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THE OVERCURRENT GRADING MECHANISM FOR FUSE, RELAY AND CIRCUIT BREAKERS FOR A TYPICAL POWER SYSTEM

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Abstract
The Power system consists of Generators, Transformers, Transmission lines, feeders and different kind of loads which play an important role somehow in the system. When a fault takes place in any part of the system that part is eliminated from the system for the proper and continuous operation without affecting the other part of system. This is done either by the Relays or by the Circuit breakers. The most important aspect of these protective devices is their time of operation. They must operate at proper time when fault occurs and must have co-ordination with other protective devices. So to co-ordinate different relays for clearing the fault "Over Current" grading is important. This paper goes through the Overcurrent Grading which is important aspect to get a better advantage in grading procedure.
Keywords: Fuse, Circuit Breakers, Relays, Overcurrent Grading

1. Introduction

The objective of this paper is to perform the Overcurrent grading of the system for a simple single line diagram. It consists of Generators, Feeders, Transformer, Motor and relays at various points. The grading is started from the load side i.e. because the minimum operating time will be at that part also as per the given information Relay B has the minimum operating time. The operating time of the relay at the load side has the minimum time and this time goes on increasing as we move towards the generator side. In case when the primary protection fails the backup protection comes into action.
Suppose the relay B in the given system fails to operate for fault then the short circuit current can affect the other part of the system. So in that case relay D acts as a backup protection. The system also has a differential protection scheme. The differential protection works only for the protected part it is covering. If any fault appears outside this differential protection the relays used for this protection will not operate.
There are some relays which are very sensitive and they cannot make correct difference between normal condition and fault condition. So for that reason differential protection is used. [2] Relay F is used for the differential protection as shown in the system diagram. Suppose I_1 and I_2 are the two currents entering and leaving respectively through the line. When fault occurs within the protected zone I_2 will reverse and restrain will be $(I_1 - I_2)/2$ and operating current is I_1+I_2. [1]

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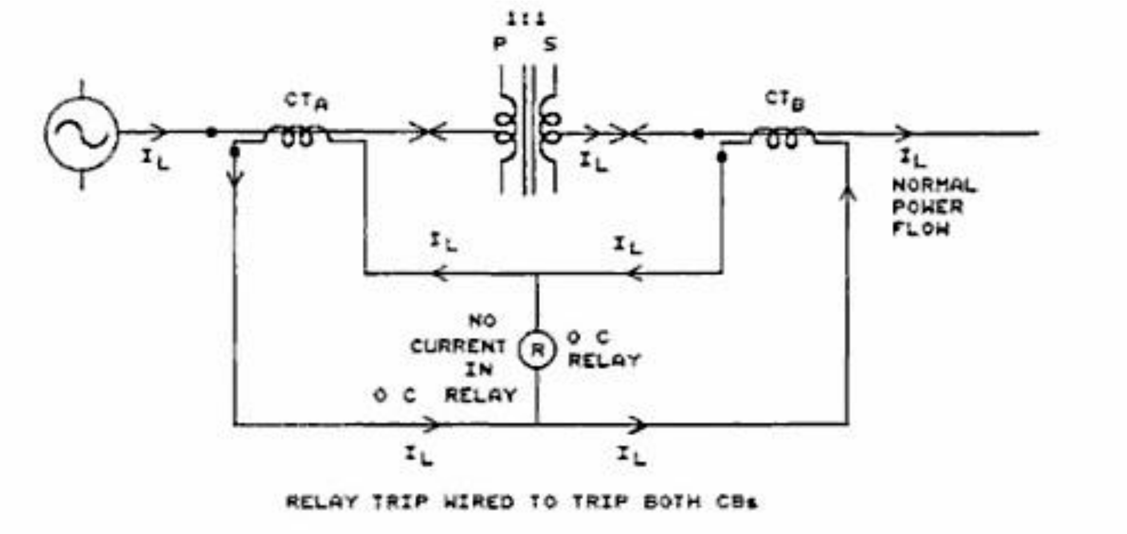

Figure 1:- Simple Differential Relay [3]

The Knee point voltage V_{knee} is defined as the point at which there is 10% increase in the voltage and corresponding 50% increase in the magnetising current. **[**1]

If suppose a fault occurs at load side, the fault current is $(15)^2$ times more than the normal operating current .This may lead to overheating and can cause fire so it becomes essential to use safety devices such as relays, circuit breakers to minimise the financial loss. Apart from the economical loss the continuity of the supply will be interrupted which is not beneficial for any generating company because they may lose some customers.

