Star-Protective Device Coordination

Theoretical Concepts

Feeder protection:

Widely used feeder protection devices are

- Fuses
- Over current protection

Fuse

The simplest form of overcurrent protection is the fuse. The fuse is capable of operating in less than 10ms for very large values of current, thus considerably limiting fault energy. They require no maintenance and are cheaper when compared to other circuit interrupting devices of equal breaking capacity. However, it does have a number of disadvantages as listed below.

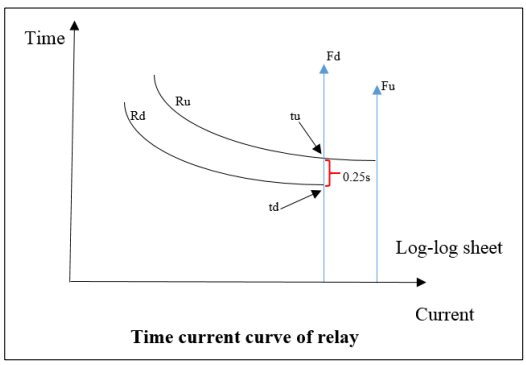
- Can be difficult to co-ordinate.
- Its characteristic is fixed.
- Needs replacing following fault clearance.
- Has limited sensitivity to earth faults.
- Causes single phasing.

Overcurrent Protection

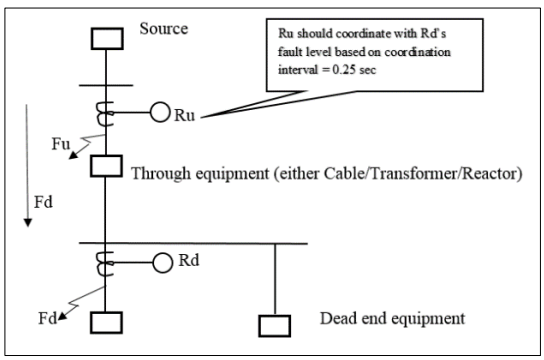
The principle of coordination refers to the procedure of setting overcurrent relays to ensure that the relay nearest to the fault location operates first and all other relays have adequate additional time to prevent them from operating. If the relay nearest to the fault location fails to clear the fault and the coordination is correct, then the next up-stream relay should operate and so on towards the source. This will only isolate faulty part of the power system and healthy part of the power will be operational. So the upstream relay has to be designed and co-ordinated with the downstream relay at the downstream equipment's fault level and each relay will have its own zone of operation. Let us consider below example.

Overcurrent relay should be set such that

a) Overcurrent pickup = 105 to 110% of full load current through relay CT.
b) Overcurrent time = greater than downstream relay Rd at downstream relay's fault level Fd.
c) Coordination interval between Ru & Rd is typically 0.25 sec for numerical relay and 0.4 sec for electromechanical relay.

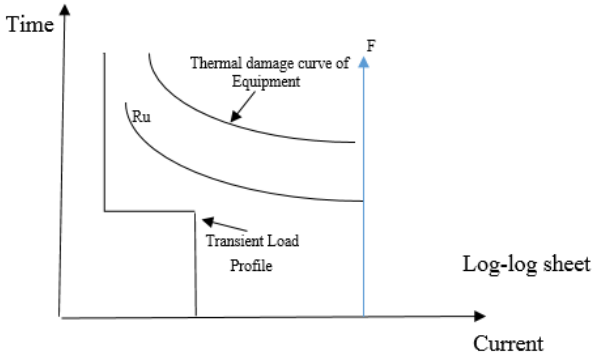


Time current curve of relay



Star-Protective Device Coordination

d) The relay setting curve should be above the transient load profile seen through Ru and below through equipment thermal damage curve. For example relay should not operate during motor starting wherein the motor draws heavy current during its acceleration.



Time current curve of relay

For these purposes, IEC 60255 defines a number of standard characteristics as follows:

a) IEC Relay characteristic equations

Relay Characteristic	Equation (IEC 60255)
Standard Inverse (SI)	$t = TMS \times \frac{0.14}{I_r^{0.02} - 1}$
Very Inverse (VI)	$t = TMS \times \frac{13.5}{I_r - 1}$
Extremely Inverse (EI)	$t = TMS \times \frac{80}{I_r^2 - 1}$
Long time standard earth fault	$t = TMS \times \frac{120}{I_r - 1}$

Where,

Ir: I/ Is

I: Measured Current

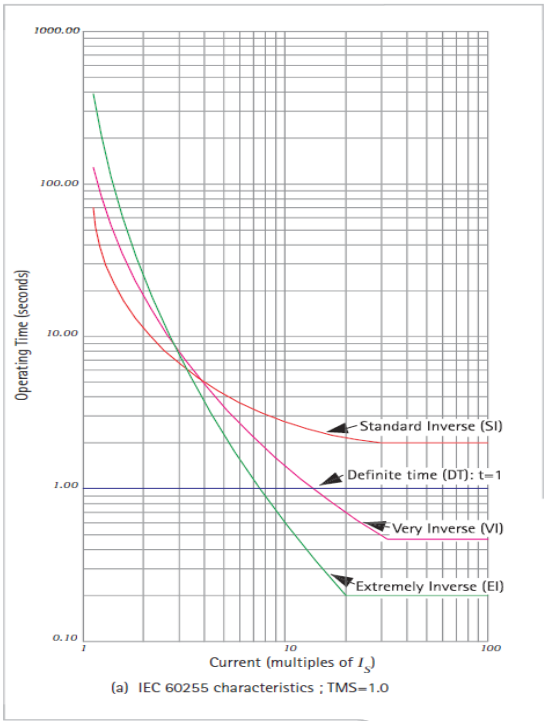
Is: Relay setting current

TMS: Time Multiplier setting

T: Relay operating time in sec

b) IEC Relay characteristic curves with time multiplier setting equal to one.

Star-Protective Device Coordination



c) Summary of operating time for multiples of Is for each curve.

Primary Current pickup	300					**A**
TMS	1					**Factor**
IEC Curve	**Standard Inverse**		**Very Inverse**		**Extremely Inverse**	
$I_{r\ PU}$	**Primary A**	**OT in sec**	**Primary A**	**OT in sec**	**Primary A**	**OT in sec**
2	600	10.03	600	13.50	600	26.67
3	900	6.30	900	6.75	900	10.00
8	2400	3.30	2400	1.93	2400	1.27
10	3000	2.97	3000	1.50	3000	0.81
15	4500	2.52	4500	0.96	4500	0.36
20	6000	2.27	6000	0.71	6000	0.20
21	6300	2.27	6300	0.71	6300	0.20
30	9000	2.27	9000	0.71	9000	0.20

Ir (pu)	**x2**	**x10**	**x20**
Standard Inverse	10	3	2.2
Very Inverse	13.5	1.5	1.1
Extremely Inverse	27	0.8	0.2

Star-Protective Device Coordination

ANSI Overcurrent Relays have different equations as follows:

Characteristic	Equation
IEEE Moderately Inverse	$t = \frac{TD}{7}\left[\left(\frac{0.0515}{I_r^{0.02}-1}\right)+0.114\right]$
IEEE Very Inverse	$t = \frac{TD}{7}\left[\left(\frac{19.61}{I_r^{2}-1}\right)+0.491\right]$
IEEE Extremely Inverse	$t = \frac{TD}{7}\left[\left(\frac{28.2}{I_r^{2}-1}\right)+0.1217\right]$
US CO8 Inverse	$t = \frac{TD}{7}\left[\left(\frac{5.95}{I_r^{2}-1}\right)+0.18\right]$
US CO2 Short Time Inverse	$t = \frac{TD}{7}\left[\left(\frac{0.02394}{I_r^{0.02}-1}\right)+0.01694\right]$

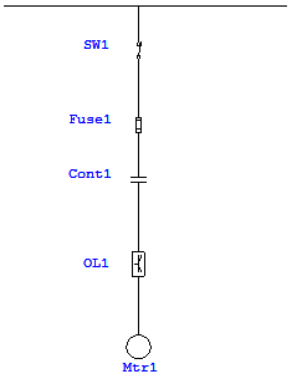
Where,

TD: Time Dial setting
Ir: I/ Is
I: Measured Current
Is: Relay setting current
t: Relay operating time in sec

Star-Protective Device Coordination

Dead End Equipment (Motor) Protection

The motors have to be protected against thermal overloads, locked rotor conditions and unbalance supply conditions.

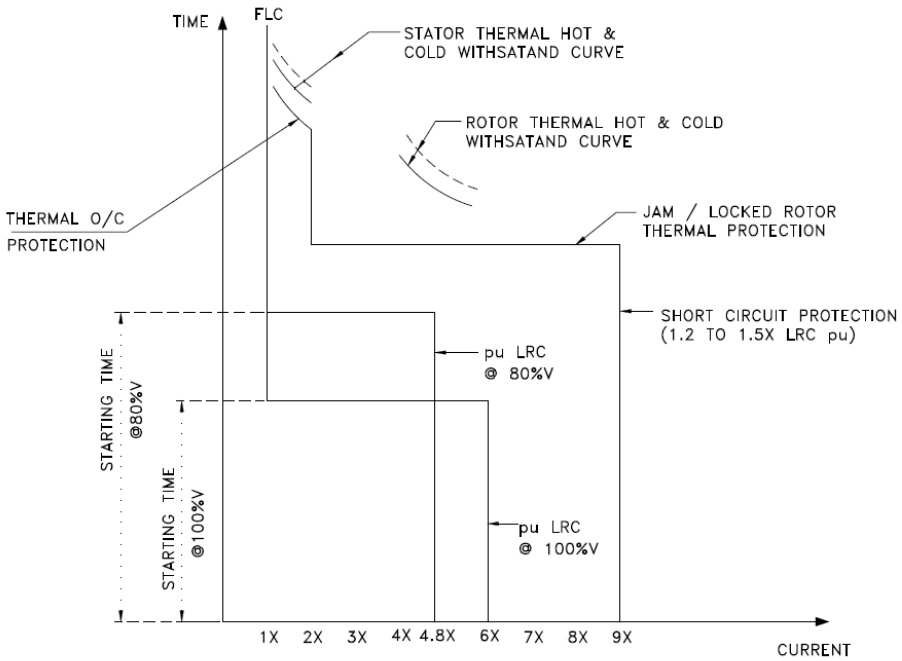


Overload Settings

a) Current pickup = 1.05 to 1.1 times full load current (FLC).
b) Time delay should be set above the motor starting time and below the motor stator thermal damage curve.

Locked Rotor or Jam or Stall Protections Settings

a) Current pickup = 1.5 to 2 times full load current.
b) Time delay should be set above the motor starting time and below the motor rotor thermal damage curve.



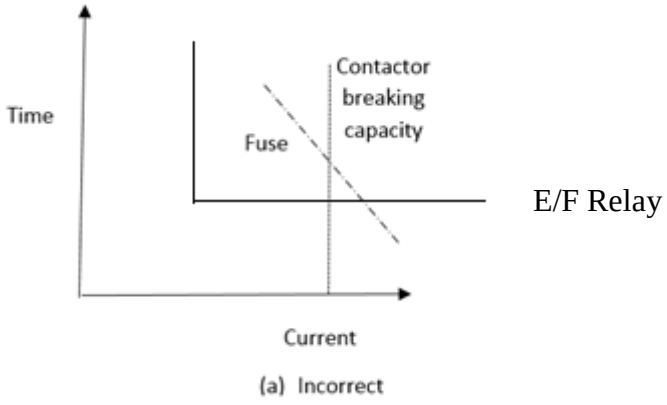
Locked Rotor Protection shall have 10-20% margin with respect to starting time of motor and thermal withstand time of motor.

Star-Protective Device Coordination

Contactor Ratings

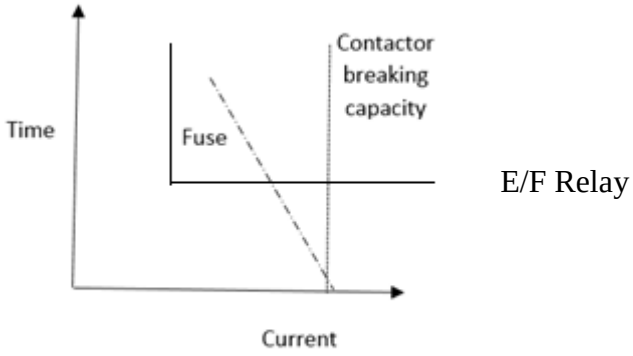
Contactor cannot break fault kA, but it can break kA of 8-10 times its rating.

In the figure (a) shown below, Earth fault (E/F) relay operates before fuse to open the contactor at kA greater than the contactor interrupting capability.



(a) Incorrect

In the figure (b) shown below, E/F relay is slower and the fuse takes over to open & not contactor at kA greater than contactor interrupting capability.



(b) Correct

Fuse Rating

Fuse ratings should be above thermal overload relay& motor start curves and should operate quickly for short circuit fault at motor terminal.

Star-Protective Device Coordination

Motor Negative Phase Sequence Settings

These settings are based on following Negative Phase Sequence (NPS) withstand values

- Continuous NPS rating I_2 p.u.
- Short time NPS I_2^2.t rating (K).

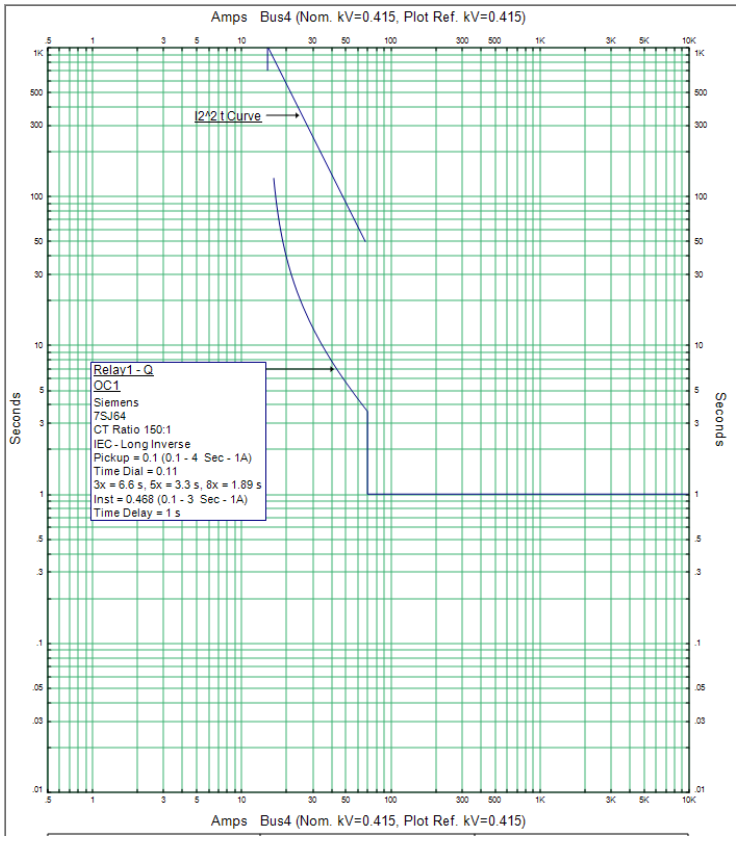
Motor continuous I_2 withstand pick up should be set based on maximum unbalance voltage that the motor can withstand as this determines the continuous I_2 flow in the motor.

For motors above 2500 kW the NPS thermal damage limit as I_2^2.t constant K is taken as 15 sec when data has to be assumed. For motors below 2500 kW it is 10 sec when data has to be assumed. Actual I_2^2.t constant K value should be obtained from vendor.

Assuming 2% unbalance in the supply voltage and LRC to be 6 times of FLC, the continuous withstand negative sequence of the motor, I_2 would be 6x2=12%.

Typical negative sequence relay setting shall be

- I_2^2.t time delay setting - The I_2 current pick up of 15%, with I_2^2.t curve set below I_2^2.t = K (Typically K = 15) withstand curve of motor.
- For faster definite time trip, the current pick up of 57% of full load current with time delay of 1 sec, this delay time is required for the coordination with downstream relay.



Star-Protective Device Coordination

Equipment Thermal Withstand Time

Any equipment thermal withstand can be plot in TCC to check protection margins.

Bus bar thermal damage curve

Bus bar ratings

Voltage = 6.6 kV

Rated current = 2000A

Short Circuit Current = 25 kA for 1 sec

For a thermal damage curve, $I^2.t=K$, where K is a constant.

Thermal withstand time at different current is given by, $t_{withstand} = Ir * \frac{tr}{Ifault}$

Thermal Damage Curve	
Fault current (A)	Withstand time (sec)
25000	1.00
20000	1.25
15000	1.67
10000	2.50
8000	3.13
5000	5.00
2000	12.50
1500	16.67

Cable Thermal Damage Curve

$I^2 \times t = K^2 \times A^2$

Where, $K = \sqrt{\frac{Kcond\text{^}2}{T} * \log(\theta f + \beta)/(\theta o + \beta)}$

I= Fault current in amperes.

t= Time in seconds

A= Cable cross section area in sq.mm

K_{cond}= Constant = 226 for copper, 148 for aluminium, 78 for steel

θ_f = Final temperature of conductor or armour (at end of short circuit)

θ_0 = Initial temperature of conductor or armour (during continuous operation)

β= Reciprocal of the temperature co-efficient of resistance of the conductor/ °C at 0°C (228 for aluminium, 202 for steel & 234.5 for copper).

