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Relay Coordination Analysis in SPDC Forcados Distribution Network for Operation, Planning and Future Expansion.

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ABSTRACT

Power protection system is increasingly challenging as fault current level increases in electrical power system due to increase in static load, introduction of heavy-duty electric motors and increase in network interconnections. In order to coordinate relays effectively, load flow study and short circuit current analysis are carried out for proper selectivity. This analysis formed basis for optimal setting of Over Current Relays (OCRs) via Standard Inverse Time-delay (SIT). The detailed survey on the existing definite time delay with current time grading amounted to higher relay current-time configuration at the upstream in the steps of 0.5s up to a minimum time of 3s and with steps of 25% rated current increment to 250%, the upstream at this setting experienced thermal overload which was resolved via SIT. The inadequate relay definite time characteristics setting causing thermal overload (I^2R) of the 25MVA and incessant tripping was resolved with SIT relay coordination scheme using Electrical Transient Analyzer Program (ETAP). This method also accommodated the associated circuit breakers response breaking capacity time (380ms to 500ms) which was a major achievement as compared to other inverse time delay characteristics such as Very Inverse Time (VIT), Extremely Inverse Time (EIT) etc.

KEYWORDS: Distribution Network, Planning and Future Expansion, Short-Circuit Current Analysis, Relay Coordination.

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1. INTRODUCTION

The Shell Petroleum Development Company (SPDC) expanded the existing Forcados Terminal facility by four new flow stations with gas gathering, central processing facility, 25 wells and 6 new platforms in Estuary. Siemens installed new switchboards in the following sites for Forcados Yokri Integration Project (FYIP): Forcados Terminal, North Bank Central Processing Facility (CPF) / Central Compression Plant (CCP), North Bank Flow Station (FS), South Bank Flow Station, Yokri Flow Station and New Estuary Flow Station.

The expansion to the existing ABB 11KV switchboard has led to frequent abnormality condition of Forcados 11/33KV distribution network which has called for "Emergency investigation, functionality relay testing and relay coordination scheme" between ABB SPAJ 140C relays monitoring the 11KV side of the network (upstream) and Siemens Siprotec 7SJ64 relays monitoring the 33KV side of the network (downstream). Though, these abnormality conditions are sensed by the protective relays at the upstream, constantly measuring the electrical quantities by making comparison with relay set values and energize the CB through the tripping coil (YO's IEE Standard). The relay configured at definite time delay presently at FOT station operates when the current exceeds the set value (pickup) (Gupta, 2004: Birla *et al*., 2006).

The improper discrimination of relay coordination in the power network has led to system tripping of the upstream relay when the downstream bus or system is faulted (Pang *et al*., 2007). It is expected that backup relays should respond immediately but the current setting (I>) of the 11KV side of the power transformer is almost the same setting as that of the 33KV side with not enough coordination time interval. This has led to the most sensitive relay element (ABB SPAJ 140C) operating before the Siprotec 7SJ64 relay.

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The existing 159% pickup low current set (I>) value of the 11/33KV at the upstream is harmful to the

25MVA power transformer. This high set value of the relays sees the fault current less than 159% but greater than 100% of the rated capacity of the 25MVA transformer as a nominal current thereby causing thermal overload that triggers the master relay associated with oil pressure trip, bulchozz trip etc. This is also applicable to a delay locked rotor starting characteristic (51LR) of the induction motor associated with the network whose starting current is 8-9 times the rated current of the motor, this also trips the downstream circuit breakers because relay selectivity is based on high current definite time characteristics (Khederzadeh, 2017). With this development above, this research shall analyze the advantage of Inverse Definite Minimum Time (IDMT) over current relay over definite time characteristic for a large distribution system.

This study will result in better and easy relay coordination approaches, both with and without Super Fault Current Limiters (SFCLs) and Distributed Generation (DG). Superconducting fault current limiter reduces the fault current level within the first cycle of fault current and also secures the interconnectors to the network.
Several authors used MATLAB 7.6 and PSAT (Power System Analysis Toolbox) to analyze a reliable and effective load flow program. The Newton Rashson Fast Decoupled Techniques was used by Idoniboyeobu and Ibeni (2017) to analyze load flow showing area of attention. This led to load shedding as the only option since the power dispatched from the grid network to the transmission substation was not sufficient therefore the power injected to substation loads are rationed on percentage of power availability. Some authors used the hand calculation or the per unit impedance method to analyze the three phase short circuit current (Zimmermam *et al*., 2005), (Kezunovic, 2017), since the pre-fault values are assumed to be 100% equipment rated values; this work shall analyze load flow study and short circuit evaluation by inputting data obtained from the field study into ETAP (Electrical Transient Analyzer Program) 19.01 software for simulation.