The insulation when subjected to over-voltage for short period of time leads to Fault current or the short circuit current.[3].The 3-phase faults are most common and causes maximum short current. The 3-phase faults type and nature are classified as

1] Phase to Ground

2] Permanent

3] Transient

4] Semi-Transient

The relay and circuit breaker location plays an important role in the system. In ideal condition the locations of these protective devices can be shown by the following Figure.

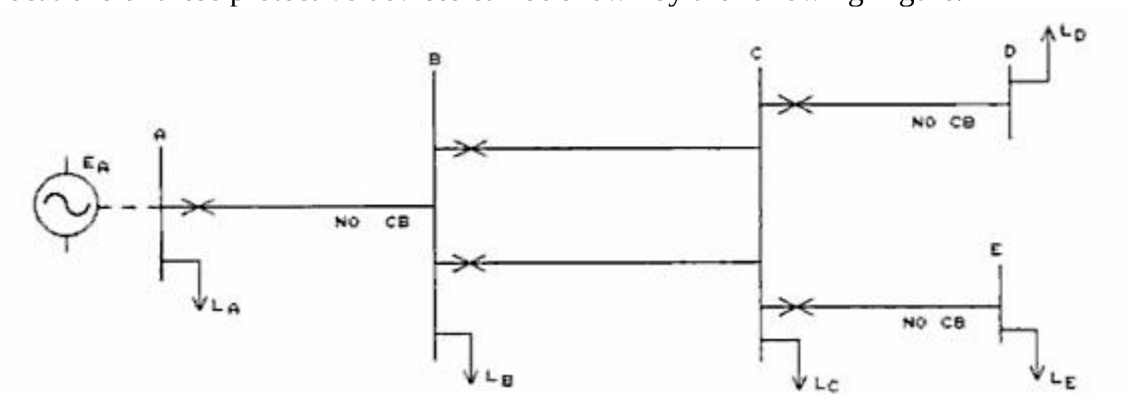

Figure 2:- Circuit breaker location [3]

Just connecting circuit breakers anywhere is not good. The circuit breakers should be connected with the co-ordination of other to get a proper back up at exact time. Thus Overlapping concept comes into the view. The Figure below shows the scheme with proper back up protection.

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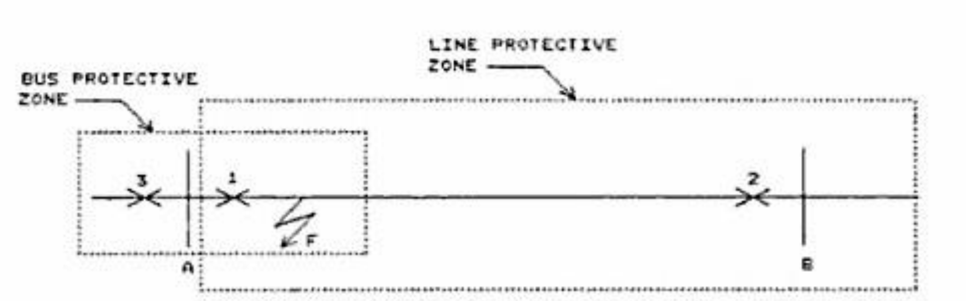

Figure 3:- Circuit breaker with Back up protection [3]

2. Analysis

The relay B has an extremely inverse characteristic which is graded with relay D. Then relay D is graded with relay E which has again the extremely inverse characteristics. In further part the relay E cannot be graded with relay F as it is the part of differential protection. So relay E is graded with relay G. With extremely inverse characteristic again relay G and relay H are graded. The relay J has an standard inverse characteristics which is given in the research paper.

