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RELAY-OPERATED ADAPTER: A SUPERIOR REPLACEMENT FOR I$_S$-LIMITER

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ABSTRACT

This paper develops an adapter suitable for uses in high voltage systems to connect series short-circuit Current Limiting Reactors (CLRs) at no constant power losses. The methodology involves the use of protective relays to open-circuit the conducting bar parallel to the Current Limiting Reactor, during fault.

KEYWORDS: Adapters, conducting bar, Current Limiting Reactor, Methodology, Power losses, Protective relays, Short-circuit currents, Terminal.

INTRODUCTION

The speed at which current reversal occurs at the isolator point in the Improved I$_S$-Limiter is very decisive in limiting the anticipated short-circuit current in a power system [1]. The adapter can offer better improvements to the I$_S$ – Limiter [2, 3, 4]. With the use of the adapter, the circuit breaker (CB) and the Current Limiting Reactor (CLR) can be coupled in a similar way to the Improved I$_S$ – Limiter arrangement as already shown in other research works [5].

The earlier work on the adapter usage mentioned above , however, did not use any particular system and more importantly, did not specify the dimensions of the adapter to help ascertain whether there shall be adequate clearances between phases or not. This work uses a 132kV, PINGGAO GROUP Circuit breaker shown in figure 1, to address this problem.

Figure 1: 132kV, PINGGAO GROUP Circuit breaker

THE CIRCUIT BREAKER (CB) COMPONENTS

The CBs are essential components of the entire HV switchgear portfolio. CBs consist of the interrupter unit, post insulator, control system, operating mechanism and the base frame (pillar) [6, 7]. At the top of the interrupter unit as well as the junction of the interrupter unit and the post insulator are terminals where the power line enters/leaves the CB. In other words, the CB is always in series with the feeder [8]. The terminals on the interrupter unit/post insulator are shown in figure 2.

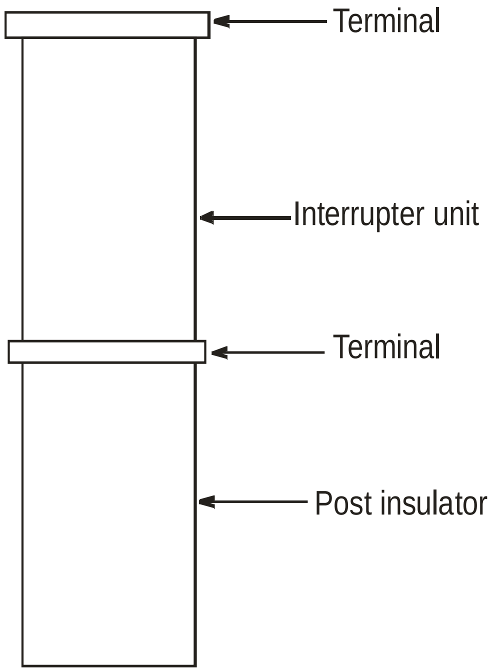


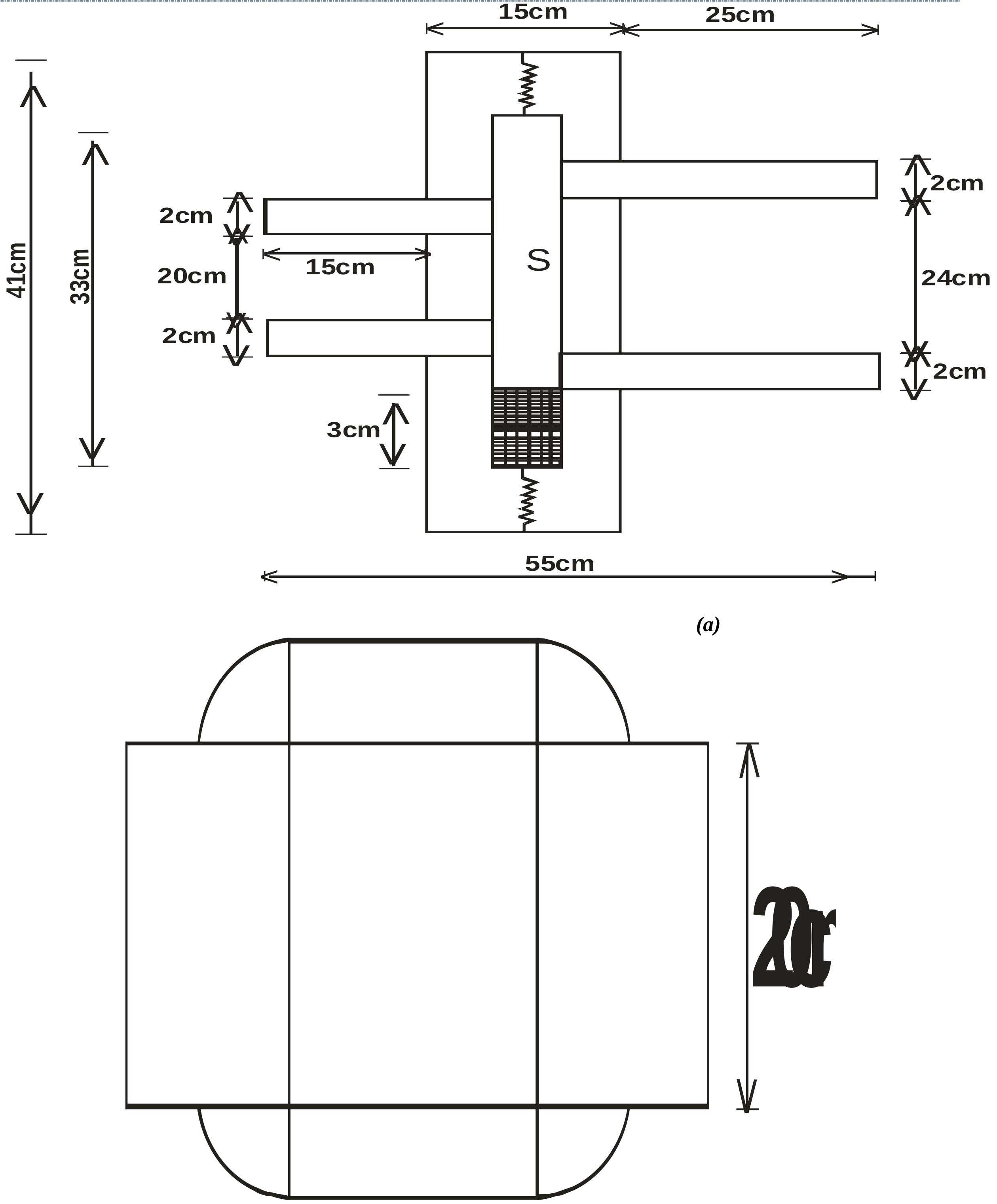
Figure 2: Post Insulator/Interrupter unit of a CB