Note:

θ_f =250Deg C for XLPE & 160deg C for PVC

θ_0 =90Deg C for XLPE & 70deg C for PVC

From above,

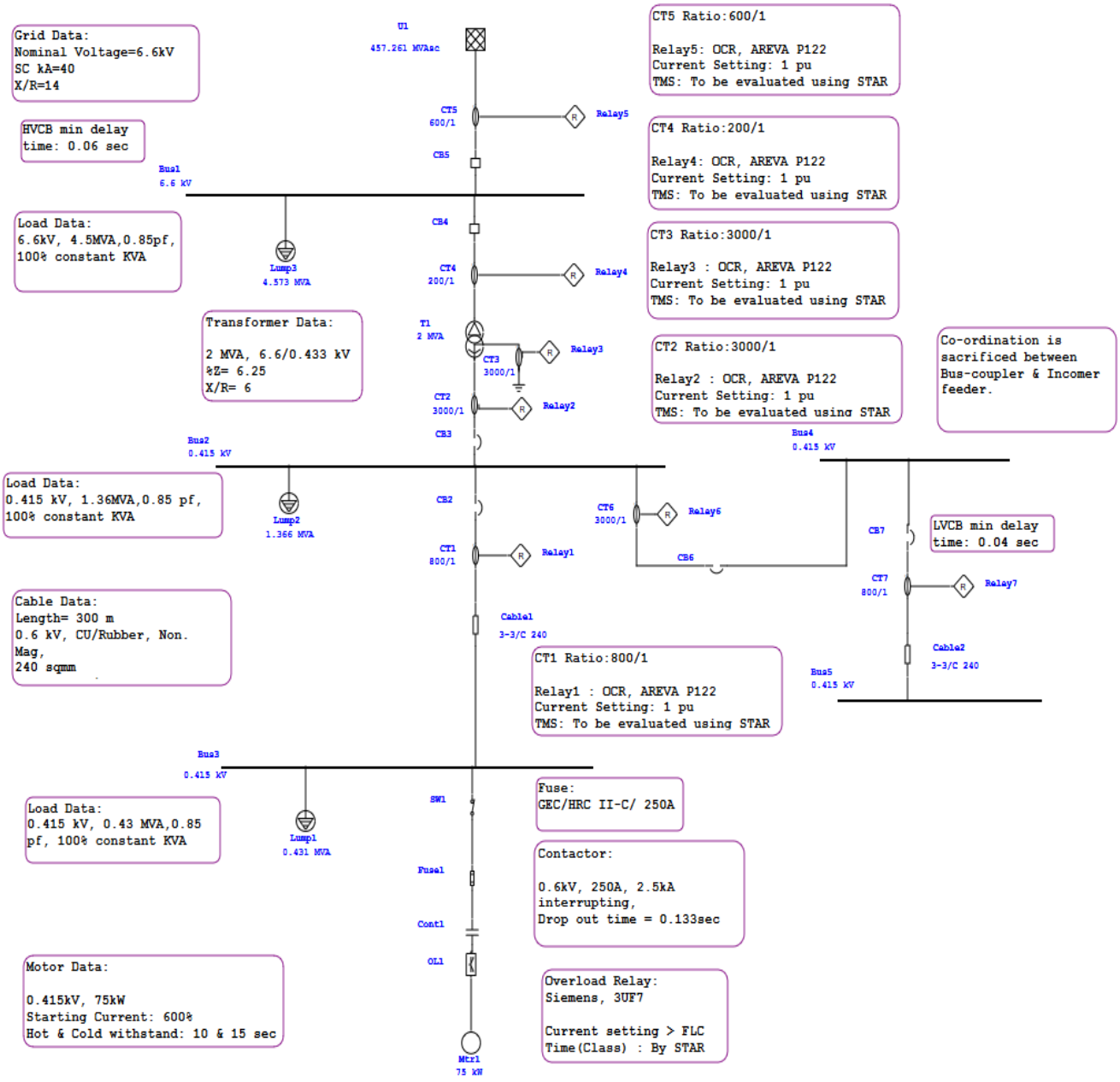
K for various cables:

	Copper	Aluminium
XLPE	K=143	K=94
PVC	K=116	K=76

Star-Protective Device Coordination

Purpose and Description

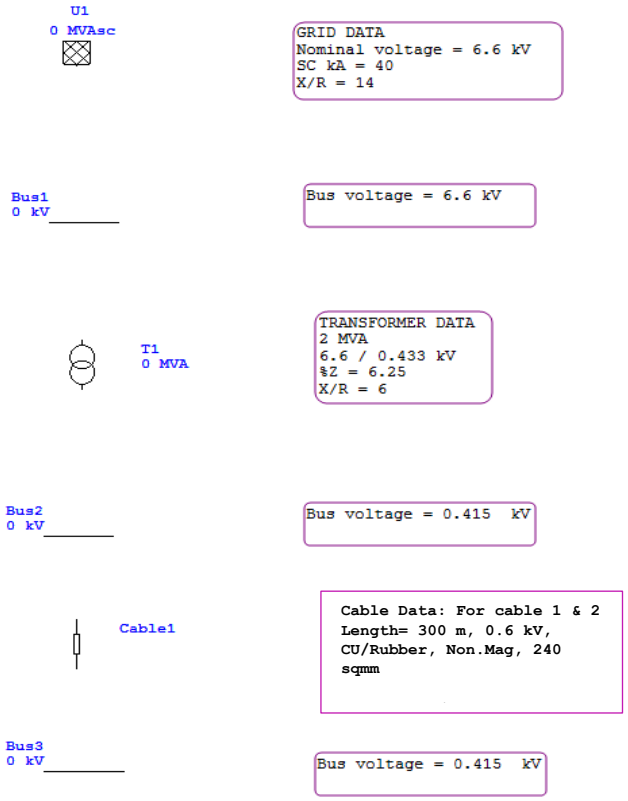
The purpose of this exercise is to coordinate relays for the reliable operation of the power system shown below.



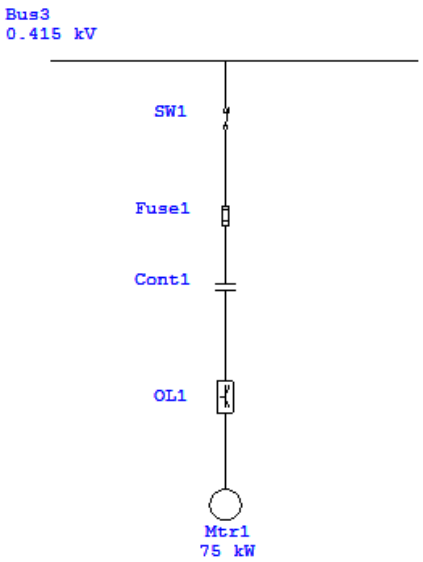
Star-Protective Device Coordination

Procedure

1. Drag and place the elements on OLV & proceed to enter data as shown below.

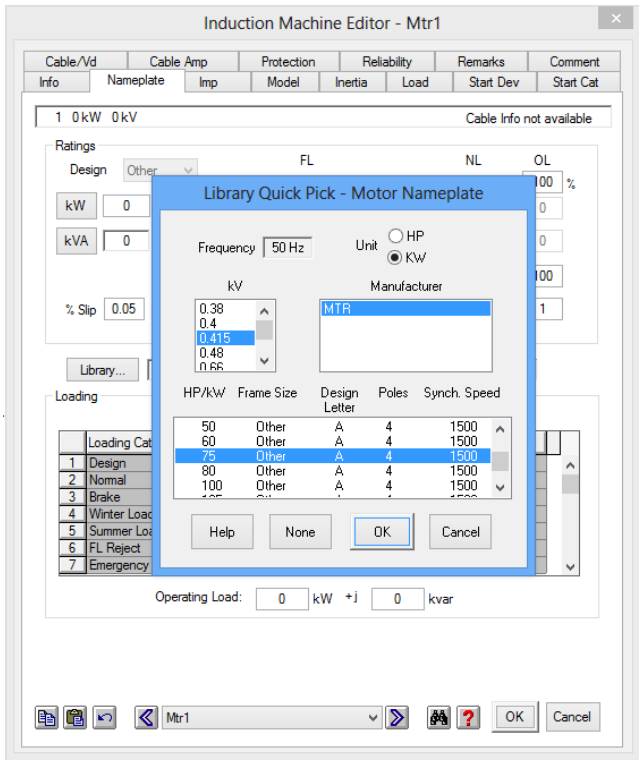


2. Drag and drop protective devices & connect them as shown below.

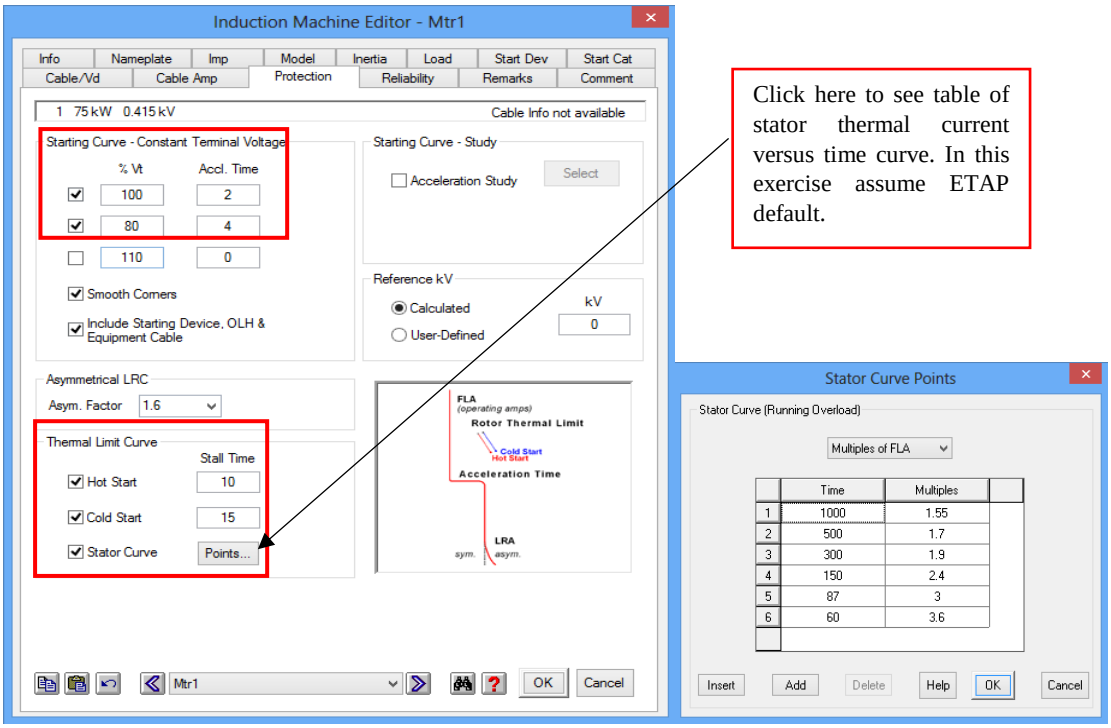


3. Double click on induction machine, go to Nameplate page and select 75kW motor with voltage rating of 0.415kV using Library button.

Star-Protective Device Coordination



4. Go to Protection page and enter data as shown below.

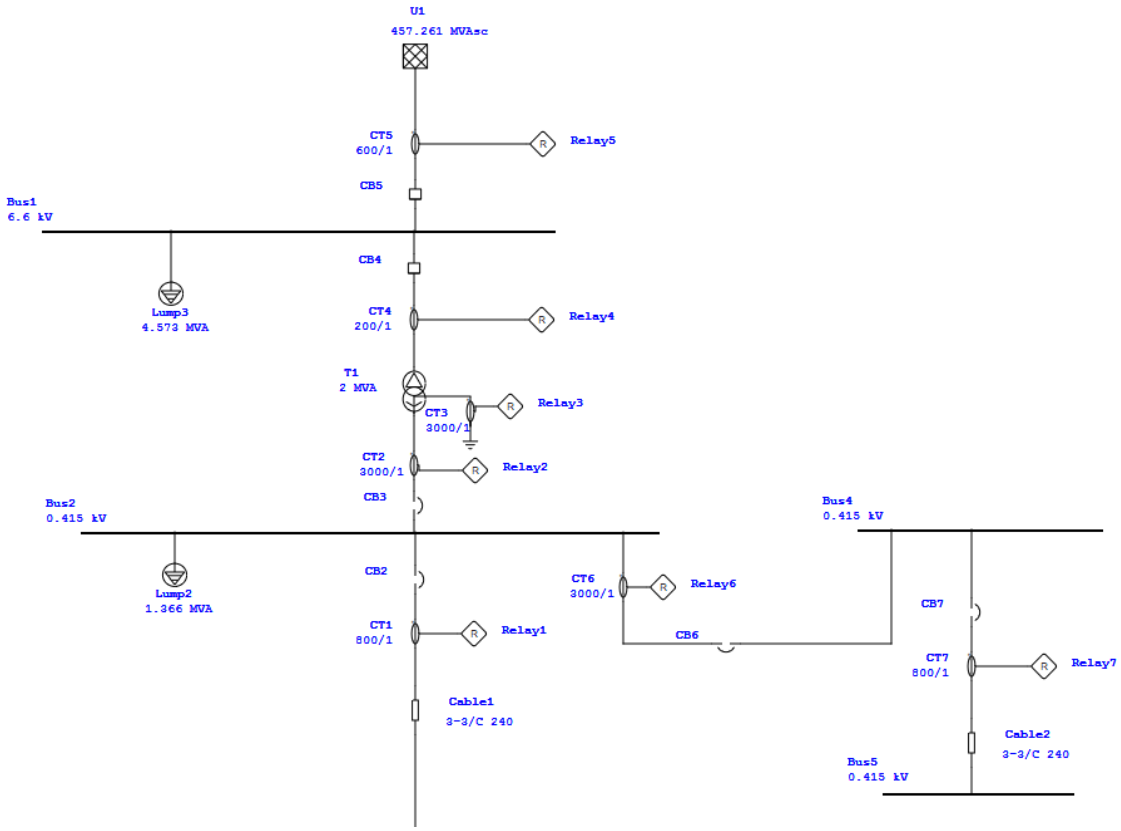


Click here to see table of stator thermal current versus time curve. In this exercise assume ETAP default.

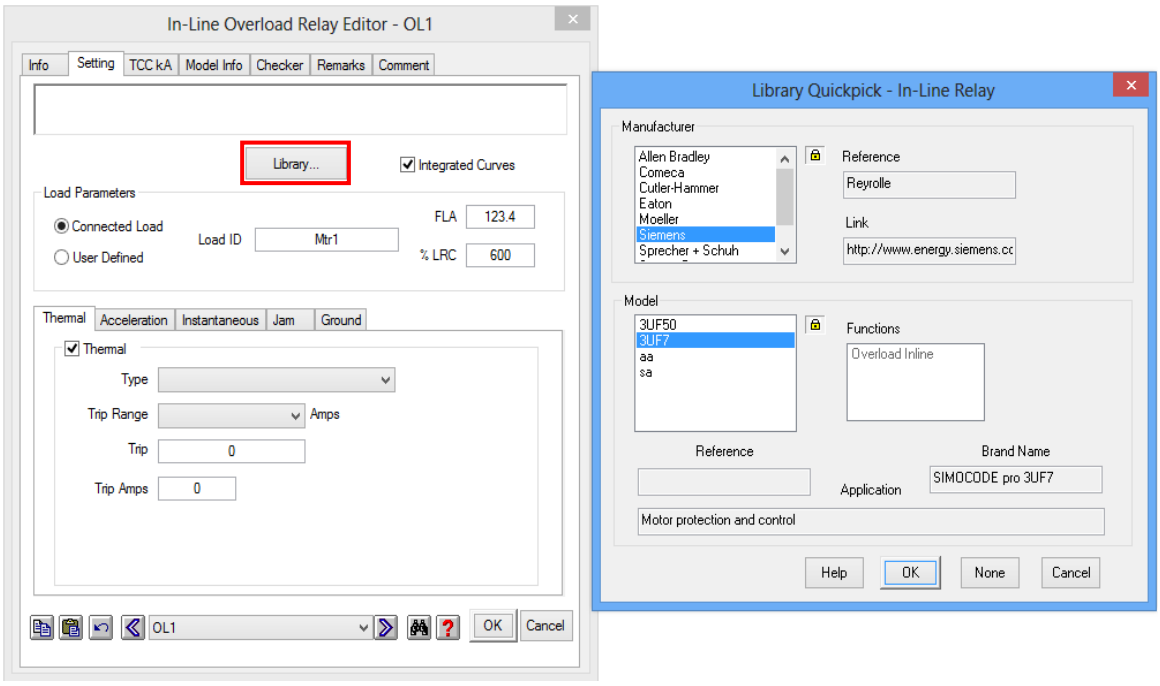
Stator curve defines the thermal limit curve for the stator. This time is provided by the motor manufacturer. This Curve can be shown on the TCC by selecting the checkbox next to Stator Curve.

