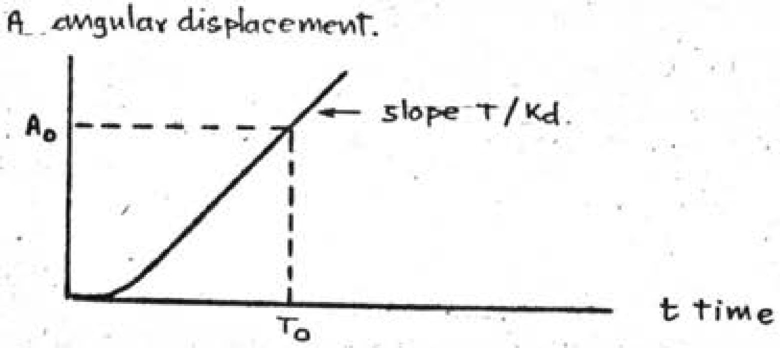

Fig.2.3-3 Angular Displacement vs time

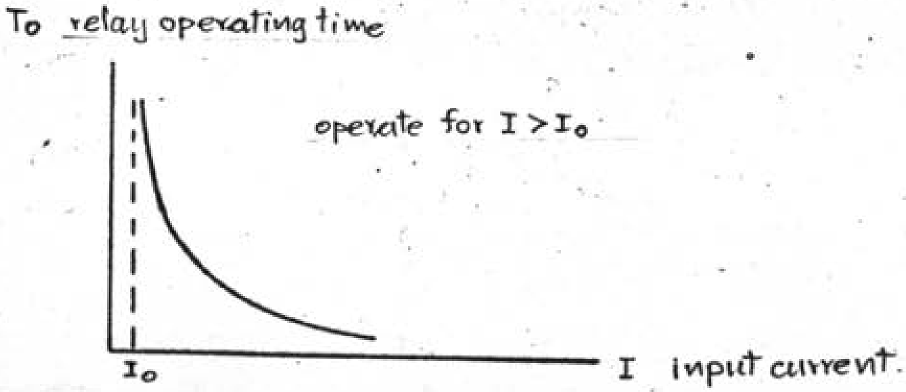

Fig.2.3-4 Relay Operating characteristic.

