OPEN ACCESS

International
Journal
Of Modern Engineering Research (IJMER)

A New Approach to Implementing Fault Current Limiting Reactors (CLRS) On Feeders with Negligible Constant Power Losses

[1]AKPEH V.A., [2]MADUEME T.C., [3]EZECHUKWU O.A.
[1]*Transmission Company of Nigeria (TCN)*
fenarasengineeringltd@gmail.com
[2]*Department of Electrical Engineering, University Of Nigeria, Nsukka, Nigeria*
theophilus.madueme@unn.edu.ng
[3]*Department of Electrical Engineering, Nnamdi Azikiwe University, Awka*

ABSTRACT:- The deficiency in the use of series current limiting reactors (CLRs) on feeders is discussed in this paper. It also suggests the use of adapters on existing circuit breakers (CBs) to mitigate this problem.

Keywords:- adapters, reactors, short-circuit currents, current limiting reactor.

I. INTRODUCTION

The increasing rate of energy demand in any modern power system imposes challenges on the development of generation and transmission systems. As an unwelcome consequence, short-circuit currents are day-to-day increasing. Many utilities all over the world are experiencing the problem of astonishing short-circuit levels. For instance, some utilities in Brazil, China, Iran and Kuwait, may be mentioned [1]. Of the numerous short circuit current reduction techniques available, the CLR is the most practical; it can reduce short-circuit current, which results from plant expansion and power source additions, to levels within the rating of the equipment on the load side of the reactor [2, 3]. However, for many decades now, its use on feeders is limited to critical feeders due to the constant power losses that it imposes on the system as it carries the full load current [4]. Recent research has given design modifications on the CB interrupter unit that results in minimal constant power losses arising from the use of series CLRs [10], but this technology cannot be used on the existing CBs. The CLR, apart from limiting short-circuit, can also provide wave shape smoothing and absorb transients caused by phase fired Silicon Controlled Rectifiers (SCRs), and provide protection to the HV rectifiers and the controller’s SCRs by limiting the current flowing during an arc or spark [5, 6].

In this paper, the use of adapters to interface the CB and the CLR to achieve minimal constant power losses even on existing CBs is given. The main objective of this work is to find a suitable way to connect the CLR such that:

- At normal condition, the CLR remains in parallel to the feeder.
- At fault condition, the CLR becomes in series with the feeder.

II. TECHNICAL SPECIFICATIONS OF CLRS

The followings are important technical parameters of CLRs:

- Nominal voltage
- Nominal frequency
- Short circuit capacity of the system
- Basic insulation level
- Continuous operating current
- Rated inductance
- Type (dry or oil immersed)
- Class (indoor or outdoor)

2.1 Selection of CLR inductance

Appropriate value of the CLR inductance, L, is dependent on the system under study. In figure 1, maximum short circuit current of a simulated system [1], is depicted as a function of CLR reactance, ωL. As seen in figure 1, as L increases, the slope of the I_{SC} – L curve decreases until the efficiency limit (in this case, 50Ω) is reached, beyond which variation of L will not significantly change I_{SC}. From the short circuit reduction point of view, this efficiency limit is an effective value for ωL. However, in practice, since transient stability, voltage stability and TRV restrictions should also be taken into consideration ωL is not necessarily selected to be the effective value.