Star-Protective Device Coordination

5. Similarly, drag and place protective devices & connect them by providing CT data as shown below.

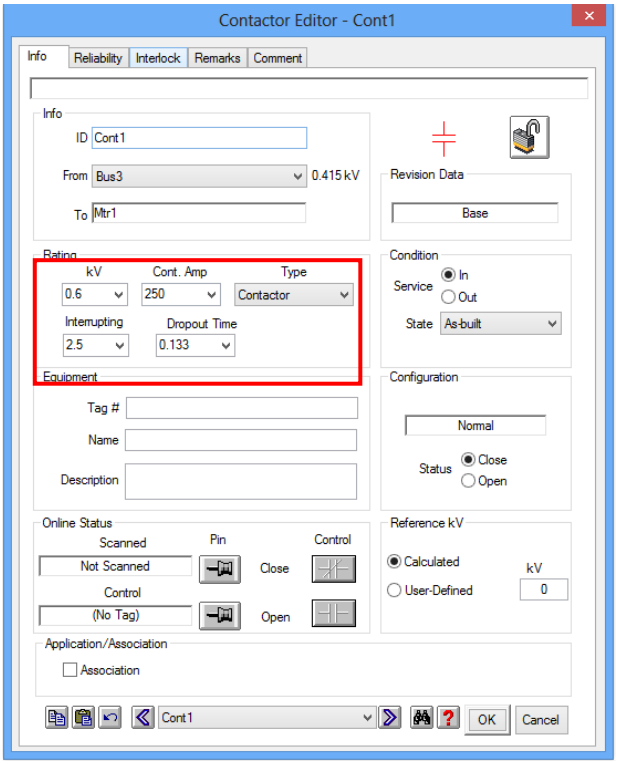


6. Click on the overload relay (OL1) and go to Setting page, select manufacturer & model from library as shown below.

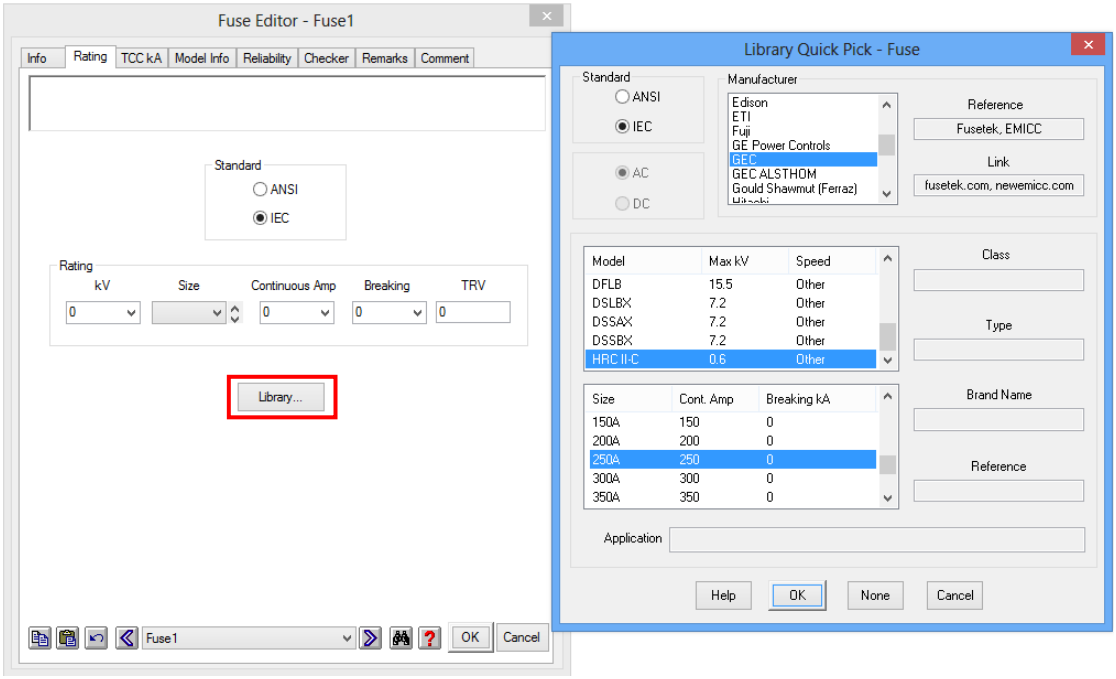


Star-Protective Device Coordination

7. Double click on the contactor (Cont1) and enter data as shown below.



8. Double click on fuse (Fuse1), and select data from Library as shown.

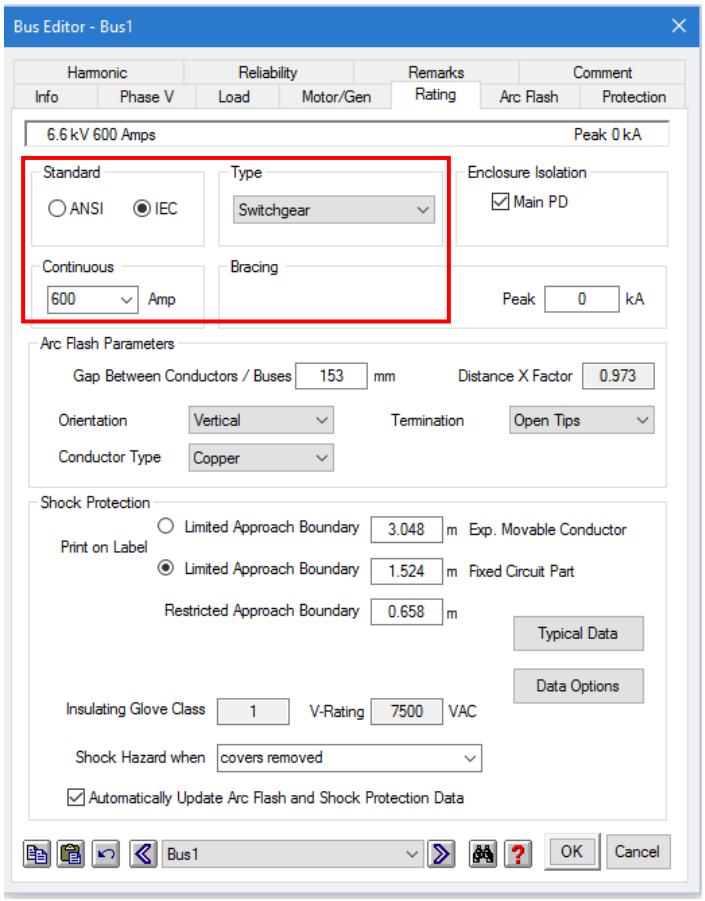


Star-Protective Device Coordination

9. Similarly, update all relay data from library in OCR page as shown in table below:

ETAP Equipment ID	Location	Equipment	Make & model from ETAP library
Relay-1	Incomer MCC	Multifunction relay	OCR, AREVA P122
Relay-2	Incomer PMCC	Multifunction relay	OCR, AREVA P122
Relay-3	Transformer neutral	Multifunction relay	OCR, AREVA P122
Relay-4	Transformer primary	Multifunction relay	OCR, AREVA P122
Relay-5	Grid relay	Multifunction relay	OCR, AREVA P122
Relay-6	Bus-coupler relay	Multifunction relay	OCR, AREVA P122
Relay-7	Outgoing relay	Multifunction relay	OCR, AREVA P122

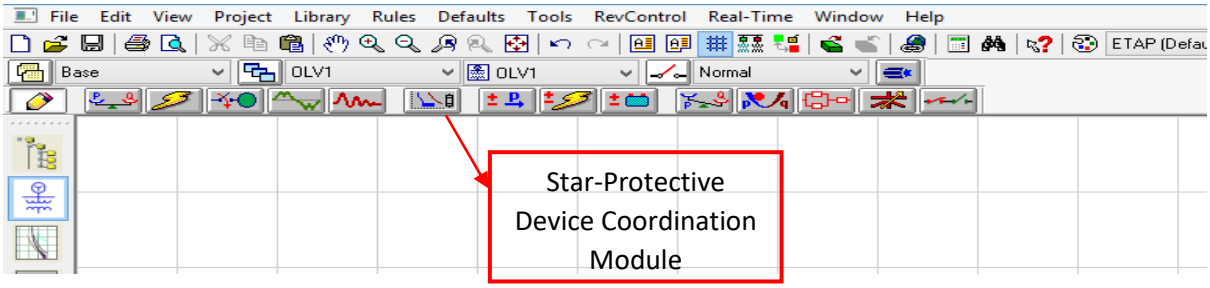
10. Update all HV & LV circuit breaker operating times. Double click on circuit breaker, go to Rating page update minimum time delay as shown.
    - LV Circuit Breaker – 0.04 sec
    - HV Circuit Breaker – 0.06 sec
11. On each bus go to rating page and update type and continuous ampere rating of bus as shown below.



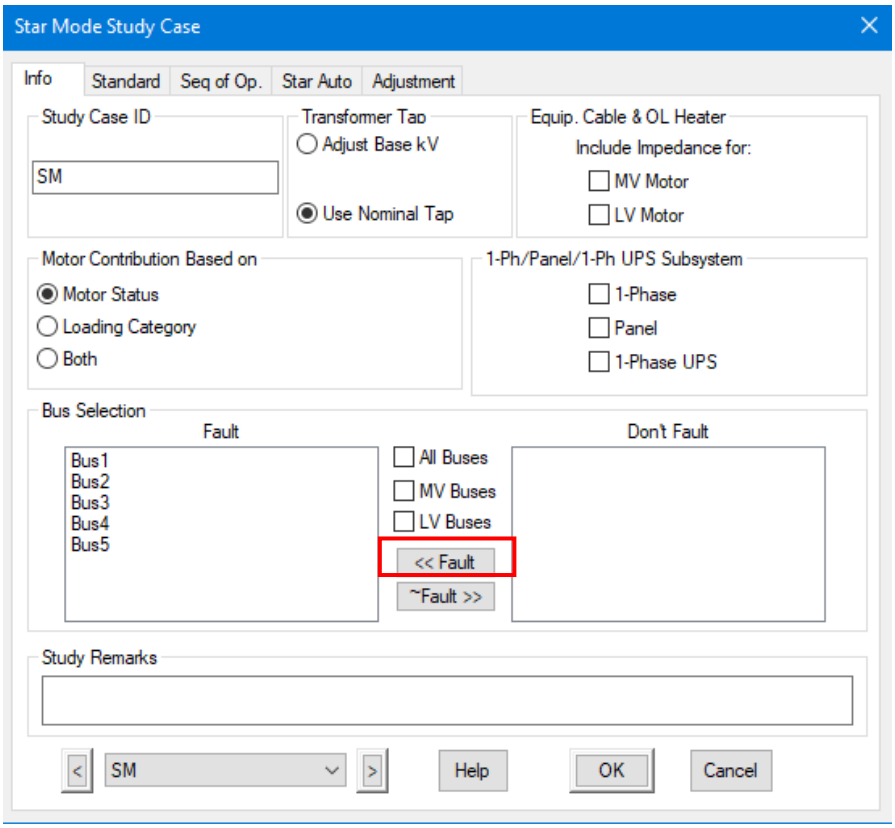
Star-Protective Device Coordination

Bus ID	Type	Rating (A)
Bus 1	Switchgear	600
Bus 2	Switchboard	3000
Bus 3	Switchboard	800
Bus 4	Switchboard	3000
Bus 5	Switchboard	800

12. Go to Star-Protective Device Coordination Module as shown below.

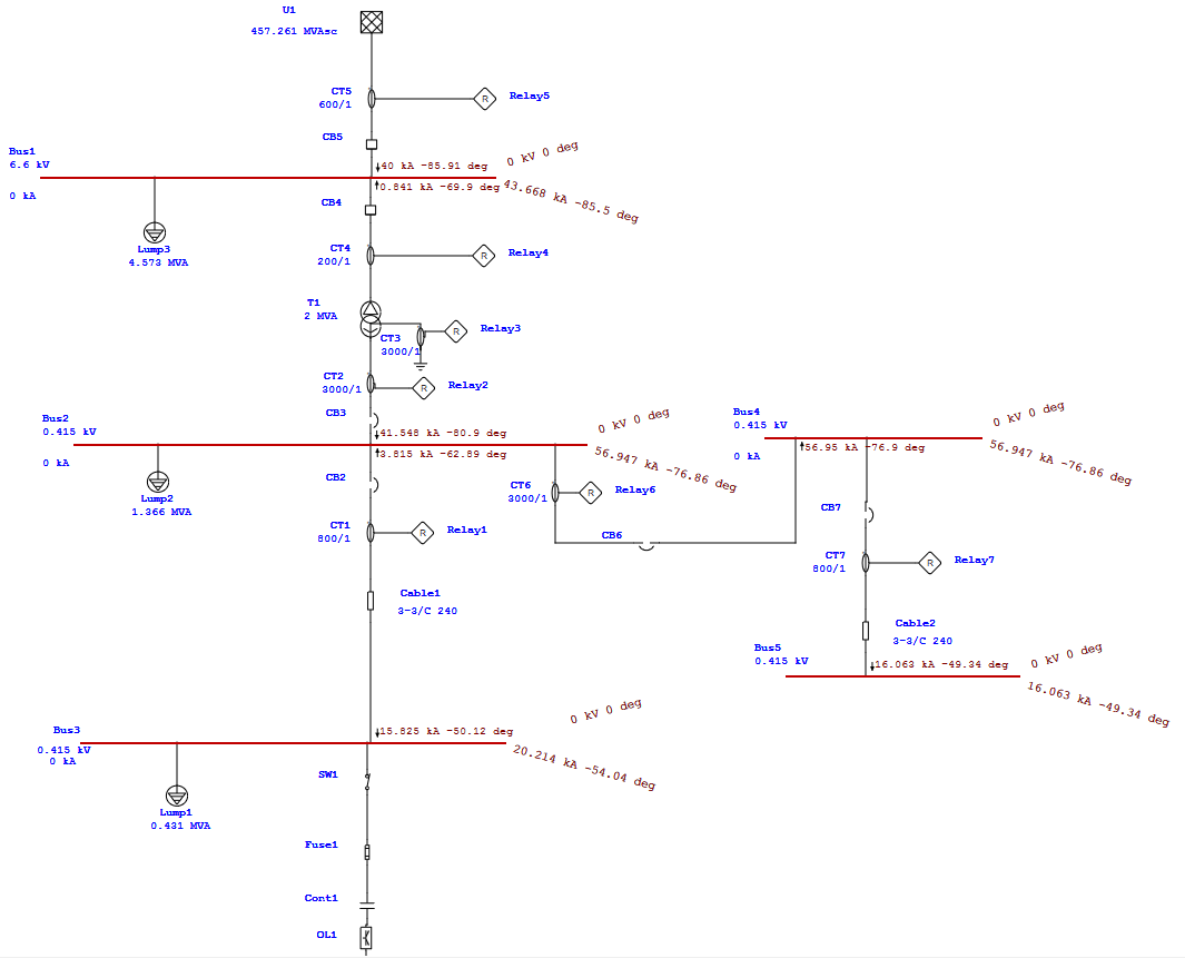


13. Click on Edit Study case, go to Info page create fault at all buses as shown below.



Star-Protective Device Coordination

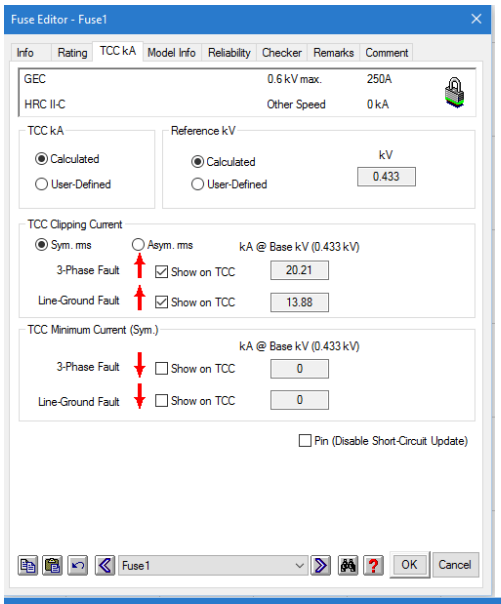
14. Click on Run/ Update Short-Circuit kA in the star toolbar.

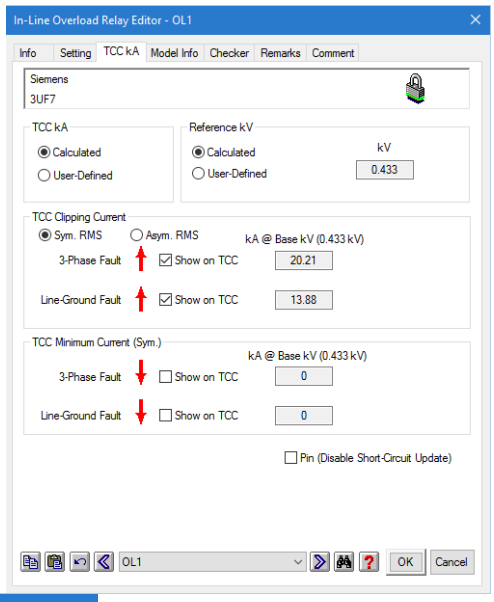


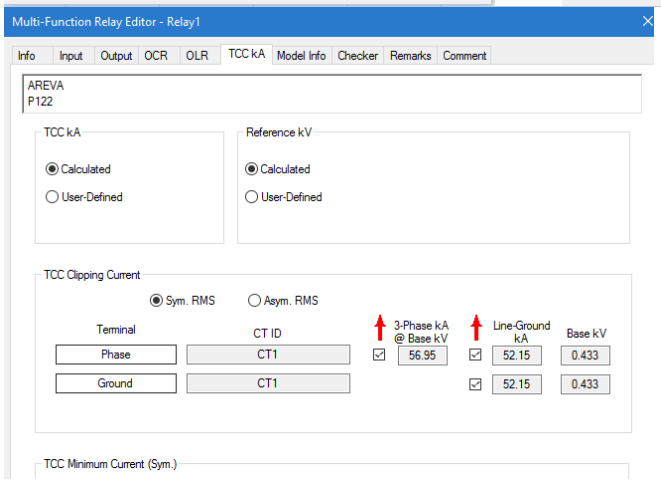
15. Double click on the fuse and go to TCC kA page and check for short circuit current is updated for TCC clipping current. Similarly check for other protective devices like Relay, MCCB, OLR and LV circuit breaker.

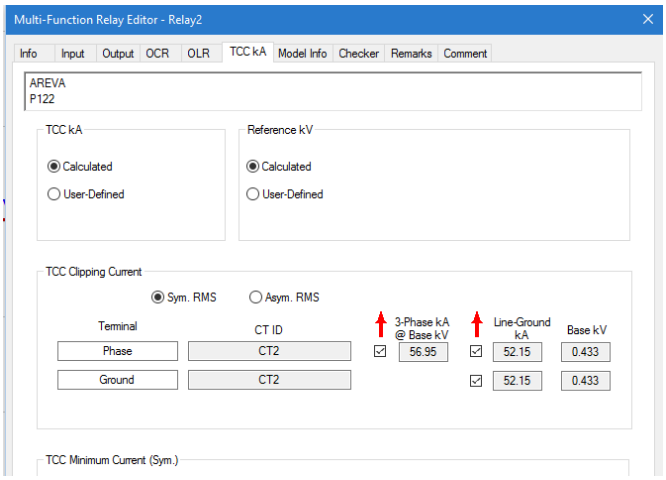
16. Select Sym. RMS fault current for all devices, which is OK for time delayed coordination.