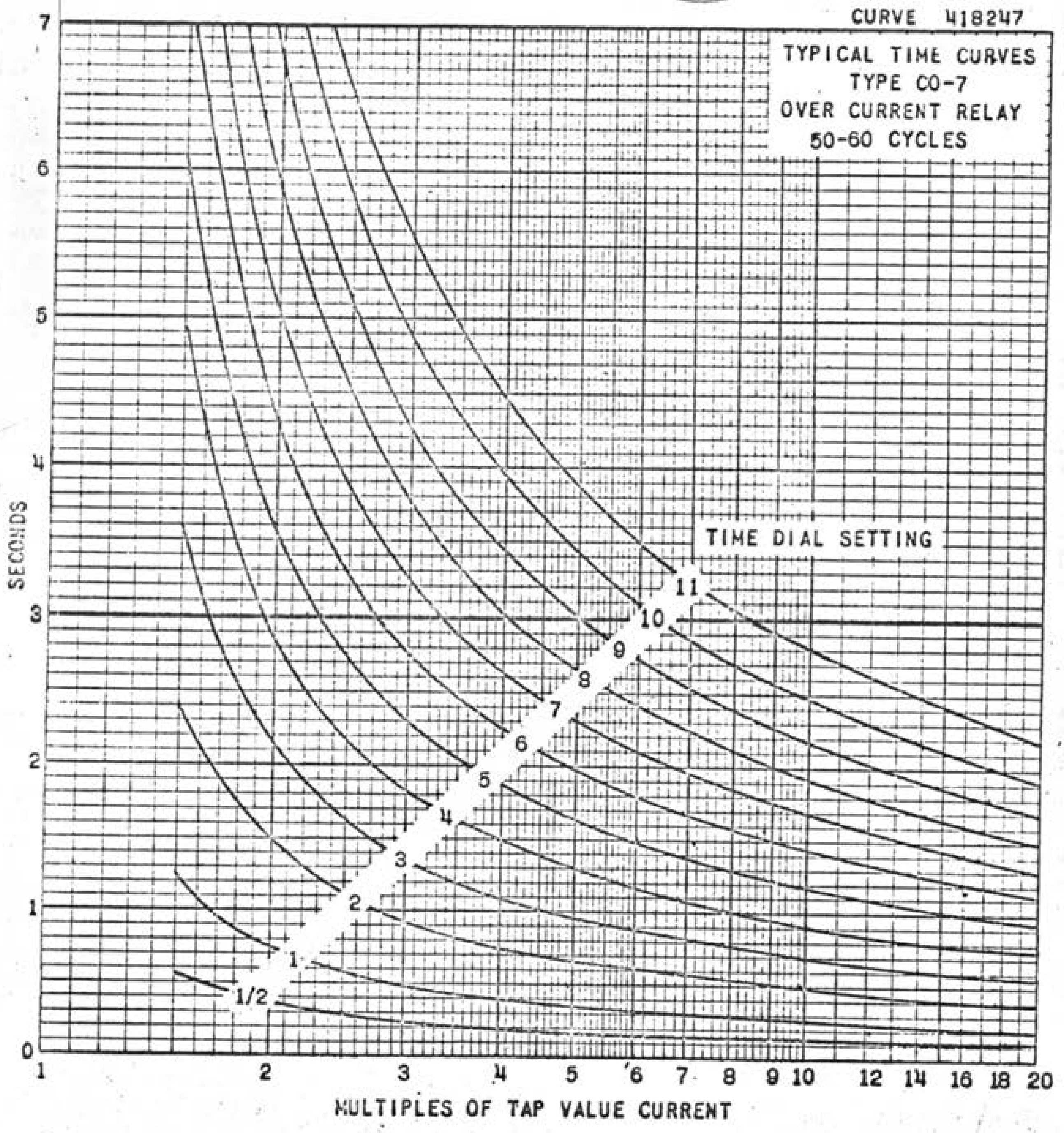

Fig.2.3-5 *Typical Time Curves of the Type CO-7 Relay.*

If the moving contact has not yet reached the stationary contacts and the actuating current decreases in magnitude below the pick-up current, the disc will continue moving by its own momentum for a short time. This is known as overtravel or overshoot of the relay. After the energy stored in the disc has transferred to the control spring, the disc resets to the initial position with the aid of the control spring torque. The time required for the moving contact to return to the initial position is the reset time.

In order to measure the degree of overtravel of the disc, a term is defined. This is the impulse margin time.[1]

$$T_{IM} = T_{OP} - T_{I}$$

where T_{IM} = the impulse margin time

T_{OP} = the operating time from time-cuurent curves at some time dial and tap-multiple setting

T_{I} = the minimum impulse time during which sufficient inertia is supplied to the disc to eventually cause the disc to coast closed, following deenergization; based upon test at the same settings and current as used to determinedT_{OP}:

The typical value of T_{IM} is about 0.03-0.05 seconds.

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[1] Westinghouse IL 41-101.1 Type CO Relay Coordination and Impulse Margin Time. Page 1.

Fig.2.3-6 shows typical reset times of inverse time-lag relays. The reset time may be longer than 100 seconds and sometimes less than 5 seconds. This depends on the time dial setting and type of the inverse time-lag relay.

Practical inverse time-lag relays are generally available for the pick-up current of 0.5-2.5 amp, 2-6 amp, and 4-12 amp. Taps on the actuating coil are 0.5/0.6/0.8/1.0/1.5/2/2.5, 2/2.5/3/3.5/4/6 and 4/5/6/7/8/10/12. Table 2.3-1 is the list of the power consumption of a typical electromechanical inverse time-lag relay.[1]

2.4 Relay Setting and Coordinating Time Interval

Consider a transmission line in Fig.2.4-1. The relays at substation A and B are to be set to protect the line. Fig.2.4-2 and Fig.2.4-3 show the relaying circuit and the d.c. trip circuit. The pick-up current of the phase overcurrent inverse time-lag relays is normally set at 200% of the full load line current.[2] The pick-up current of the ground overcurrent inverse time-lag relays is set at 10-30 % of the full load line current.[3] The time dial setting is

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[1] Westinghouse IL 41-101H1 Type CO Overcurrent Relay.Page.6

[2] Westinghouse Electric Corporation. Relay-Instrument Devision. Applied Protective Relaying Chapter 8 page 23.