Calculation of Fault current at different Fault levels

1] For 11kV and 3-phase fault level of 294 MVA

$$I_{fault} = \frac{294*10^6}{\sqrt{3}*11*10^3} = 15430.99A$$

2] For 11kV and 3-phase fault level of 237 MVA and with one feeder having a fault level of 198 MVA

$$I_{fault} = \frac{237*10^6}{\sqrt{3}*11*10^3} = 12.43kA$$

$$I_{fault} = \frac{198*10^6}{\sqrt{3}*11*10^3} = 10.39kA$$

3] For 3.3 kV and fault level of 41.3 MVA

$$I_{fault} = \frac{41.3*10^6}{\sqrt{3}*3.3*10^3} = 7225.62A$$

For 160A H.R.C Fuse (A)

The characteristics of this fuse can be plotted directly and is shown on the graph attached. The following data is used to plot the graph.

Fault Current (A)	430	650	1150	2000	3506
Arc extinction time (s)	100	10	1.0	0.1	0.01

Table 1:- 160A HRC fuse characteristics

For relay A the characteristics are drawn below

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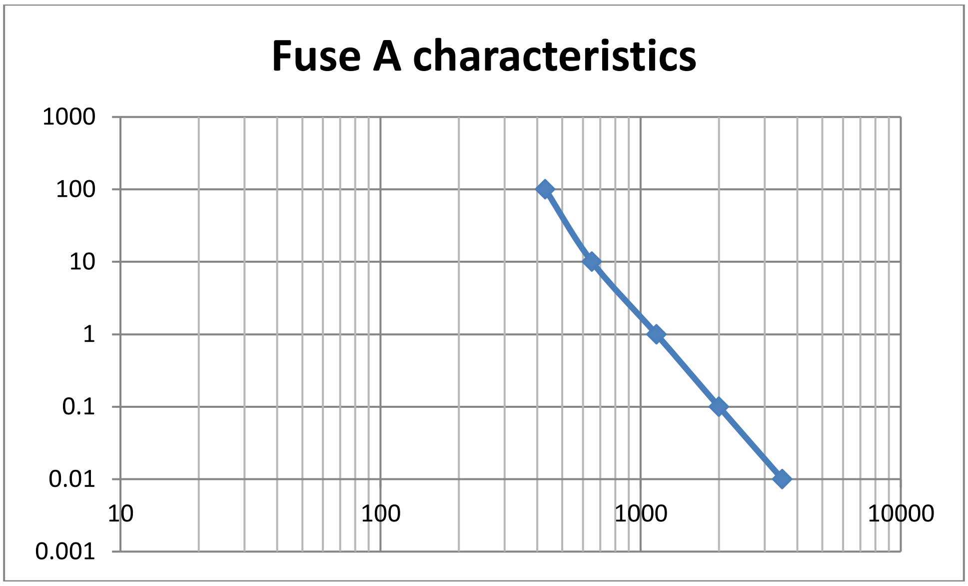

Graph 1:- Characteristic for fuse A

For Relay B

As given in the research paper

IDMT characteristics	Extremely Inverse
IDMT current setting	1.0In
Time multiplier setting	0.1
Instantaneous current setting	No

Table 2:- Characteristic details of relay B

Hence as per the given data current setting=100A

Time multiplier setting TMS=0.1

$$Ifault = \frac{41.3*10^6}{\sqrt{3}*3.3*10^3} = 7225.6A$$

Therefore by using the formula of extremely inverse characteristics

$$t = \frac{80*TMS}{[I/Is]^2 - 1} = \frac{80*0.1}{[7225.6/100]^2 - 1} = 0.015s$$

Multiple of setting	Current at 3.3kV	Operating time at TMS= 0.1
2	200	2.66
4	400	0.53
6	600	0.22
8	800	0.12
10	1000	0.08
12	1200	0.05
14	1400	0.04
16	1600	0.03
18	1800	0.02
20	2000	0.02

Table 3:- Operating time for relay B

But the required minimum operating time as per given guide lines is 0.02s so it will operate at this time only as it is shortest time interval.