THE CB POST INSULATOR/INTERRUPTER UNITS

As seen in figures 1 and 2, these are spaced 135 centimeters between phases. The terminals are 30 centimeters wide, while the termination points are 20 centimeters wide as shown in figure 3(b).

THE ADAPTER

The adapter for fitting on the circuit breaker terminal is shown in figure 3. The cross-sectional area of the sliding rod, S, is the same as that for the circuit breaker moving contact rod. This should be so since their current densities should be the same [9]. The adapter shown in figure 3(a) is meant for 132kV circuit breaker terminal which is 20cm wide as shown in figure 3(b). The sliding rod S is inside an insulated casing.



(a)

(b)

Figure 3: Dimensions (a) for the adapter and (b) for the existing CB terminal

THE ADAPTER DIMENSIONS

The terminals of the adapter are 2cm tick and 20cm wide. The CB terminal is 30cm wide and the maximum conducting width of the adapter is 28cm as can be seen from figure 3 (a), so there shall be no compromise in clearances between poles (phases) for horizontal orientation of the adapter.

PARTS OF THE ADAPTER

The parts of the adapter are as explained with the aid of figure 4.

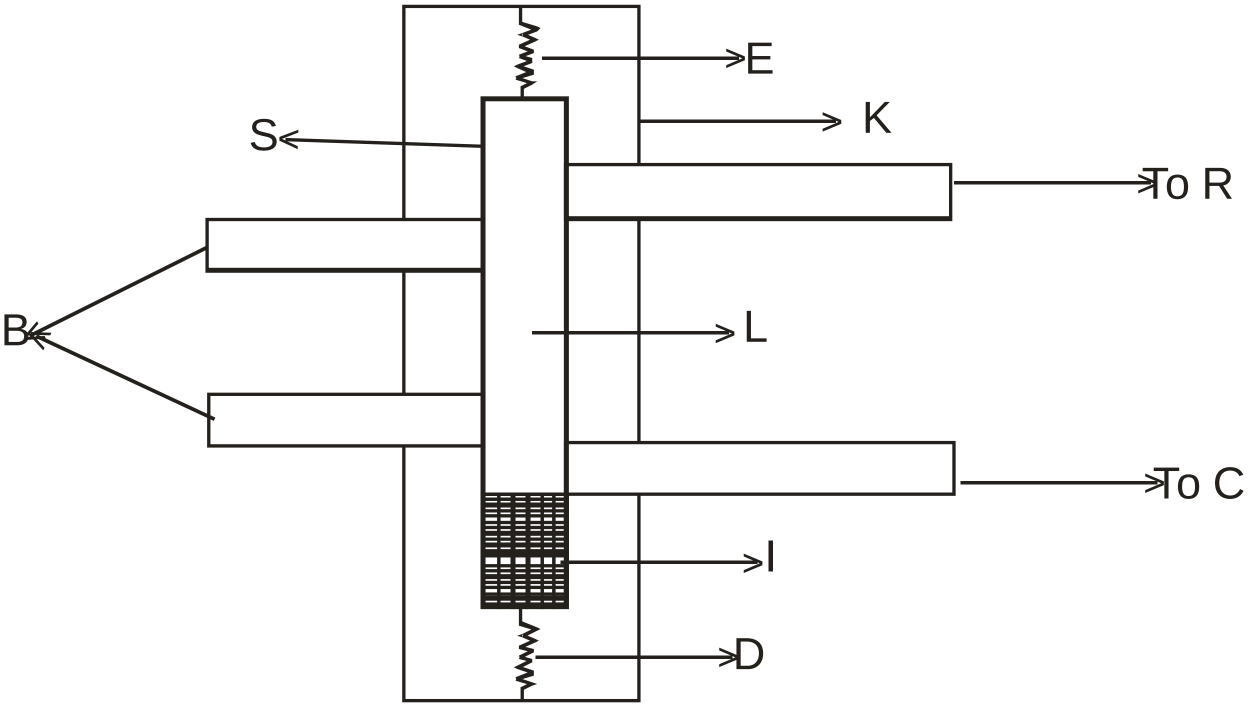


Figure 4: Parts of the adapter explained

Legend to figure 4

B = supply contact to CB
C = CLR bypass bar
D = spring (discharges to open-circuit C i.e. pushes S to bring I part of S in contact with C)
E = spring (discharges to close C back to circuit after fault is cleared)
I = non-conducting part of S that open-circuits C during fault
L = conducting part of S always in contact with R and B but closes and opens C during normal and fault condition respectively
R = Current Limiting Reactor
S = moveable (sliding) contact rod
K = insulated casing