The choice of discrimination and selectivity depends on the time curve characteristics used for relay coordination for power system network to execute appropriate commands to isolate only faulty component from the healthy system (Akim *et al*., 2008).
The operational time of relays is increased from the downstream to the upstream. This is implemented using over-current relay (OCR) with definite or inverse time characteristic which is shorter for higher fault current (Hossain *et al*., 2015). Time graded protection is best suited for radial network and the downstream is set to the shortest time delay in order for relay protection sequencing operation.
This paper shall implement the SIT method to resolve the frequent tripping of the power distribution system though, the downstream can be configured with definite time delay.

1. MATERIALS AND METHOD

The materials used for this research work are: Single Line Diagram (SLD) and data from field. AutoCAD 2018, ETAP 19.01 and Omicron CMC 356 were also used as tools for design, simulation and relay secondary injection. The method involved load flow study, short circuit current calculation and relay coordination with SIT.

2.1 Single Line Diagram (SLD) of 11/33kv Distribution System

The symbolic representation of FOT network showing six (6) 11.25MVA generators being synchronized based on the proportion requirement of load demand, two (2) 25MVA 11/33KV power transformers, and one transmission line available at the moment but this research shall consider single and double transmission line as shown in Figure 1.

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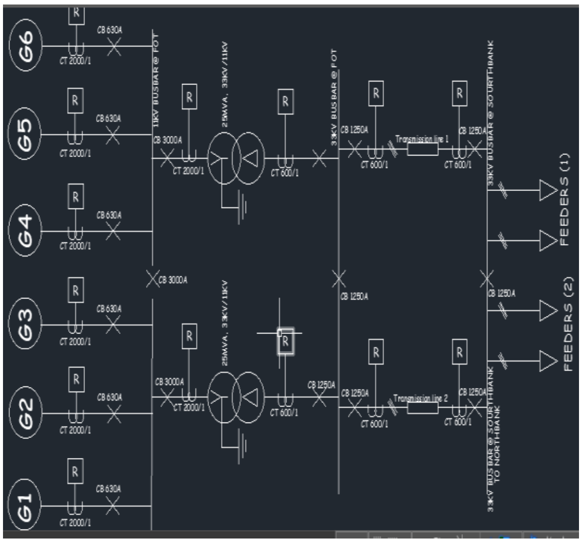

Figure 1: SLD of 11/33kv Power Distribution Network of Forcados Terminal.

2.2 Practical Data Consideration Embedded into Etap 19.01

The system parameters obtained from Figure 1 as shown in Table 1 are configured into the Etap software for Load Flow Analysis (LFA) and Short Circuit Analysis (SCA).

Table 1: System Parameter Embedded into ETAP Software for Simulation.

Parameter/ System	CTs	% Z	(I_R) (A)	(I_{SC}) KA
GT:11KV, 11.25MVA	2000:1	19	590.5	3.11
TR:11/33KV, 25MVA,	2000:1 600:1	10	437.4	4.37
Line: 33KV (3.5KM)	600:1	9.7	437.4	4.51
Feeders(1) 6.5MVA	600:1	6.5	113.7	1.75
Feeders(2) 12MVA	600:1	6.5	209.9	3.23

Source: Forcados Yokri Integration Project.

The Full Load Current (FLA (A)) is determined with (1) while the Short Circuits (SCC (KA)) is evaluated with (2).

$$I_{FLA} = \frac{MVA}{\sqrt{3}\,X\,KV} \quad (1)$$

$$I_{SC} = \frac{I_{FLA}}{\%Z} \quad (2)$$

Where:
MVA: Rated Power
KV: Line voltage
%Z: Percentage Impedance
I_{FLA}: Rated Current or Full Load Current
I_{SC}: Short Circuit Current

The system simulation of Figure 2(a) and Figure 2(b) shows the steady state current of individual devices is less than the rated current of associated devices. This satisfies the general operational principle of a typical distribution network. Consequently, with six generators in operation with load capacity of 37MVA, each generator current is 299.4A and three generators in operation with load capacity of 24MVA resulting to individual source current of 379.4A which is less than the rated of 590.5A.