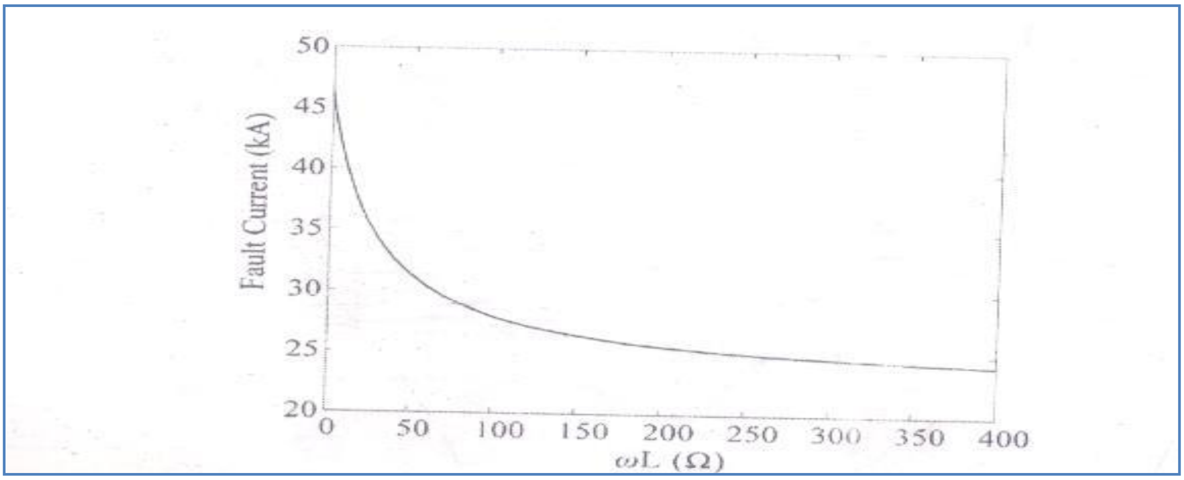


Figure 1: Effect of inductance on fault current level.

III. CLR CONNECTION

As mentioned earlier, the only way to achieve minimal constant power losses in implementation of CLRs on feeders is by a connection arrangement where the CLR though permanently connected to the feeder, shall carry an infinitesimal fraction of the full load current rather than the full load current, during normal condition; but during fault condition, carries the full current. This is shown in figure 2.

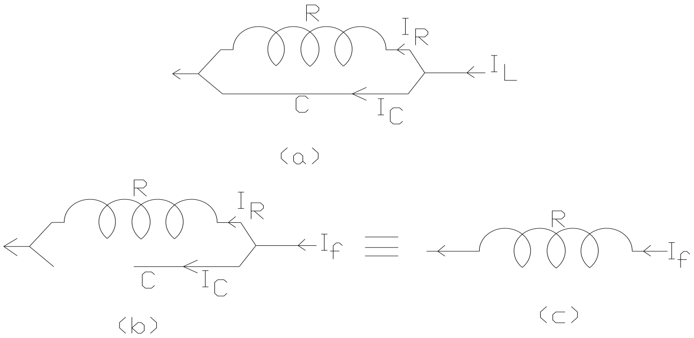


Figure 2: CLR connection during (a) healthy condition and (b)/(c) fault condition.

In figure 2, R is the CLR; C is the CLR bypass bar; I_R *is the current through the CLR;* I_C *is the current through the CLR bypass bar;* I_L *is the normal load current;* I_f *is the fault current.*

As seen in figure 2, (a) represents the proposed connection during normal condition, while (b) represents the proposed connection (open circuited C) during fault. At normal condition, $I_C >> I_R$ (or $I_R \approx 0$ and $I_C \approx I_L$), meaning infinitesimal losses across R. Open circuiting C before opening the circuit breaker (CB) would bring R in series with the feeder as shown in figure 2(c) (i.e. figure 2(b) redrawn).

The questions now are:

- At what point on the feeder can this connection be achieved?
- How could C be open-circuited during fault and closed back after fault?
- How could open circuiting C just before opening the CB be achieved?

Answers to the above questions are provided in this paper.

IV. THE CIRCUIT BREAKER (CB)

The CBs are essential component of the entire HV switchgear portfolio. They are important part of live tank breakers, dead tank breakers, gas insulated switchgear, any hybrids, for example, mixed technology switch system and generator CBs. CBs consist of the interrupter unit, post insulator, control system, operating mechanism and the base frame (pillar) [7, 8].

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. The terminals on the interrupter unit/post insulator are shown in figure 3.