OPERATING THE ADAPTER IN THE CIRCUIT

Open circuiting and closing the CLR by-pass bar, **C**, is triggered by a relay different from the relay for tripping the feeder CB. However, the relays are fed the same current quantity from the same current transformer (CT). The relays are located in the control room, while the CTs, the circuit-breaker and the current limiting reactor are located in the switch yard as shown in the block diagram of figure 5 [10].

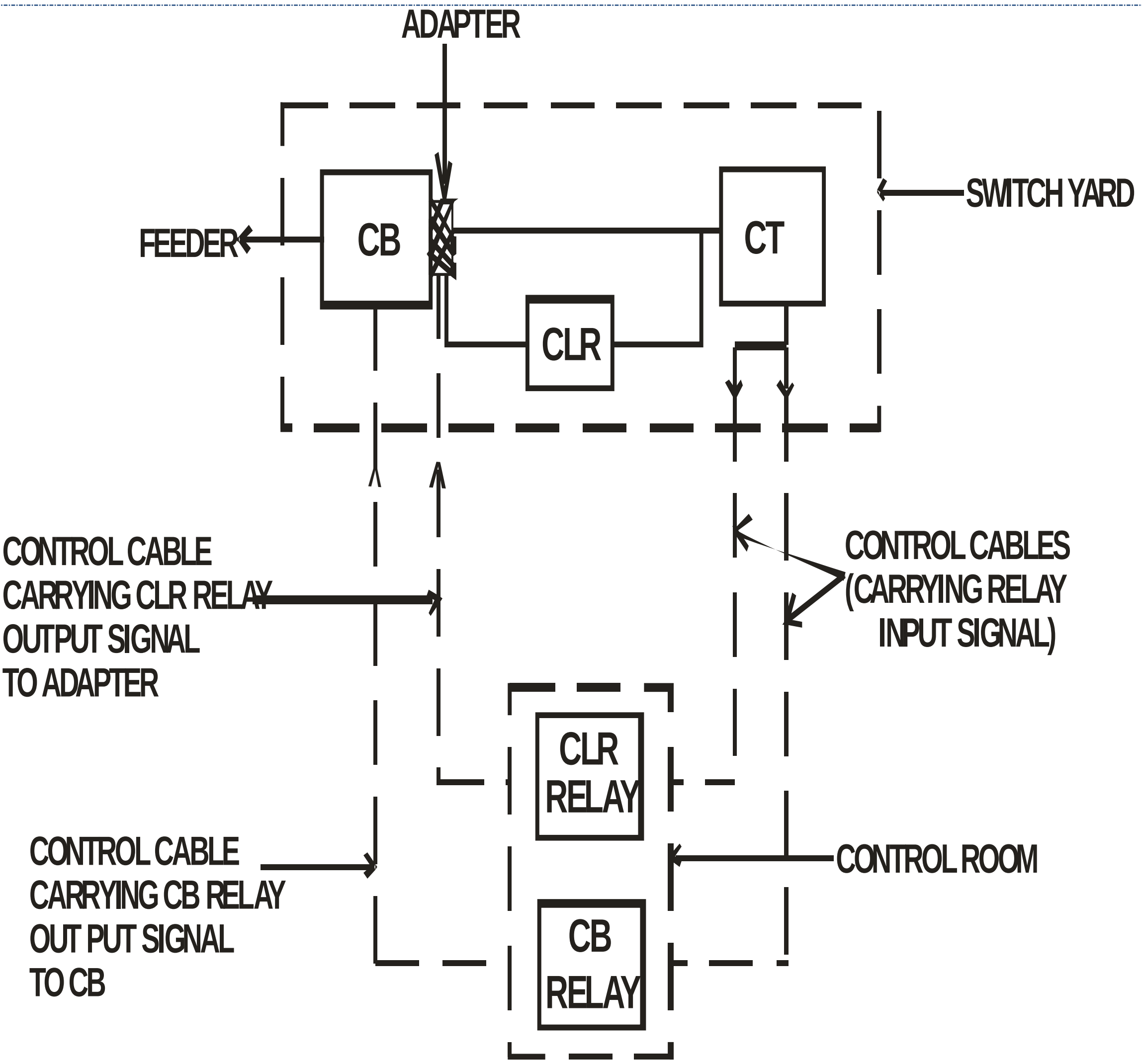


Figure 5: Block diagram showing the locations of CB, Adapter, CLR, CT and Relays.

RELAY CO-ORDINATION

Co-ordination of relays is an integral part of the overall system protection and is absolutely necessary to:

- Isolate only the faulty circuit or apparatus from the system.
- Prevent tripping of healthy circuits or apparatus adjoining the faulted circuit or apparatus.
- Prevent undesirable tripping of other healthy circuits or apparatus elsewhere in the system when a fault occurs somewhere else in the system.
- Protect other healthy circuits and apparatus in the adjoining system when a faulted circuit or apparatus is not cleared by its own protection system.

METHODS OF RELAY CO-ORDINATION

A correct relay co-ordination can be achieved by one or all of the following methods:

- Current graded systems
- Time graded systems
- A combination of time and current grading.