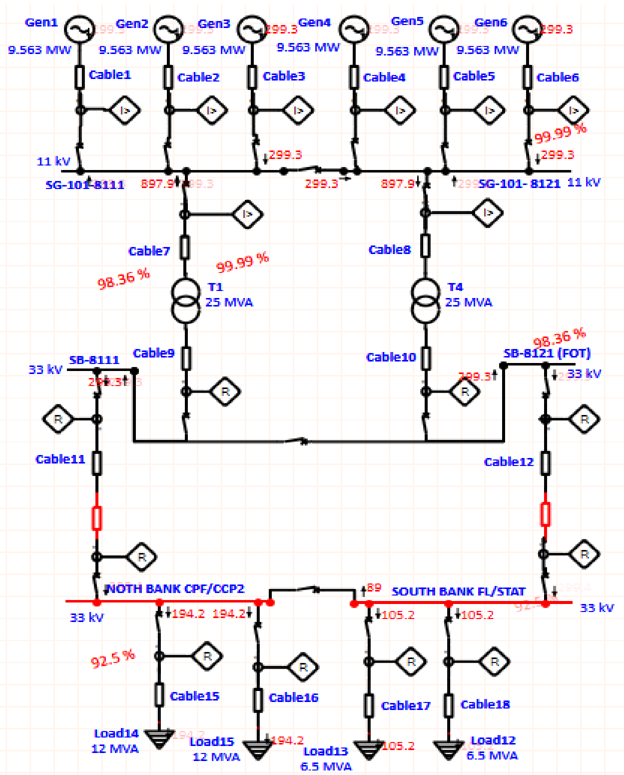

Figure 2(a): Load Flow Analysis (LFA) of six generators in synchronism with 33KV 37MVA load capacity.

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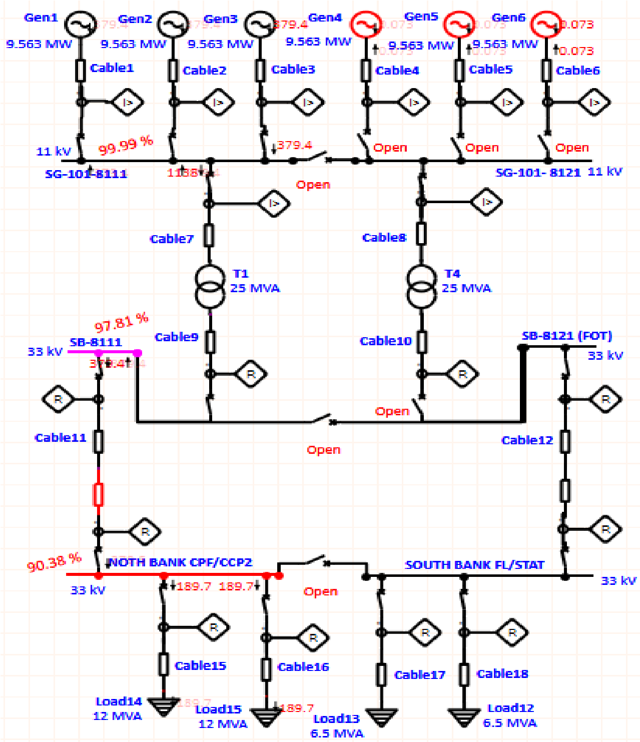

Figure 2(b): Load Flow Analysis (LFA) of 3 generators in synchronism with 33KV 24MVA load capacity of feeders.

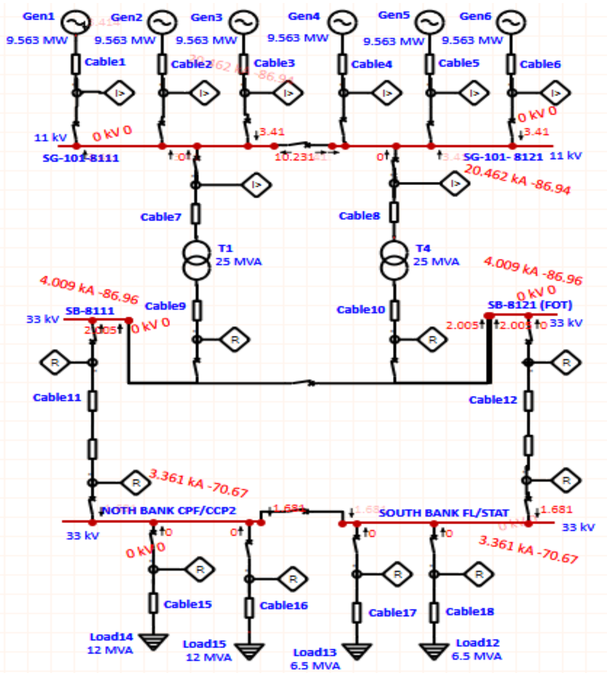

Figure 3(a): ETAP Simulation of Short Circuit Analysis (SCA) (100% Capacity on 33KV Switchboard) 11/33kv Power Distribution Network