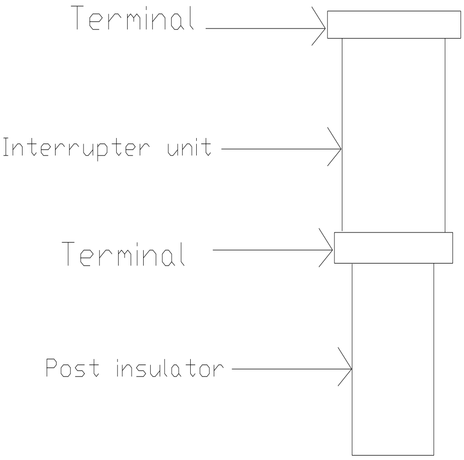
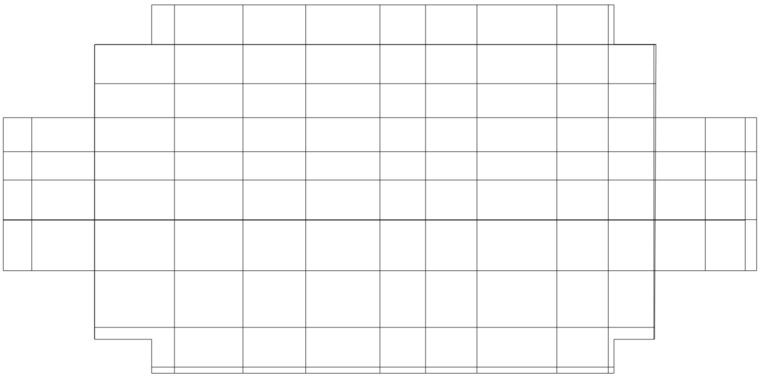


Figure 3: Post Insulator/Interrupter unit of a CB

4.1 THE CB TERMINALS

No modification is required on this terminal for the adapter to be fitted onto it. This is explained with the aid of figure 4.



(a)