Star-Protective Device Coordination

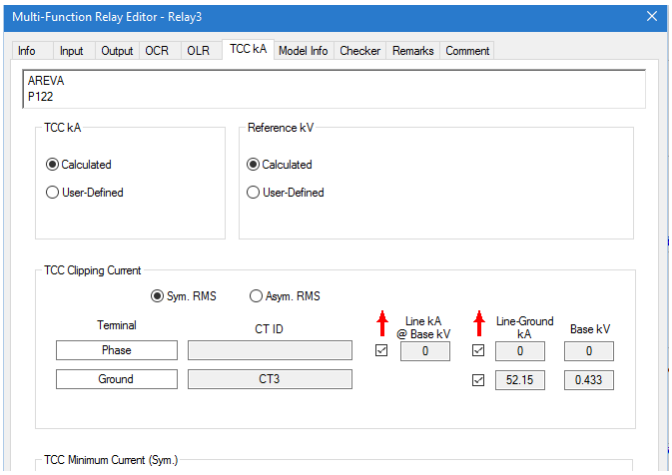


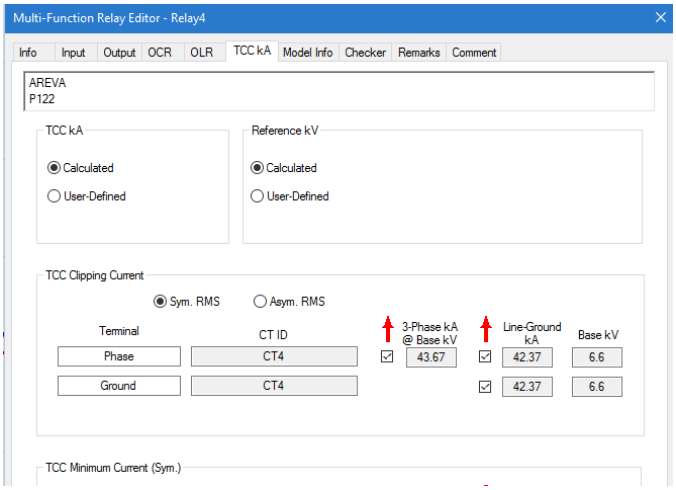


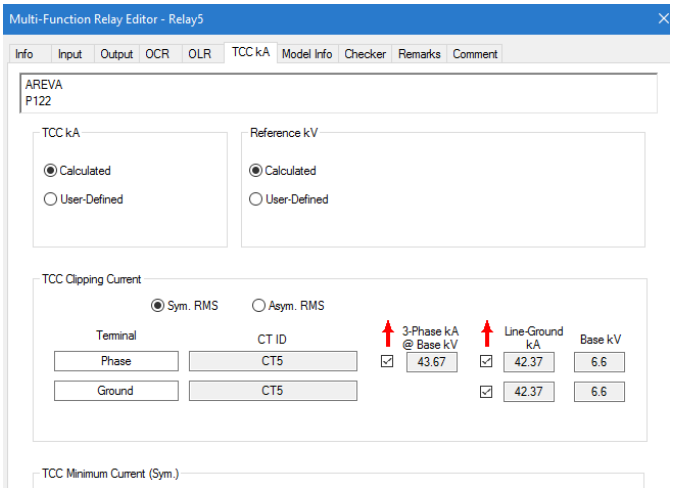




Star-Protective Device Coordination

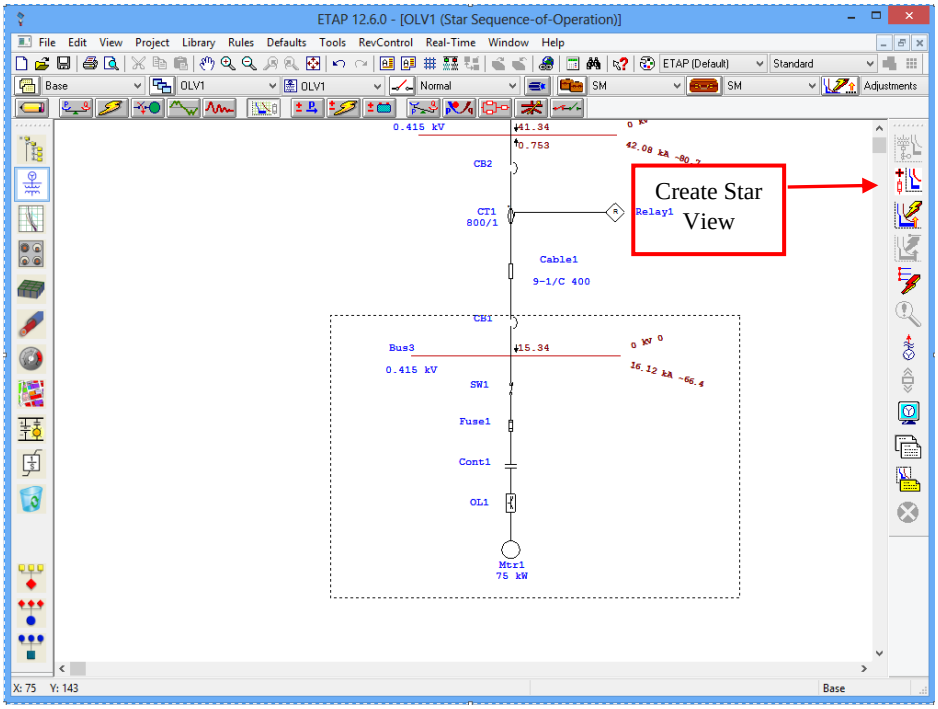




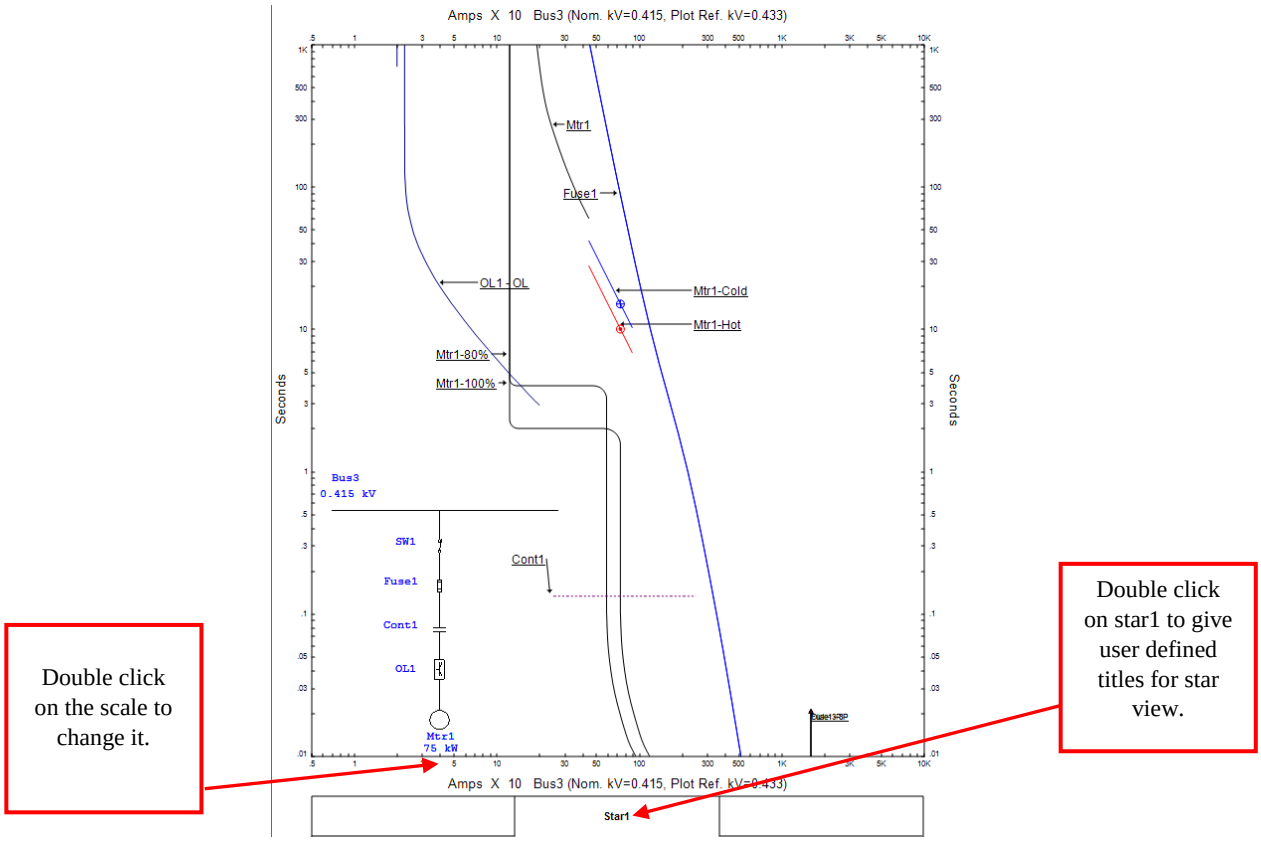


Star-Protective Device Coordination

17. Make window around motor along with its protective devices (i.e. OLR, Contactor, fuse & CB) using left mouse click and click on Create Star View to plot TCC curve.

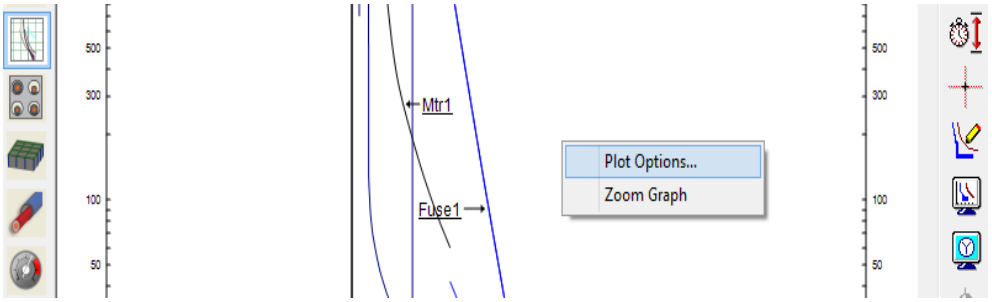


18. A TCC star view (i.e. Star 1) is created as shown below:

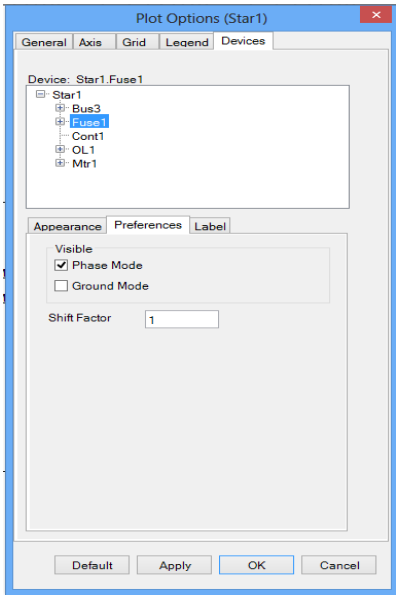


Star-Protective Device Coordination

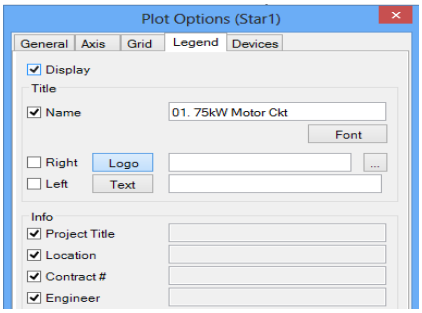
19. Right click on the TCC window and click on Plot Options to edit the properties of plots.



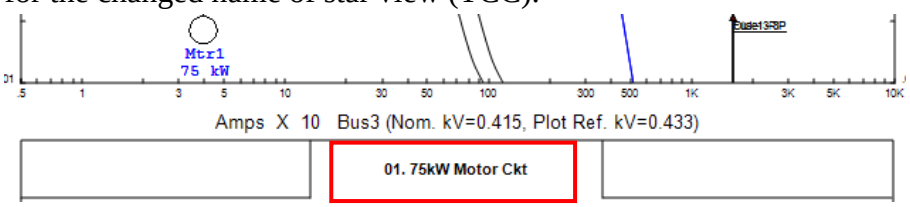
Using plot options, we can hide or unhide the devices. For this right-click on the star view > Plot Options > Devices > Preferences & check phase & ground mode for visibility.



20. Go to Legend page, rename “Star1” to “01. 75KW Motor Ckt”. Click OK to save the name.

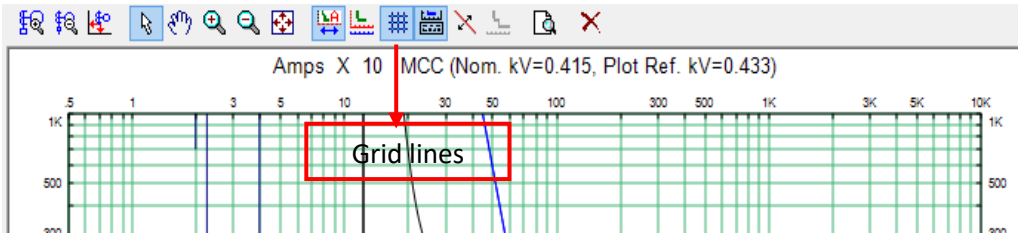


21. Check for the changed name of star view (TCC).



Star-Protective Device Coordination

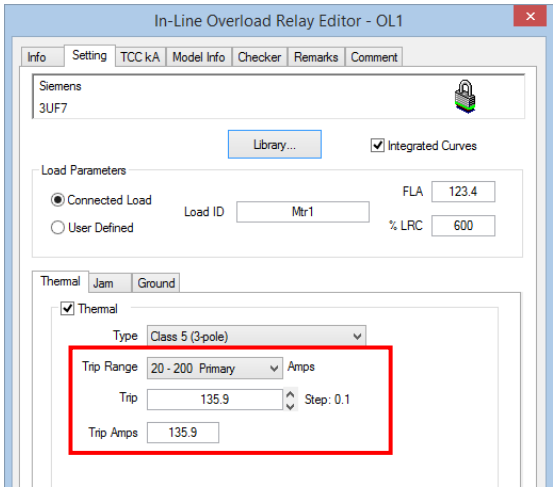
22. Show the grid lines by clicking on the Show Grid on the top of the TCC.



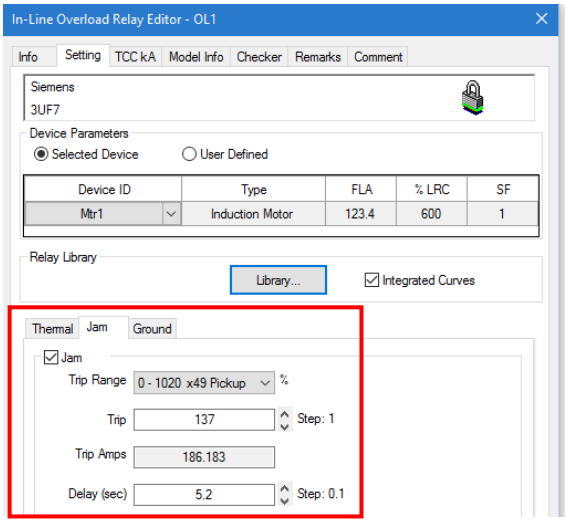
23. Set the motor protection as given below.

Double click on overload relay, go to settings page & set the following:

1. Click on Thermal page for over current or over load setting:
   - Current pickup = 1.1 times of FLC of motor (123.5 * 1.1 = 135.9 A).
   - Time delay should be above motor start & below stator thermal damage curve.

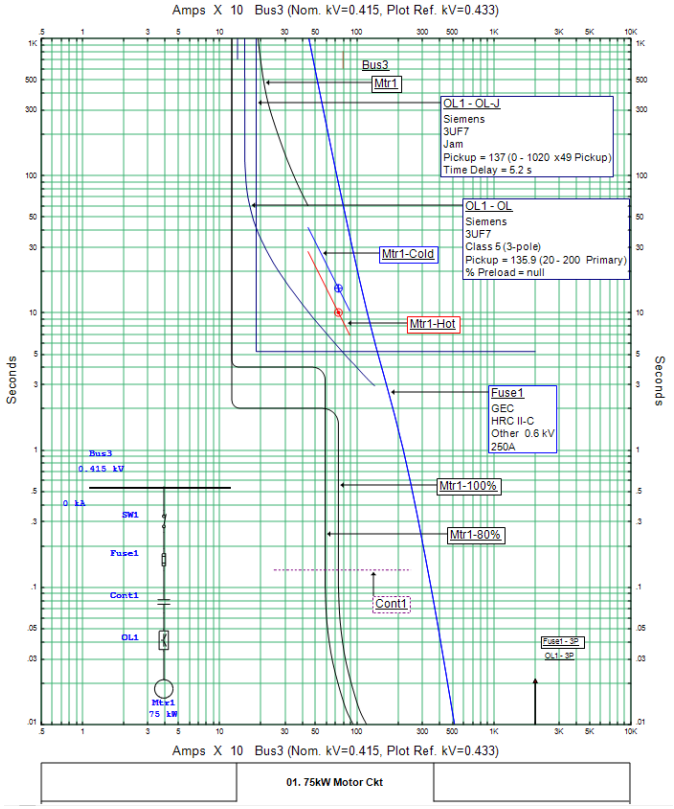


2. Click on Jam page for locked rotor or jam or stall protection.
   - Current pick up (Trip) = 150% of FLC of motor = 137% of thermal overload pickup
   - Time delay should be above motor start & below stator thermal damage curve.