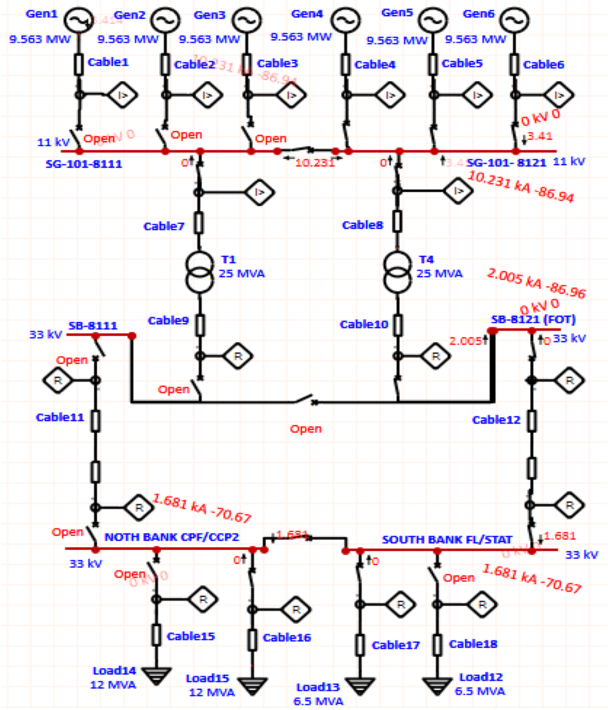

Figure 3(b): ETAP Simulation of Short Circuit Analysis (SCA) (50% Capacity on 33KV Switchboard) 11/33kv Power Distribution Network

Figure 3(b) is the present configuration of FOT 11/33KV distribution system, where Southbank Flow Station operates at an average power of 6.5MVA and North Bank Central Processing Facility (CPF) / Central Compression Plant (CCP), North Bank Flow Station (FS) also operates at an average power of 12MVA. However, this study shall consider present status and 100% 33kv short circuit current for its relay coordination.

2.3 Study of Existing Relay Coordination.

The comprehensive investigation and integrity test on 11/33KV switchboard at FOT, protection scheme on 27th January, 2021 showed that the relays are functional but not coordinated. The data in Table 2 shall be embedded into Etap 19.0.1 software for simulation and the sequence of operation is reported.

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Table 2(a): Existing Relay Configuration of SPAJ 140C (SGF-008, SGB-107, SGF-107) on 06-TR-08111 – 11KV /25MVA-L11

Relay Para-Meter	Settings (Stage 1)	Settings (Stage 2)
I > (A)	1.04	0.66
T > (S)	1.20	1.4
I >> (A)	7.90	3.5
T >> (S)	0.04	0.9
I_O > (A)	0.45	0.1
T_O > (S)	2.00	0.9
I>>>(A)	∞	∞

Table 2(b): Existing Relay Configuration of SIPROTEC 7SJ64 on TR-08111 – 33KV /25MVA Incomer L13

Relay Para-Meter	Settings	Time Delay
I > (A)	1.15A	1.2s
I >> (A)	6.0A	0.7s
I_O > (A)	0.1A	0.7s

Table 2(c): Existing Relay Configuration of SIPROTEC 7SJ64 on TR-08111 – 33KV /25MVA Outgoing

Relay Para-Meter	Settings	Time Delay
I > (A)	2.00A	0.5s
I >> (A)	5.30A	0.5s
I_O > (A)	0.17A	0.1s

Table 2(d): Existing Relay Configuration of SIPROTEC 7SJ64 on 52-OHL – 33KV / Incomer F3 @ Southbank

Relay Para-Meter	Settings	Time Delay
I > (A)	1.20A	0.6s
I >> (A)	5.00A	0.3s
I_O > (A)	0.10A	0.3s

Table 2(e): Existing Relay Configuration of SIPROTEC 7SJ64 on Feeder to Nothbank.

Relay Para-Meter	Settings	Time Delay
I > (A)	1.80A	0.6s
I >> (A)	5.00A	0.3s
I_O > (A)	0.10A	0.3s

Relay functionality test carried on the Table 2(a – e) with the aid of Omicron CMC 356 secondary current injection test set confirmation statisfactory status of the ralays. However, test on SPAJ 140 shows that stage 1 settings are active and stage 2 settings are non – active as shown in Plate 1.