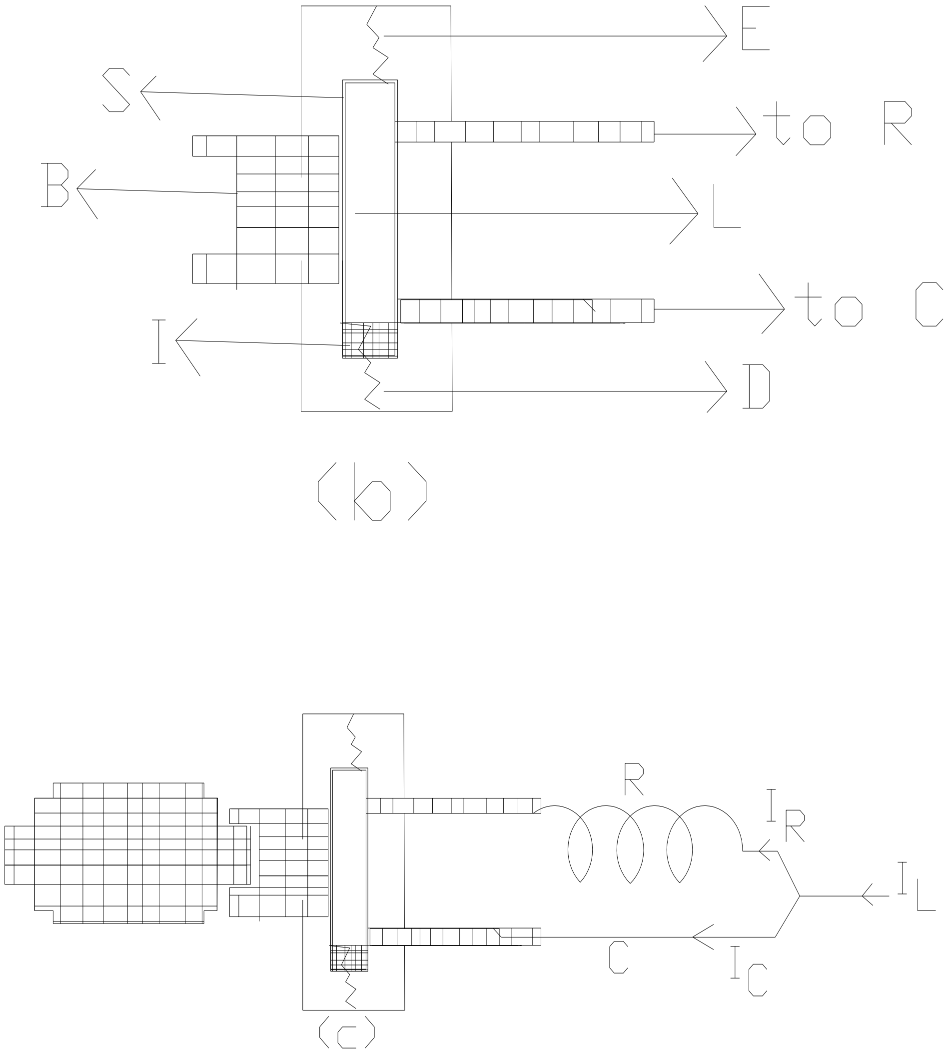


Figure 4: The CB terminal, the adapter and the CLR

B = supply contact to CB; R = CLR; C = CLR bypass bar; S = moveable (sliding) contact rod; I_C *= current through C; I = non-conducting part of S that open-circuits C during fault;* I_R *= current through the CLR; L = conducting part of S always in contact with R and B but closes and opens C during normal and fault condition respectively;* I_L *= normal load current; D = spring (discharges to open-circuit C i.e. pushes S to bring I part of S in contact with C);* I_F *= fault current; E = spring (discharges to close C back to circuit after fault is cleared).*

Figure 4(a) shows the CB terminal where no modification is required for fitting the adapter. (b) Is the adapter on which both the CB terminal and figure 2 are connected as shown in (c).

Notice from figure 4(b) that **S** is a sliding contact rod that comprises the conducting part, **L**, and the non-conducting part, **I**. Open-circuiting **C** is achieved when the spring, **D**, discharges and pushes the sliding contact rod, **S**, bringing **C** completely in contact with **I** part of **S**. This should happen during fault, just before the breaker starts interrupting the fault current. There should be an interlock between the adapter and the CB such that the CB cannot close if the spring, **E** is discharged. This ensures that the CLR remains in series should the CB be closed on fault. However, E should be programmed to automatically discharge and maintain R-C parallel (R//C) arrangement after successful closure of the CB.

V. RELAY CO-ORDINATION

Open circuiting and closing the conductor, **C**, shall be triggered by a relay different from the relay for tripping the feeder CB. Protection against excess current was naturally the earliest protective system to evolve. From this basic principle, the graded over current system, a discriminative fault protection has evolved. Over-current protection is directed entirely to the clearance of fault [9]. In this section, the third question asked in section 3 on how to open-circuit **C** at fault just before the CB opens, shall be answered.

5.1 Discrimination by time

In this method, an appropriate time interval is given by 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 5** to illustrate the principle.

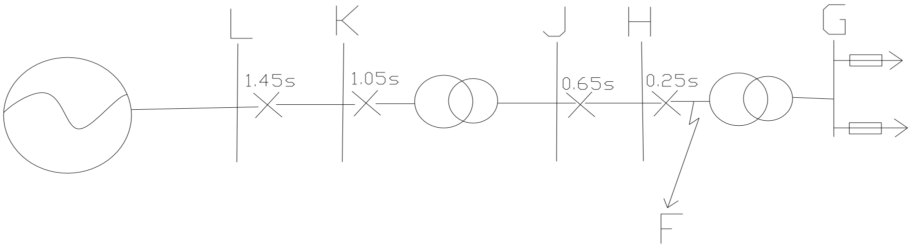


Figure 5: Radial system with time discrimination

Circuit breaker protection is provided at 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 5, the operation of relay 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 H (i.e. J, K, and L) are progressively delayed for 0.4s from H (i.e. 0.65s, 1.05s, and 1.45s) as shown. This means longest clearing time for faults near the source, which is a disadvantage. From figure 5, the breaker H, is typically a feeder CB and further delaying it by say 0.1s is okay, such that the CLR bypass bar, C, can be open-circuited in 0.25s while the feeder breaker H, operates 0.1s after, (i.e. at 0.35s).