[3] Ibid.

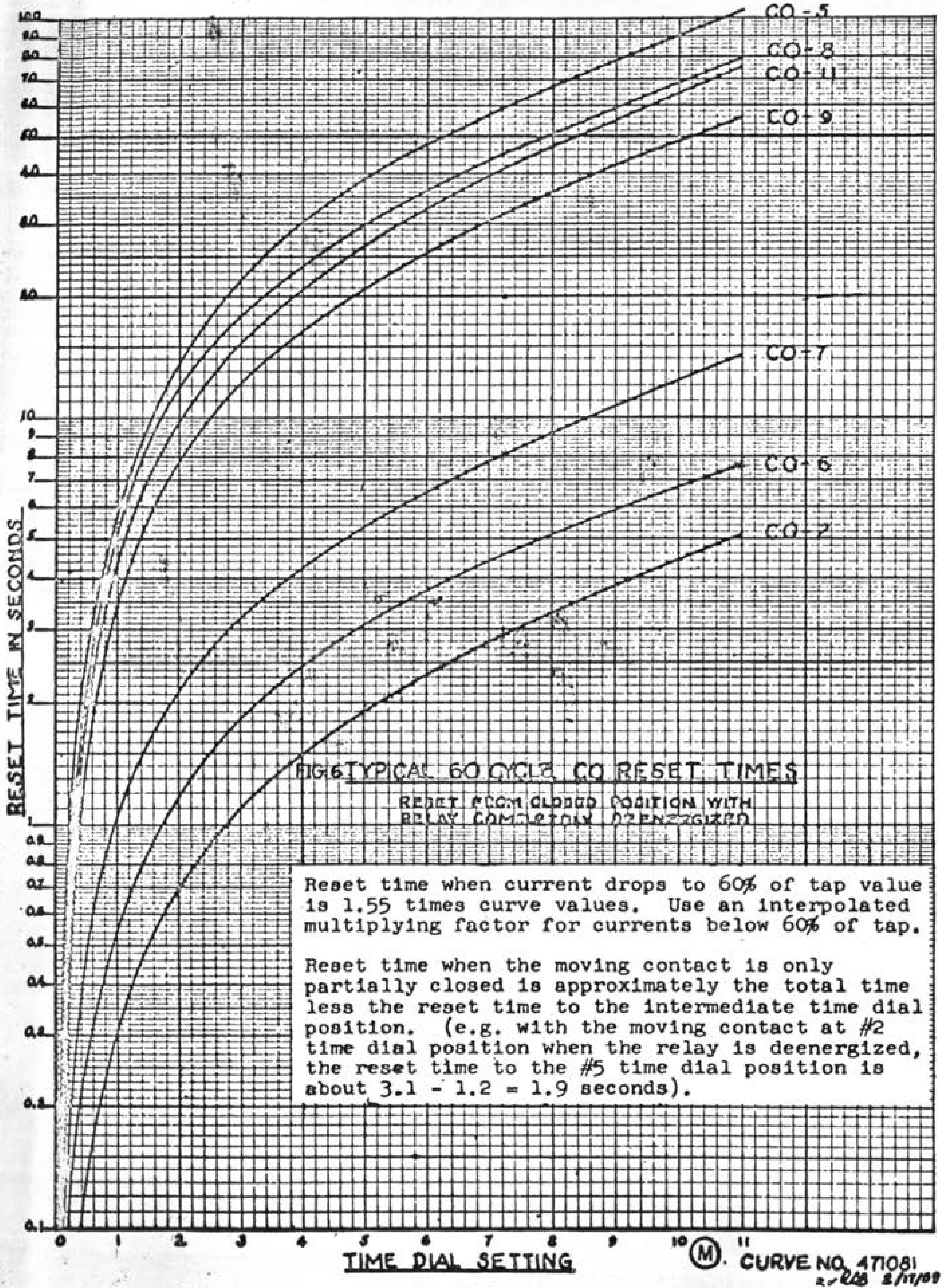

FIG 6 TYPICAL 60 CYCLE CO RESET TIMES

RESET FROM CLOSED POSITION WITH RELAY COMPLETELY DEENERGIZED

Reset time when current drops to 60% of tap value is 1.55 times curve values. Use an interpolated multiplying factor for currents below 60% of tap.