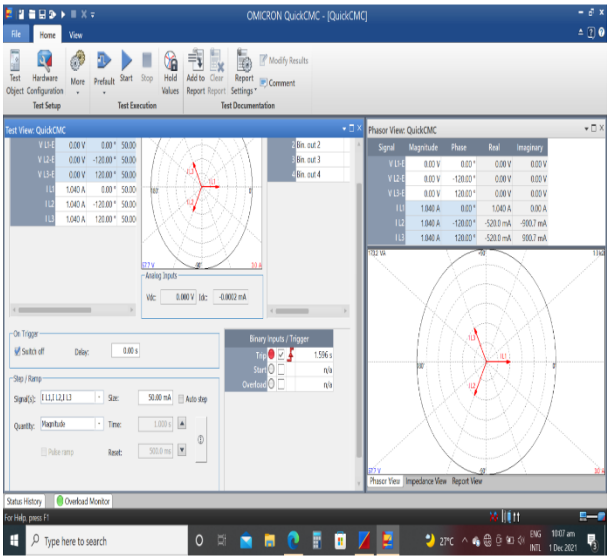

Plate 1: Omicron CMC 356 display of SPAJ 140C relay testing.

The observation of the existing settings and simulation of the existing relay set values are discussed:

i. Table 2 (a & b), 33KV current of 690A (1.15In) amount to 2070A (1.035In) on the 11KV both with a definite delay time of 1.2Secs. The time delay may not allow for adequate discrimination though there is setting increase of 0.005A i.e. (1.04A - 1.035A).
ii. Table 2(a) up to Table 2(e) are embedded into Etap and the simulated Figure 4 showed poor relays coordination. The tripping sequence from upstream to downstream when the downstream is faulted is due to poor selectivity study of relay coordination.
iii. The pickup set value of the 11/33KV zone (upstream) is above 157% rated current of the 25MVA power transformer, hence, fault within the range 100% to 157% of 25MVA rated current resulted to in thermal trip, oil pressure trip, alarm trip and buchholz trip which are all wired via the master relay causing the circuit breaker to open without indication on SPAJ 140C relay on the 11KV

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switchboard and in turn introduced inter-trip on the SIPROTEC 7SJ64 relay, 33KV switchboard at FOT. This is the major reason why inter-trip occurred without indication or causes due to trips wired via master relay.

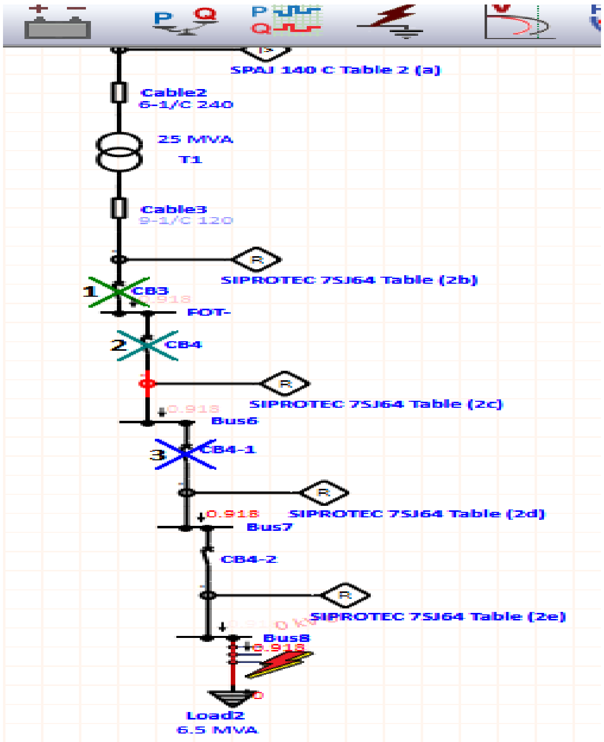

Figure 4(a): Poor coordination as system is faulted at downstream (Southbank).

The simulation showed that as fault occurred at the outgoing 33KV FOT bus, the 7SJ64 Table (2b) incomer relay respond first before the outgoing 7SJ64 (2b) relay as shown in Figure 4(b). This is also poor relay coordination at FOT. Generator relays were not considered in simulation since Siemens study data record were not captured but shall be discussed later.