5.2 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 6 illustrates the method.

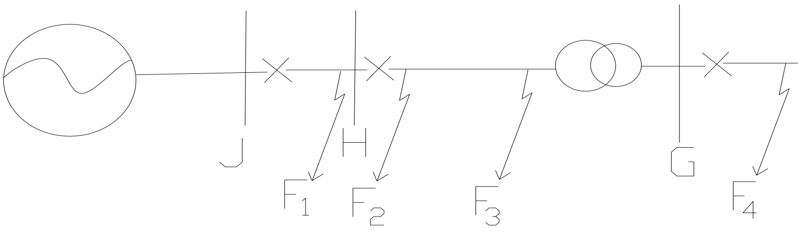


Figure 6: Radial system with current discrimination

As stated earlier, because of the variation of the fault current with the position of the fault, breaker G would clear F_4 faster than the ones behind it (i.e. H and J), while breaker H would clear F_2 and F_3 faster than breaker 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%. Discrimination by current is therefore, not a practical proposition for correct grading between the circuit breakers J and H.

5.3 Discrimination by both time and current

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 7, which is identical to figure 5 except that typical system parameters have been added [9] and, with relay over current characteristic assumed to be extremely inverse as for the type CDG 14 relay, the followings were reached:

- Relay at H must discriminate with 200A fuse at fault level up to 35.7MVA, (i.e. 6260A at 3.3KV or 1880A at 11KV).
- Relay at J must discriminate with relay at H at fault level up to 98.7MVA, (i.e. 17280A at 3.3KV or 5180A at 11KV).
- Relay at K must discriminate with that at J at fault level up to 123MVA, (i.e. 21500A at 3.3KV or 538A at 132KV).
- Relay at L must discriminate with that at K at fault level up to 1540MVA, (i.e. 270000A at 3.3KV or 6750A at 132KV).

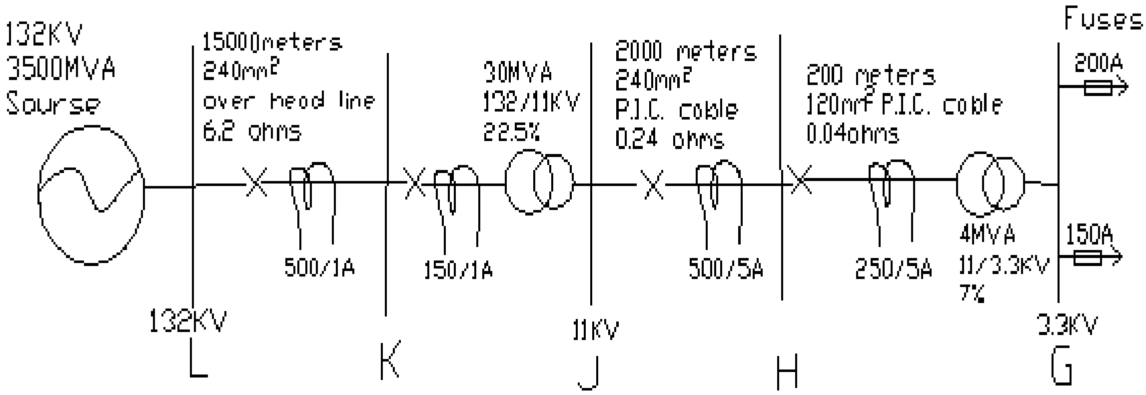


Figure 7: Time and current grading

A comparison between the relay operating times shown in figure 5 and the times obtained from the discrimination curves of figure 7 at maximum fault levels [9] reveals significant differences as summarized in table 1. Table 2 shows the clearance times for the relays at minimum fault levels (i.e. for faults at the remote ends of the protected sections). The time multiplier settings, (TMS), for H, J, K and L are 0.2, 0.7, 0.25 and 0.9, respectively.

Table 1: Comparison of operating times from figure 5 and discrimination curves of figure 7 at maximum fault level.