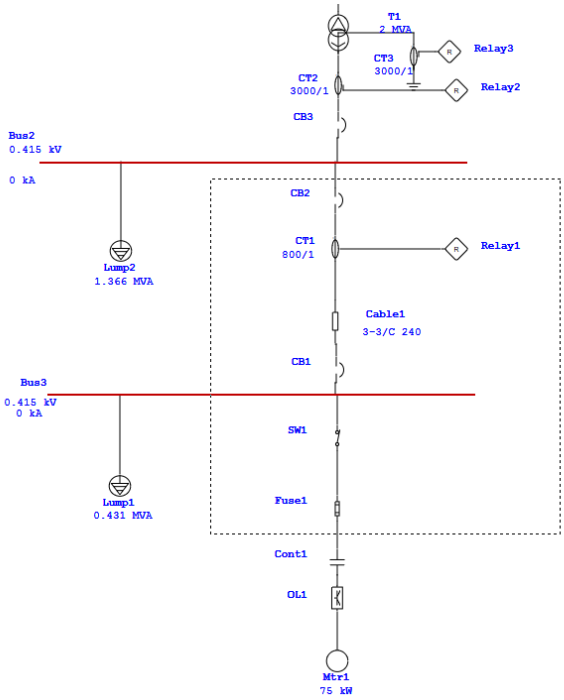


Star-Protective Device Coordination

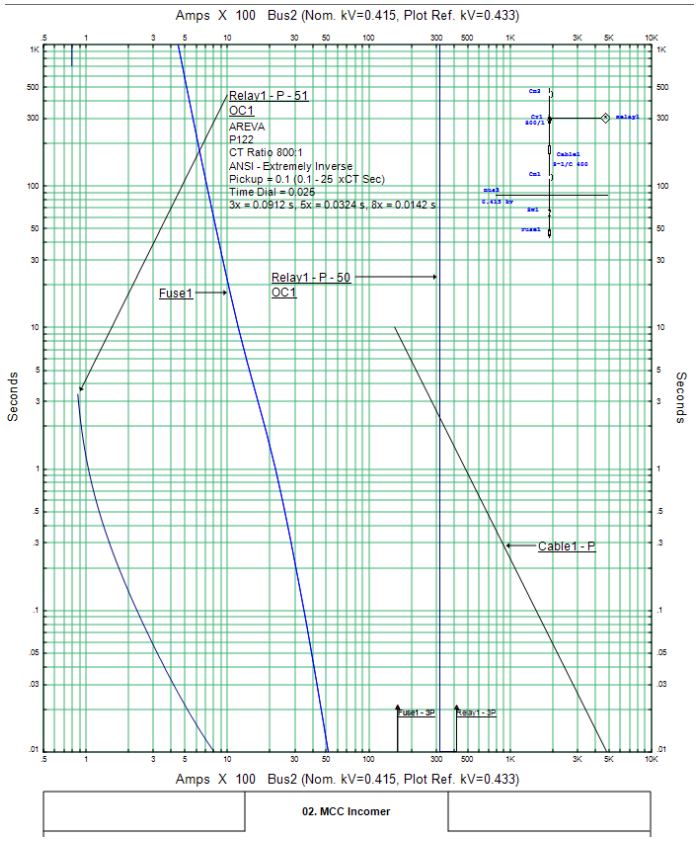
24. Adjust the time delay using time handle on the OLR jam protection curve. Set it above motor starting curve and below the motor stator & rotor thermal damage curve.



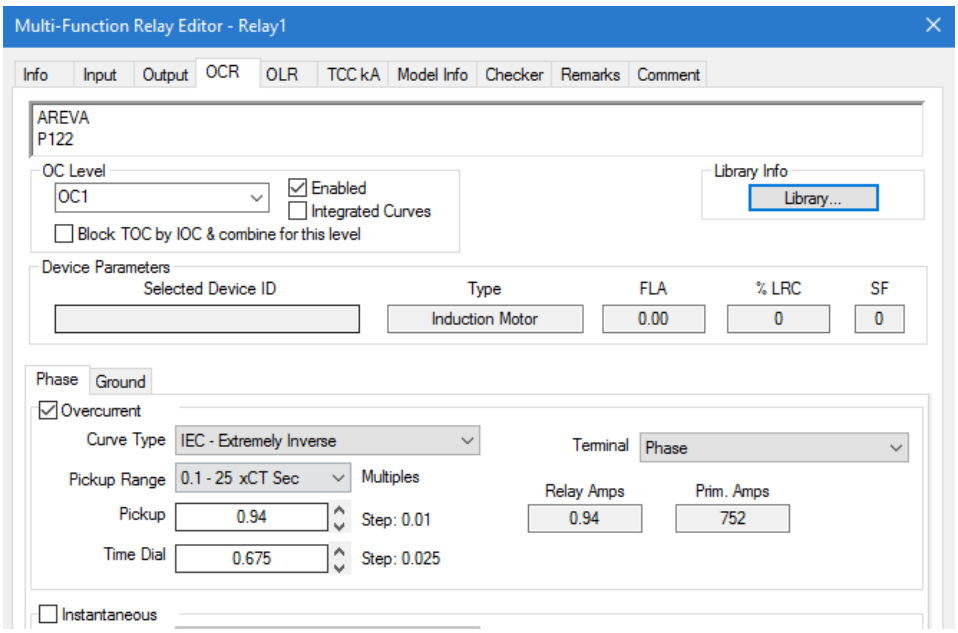
25. Go to OLV, make window as shown below using left mouse click and click on create star view (Star1) to plot TCC curve. Rename “Star1” to “02. MCC Incomer”.



Star-Protective Device Coordination

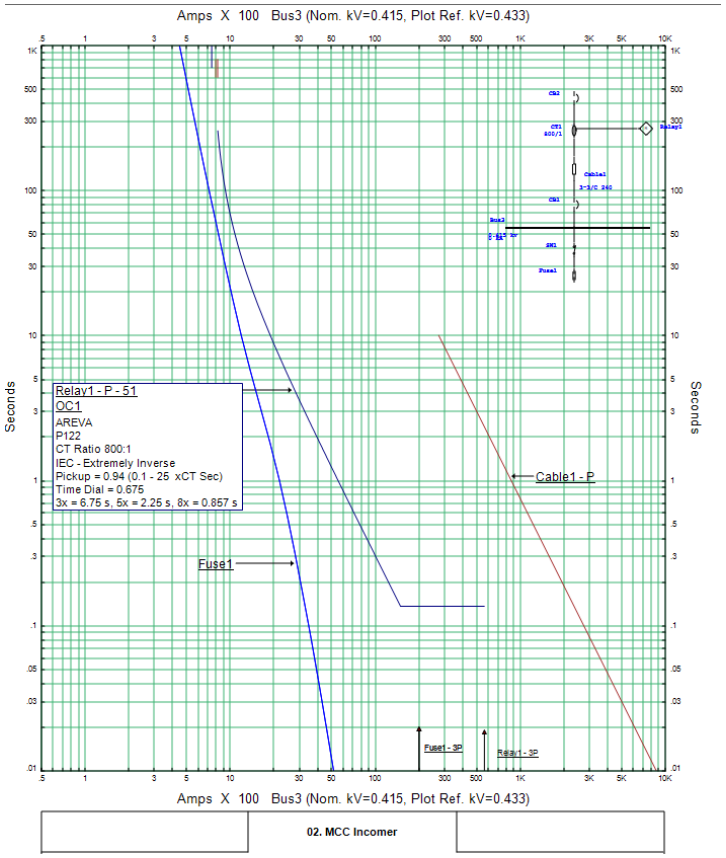


26. Double click on relay1, go to OCR page and enter curve type as IEC –extremely inverse & pickup value as 0.94 (i.e. 800 * 0.94 = 752 A) in Phase page as shown.

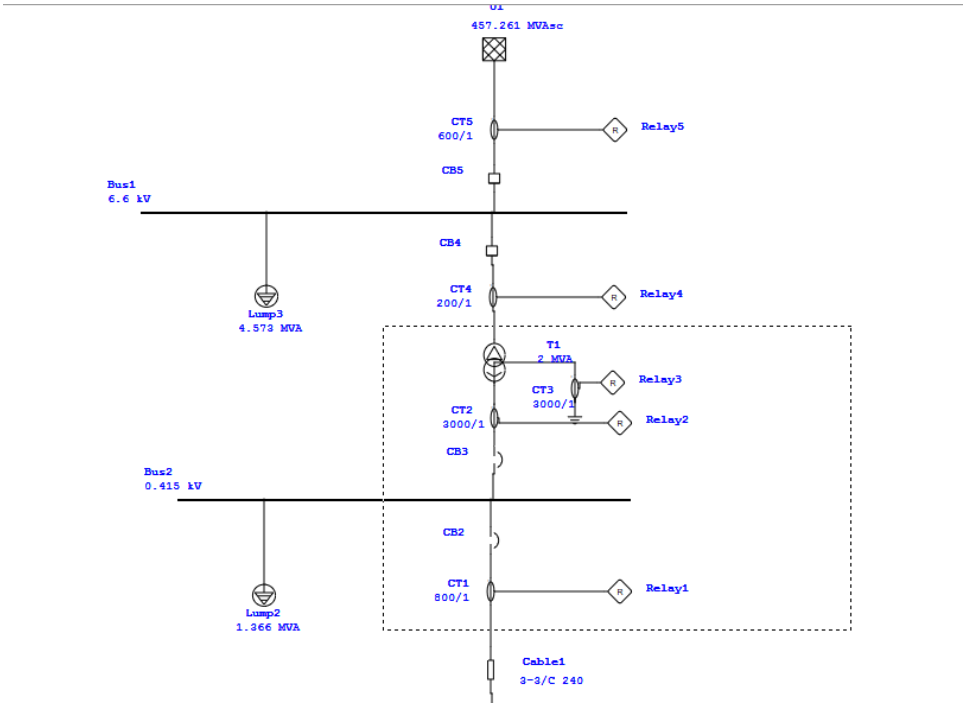


Star-Protective Device Coordination

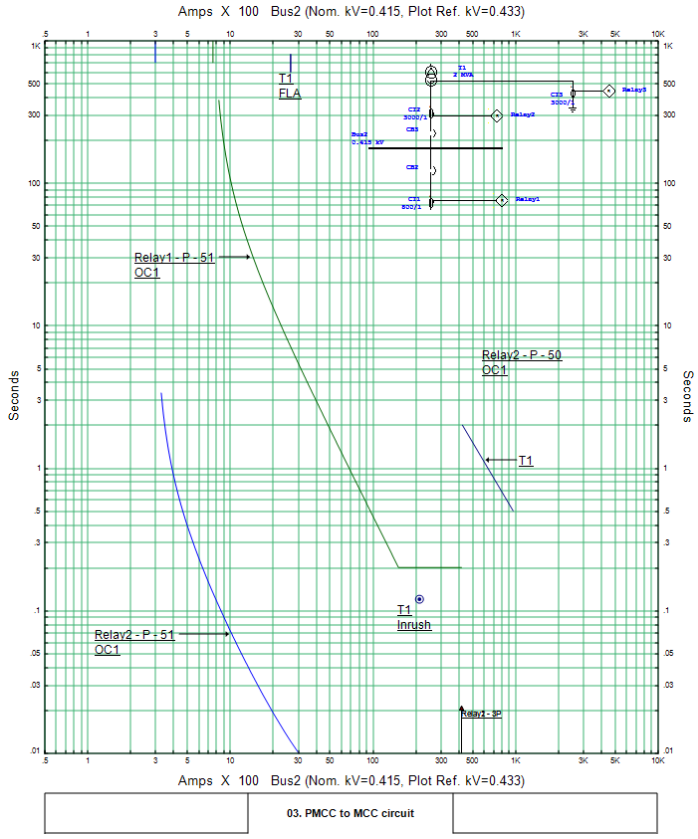
27. Adjust the time delay by using time handle on plot such that it is above characteristics of fuse and below the MCC incomer cable thermal withstand characteristics.



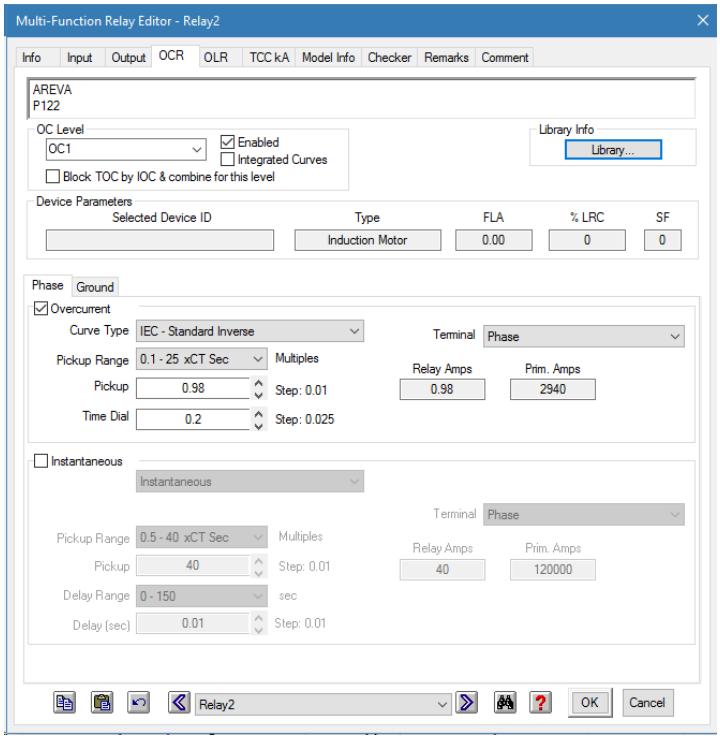
28. Go to OLV, make a window around MCC incomer relay and PMCC incomer relay as shown and create new star view and rename to “03. PMCC to MCC circuit”.



Star-Protective Device Coordination

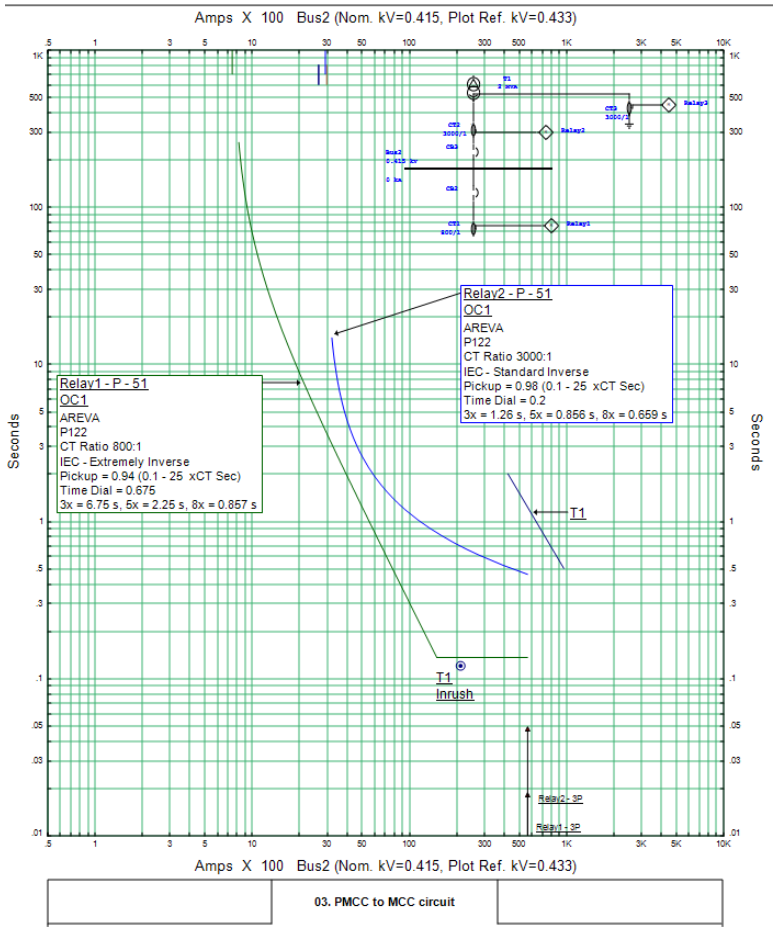


29. Double click on relay2, Go to OCR page and enter curve type as IEC –standard inverse & pickup value as 0.98 (i.e. 1.1 times of transformer secondary full load current / CT ratio) in Phase page as shown below.

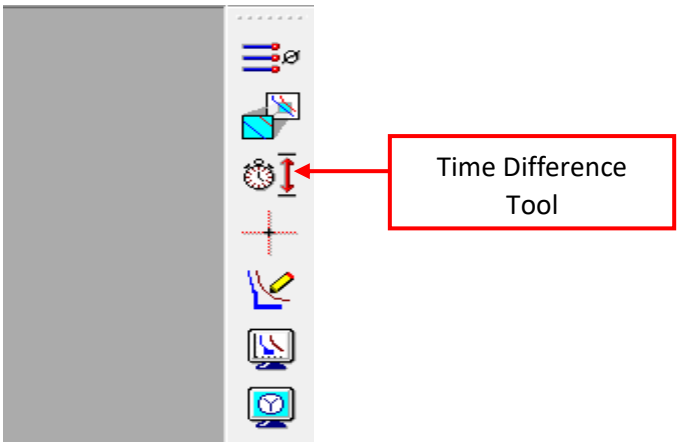


Star-Protective Device Coordination

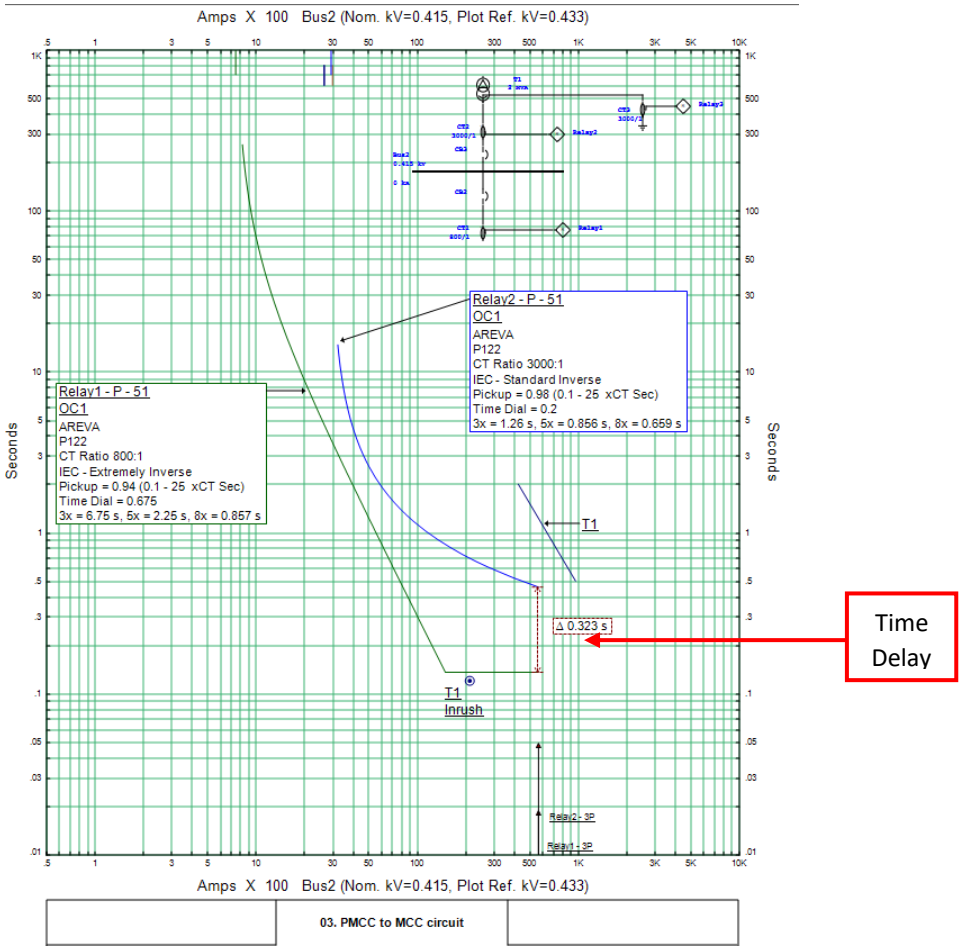
30. Adjust the time delay by using time handle on plot such that it is above characteristics of relay1 and below the Transformer thermal withstand characteristics.