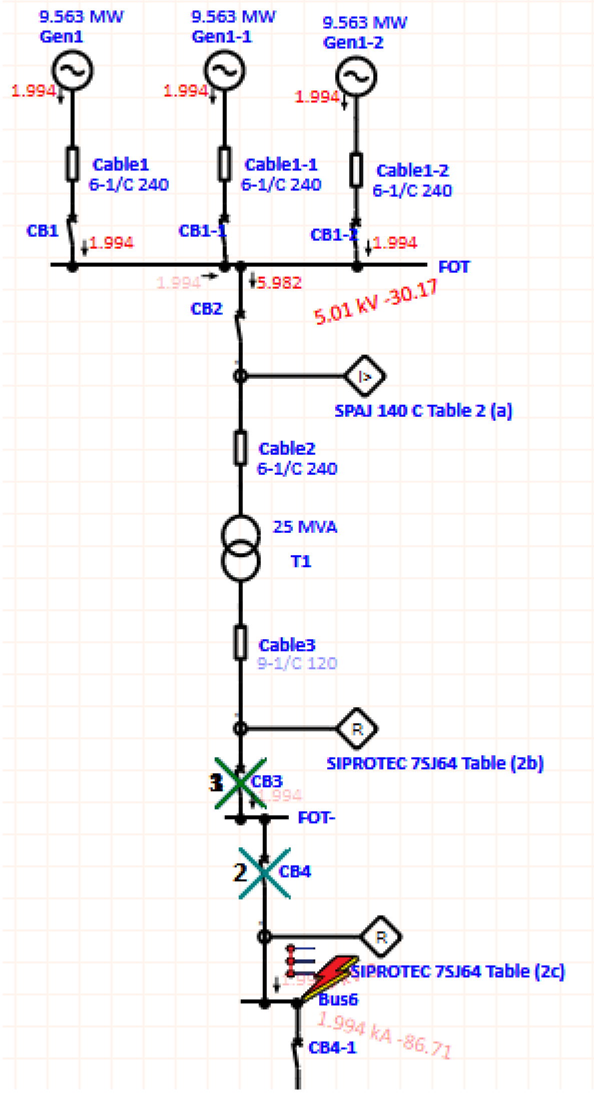

Figure 4(b): Poor coordination with 33KV FOT Outgoing Bus Faulted.

2.4 Relay Coordination of Overcurrent Protection for 11/33KV Distribution System

Generally the magnitude of fault current is inversely proportional to the operating time of Over Current Relay. The inverse time-delay OCR is mainly used in large distribution network. The parameters associated with operating characteristics are the relay pick-up (I_P) and time delay setting (TDS) as given in (3).

$$t = \frac{a \ .TDS}{\left(\frac{I_{SC}}{I_P}\right)^{\beta} - 1} \qquad (3)$$

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Where, plug setting multiplier (PSM) $= {}^{I_{SC}}\!/_{I_P}$; and the value of α *and* β depend on the protection characteristics shown in Table 3.

Table 3: IEEE and IEC Constant of Relay Curves

Curve type	α	β
standard inverse	0.02	0.14
Very inverse	1.0	13.5
Extremely inverse	2.0	80.0
Long-time inverse	1.0	120.0

Source: https//www.jcalc.net/idmt-relay-time.

Base on IEEE and IEC, the inverse current characteristics curve of OCRs uses PSM in steps of 25% ranging from 50% to 200%. PSM differ depending on the type of inverse OCR characteristics curve as shown in Table 3.

From (3), we deduce:

$$t = \frac{\alpha K}{(PSM)^{\beta} - 1} \qquad (4)$$

The minimum summation of coordination time of all associated relays:

$$min\ \ T = \sum_{i=1}^{m} C_i K_i \qquad (5)$$

Where,

$$C = \frac{\alpha}{(PSM)^{\beta} - 1} \quad and \quad K = TDS$$

The pre-fault current is stated in Table 1 (FLA), minimum fault and maximum fault through each relay is considered base on the fault range associated with each bus bar is stated below.

Bus '3' : 0.855KA ≤ IF ≤ 3.328KA

Bus '2' : 0.921KA ≤ IF ≤ 4.009KA

Bus '1' : 3.41KA ≤ IF ≤ 20.462KA

(Note: Bus 1: SG-101-8111 & 8121, Bus 2: SB 8111/8121, Bus 3: Southbank FL/STAT)

Where α is 0.14 and β is 0.02 for standard inverse relay settings, PSM (plug setting multiplier) is (fault current IF /rated current In). K= TP = TK = (TMS) = (TDS) = time multiplier setting or time delay setting. In this coordination, we considered In = Is = set pick–up current and the minimum fault current at location F_3 (Southbank feeder); I_{Fmin} = 855A. We assumed the time of operation R_{15} and R_{16} to be 0.5sec, thus,

$$t = \frac{0.14 \times T_p}{\left(\frac{855}{210}\right)^{0.02} - 1} = \frac{0.14\ T_p}{4.07^{0.02} - 1} = 4.92 T_p$$