Relay	Fault level (MVA)	Time from figure 5 (seconds)	Time from figure 7 (seconds)
H	98.7	0.25	0.07
J	123	0.65	0.33
K	1540	1.05	0.07
L	3500	1.45	0.25

Table 2: Clearance times of the relays at minimum fault level.

Relay	Fault level (MVA)	Time from figure 7 (seconds)
H	35.7	0.17
J	98.7	0.42
K	123	0.86
L	1540	0.39

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 5. This is shown in table 3.

Table 3: Average operating time of relays compared with the operating time of figure 5.

Relay	Fault level (max./min. MVA)	Times from figure 7 (min./max. seconds)	Average time (seconds)	Time from figure 5 (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	1540/123	0.07/0.86	0.465	1.05
L	3500/1540	0.25/0.39	0.32	1.45

Table 3 shows that at 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.

VI. DISCUSSIONS

6.1 CLR connection

From figure 2(a), the reactance of the CLR, X_R is parallel to the reactance of the CLR bypass bar, X_C, (X_R // X_C). With $X_R >> X_C$, the equivalent reactance, X_{eq} of the circuit shall be less than X_C. This implies that no power losses are encountered under parallel connection of R and C in the circuit. Also, with $X_R >> X_C$, the CLR could be shorted out by the CLR bypass bar, C, under parallel arrangement of R and C in the circuit. This again is a desirable result as no constant power losses shall be recorded at normal system condition.

6.2 Bringing the CLR in series with the feeder during fault

From figure 4(c), the sliding rod, S, is in constant contact with 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. Again, from figure 4(c), 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 (When E discharges, D is charged, and vice versa). It is true that there shall be a little energy loss due to friction but, the momentum (the product of the mass of S and its velocity) gathered by S, balances the frictional losses, so there could be 100% re-utilization of energy. Hence, no charging system (motor) is required unless it is vertically arranged, in which case, gravitational force is encountered. Based on the above discussion, it is recommended that the adapter be connected in an orientation that leaves S align horizontally. Also, S should be properly greased to reduce friction.

6.3 Relay co-ordination

Co-ordination by time alone is all that is required between the CLR relay and the feeder relay since both are in the same place and are 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 5, means longest fault clearing time for faults closest to the power source. After discriminating these relays, the feeder relay time should then be assigned to the CLR relay, while the feeder relay be delayed by say 0.1s for the fault near it, such that, for the case at hand, tables 1, 2 and 3 becomes tables 4, 5 and 6 respectively, as shown. The 0.1s delay on H is achieved by adjusting its TMS to 0.49, while the TMS for the CLR relay is 0.2.

Table 4: Relay operating time at maximum fault level.

Relay	Fault level (MVA)	Time (seconds)
CLR	98.7	0.07
H	98.7	0.17
J	123	0.33
K	1540	0.07
L	3500	0.25

Table 5: Relay operating time at minimum fault level.

Relay	Fault level (MVA)	Time (seconds)
CLR	35.7	0.17
H	35.7	0.417
J	98.7	0.42
K	123	0.86
L	1540	0.39

Table 6: Average operating time of relays compared with operating times from figure 5.

Relay	Fault level (max. /min. MVA)	Time (min./max. seconds)	Average time (seconds)	Time from figure 5
CLR	98.7/35.7	0.07/0.17	0.12	-
H	98.7/35.7	0.17/0.417	0.294	0.25
J	123/98.7	0.33/0.42	0.375	0.65
K	1540/123	0.07/0.86	0.465	1.05
L	3500/1540	0.25/0.39	0.32	1.45

From tables 4, 5 and 6, it is clear that the deliberate introduction of a little time delay on the feeder relay H, to allow series connection of the CLR before its operation has no bad effect on the discrimination already achieved between H, J, K and L. The curves of the operating times of the feeder CB at H and CLR series connection times for fault level between 35.7MVA and 98.7MVA are shown in figure 8. As seen from both tables 4 and 5 and figure 8, the TMS of 0.2 and 0.49 respectively for CLR and CB relays at H gave 0.1s discrimination for maximum fault level (98.7MVA) and up to 0.247s discrimination for minimum fault level (35.7MVA). Tables 4 and 5 show no compromise in the discrimination between the relay H and the relay J behind it.