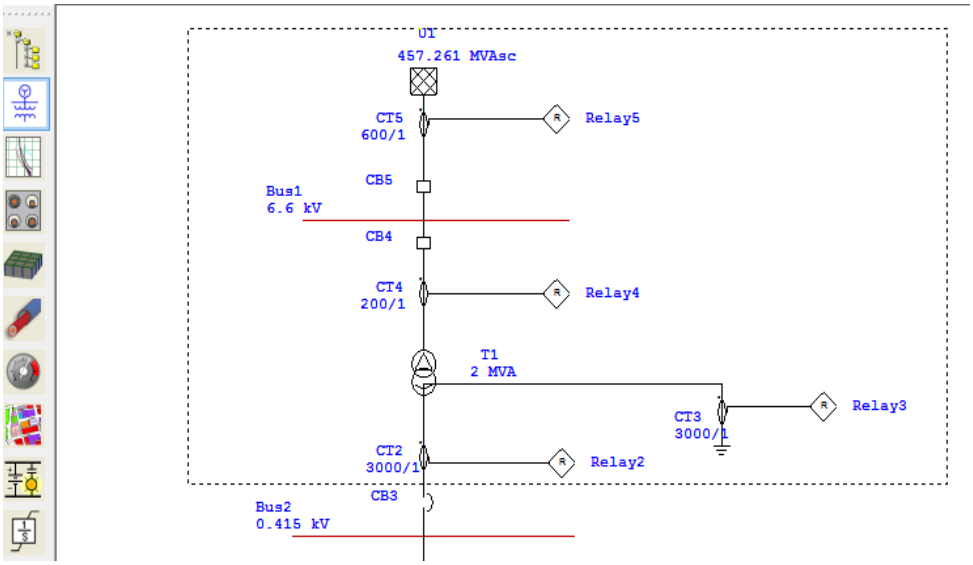
31. Check the time delay of Relay2 by using time handle such that it is above the Relay1 curve with time difference of 300ms by using Time Difference tool.



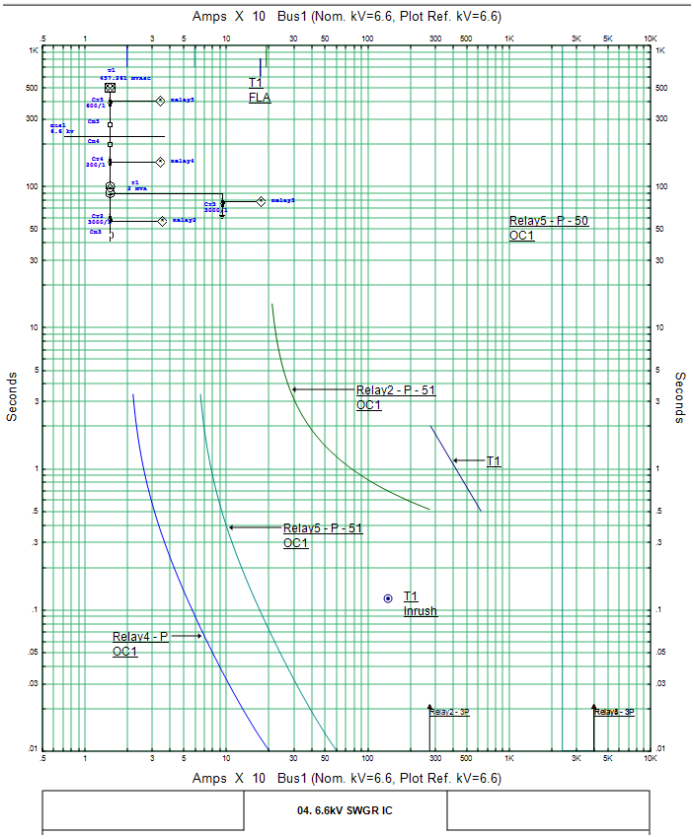
Star-Protective Device Coordination



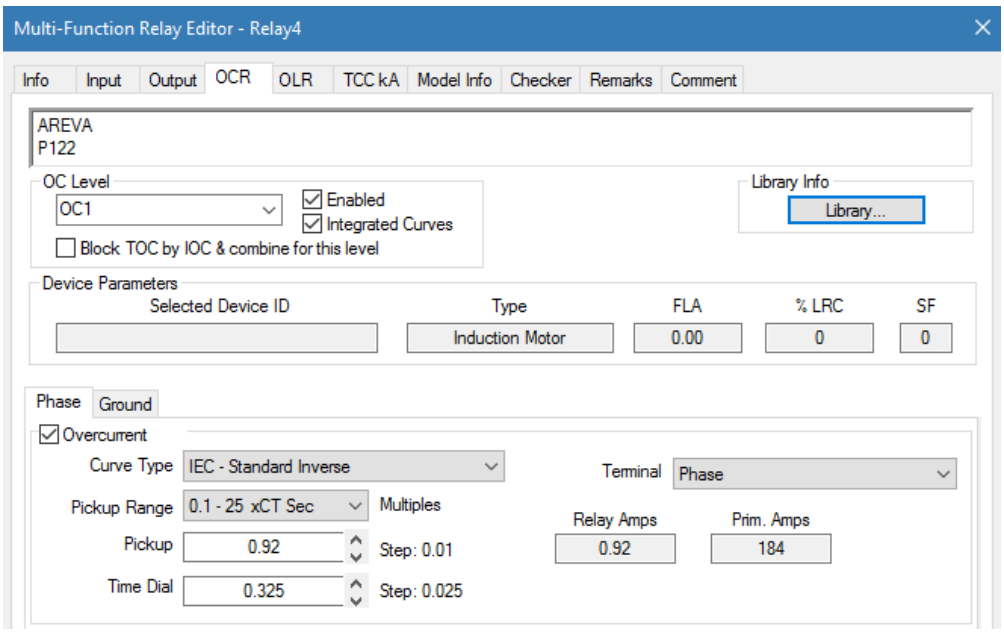
32. Go to OLV make window as shown below and click on Create Star View to plot TCC curve.



Star-Protective Device Coordination

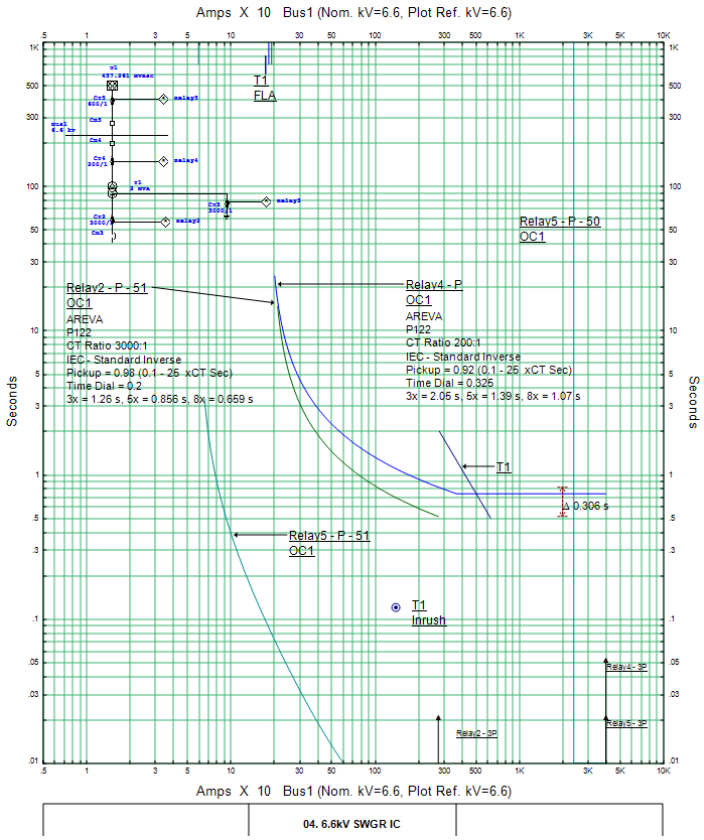


33. Double click on relay4, go to OCR page and enter curve type as IEC –standard inverse & pickup value as 0.92 (i.e. 1.05 times of transformer primary full load current / CT ratio) in Phase page as shown below.



Star-Protective Device Coordination

34. Adjust the time delay by using time handle on plot such that it is above characteristics of relay2, transformer inrush current and below the transformer thermal withstand characteristics. Also check the time difference between relay2 & relay 4 by using Time Difference tool.



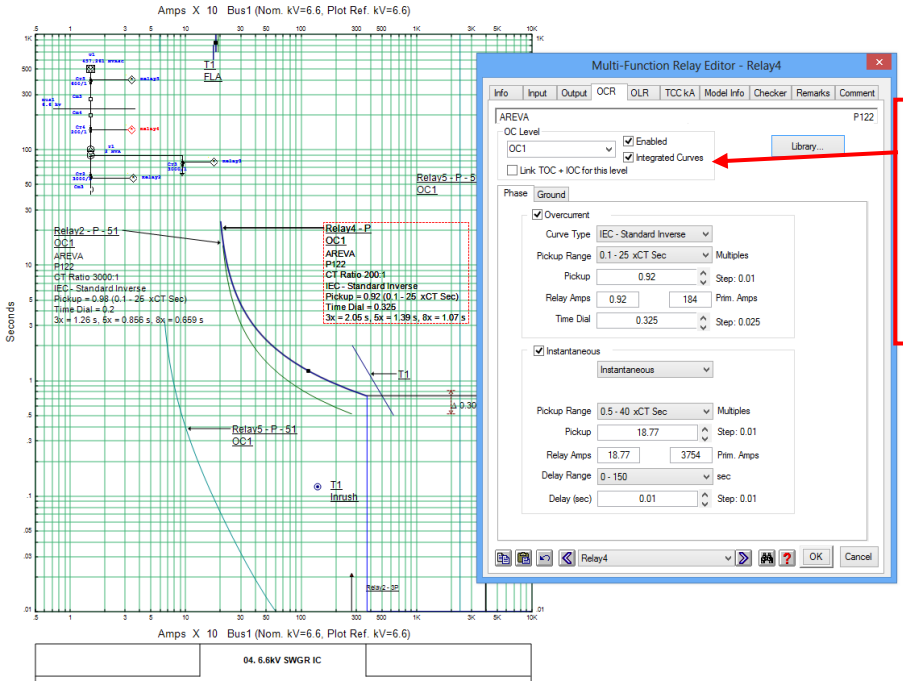
35. Here fault current seen by the transformer incomer relay is as per the table shown below.

Fault location	**Fault current seen by transformer incomer relay at 6.6kV in kA**
Fault at transformer secondary (0.415 kV side)	2.71
Fault at transformer primary (6.6 kV side)	40.05

From above table, fault level difference for the fault created at primary & reflected fault current seen at primary for secondary fault is more. So the transformer incomer relay instantaneous overcurrent protection is enabled for fault current above 140% above the transformer secondary fault level.

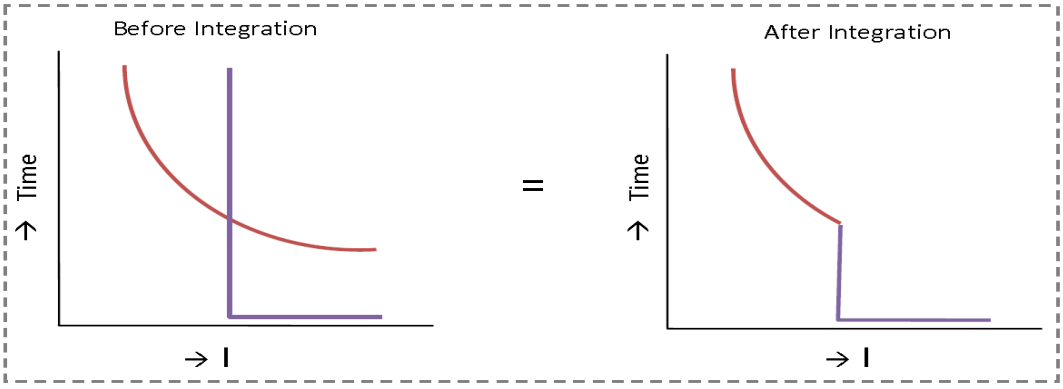
Star-Protective Device Coordination

36. Set the instantaneous current protection setting as 18.77 (i.e. 1.4 times above the transformer secondary fault level / CT ratio) and time delay at minimum time say 0.01 sec.



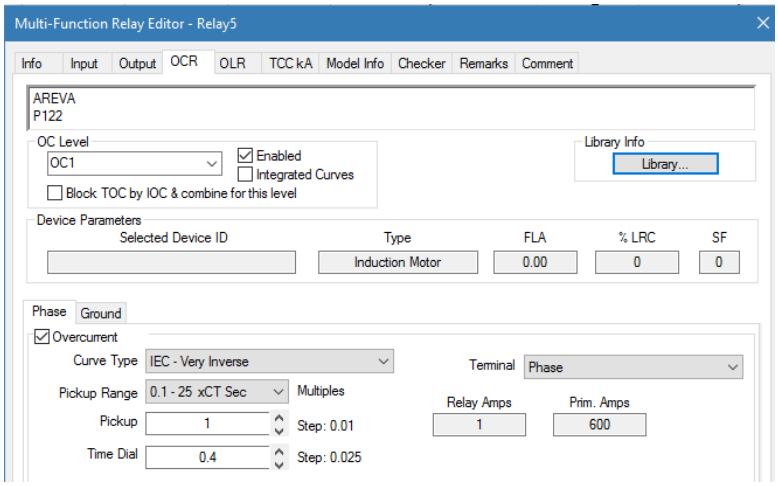
Check the radio button to integrate overcurrent and instantaneous curves in the graph.

Note: Relay curve integration of two types of cures of same relay is shown below.

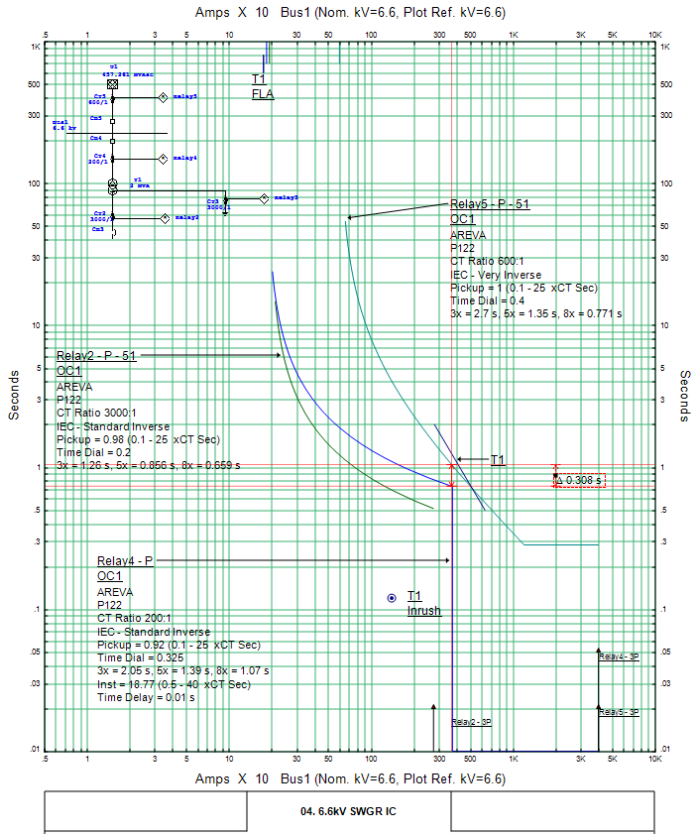


Star-Protective Device Coordination

37. Double click on relay5, go to OCR page and enter curve type as IEC –very inverse & pickup value as 1 (i.e. 100% CT ratio) in Phase page as shown.