Since t = 0.5s, Tp =0.5/4.92 = 0.102 ≈ 0.1; this implies that if the relay R_{15} is set at 1.0 (TMS), it will operate in 4.92 seconds. TMS (Tp) is set to 0.1 since the R_{15} is required to operate in 0.5 second at a fault of 855A. The maximum three phases fault occur at point F_3, I_{Fmax} = 3,328A, then the time R_{15} will take to trip is: $t = \frac{0.14 \times 0.1}{\left(\frac{3328}{210}\right)^{0.02} - 1} = \frac{0.014}{15.85^{0.02} - 1} = 0.25\ seconds$

As the fault current increases, the PSM also increases (from 4.07 to 15.85) and the tripping time decreases (from 0.5 to 0.25s). In this network relay R_{15}, R_{16}, R_{17} and R_{18} must not operate less than 0.5sec at F3 minimum fault current.

For R_{13}, R_{14}: I_n = 437.4A, t = (0.25 + 0.5)

$$= \frac{0.14\ T_p}{\left(\frac{3328}{437.4}\right)^{0.02} - 1} = \frac{0.14\ T_p}{7.6086^{0.02} - 1} = 3.38\ T_p$$

The maximum fault current associated with relay R_{13} and R_{14} is I_{Fmax}=3328A. The operating time of R_{13} for this current is $t_{(13)\ max}$ = 3.38T_p. Where T_p is 0.2, $t_{(13\ or\ 14)\ max}$ = 0.75s, $t_{(13)\ min}$ = 2s. If it desire for the protection engineer to use the minimum fault current of 855A for R_{13} and R_{14} to trip at 0.75s, then T_p is 0.07 which is less than time delay setting of R_{15} since the nominal rating of R_{15} =210A is not equal to R_{13} = 437.4A. For proper coordination system, switching to star system mode in Etap 19.01 software, the time delay setting T_p can be configured in the sequence of: 0.1, 0.12, 0.16, 0.21, 0.26 and 0.27 at the upstream and tripping sequence shown in Figure 5.

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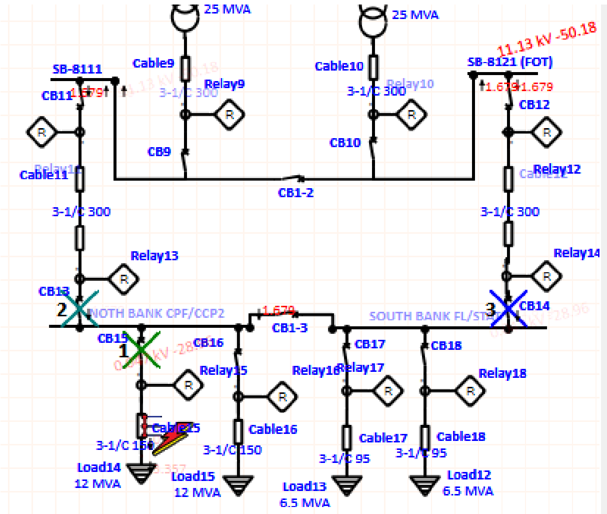

Figure 5(a): Relays Sequence of Operation with Fault on Bus 15.

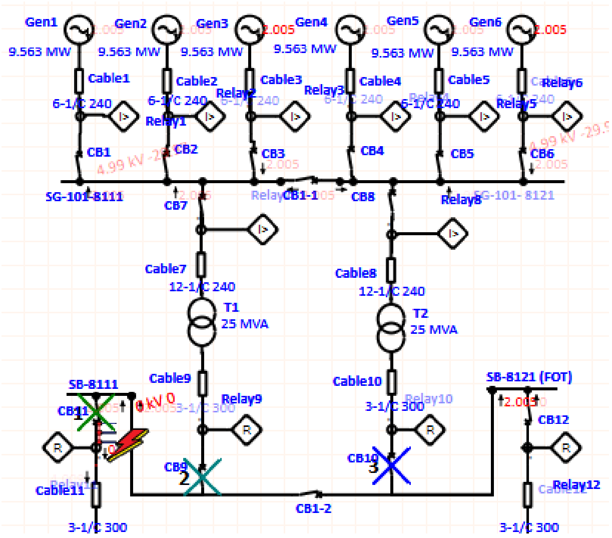

Figure 5(b): Relays Sequence of Operation with Fault on Connector between CT5 & Cable 11 (Adjacent Bus SB-8111).