A common aim of all these methods is to give correct discrimination or selectivity of operation. That is to say that each protective system must select and isolate only the faulty section of the power system network, leaving the rest of the healthy system undisturbed. This selectivity and co-ordination aim at choosing the correct current and time settings or time delay settings of each of the relays in the system network.

RELAY CO-ORDINATION PROCEDURE

Correct relay application requires knowledge of the fault current that can flow in each part of the network. Since large scale tests are normally impracticable, system analysis must be used. It is generally sufficient to use machine transient reactance, X'_d and to work on the instantaneous symmetrical current [11].

The basic rules for correct relay co-ordination can generally be stated as follows:

- Whenever possible, use relays with the same operating characteristics in series with each other.
- Make sure that the relay farthest from the source has current setting equal to or less than the relays behind it. That is, the primary current required to operate the relay in front is always equal to or less than the primary current required for operating the relay behind it.

PRINCIPLES OF TIME/CURRENT GRADING

Among the various possible methods used to achieve correct relay co-ordination are those using either time or over-current or a combination of both time and over-current. The common aim of all three methods is to give correct discrimination. That is to say, each must select and isolate only the faulty section of the power system network, leaving the rest of the system undisturbed [11].

DISCRIMINATION BY TIME

In this method, an appropriate time interval is given to each of the relays controlling the CB in a power system to ensure that the breaker nearest to the fault opens first. A simple radial distribution system is shown in figure 6, to illustrate the principle.

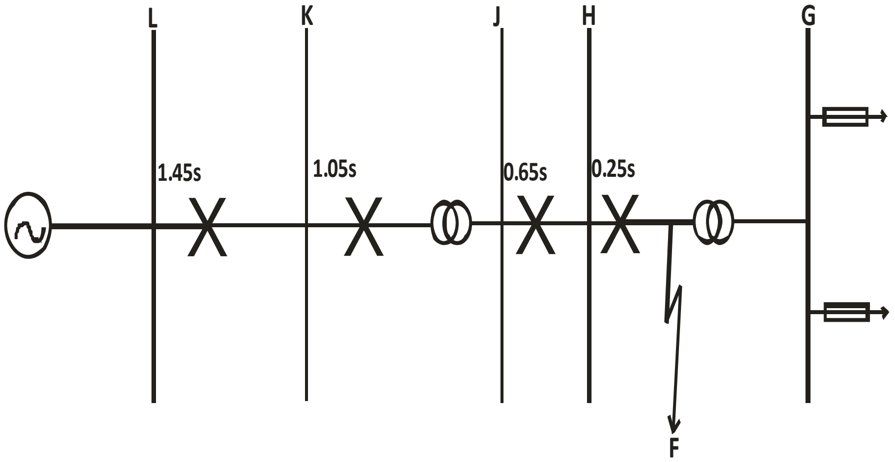


Figure 6: Radial system with time discrimination

Circuit breaker protection is provided at stations H, J, K and L, that is at the in-feed end of each section of the power system. Each protection unit comprises a definite time delay over-current relay in which the operation of the current sensitive element simply initiates the time delay element. It is the time delay element that provides the means of discrimination. As seen in figure 6, the operation of the relay at station H is delayed 0.25s to give room for the fuse to blow for the fault on the secondary side of transformer, G. The relays behind station H (i.e. stations J, K and L) are progressively delayed for 0.4s from station H (i.e. 0.65s, 1.05s, and 1.45s respectively) as shown.

DISCRIMINATION BY CURRENT

Discrimination by current relies on the fact that the fault current varies with the position of the fault because of the difference in impedance values between the source and the fault. Hence, typically, the relays controlling the various CBs are set to operate at suitably tapered values such that only the relay nearest to the fault trips its breaker. Figure 7 illustrates the method.

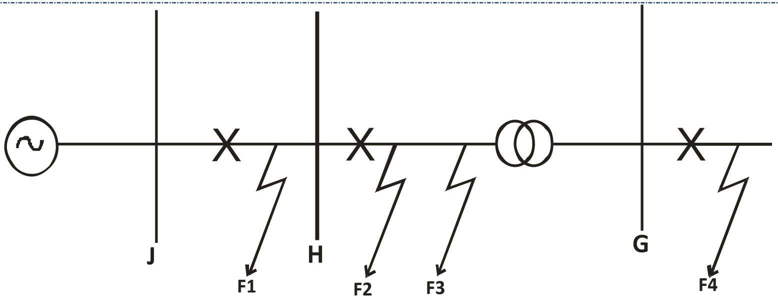


Figure 7: Radial system with current discrimination

Because of the variation of the fault current with the position of the fault, the breaker at station G would clear F_4 faster than the ones behind it (i.e. stations H and J), while the breaker at station H would clear F_2 and F_3 faster than the breaker at station J. However, it is not practical to distinguish between a fault at F_1 and F_2 since the distance between them may be only a few meters, corresponding to a change in fault current of approximately 0.1%. Also, in practice, there could be variation in the source fault level to a lower value. At this lower fault level, the fault current should be lower than the initial value even for a fault close to station J, such that a relay set at the initial value would not protect any of the cable section concerned. Discrimination by current is therefore not a practical proposition for correct grading between the circuit breakers at stations J and H.

DISCRIMINATION BY BOTH TIME AND CURRENT

Each of the two methods described so far has fundamental disadvantage. In the case of discrimination by time alone, the disadvantage is due to the fact that the more severe faults are cleared in the longest operating time. On the other hand, discrimination by current can be applied only where there is appreciable impedance between the two CBs concerned.