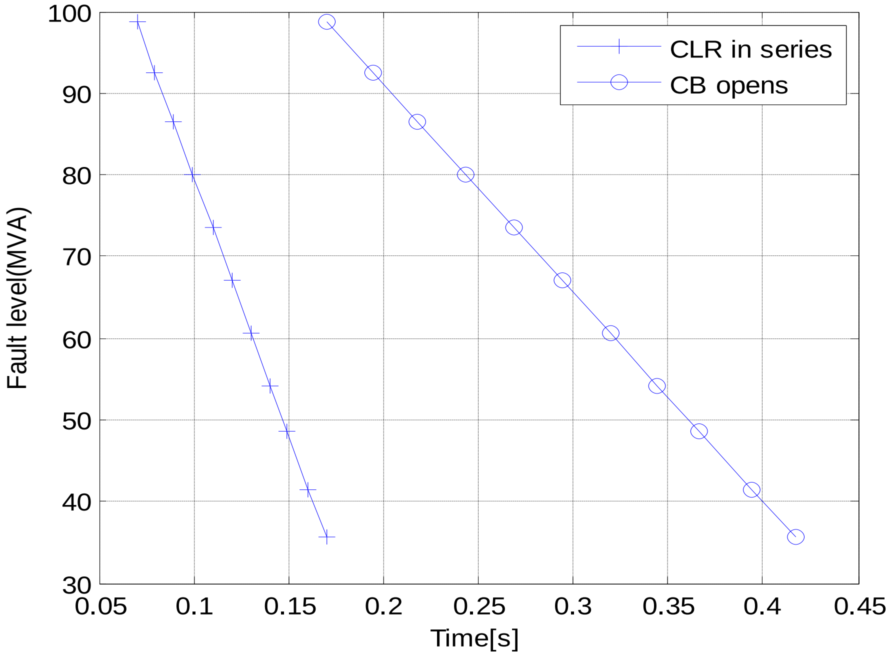


Figure 8: Curves of CLR series connection time and feeder CB opening time

Based on the above discussion, it is therefore recommended that the discrimination by time alone as said earlier, between the feeder CB relay and the CLR relay should be achieved by using relays with the same operating characteristics for the series operation of CLR/feeder CB arrangement and the CBs behind the feeder CB. It is also recommended that there should be a permissive arrangement that allows the feeder breaker to clear the fault only when the CLR is in series. This would ensure that rather than the feeder breaker clearing the fault when the CLR is in parallel (i.e. in event that open circuiting the conductor C fails), the backup breaker clears it after an acceptable short delay as seen in the table 4 (0.26s for maximum fault level).

The prototype connection that gives the desired result is shown in figure 9. As seen from figure 9, no modification is needed to implement this on an existing CB.