CT knee point voltage for relay B = I_{fault}*(5/100)*(0.05+0.1) = 7225.6*0.05*0.15= 54.19V

For 100A Fuse (C)

$$I_{fullload} = \frac{200*10^3}{\sqrt{3}*3300*0.8} = 43.73A$$

$$I_{fullload} = 43.73*5 = 218.65A$$

Maximum fault current at 3.3kv bus bar will be

$$I_{faultcurrent} = \frac{41.3*10^6}{\sqrt{3}*3.3*10^3} = 7225.62A$$

Fuse characteristics for 100A fuse is given in the table below

Current (I)	Arc extinction Time
300	120
400	25
500	7.0
600	2.2
700	0.9
800	0.45

Table 4:- Fuse characteristic for 100A fuse

Now for the Current setting following factors must be considered when setting the relay pick up current;

1) Transformer full load current plus some allowance for overloading
2) Resetting of relay

Considering 10% transformer overloading we get;

$$I_s = 218.69*\frac{1.1}{0.95} = 253.22A$$

The relay pick up current should be 3 to 4 times of fuse rating to ensure correct grading hence;

$4*100 = 400A$

In terms of CT ratio this is 400/1000=0.4

I_s=0.4 => 400A

The fuse has I2t characteristics. The extremely inverse characteristic is also an I2t characteristic, and is therefore selected to grade with the fuse. The extremely inverse characteristics is given by

$$t = \frac{80*TMS}{\left(\frac{I}{I_s}\right)^2 - 1}$$

When grading the relay with a downstream fuse the grading margin is given by

$Margin = 0.4t_f + 0.15$

Where tf is the nominal fuse operating time. Also the required relay operating time for the relay is given by

$t_r = t_f + 0.4t_f + 0.15$; Using the characteristics data the following table can be drawn

Current(A)	Time(S)	Margin(S)	Relay time(S)
300	120	48.15	-
400	25	10.15	35.15
500	7	2.95	9.95
600	2.2	1.69	3.89
700	0.9	0.51	1.41
800	0.45	0.33	0.78

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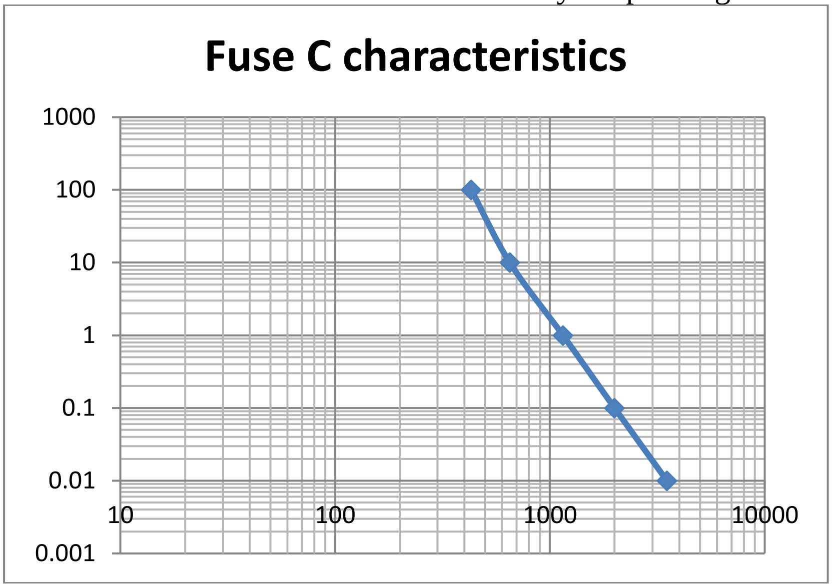
Table 5:- For relay C operating time



Graph 2:- Characteristic For fuse C

Since the fuse has instantaneous characteristics and a relay is used in the upstream protection, also the relay B has a minimum operating time of 0.02 sec hence it is good to avoid the grading of this fuse with the upstream relay.