Because of the limitations imposed by the independent use of either time or current co-ordination, the inverse time over-current relay characteristic has evolved. With this characteristic, the time of operation is inversely proportional to the fault current level, and the actual characteristic is a function of both "time" and "current" settings.

With figure 8, which is identical to figure 6 except that typical system parameters have been added and, with relay over-current characteristic assumed to be extremely inverse as for the type CDG 14 relay [11], the followings were reached upon referring all the system impedances to a common base of 10MVA while noting that:

$$\frac{(kV).(kV)}{impedance(Z)} = \text{MVA}:$$

7% impedance 4MVA transformer becomes $\frac{7}{100}$ x $\frac{10}{4}$ x 100 = 17.5% impedance on 10MVA base

0.04 ohms 11kV cable between stations H and G becomes $\frac{0.04\ X\ 10}{11\ X\ 11}$ x 100 = 0.33% impedance on 10MVA base.

0.24 0hms 11kV cable between J and H becomes $\frac{0.24\ X\ 10}{11\ X\ 11}$ x 100 = 1.98% impedance on 10MVA base.

22.5% impedance 30MVA transformer becomes $\frac{22.5}{100}$ x $\frac{10}{30}$ x 100 = 7.5% impedance on 10MVA base.

6.2 ohms 132kV overhead line between L and K becomes $\frac{6.2\ X\ 10}{132\ X\ 132}$ x 100 = 0.36% impedance on 10MVA base.

3500MVA 132kV source becomes $\frac{10}{3500}$ x 100 = 0.29% impedance on 10MVA base.

Now, the fault current or fault MVA contributed by the supply source is limited by the impedance between the supply source and the fault point, such that:

(1) The relay at station H is responsible for faults between stations H and G and as such sees the impedance between the supply source and the fault point, namely:
(17.5 + 0.33 + 1.98 + 7.5 + 0.36 + 0.29)% = 27.96% impedance for a fault at its remote end (i.e. at or very close to station G), or (27.96 – 17.5 – 0.33) % = 10.13% impedance for a fault at its station. This means that the relay at station H can clear a minimum fault level of $\frac{10}{27.96\%}$MVA = 35.7MVA and a maximum fault level of $\frac{10}{10.13\%}$MVA = 98.7MVA.

(2) The relay at station J is responsible for faults between stations J and H and as such sees the impedance between the supply source and the fault point, namely: (27.96 – 17.5 – 0.33)% = 10.13% impedance for a fault at its remote end (i.e. at or very close to station H), or (10.13 – 1.98)% = 8.15% impedance for a fault at its station. This means that the relay at station J can clear a minimum fault level of $\frac{10}{10.13\%}$MVA = 98.7MVA and a maximum fault level of $\frac{10}{8.15\%}$MVA = 123MVA.

(3) The relay at station K is responsible for faults between stations K and J and as such sees the impedance between the supply source and the fault point, namely: (10.13 – 1.98)% = 8.15% impedance for a fault at its remote end (i.e. at or very close to station J), or (8.15 – 7.5)% = 0.65% impedance for a fault at its station. This means that the relay at station K can clear a minimum fault level of $\frac{10}{8.15\%}$MVA = 123MVA and a maximum fault level of $\frac{10}{0.65\%}$MVA = 1538MVA.

(4) The relay at station L is responsible for faults between L and K and as such sees the impedance between the supply source and the fault point, namely: (8.15 – 7.5)% = 0.65% impedance for a fault at its remote end (i.e. at or very close to station K), or (0.65 – 0.36)% = 0.29% impedance for a fault at its station. This means that the relay at station L can clear a minimum fault level of $\frac{10}{0.65\%}$MVA = 1538MVA and a maximum fault level of $\frac{10}{0.29\%}$MVA = 3448.3MVA.

The above results mean that:

- Relay at station H must discriminate with 200A fuse at fault level up to 35.7MVA, (i.e. $\frac{35700000}{\sqrt{3}X\ 3300}$ = 6246A at 3.3KV or $\frac{35700000}{\sqrt{3}X\ 11000}$ = 1874A at 11KV).

- Relay at station J must discriminate with relay at station H at fault level up to 98.7MVA, (i.e. $\frac{98700000}{\sqrt{3}X\ 3300}$ = 17268A at 3.3KV or $\frac{98700000}{\sqrt{3}X\ 11000}$ = 5180A at 11KV).

- Relay at station K must discriminate with that at station J at fault level up to 123MVA, (i.e. $\frac{123000000}{\sqrt{3}X\ 3300}$ = 21519A at 3.3KV or $\frac{123000000}{\sqrt{3}X\ 132000}$ = 538A at 132KV).

- Relay at station L must discriminate with that at station K at fault level up to 1538MVA, (i.e. $\frac{1538000000}{\sqrt{3}X\ 3300}$ = 269080A at 3.3KV or $\frac{1538000000}{\sqrt{3}X\ 132000}$ = 6727A at 132KV).