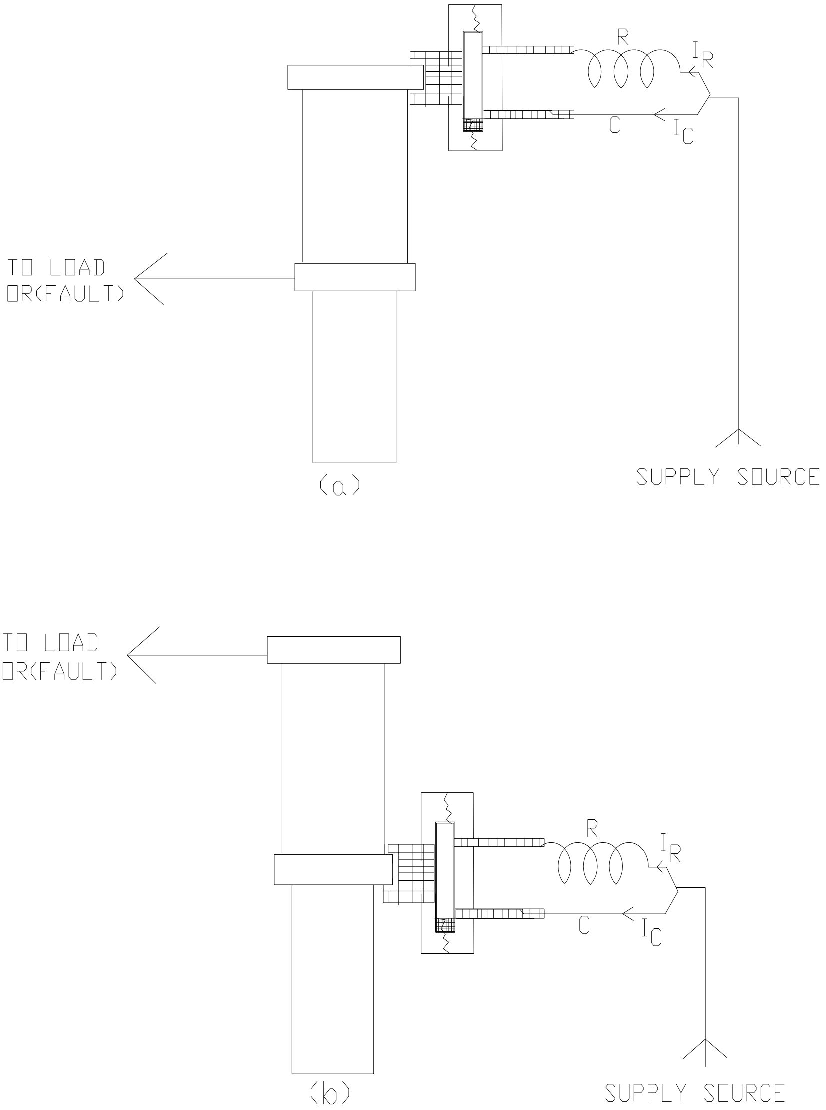


Figure 9: CLR/CB prototype connection

In figure 9, R is the CLR; C is the CLR bypass bar; I_R *is the current through the CLR;* I_C *is the current through the CLR bypass bar.*

VII. CONCLUSIONS

In this paper, an approach to implementing fault current limiting reactors on feeders with negligible constant power losses is presented. It is well suited on existing CBs to accommodate more loads.

REFERENCES

[1]. H. Seyedi, B. Tabei, "Appropriate Placement of Fault Current Limiting Reactors in Different HV Substation Arrangements", Scientific Research, Circuits and Systems, 2012, 3, 252 – 262.

[2]. www.trenchgroup.com, "Current Limiting & Power Flow Control Reactors – Air Core Reactors," Trench Group, 2014.

[3]. en.wikipedia.org/wiki/current_limiting_reactor, "Current Limiting Reactor – Wikipedia", The Free Encyclopedia.

[4]. B.R. Gupta, "Generation of Electrical Energy," Eurasia Publishing House (P) Ltd, 7361, Ram Nagar, New Delhi – 110 055, 2012, pp. 275-280.

[5]. www.nwl.com/files/file/Tech%20Bulletins/222.pdf, "Current Limiting Reactors (CLR)," Technical Overview …-Nwl.com.

[6]. www.neundorfer.com/.../Neundorfer_ "Understanding Current Limiting Reactors (CLRs)."

[7]. L. Heinemann, Huan Xin Chi, ABB AG, Germany, "Technology Benchmark of Operating Mechanisms for High Voltage Switchgear."

[8]. www.energy.siemens.com/.../high_voltage.../circuit-breaker/portfolio_en... "High - Voltage Circuit Breakers – Siemens".

[9]. General Electric Company (GEC), "Protective Relay Application Guide, GEC Measurements Plc," 1987, pp. 129 – 134.

[10]. Akpeh V.A., Madueme T.C., Ezechukwu O.A., Ogboh V.C., Echedom V.C., "A Methodology for Implementing Fault Current Limiting Reactors (CLRs) on Feeders with Minimal Constant Power Losses", Global Journal of Engineering, Design & Technology, Vol.4 (5):1-7.