For Transformer

For LV relay (D)

$I_s = I_{motor}*(N-1) + I_{full\ load}$ on sec of transformer

$$I_{motor} = 200*10^3 / \sqrt{3}*3300*0.8 = 43.73A$$

$$I_{fullload} on \sec = 5*10^6 / \sqrt{3}*3.3*10^3 = 874.77A$$

$$Is = 43.73*4 + 874.77 = 1049.69A$$

Allow 10% overloading and take into account that relay resets at 95% of the setting

$$I_s = \frac{1049.69*1.10}{0.95} = 1215.43A$$

In terms of CT ratio this is;

1215.43/1000=1.215

Selecting I_s =1.2=> 1200A primary

Selecting the characteristics, as there is downstream protection details given we will use Extremely Inverse characteristics. The operating time of (0.02+0.4) sec at fault current is required for correct grading. Consider TMS=1 in this case

$$t = \frac{80*TMS}{[I/Is]^2 - 1}$$

$$= \frac{80*1}{[7225.62/1200]^2 - 1} = 2.26$$

However the required operating time is 0.42 seconds

Required TMS = 0.42/2.26=0.18

Select TMS=0.2, therefore the operating time at 7225.62A will be

t = 2.26*0.2=0.4s

Set the Hi set to infinity.

Multiple of setting	Primary current at 3.3kv(A)	Current at 11 kV (A)	Operating time for TMS=1 (s)	Operating time for TMS=0.2 (s)
2	2400	720	26.7	5.34
3	3600	1080	10	2.00
4	4800	1440	5.33	1.06
5	6000	1800	3.33	0.66
6	7200	2160	2.28	0.45
6.02	7225.62	2167.5	2.26	0.45

Table 6:- Calculated time of operation for relay D

Knee point Voltage for relay D is = (7225.62)*(5/100)*(0.15) = 54.19V

D) Setting for HV relay (E)

The LV relay is set at 1200A. For proper co-ordination the pickup current of HV relay must be set above the LV relay.

The LV relay is set at 1200A=> 360A at 11kV

Set HV relay 10% above LV relay

Is=360*1.1=396A

396/300=1.32

Therefore select Is =1.3=>390A

For this case also the extremely inverse characteristics will be used to grade with LV relay. Consider TMS=1 in this case.

$$t = \frac{80 * TMS}{[I / Is]^2 - 1}$$

$$t = \frac{80 * 1}{[2167.5/390]^2 - 1} = 2.67s$$

In this case a grading margin of 0.4 second is required. However because of star-Delta transformer configuration care must be taken to ensure grading under a 2-1-1 current distribution due to phase to phase fault. Hence the operating time of the LV relay at 0.866 times the maximum LV fault current level must be calculated.

0.866*7225.62=6257.38A

$$t = \frac{80 * 0.2}{[6257.38/1200]^2 - 1} = 0.61.s$$

Therefore for the HV relay at a fault current of 2167.5A the operating time of at least 1.11s is required.

Required operating time= (0.4+0.61) =1.11s

Required TMS=1.11/2.67=0.42

Select TMS=0.4

Therefore the operating time =0.4*2.67=1.05

Hi-set can be set to 120%-130% of the maximum LV fault level. This will give fast clearing times for faults on the transformer HV bushings and part of the way into the transformer.

Hi-set = 1.2*(2167.5/390) =6.669 times

Therefore select Hi-set=390*7=2730A

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Multiple of setting	Current at 3.3kV (A)	Current at 11kV (A)	Operating time at TMS=1 (s)	Operating time at TMS=0.4 (s)
2	2600	780	26.8	10.72
3	3900	1170	10.39	4.15
4	5200	1560	5.35	2.14
5	6500	1950	3.35	1.34
6	7800	2340	2.30	0.92
6.5	8450	2535	1.93	0.77

Table 7:- Calculated time of operation for relay E

Knee point Voltage for relay E = (2167.68)*(5/300)*(0.15) = 5.41V

For Relay F

Relay F is part of the differential protection. The differential protection cannot be graded [3] with other relays used in the given system diagram. The differential protection operates only when the fault occurs within the protected zone. It does not sense the fault outside the zone of differential protection. Consider two currents I_1 and I_2 in this scheme, the relay will operate or restrain depending upon which current is higher. When fault occurs in protected zone both current flows in one direction resulting to produce torque which trip the circuit in the circuit breakers. [4]