3 RESULTS AND DISCUSSION

The load flow analysis in Figure 2, shows that the steady state current of FOT is less than the full load current which satisfies configuration of power distribution system. The short circuit current analysis in Figure 3 shows the level of current 20.5KA at the upstream and 3.3KA at the downstream which is used in the planning stage of relay coordination. The definite time relay coordination with time and current grading is inadequate for FOT protection scheme as current/time setting at the upstream is too high to cause thermal overload, hence the SIT in this paper (Figure 5) proffers solution for large distribution system. The high set definite time relay has been responsible for incessant tripping at the upstream when operational current exceeds the rated current of 25MVA yet less than the low current set (I>) value. The simulated results in Table 4 shows the tabula fault locations and their tripping sequence.

Table 4(a): Fault at Bus 15 and Sequence of Relays Operation.

Sequence-of-Operation Events - Out...

3-Phase (Symmetrical) fault on bus: Bus15

Data Rev.: Base Config: Normal

Time (ms)	ID	If (kA)	T1 (ms)
246	Relay15	3.357	246
326	CB15		80.0
617	Relay13	1.679	617
617	Relay14	1.679	617
697	CB13		80.0
697	CB14		80.0
822	Relay11	1.679	822
822	Relay12	1.679	822
902	CB11		80.0
902	CB12		80.0
1079	Relay9	1.679	1079
1079	Relay10	1.679	1079
1159	CB9		80.0
1159	CB10		80.0

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Table 4(b): Fault at adjacent Bus SB-811 and Sequence of Relays Operation.

Sequence-of-Operation Events - Out...

3-Phase (Symmetrical) fault on connector between CT5 & Cable11. Adjacent bus: SB-8111

Data Rev.: Base Config: Normal

Time (ms)	ID	If (kA)	T1 (ms)
495	Relay11	4.009	495
575	CB11		80.0
952	Relay9	2.005	952
952	Relay10	2.005	952
1032	CB9		80.0
1032	CB10		80.0
1182	Relay7	6.014	1182
1182	Relay8	6.014	1182
1242	CB7		60.0
1242	CB8		60.0
2699	Relay1	2.005	2699
2699	Relay2	2.005	2699
2699	Relay3	2.005	2699
2699	Relay4	2.005	2699
2699	Relay5	2.005	2699
2699	Relay6	2.005	2699
2782	CB1		83.0
2782	CB2		83.0
2782	CB3		83.0
2782	CB4		83.0
2782	CB5		83.0
2782	CB6		83.0

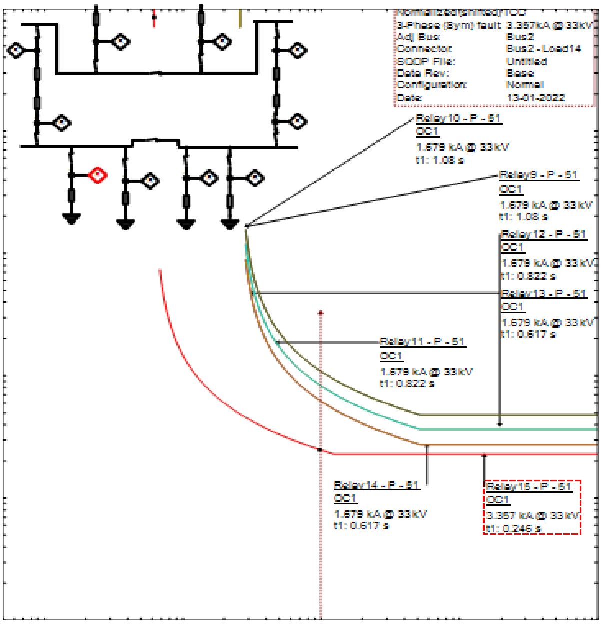

Figure 6: Effective Time Sequence of Operation graph – Fault on Bus 15.

4. CONCLUSION

The configured definite relay setting of Forcados Terminate is inadequate, this study shows that standard inverse time relay configuration provide solution to the system as well as large power distribution system. The power distribution network also showed high short circuit rating at the generation bus. From our findings, incorporation of limiter such as Superconducting Fault Limiter (SFCL) at the upstream to minimize fault level when the system synchronism is above three generators is recommended for FOT power distribution.

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NOMENCLATURE

Symbols	Description	Unit
T	Time in seconds	s or ms
PSM	Plug Setting Multiplier	-
P	Power	VA
V	Voltage	V
I	Current	A
Z	Impedance	Ω
TDS	Time Delay Setting	-