Reset time when the moving contact is only partially closed is approximately the total time less the reset time to the intermediate time dial position. (e.g. with the moving contact at #2 time dial position when the relay is deenergized, the reset time to the #5 time dial position is about 3.1 - 1.2 = 1.9 seconds).

Fig.2.3-6

Table 2.3-1

		VOLT-AMPERES				
AMPERE RANGE	TAP	AT TAP VALUE CURRENT	AT 3 TIMES TAP VALUE CURRENT	AT 10 TIMES TAP VALUE CURRENT	AT 20 TIMES TAP VALUE CURRENT	POWER FACTOR ANGLE Ø
	0.5	3.88	20.7	103	278	68
	0.6	3.93	20.9	107	288	67
	0.8	3.93	21.1	114	320	66
0.5/2.5	1.0	4.00	21.6	122	356	64
	1.5	4.08	22.9	148	459	61
	2.0	4.24	24.8	174	552	58
	2.5	4.38	25.9	185	640	56
	2	4.06	21.3	111	306	66
	2.5	4.07	21.8	120	342	63
	3	4.14	22.5	129	366	63
2/6	3,5	4.34	23.4	141	413	62
	4	4.34	23.8	149	448	61
	5	4.40	25.2	163	530	59
	6	4.62	27	183	624	58
	4	4.24	22.8	129	392	64
	5	4.30	24.2	149	460	61
4/12	6	4.62	25.9	168	540	60
	7	4.69	27.3	187	626	58
	8	4.80	29.8	211	688	55
	10	5.20	33	260	860	51
	12	5.40	37.5	308	1032	46

determined by knowing the operating characteristics of the relays at substation B which are determined by the settings of the relays at the next right-hand substation. Actually, the settings are begun at the farthest substation from the power source and continued successively to the power source. Fig.2.4-4 shows the graphical method of choosing the time dial of the relay at substation A. Knowing the maximum fault current, for a fault at point C, the operating time of the relays at substation B can be determined. This time interval corresponds to the time OW in Fig.2.4-4. In practice the fault current at point C is approximately equal to the fault current for a fault at substation B. Therefore fault current calculations in a power system are calculated for each bus fault. For a fault at point C close to the breaker at substation B, the relays at substation A and B see the same fault current (shunting current component through the capacitive reactance from line to ground is practically ignored). The operating time of the relays at substation A corresponding to this fault current should be delayed to permit the relays at substation B to clear the fault at point C. This corresponds to the time OS. The coordinating time interval is WS which must make allowance for the followings[1]:-

1. error in fault current calculations
2. current transformer ratio errors

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[1] Westinghouse IL 41-101.1 Type CO Relay Coordination and Impulse Margin Time. Page 3.