$I_f = (294*10^6/1.732*11*10^3)=15431.45A$

$K_s= [0.023*I_f*(X/R+55)] + [0.9*(X/R+26)] =[0.023*15431.45*(1/450)*75]+[0.9*46] = 100.55$

K_t=1 for instantaneous operation

$I_s=2.5*I_{charging}=2.5*45=112.5A$

Therefore Knee voltage is given by

Knee Voltage= K_s* K_t*I_n*(Rct+2Rl) = 100.55*1*0.15*1= 15.08V

For Relay G

Let TMS=1

I=2730A

I_s= 1.1*(420/0.95) = 486.31A

In terms of CT ratio this is 486/450=1.08

Select I_s =1=> 450 A primary

$$t = \frac{80*TMS}{\left(\frac{I}{I_s}\right)^2 - 1} = \frac{80*1}{[2730/450]^2 - 1} = 2.23s$$

$$t = \frac{80*TMS}{[I/Is]^2 - 1} = \frac{80*0.4}{[2730/390]^2 - 1} = 0.66s$$

But the required time is 0.4+ 0.66=1.06s

Therefore required TMS=1.06/2.23=0.47

Consider TMS=0.45

Multiple of setting	Current at 11kV (A)	Current at 3.3kV	Operating time for TMS=1	Operating time for TMS=0.45
2	900	3000	26.66	12.15
3	1350	4500	10	4.5
4	1800	6000	5.33	2.39
5	2250	7500	3.33	1.49
6	2700	9000	2.28	1.02

Table 8:- Calculated time of operation for relay G

$I_{fault} = (237*10^6)/(1.73*11*10^3) = 12439.27A$

Knee point Voltage = (12439.27)*(5/450)*(0.15) = 20.73

For Relay H

$I_{fault} = (294*10^6/1.73*11*10^3)$ =13872.83A

I_s=2775*1.1/0.95= 3213.15A

CT ratio is 3213.15/3000=1.07

I_s=1=>3000A

Consider TMS=1

Therefore

$$t = \frac{80*TMS}{[I/Is]^2 - 1} = \frac{80*1}{[13872.83/3000]^2 - 1} = 3.93s$$

But required operating time is 0.4+1.06=1.46s

Therefore required TMS=1.46/3.93=0.37

Consider TMS=0.35

Multiple of setting	Current at 11kV	Current at 3.3kV	Operating time at TMS=1 (s)	Operating time at TMS = 0.35
2	6000	20000	26.66	9.33
2.5	7500	25000	15.23	5.33
3	9000	30000	10	3.5
3.5	10500	35000	7.11	2.48
4	12000	40000	5.33	1.86
4.5	13500	45000	4.15	1.45