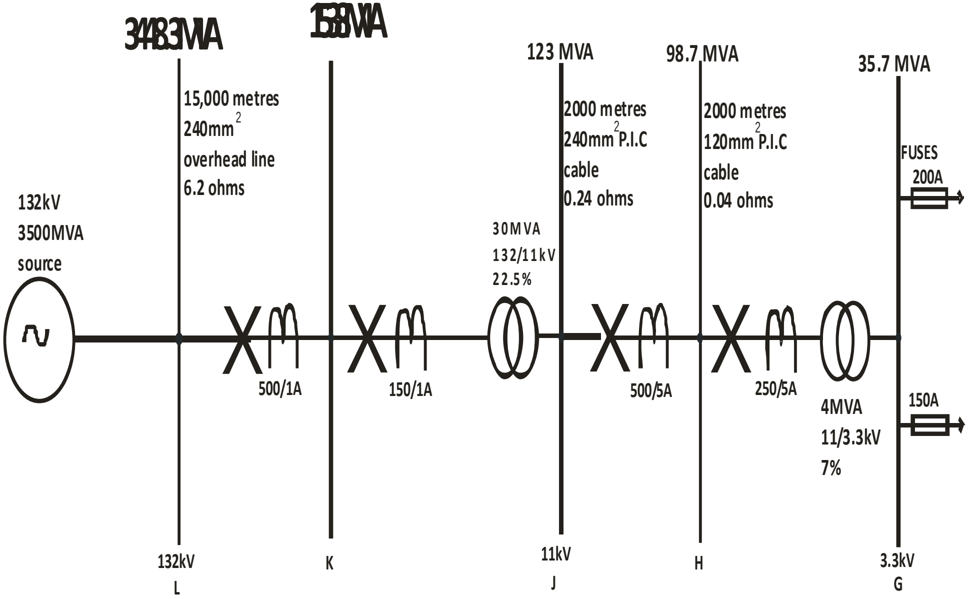


Figure 8: Time and current grading

A comparison between the relay operating times shown in figure 6 and the times obtained from the discrimination curves of figure 8 at maximum fault levels reveals significant differences as summarized in table 1. Table 2 shows the clearance times for the relays from the discrimination curves of figure 8 at minimum fault levels (i.e. for faults at the remote ends of the protected sections).

Table 1: Comparison of operating times from figure 6 and discrimination curves of figure 8 at maximum fault level.

Relay station	Fault level (MVA)	Time from figure 6 (in seconds)	Time obtained from discrimination curves of figure 8 (in seconds)
H	98.7	0.25	0.07
J	123	0.65	0.33
K	1538	1.05	0.07
L	3448.3	1.45	0.25

Source: [General Electric Company (GEC) protective relay application guide, 1987]

Table 2: Clearance times of the relays from the discrimination curves of figure 8 at minimum fault level.

Relay station	Fault level (MVA)	Time from the discrimination curves of figure 8 (in seconds)
H	35.7	0.17
J	98.7	0.42
K	123	0.86
L	1538	0.39

Source: [General Electric Company (GEC) protective relay application guide, 1987]

To finalize the co-ordination study, it is necessary to access the average operating time for each extremely inverse over-current relay at its maximum and minimum fault levels and to compare this with the operating time shown in figure 6 for definite time over-current relay. This is shown in table 3. It should be noted that the table (i.e. table 3) is obtained from tables 1 and 2, by getting the average relay operating times from discrimination curves of figure 8 (i.e. the average of relay time of operation for maximum fault level and minimum fault level as seen from the discrimination curves of figure 8.

Table 3: Average operating time of relays compared with the operating time of figure 6.

Relay station	Fault level (max./min. MVA)	Relay operating times from discrimination curves of figure 8 (i.e. relay operating times for maximum/minimum fault levels in seconds)	Average operating time (in seconds) i.e. the average operating time of relay for the maximum and the minimum fault level	Relay operating time from figure 6 (in seconds)
H	98.7/35.7	0.07/0.17	0.12	0.25
J	123/98.7	0.33/0.42	0.375	0.65
K	1538/123	0.07/0.86	0.465	1.05
L	3448.3/1538	0.25/0.39	0.32	1.45

Source: [General Electric Company (GEC) protective relay application guide, 1987]

Table 3 clearly shows that when there is a large variation in fault current along the system network, the overall performance of the inverse time over current relay is far superior to that of the definite time-over current relay.

ADAPTER/CB RELAYS CO-ORDINATION

Co-ordination by time alone is all that is required between the CLR relay and the feeder CB relay since both are in the same place and fed by the same current transformer, CT, (meaning they see the same fault level at any instant). However, since the feeder relay has to co-ordinate with the relays behind it in the system, there should first be discrimination between the feeder CB relay and the relays behind it by inverse time over current principle, since discriminating these relays by time alone, as seen from figure 6, means longest fault clearing time for faults closest to the power source [11]. After discriminating these relays, the feeder relay time should then be assigned to the CLR relay, while the feeder relay is delayed by 0.1s for the fault near it, such that, for the case at hand, tables 1, 2 and 3 become tables 4, 5 and 6 respectively.

Table 4: Relay operating time at maximum fault level.

Relay station	Fault level (MVA)	Time (seconds)
CLR	98.7	0.07
H	98.7	0.17
J	123	0.33
K	1538	0.07
L	3448.3	0.25

Table 5: Relay operating time at minimum fault level.

Relay	Fault level (MVA)	Time (seconds)
CLR	35.7	0.09
H	35.7	0.236
J	98.7	0.42
K	123	0.86
L	1538	0.39

Table 6: Average operating time of relays compared with operating times from figure 6.