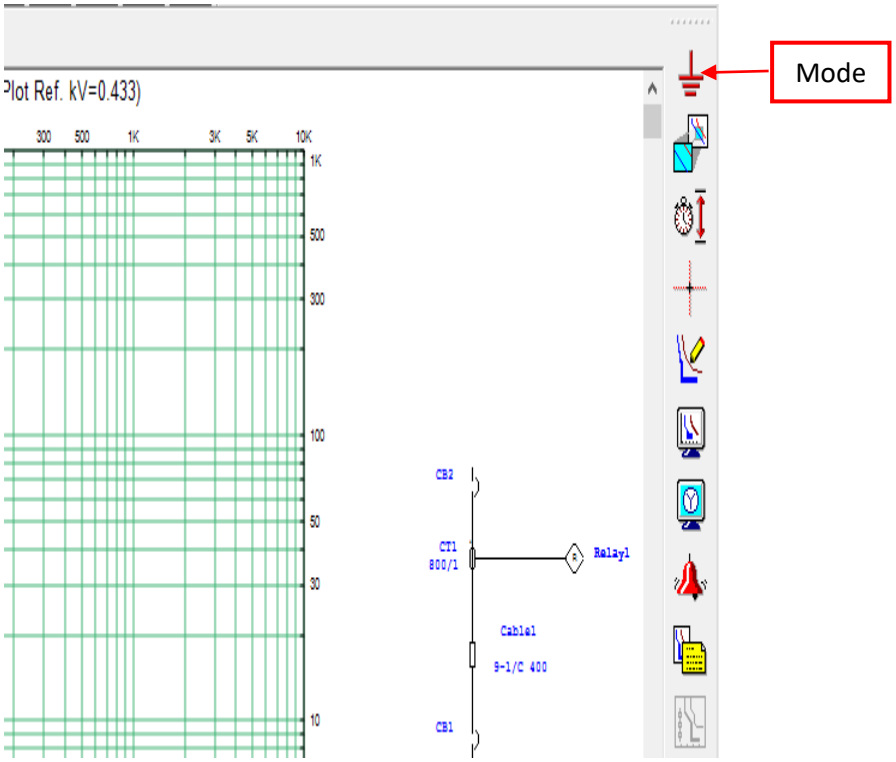
38. Adjust the time delay by using time handle on plot such that it is above characteristics of relay4. Also check the time difference between relay4 & relay5 by using Time Difference tool.



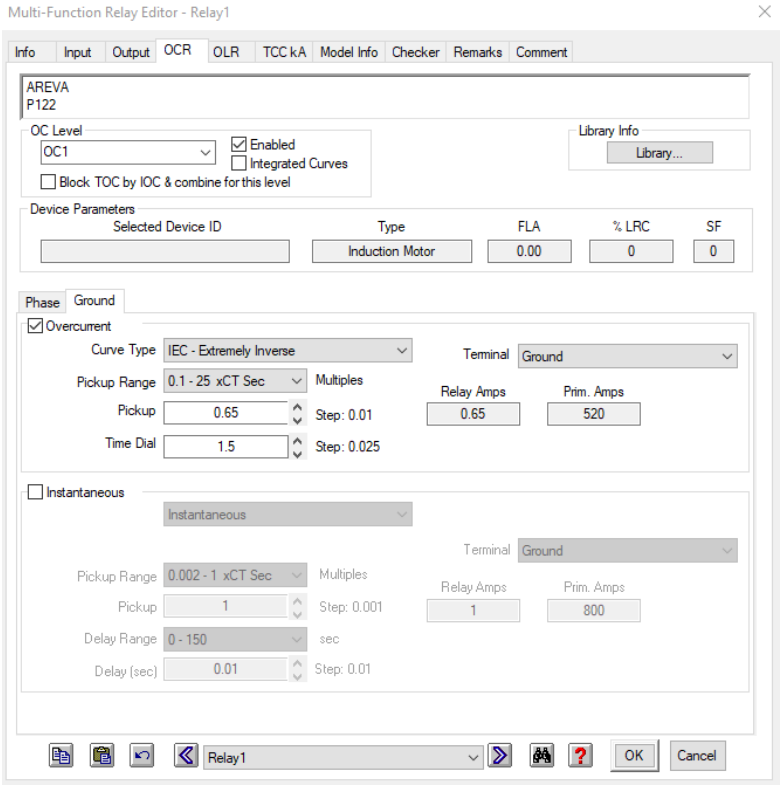
Star-Protective Device Coordination

Earth Fault Protection Settings

1. Open “02. MCC Incomer” star view TCC plot, click on Mode to view earth fault view.

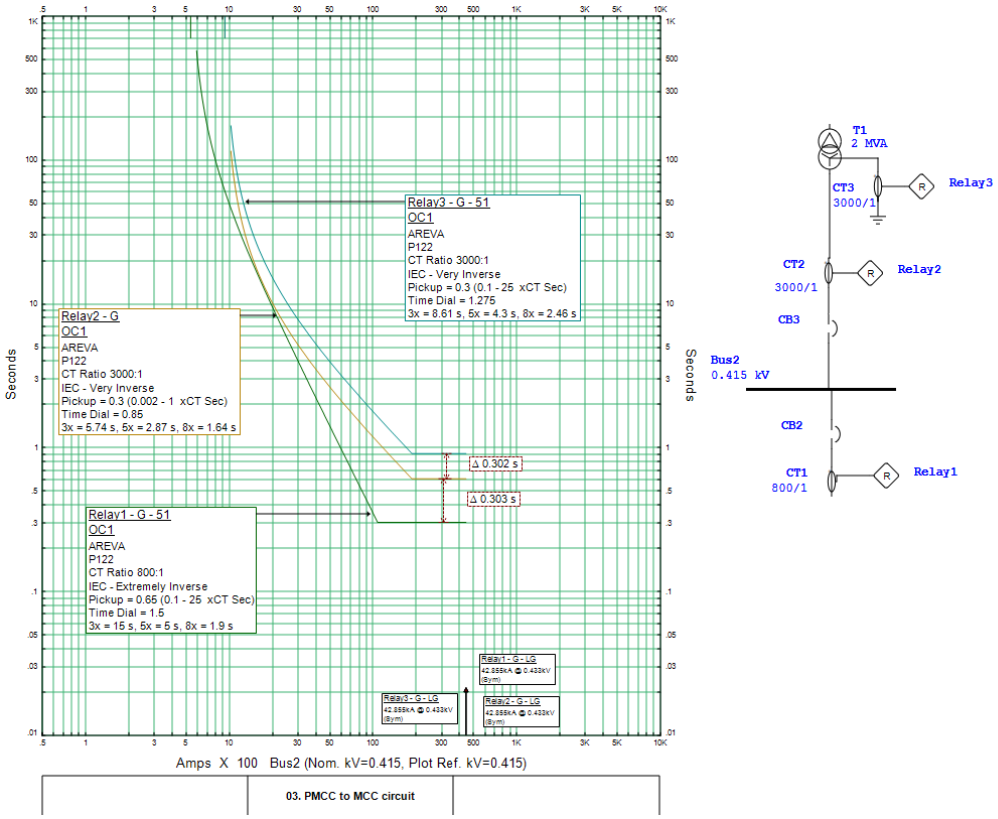


2. Double click on relay1, go to OCR page and enter curve type as IEC –Extremely inverse & pickup value as 0.65 in earth page as shown, so that relay 1 will get co-ordinate with fuse in ground setting as well.



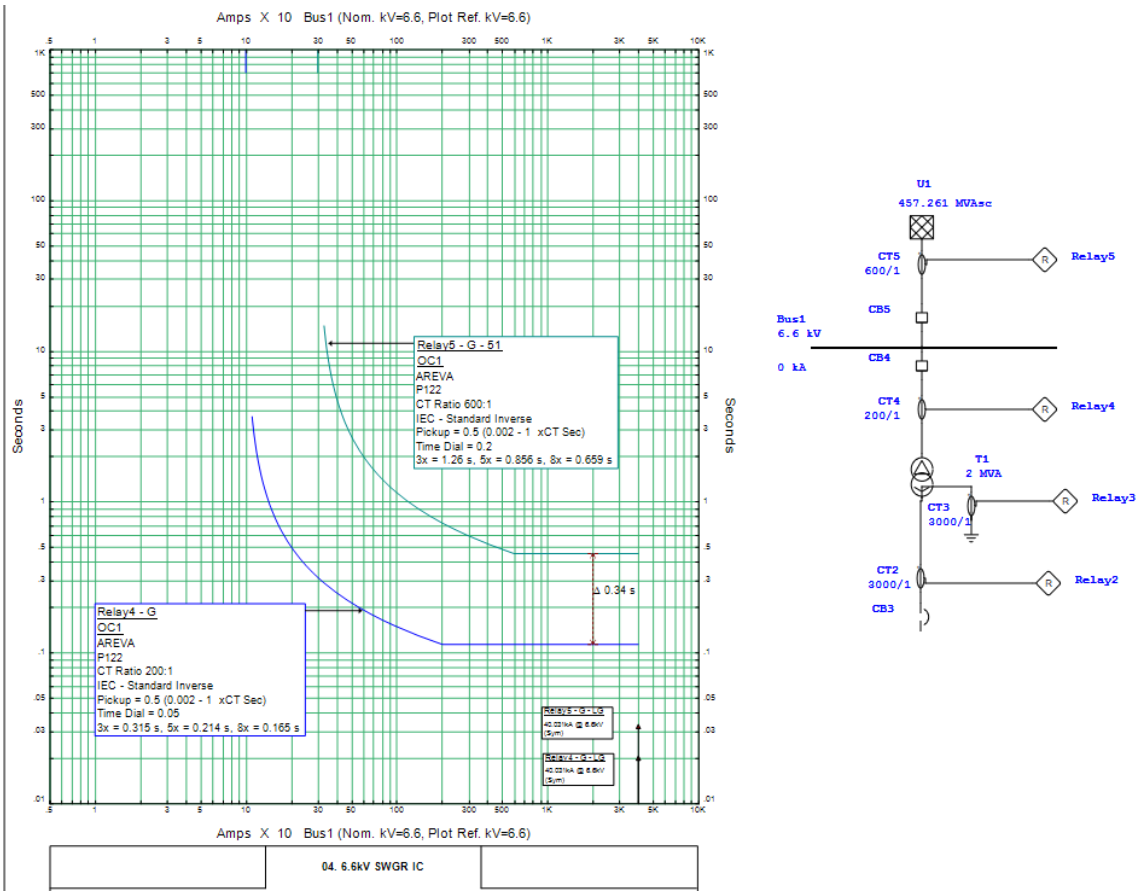
Star-Protective Device Coordination

3. Adjust curve time by using time handle (set TMS = 1.5).
4. Open “03.PMCC to MCC Circuit” TCC plot, click on Mode to view earth fault view. Double click on relay 2, go to OCR page and enter curve type as IEC –Very inverse & pickup value as 0.3 in earth page.
5. Similarly, double click on relay 3, go to OCR page and enter curve type as IEC –Very Inverse & pickup value as 0.3 in earth page.
6. Adjust the time delay by using time handle on plot such that minimum discrimination between the relay curves is closed to 300ms as shown below.



7. Open “04. 6.6KV SWGR IC” TCC plot, click on Mode to view earth fault view. Hide relay2 & relay3 curves from TCC plot using plot options. Double click on relay4, go to OCR page and enter curve type as IEC –standard inverse & pickup value as 0.5 in earth page.
8. Similarly, double click on relay5 and go to OCR page. Enter curve type as IEC – standard inverse & pickup value as 0.5 in earth page.
9. Adjust the time delay by using time handle on plot such that minimum discrimination between the relay curves is closed to 300ms as shown below.

Star-Protective Device Coordination

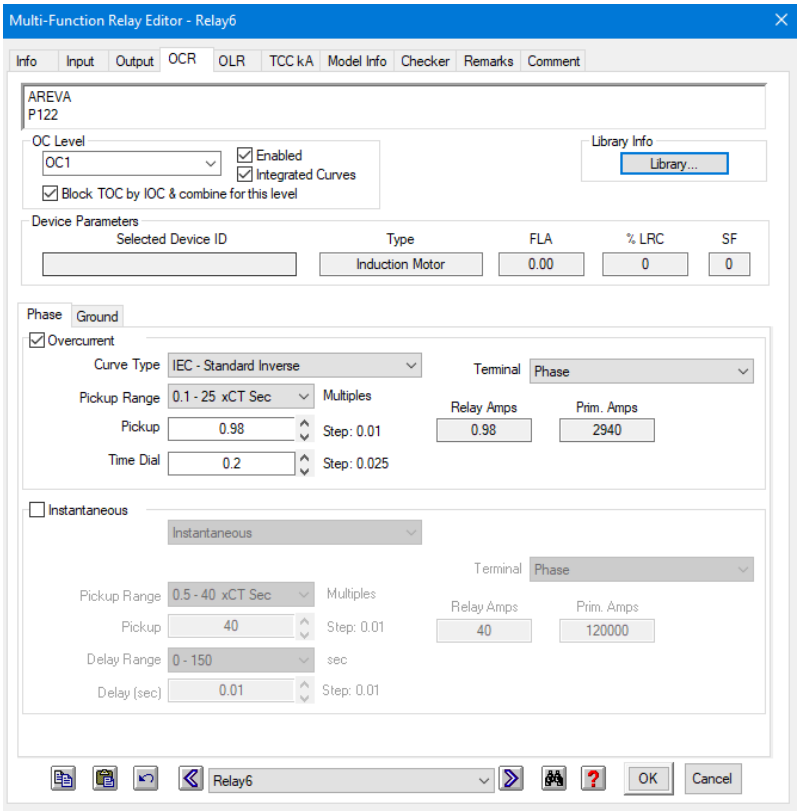


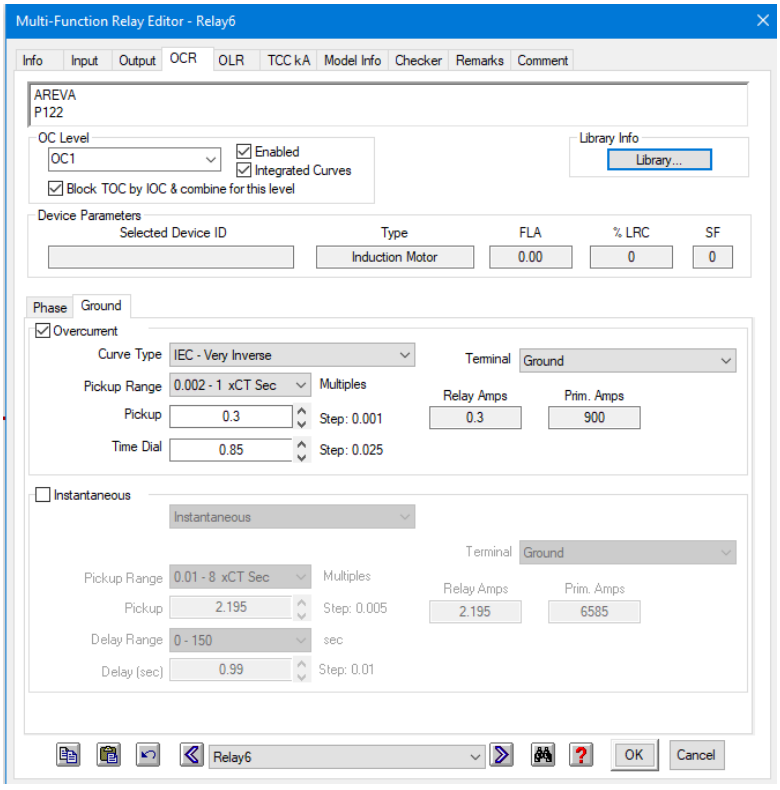
10. Note that, in this case the co-ordination between **bus coupler & incomer relay** is sacrificed.

    Hence set the Phase and Ground settings of bus coupler relay i.e. Relay 6 as same as incomer relay (i.e.Relay2) settings. Also give the outgoing cable feeder relay i.e. Relay 7 settings as same as Relay 1 settings.