Table 9:- Calculated time of operation for relay H

Knee point voltage = (15430.99)*(5/3000)*(0.15) = 3.85V

For Relay J

I_s = 1.1*3213.15=3534.46A

In terms of CT ratio = 3534.46/3000=1.17

Select I_s=1.15=> 3450A

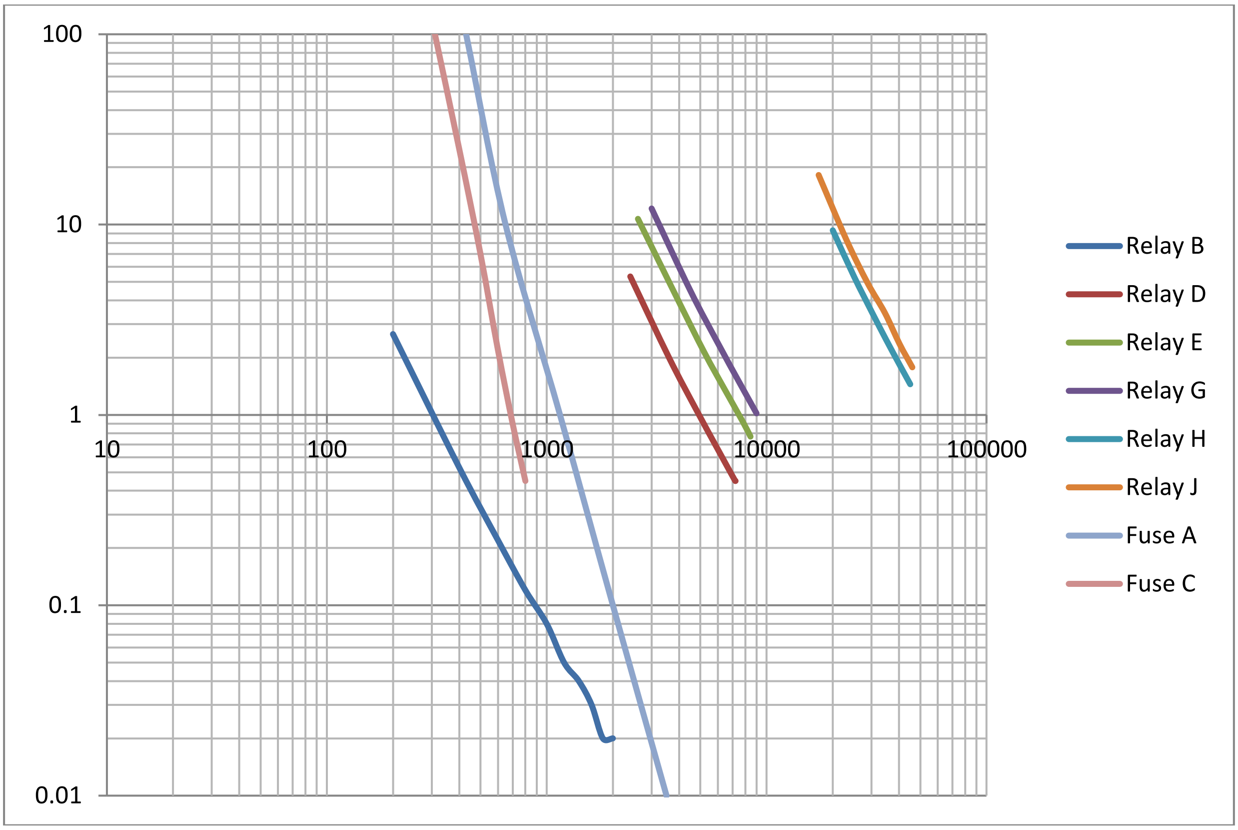
As given in the guide lines, it is said to use standard inverse characteristic for relay J, but the relays used in downstream have the extremely inverse characteristics so further calculation is done by considering relay J with extremely inverse characteristics. TMS=0.45 (given value)

$$t = \frac{80*TMS}{[I/Is]^2 - 1} = \frac{80*0.45}{[15430.99/3000]^2 - 1} = 1.414s$$

Multiples of setting	Current at 11kV	Current at 3.3kV	Operating time at TMS=1 (s)	Operating time at TMS = 0.45
1.5	5175	17250	40.5	18.22
2	6900	23000	18.64	8.38
2.5	8625	28750	11.01	4.95
3	10350	34500	7.33	3.44
3.5	12075	40250	5.26	2.36
4	13800	46000	3.96	1.78

Table 10:- Calculated time of operation for relay J

The graph for all the above relays is drawn below;



Graph 3:- Characteristics Of all the relays and fuse given in system

3. Conclusion

The Overcurrent grading for the given system diagram in the research paper is completed. The grading in done in such a way that if by fault any relay does not operates for the fault current then the relay next after it will act as an back-up. This makes the system more reliable and keeps the system working by isolating the faulty part. In this case the relay which is connected at downstream has the minimum time of operation and this time goes on increasing as we move towards the generator side From the graph shown above it can be clearly seen that the relay B which is connected to the load side has the minimum operating time and the relay connected towards the load side has more operating time. The differential protection senses the fault within its range and operates accordingly. This type of grading scheme is important to detect and clear the fault in minimum time so that the fault current cannot damage the instruments which are connected in the system as they are expensive and replacing them can take a lot of time.

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