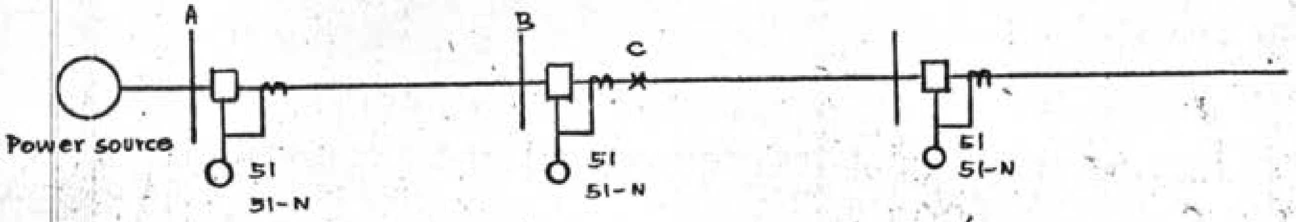
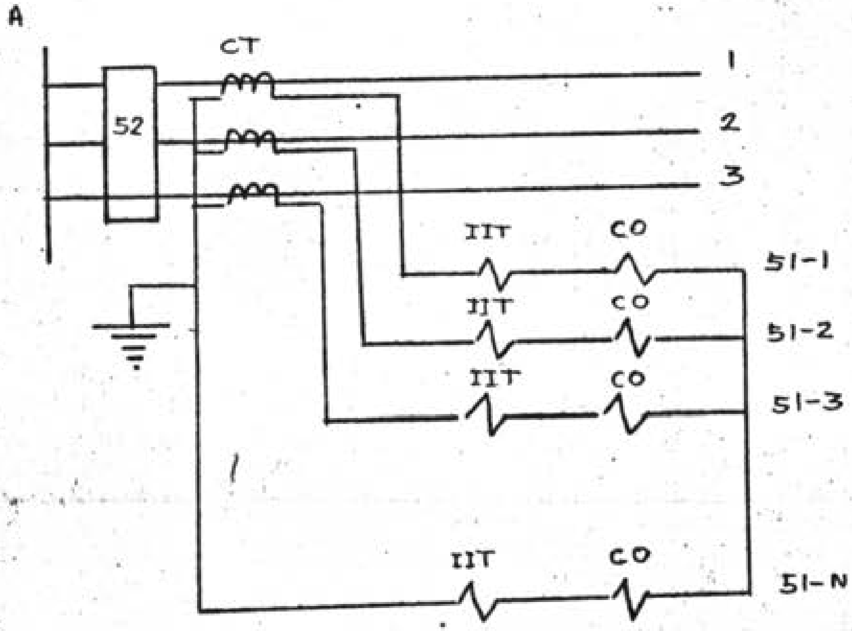


Fig.2.4-1 Transmission Line.



IIT = instantaneous unit actuating coil.
CO = inverse-time-lag actuating coil
52 = power circuit breaker.
51 = phase overcurrent relay.
51-N = ground overcurrent relay.
CT = current transformer.

Fig.2.4-2 Relaying Circuit for Overcurrent Line Protection.

52TC = trip coil of power circuit breaker.
52a = disagreement contact of the breaker.
IIT - instantaneous trip contact
CO - time delay contact.
ICS - indicating contactor switch.