Relay	Fault level (max./min. MVA)	Relay operating time for maximum/minimum fault levels in seconds.	Average time (seconds)	Time from figure 6
CLR	98.7/35.7	0.07/0.09	0.08	-
H	98.7/35.7	0.17/0.236	0.203	0.25
J	123/98.7	0.33/0.42	0.375	0.65
K	1538/123	0.07/0.86	0.465	1.05
L	3448.3/1538	0.25/0.39	0.32	1.45

The 0.1s delay on relay at station H is achieved by adjusting its time multiplier setting (TMS) to 0.1, while the time multiplier setting (TMS) for the current limiting reactor (CLR) relay is set at 0.04 as shown below:

For a fault current of 5180A at 11kV, C.T. ratio of 250/5A, and normal full load current of 105A (i.e. 350A at 3.3kV), the settings are as follows:

Secondary value of short-circuit current = 5180 x $\frac{5}{250}$ = 103.6A

Secondary value of full load current = 105 x $\frac{5}{250}$ = 2.1A

With 100% current setting, relay current setting I_s = 2.1A

Therefore plug setting = 2.1

Fault current of 103.6A corresponds to 49.333333 times I_s, i.e.

$$\text{Multiples of plug setting, MPS} = \frac{103.6}{2.1} = 49.333333$$

Now, for the two relays (the CLR and the CB relays) seeing the same magnitudes of fault current to operate in 0.07 seconds and 0.17 seconds respectively after occurrence of a fault, their time multiplier settings, TMS, has to be as follows:

Using the equation:

$$t = TMS \times TM \quad (1)$$

Where

t = the desired time of relay operation

TM = relay time of operation obtained from the standard Inverse Definite Minimum Time (IDMT) Curve at TMS = 1

OR

From table 7, for a standard inverse relay [12] at TMS = 1

Table 7: Relay characteristics to IEC 60255

RELAY CHARACTERISTIC	EQUATION
Standard Inverse	$t = TMS \times \frac{0.1400}{(I_r^{0.02} - 1)}$
Very Inverse	$t = TMS \times \frac{13.5}{(I_r - 1)}$
Extremely Inverse	$t = TMS \times \frac{80}{(I_r^2 - 1)}$
Long time standard inverse	$t = TMS \times \frac{120}{(I_r - 1)}$

$$TM = \frac{0.1400}{(I_r^{0.02} - 1)} \quad (2)$$

Where

$I_r = (I/I_s)$ = multiples of plug setting

I = secondary value of short-circuit current

I_s = relay setting current

For t equal to 0.07 seconds and I_r equal to 49.333333 for the CLR relay,

$$TMS = \frac{0.07 \times [(49.333333)^{0.02} - 1]}{0.14}$$

$$= 0.04$$

For t equal to 0.17 seconds and I_r equal to 49.333333 for the CB relay,

$$TMS = \frac{0.17 \times [(49.333333)^{0.02} - 1]}{0.14}$$

$$= 0.1$$

The response of the CLR series connection time and feeder CB opening time for a fault level of 5.18kA limited downwards to 1.8738kA is shown in figure 9, while the graphics is shown in table 8.

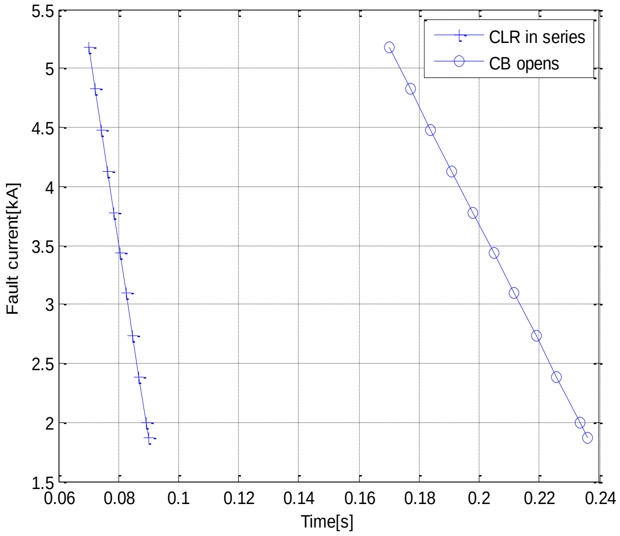
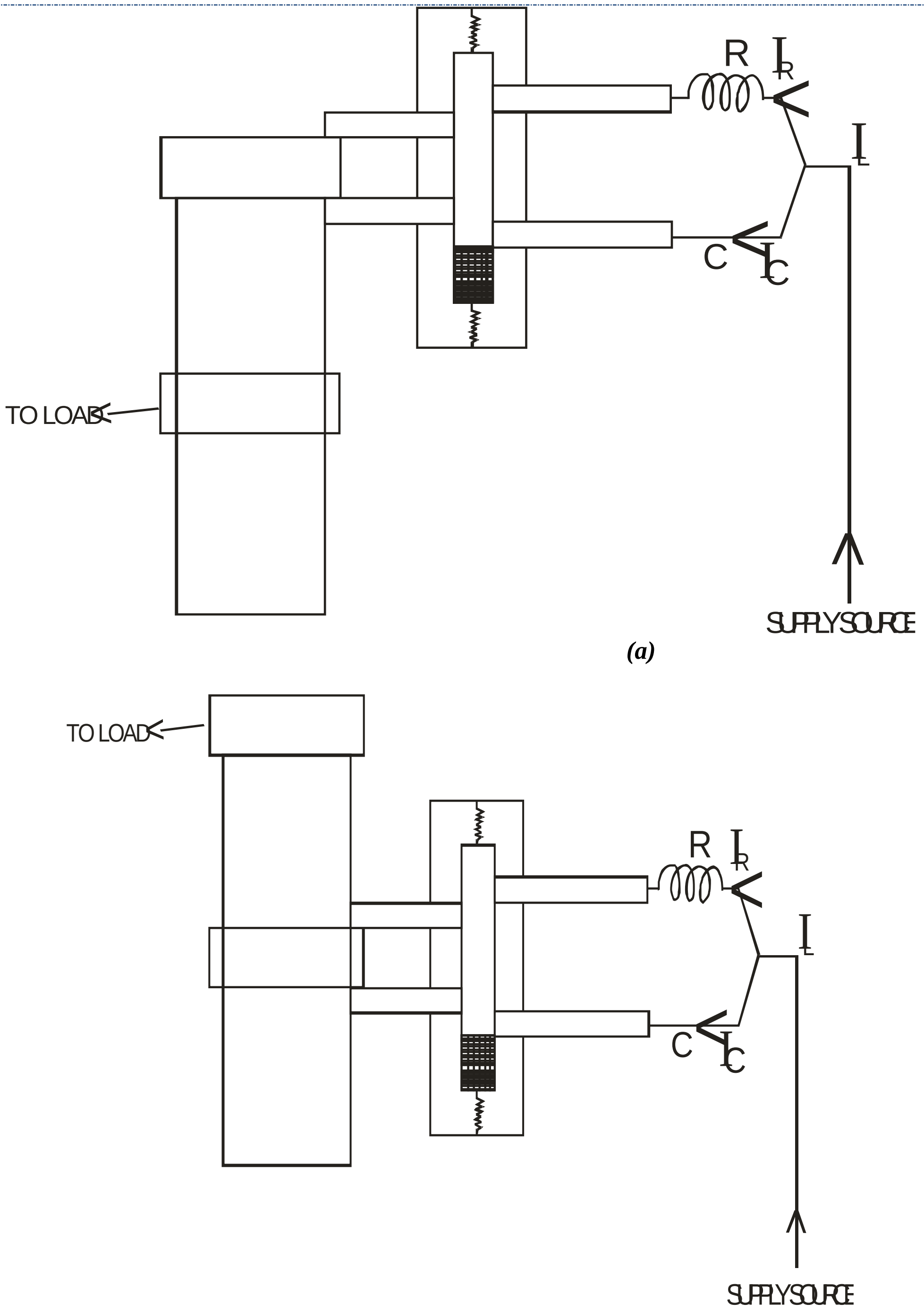