Star-Protective Device Coordination

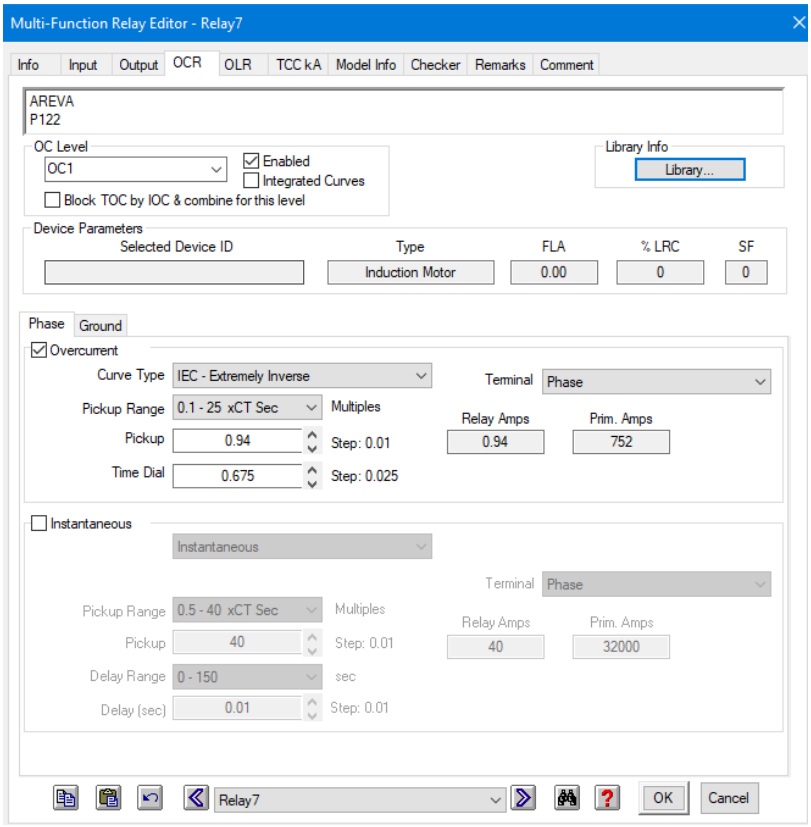
Relay 6 Phase and Ground settings:

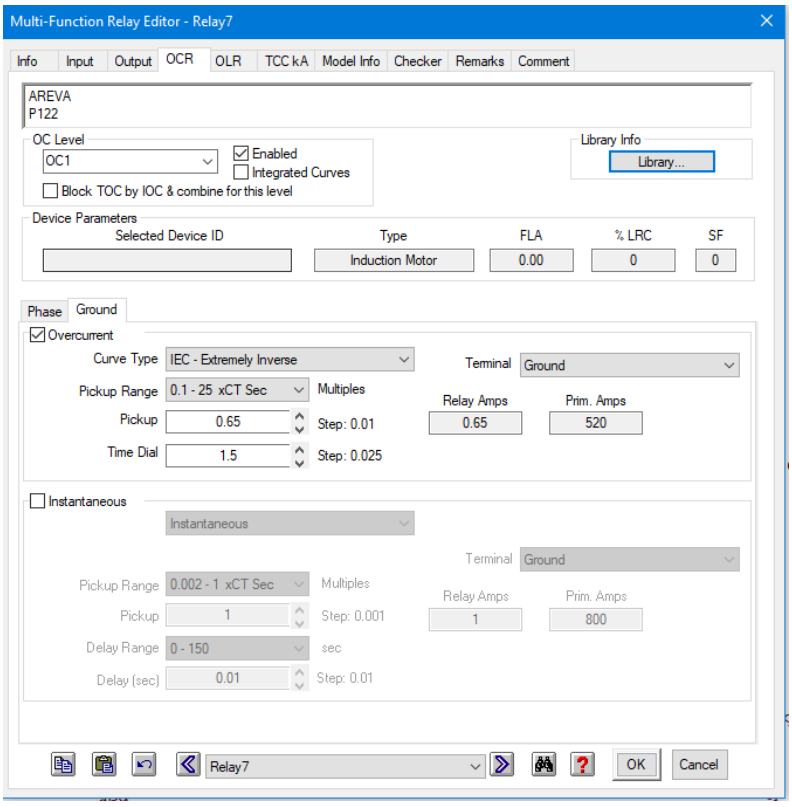




Star-Protective Device Coordination

Relay 7 Phase and Ground settings:

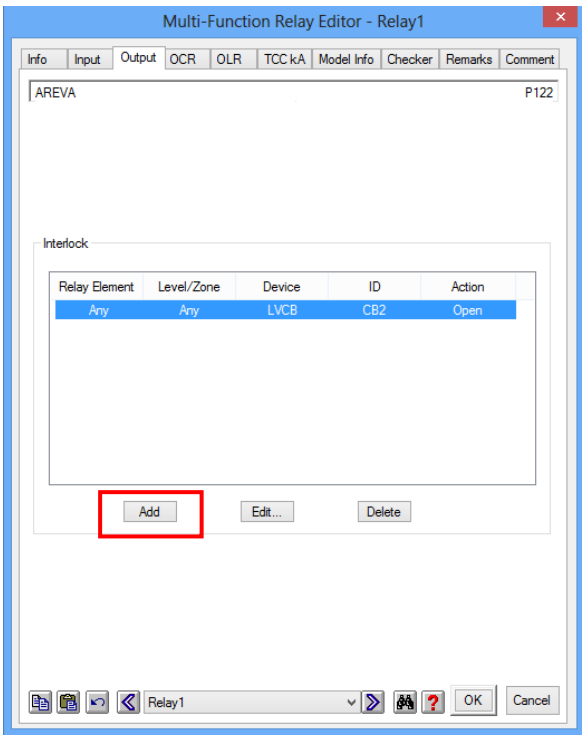




Star-Protective Device Coordination

To check sequence of operation

1. Double click on Relay1, go to Output page and then click on Add to interlock Relay1 with CB2 as shown below.

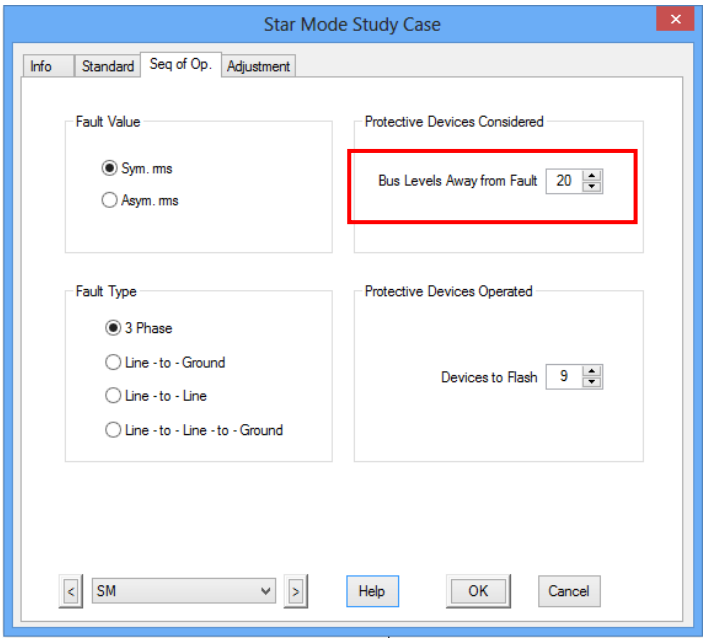


2. Similarly update all relay interlock as given in the table below.

Relay ID	Interlock Editor page settings				
	Relay Element	Level/Zone	Device	ID	Action
Relay 1	Any	Any	LVCB	CB2	Open
Relay 2	Any	Any	LVCB	CB3	Open
Relay 3	Any	Any	LVCB	CB3	Open
Relay 4	Any	Any	HVCB	CB4	Open
Relay 5	Any	Any	HVCB	CB5	Open
Relay 6	Any	Any	LVCB	CB6	Open
Relay 7	Any	Any	LVCB	CB7	Open

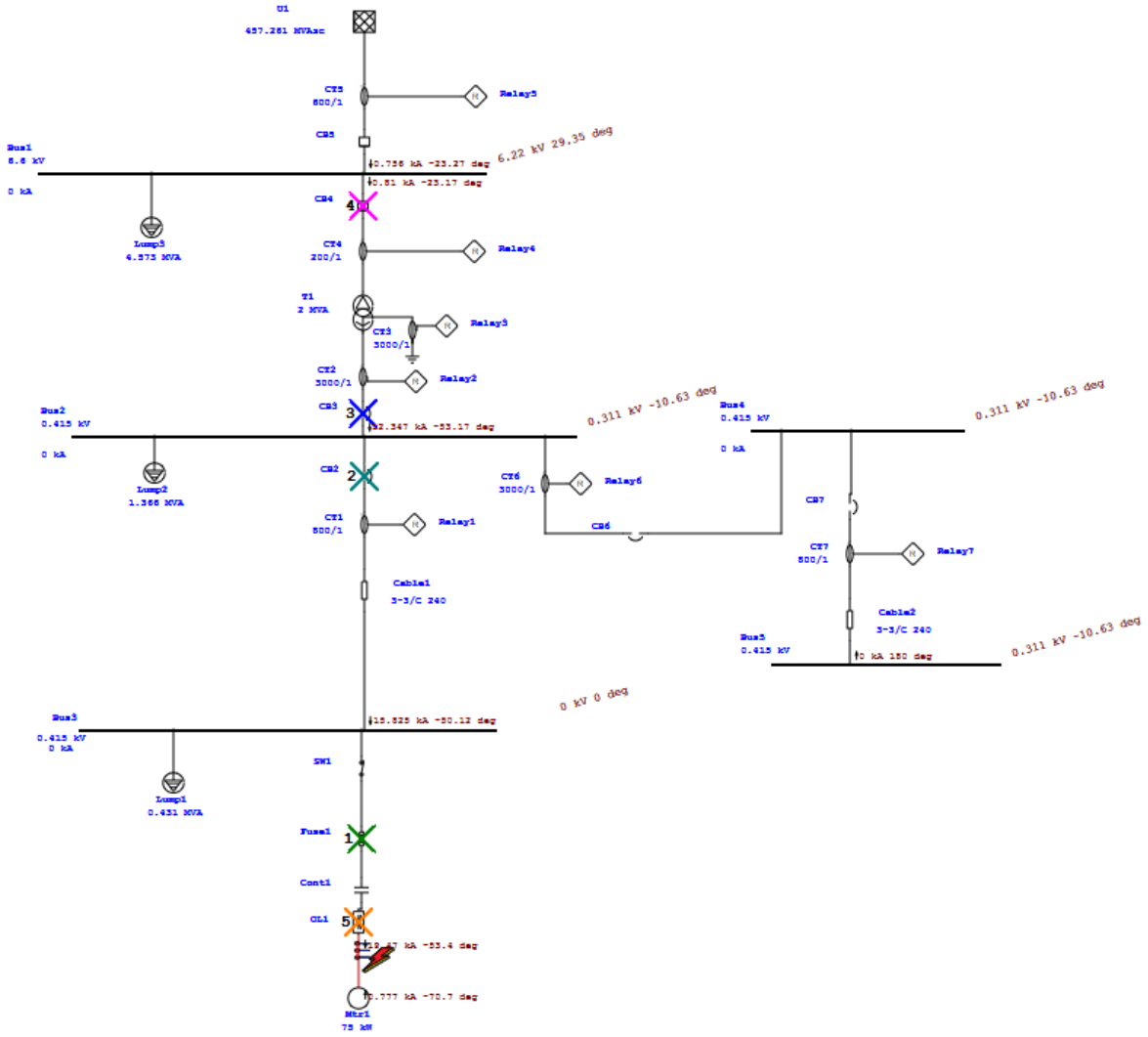
3. Go to study case and click on Seq of Op. page. Check below details. Bus Levels away from the fault as to be 20.

Star-Protective Device Coordination



Star-Protective Device Coordination

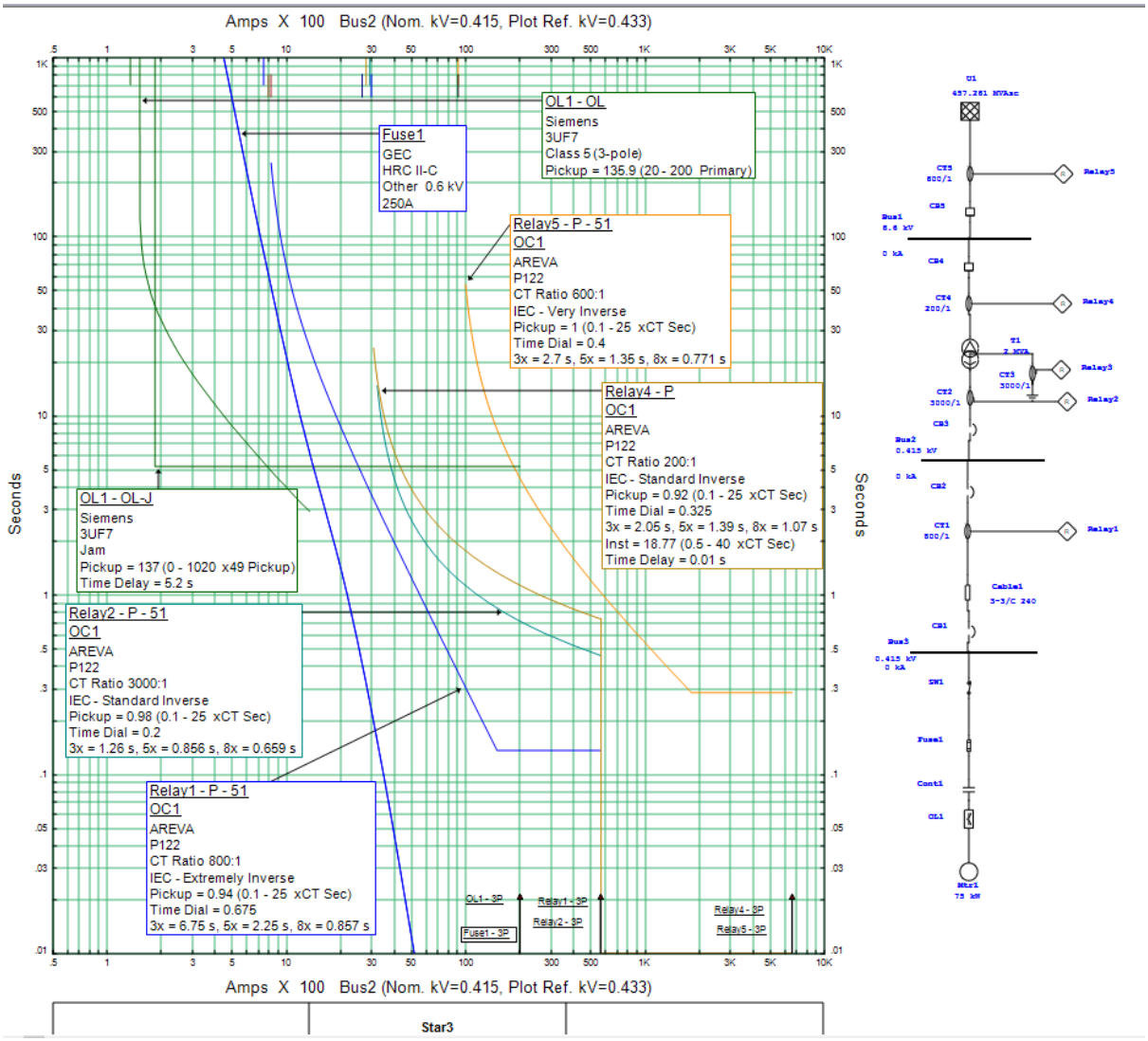
4. Click on Fault Insertion and apply fault at motor terminals. Check for the flashing devices to know the sequence of operation.



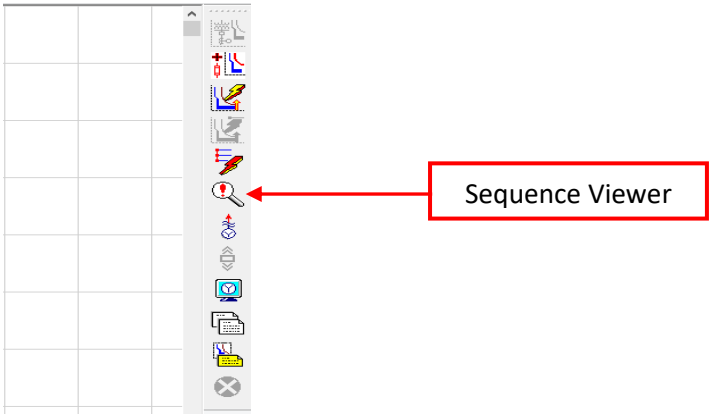
5. To check the normalized star view, create one more star view with all protection devices and click on Normalized TCC in star view toolbar.
   Normalized (Shifted) TCC mode provides a graphical view (TCC plot) of the operation times of protective devices based on their corresponding settings and characteristics for specified fault location and type i.e. curves are shifted by a factor calculated based on the ratio of the through fault current seen by a PD and the total fault current at the point of the fault. The effected TCC curves are then shifted according to the total fault current.

   Note: *Fixed curves/points (equipment damage curve, motor starting curve, FLA Marker, Fault Arrow) are not displayed in the Normalized TCC view as they are not applicable to this mode.*

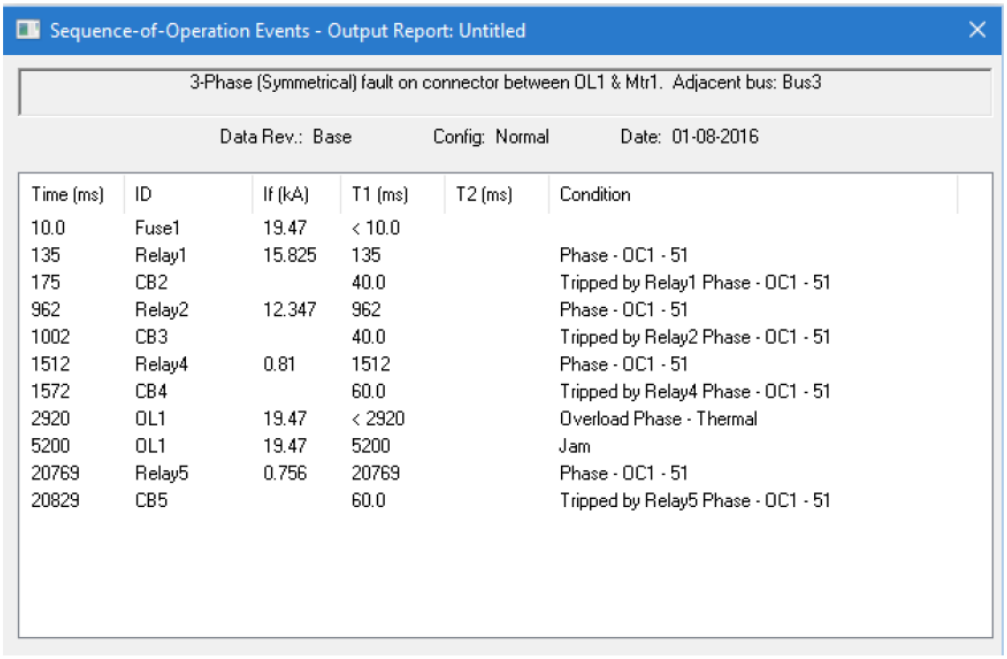
Star-Protective Device Coordination



6. Click on Sequence Viewer to view sequence of operation events with time.



Star-Protective Device Coordination



Observation:

3- phase fault applied on motor terminal: current of 15.825 kA flows at 0.415kV level				
Element	**Location**	**Operating time (sec)**	**Time diff with downstream element (sec)**	**Remark**
Fuse 1	Motor feeder	0.010	0.010	Minimum operating time OK
Relay 1	MCC incomer	0.135	0.125	Fuse-Relay >150ms OK
Relay 2	PMCC incomer	0.962	0.827	Relay-Relay >300ms OK
Relay 4	Transformer incomer	1.512	0.55	Relay-Relay >300ms OK
Relay 5	6.6kV SWGR incomer	20.769	19.25	Relay-Relay >300ms OK