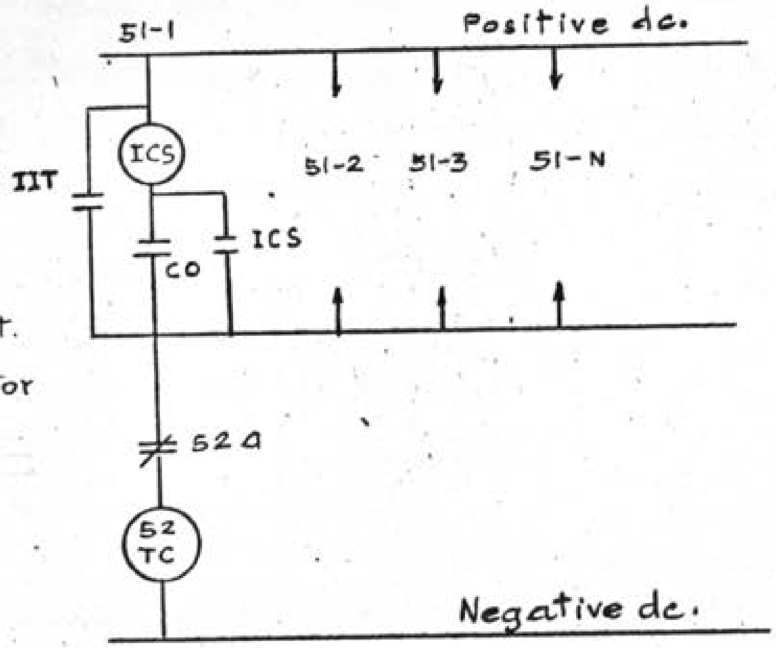
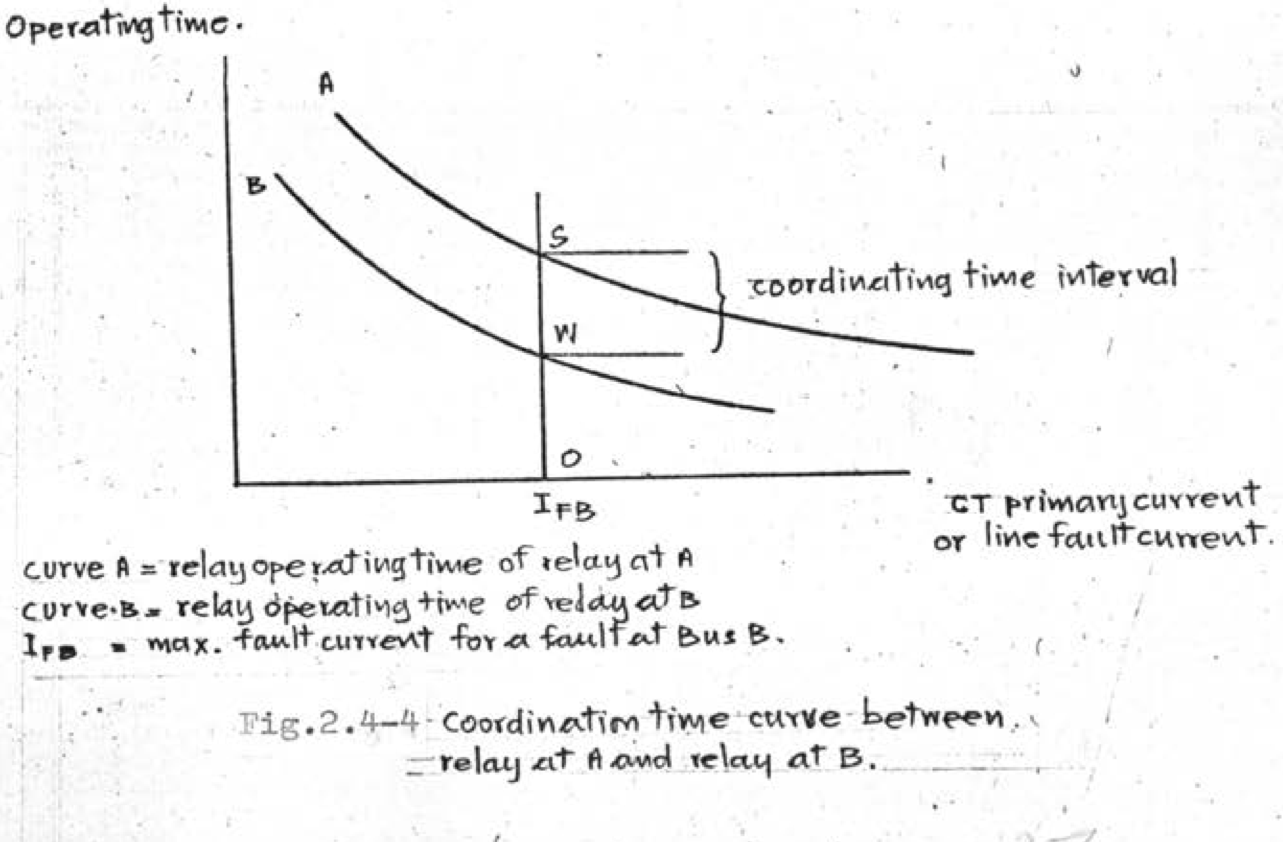


Fig.2.4-3 Auxiliary d.c. trip circuit.



curve A = relay operating time of relay at A
curve B = relay operating time of relay at B
I_{FB} = max. fault current for a fault at Bus B.

Fig.2.4-4 Coordination time curve between relay at A and relay at B.

3. setting errors
4. relay operating time variations
5. relay overtravel
6. breaker operating time

The recommended coordinating time interval is 0.5 seconds.[1] The relay coordinations are carried out between phase relays at substation A and phase relays at substation B and also between the ground relay at substation A and the ground relay at substation B.

The ground and phase instantaneous pick-up currents of the relays at substation A are determined by the maximum line fault current and the maximum ground fault current at the substation B, multiplied by a factor of about 1.35 so that the instantaneous trip occurs only for a fault within the line section A-B.[2]

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[1] Ibid.

[2] Westinghouse Electric Corporation Relay Instrument Devision. Applied Protective Relaying. Newark. New Jersey. Chapter 8 Page 22.