Figure 9: Response curves of CLR series connection time and feeder CB opening time

Table 8: CLR connection time and the corresponding CB opening time for 5.18kA fault level limited with CLR downwards to 1.8738kA.

FAULT CURRENT (kA)	CLR CONNECTION TIME IN SECONDS	CB OPENING TIME IN SECONDS
5.1800	0.0700	0.1700
4.8300	0.0721	0.1770
4.4800	0.0742	0.1840
4.1300	0.0764	0.1910
3.7800	0.0785	0.1979
3.4300	0.0806	0.2049
3.1000	0.0826	0.2115
2.7300	0.0848	0.2189
2.3800	0.0869	0.2259
2.0000	0.0892	0.2335
1.8738	0.0900	0.2360

The prototype connection that gives the desired result is shown in figure 10. To implement this on an existing CB, no modification is required on the CB terminals.



(a)

(b)

Figure 10: CLR/CB prototype connection very suitable for existing CBs

Legend to figure 10

R = Current Limiting Reactor
I_R = Current through the Current Limiting Reactor
C = Current Limiting Reactor bypass bar
I_C = current through the Current Limiting Reactor bypass bar

DISCUSIONS

INTERFACING THE CB/CLR WITH THE ADAPTER

BRINGING THE CLR IN SERIES WITH THE FEEDER DURING FAULT

From figures 10, the sliding rod, S, is in constant contact with CLR, R. At the parallel arrangement of R and C, the L part of S is in contact with R. At series connection of R with the feeder, the L part of S is in contact with R. During the process of open-circuiting C, the L part of S is also in contact with R. Finally, when returning C back to the circuit, the L part of S is as well in contact with R. The result of L, the conducting part of the rod S, being in steady contact with R is that during the time S makes or breaks contact with C, no arc shall be involved, so arc energy management is not an issue [5].

Again, from figures 4 and 10, it is clear that there shall be re-utilization of energy between the springs D and E. The potential energy stored in the spring D, (which should be pre-charged at the factory by the manufacturer), turns to the kinetic energy required to push S. This kinetic energy converts to potential energy stored in the spring, E, as the force charges it (spring E), i.e. when E discharges, D is charged, and vice versa.

RELAY CO-ORDINATION
From tables 4, 5 and 6, it is clear that the deliberate introduction of a little time delay on the feeder relay at station H, to allow series connection of the CLR before its operation has no bad effect on the discrimination already achieved between stations H, J, K and L. As seen from both tables 4 and 5, and figure 9, the TMS of 0.04 and 0.1 respectively for CLR and CB relays at station H gave 0.1s discrimination for maximum fault level (98.7MVA) and up to 0.146s discrimination for minimum fault level (35.7MVA). Tables 4 and 5 show no compromise in the discrimination between the relays at stations H and J [5].

CONCLUSIONS
Adapters very suitable for coupling series short-circuit Current Limiting Reactors and circuit breakers on feeders to achieve no constant power losses have been presented in this paper. Its use is not restricted to any high voltage level. Unlike the I_S-Limiter, none of its parts need to be replaced when it operates [2, 3, 4]. It is therefore really superior to the I_S-Limiter.

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