Co-ordination of Overcurrent Relay in Interconnected Power System Protection: Practical Implication, Benefit and Prospects

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***Abstract*-- Overcurrent relays (OCRs) are one of the most common protective devices implemented in power systems to protect electrical components from faults. In order to obtain much improved protection by these protective devices, a precise coordination of these systems must be applied. One of the problems in power systems, which is very common, is when a fault occurs in a plant, and two, three or even several OCRs operate instead of the designated relay at that particular fault location. In this work, the technical data of 2X15MVA, 33/11KV Maitama injection substation was collected and used for modelling relay coordination for the station. After the coordination, the result shows that 33KV feeder will trip on over current and earth faults if the secondary current of the CT exceeds 1.32A and 0.264A within 0.021s and 0.00167 respectively. For the 11KV outgoing feeder, it will trip on over current and earth faults if the secondary current of the CT exceeds 0.88A and 264mA within 12.5ms and 1.7ms respectively. From these results, it is noted that earth faults trip faster than overcurrent fault; this is because of the harmful nature of earth. If it's not isolated fast in an interconnected system, it will cause a lot of damage to both power system components and personals.**

***Index Term* -- Relay coordination, Interconnected power system, Tripping unit, Protection, Injection substation**

I. INTRODUCTION

For power system to have normal operation without electrical failure and damage to the equipment, two alternatives are available to the designer, one is to design the system so that fault will not occur and the other is to accept the possibility of faults and take steps to guard against the ill effects of such faults. It is possible to minimize fault to a large extent by careful system design, proper operational coordination and maintenance. It is also obviously not possible to design a system that is 100% free from fault, so the possibility of fault must be accepted and the necessity of protection scheme must be realised [1]. Since power system developments change its structure, the power system protection becomes very vital. As the designer or engineer of the system struggles with devising a system arrangement, the engineer simply cannot build a system which will never fail regardless of any reasons. This is where protection system and protective relays become important. For designing the protective relaying, understanding the fault characteristics is required. Related to this, protection engineer should be conversant about tripping characteristics of various protective relays. The designer of protective relaying has to ensure that relays will be able to detect abnormal or undesirable conditions and then trip the circuit breaker to disconnect the affected area without affecting other undesired areas. Statistical evidence has shown that large number of relay tripping is caused by improper or inadequate settings of the device and not just because of genuine faults [2, 3]

Protection scheme required for the protection of power system components against abnormal conditions such as faults, overvoltages, etc. essentially consist of protective relaying and circuit breaker. Protective relay functions as monitoring or sensing device, it senses the fault, determines its location and finally, it sends a tripping command to the appropriate circuit breaker. The circuit breaker after getting the command from the protective relay disconnects the faulted element, thus protective relay which is the brain behind the protective scheme, plays a vital role. Therefore, proper care should be taken in designing and selecting an appropriate protective relay which is reliable, efficient and fast in operation [1]. This can be very expensive. To reduce such cost, a balance needs to be struck between the cost of the protection and the degree of safety to the equipment [4]. Among several power system components, interconnected power system is one of the most important components of the power system network and is mostly affected by several types of faults. Generally, 80 -90% of the faults occur on interconnected power system and the rest from substation equipment and bus bar combined [5]. If any fault or disturbances occurred in an interconnected power system and is not detected, located, and eliminated quickly, it may cause instability in the system and causes significant changes in system quantities like over-current, under or over voltage, and others. The purpose of this work is to

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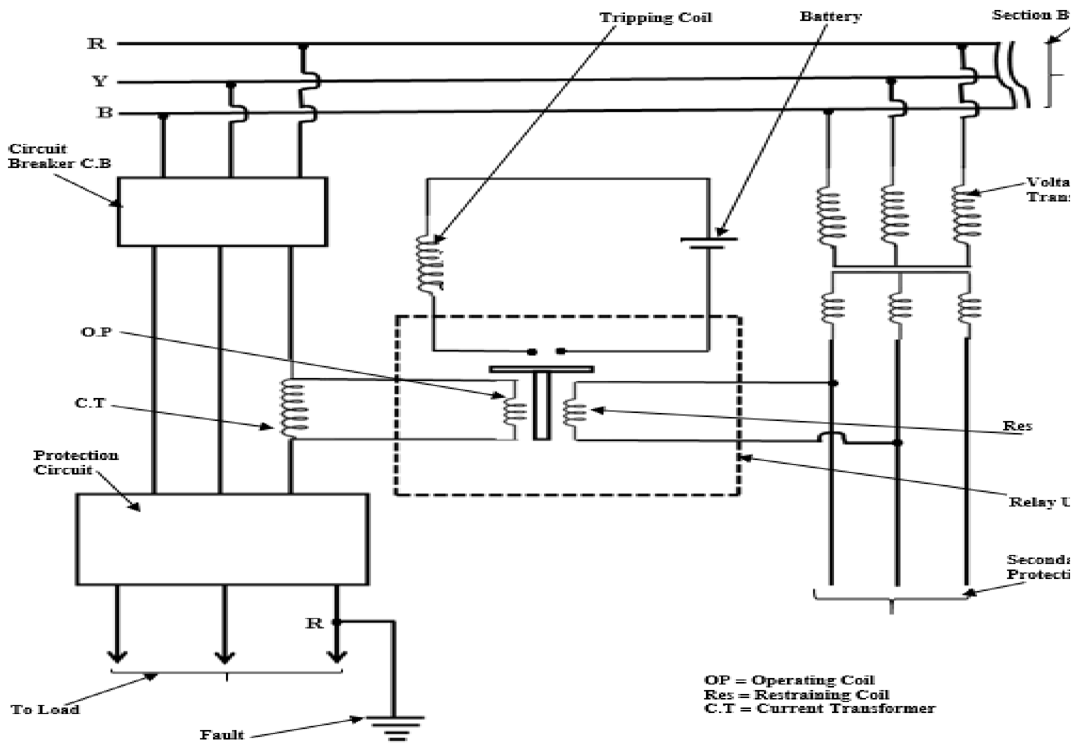

Fig.1. Shows the single line diagram of protection principle.

demonstrate the operation of relays in fault detection, also operation of tripping units and relays in injection substation. The single line diagram of protection principle is as shown in Fig. 1.

In Figure 1, Instrument transformer transforms or reduces the measured quantities (such as current and voltage) from the main lines to lower quantities suitable for relay operation. In case of current transformer, it reduces the operating current of the power system to lower value which can be managed by the relay. The relay is pre-set at a certain value depending on the load current and remains dormant during normal or steady operation mode. When fault occurs in protective circuit, heavy current flows. As soon as relay contacts closes, current flows from the battery to the tripping coil of the circuit breaker which in turn isolates the faulty part of the circuit. In order to attain the desired reliability, the power system network is divided into different protection zones like; generator protection, transformer protection, bus bar protection, transmission line protection, feeder protection, etc. The earliest method of protection was the fuse. The fuse finds its use primarily in Distribution Circuits due to its cheapness and simplicity. The correct function of the protective schemes involves the relaying equipment, in addition to the current transformer (CT) and voltage transformer (VT), as well as good and reliable tripping unit [1].

These protective relays are normally connected on the secondary or low voltage (LV) sides of the CTs and VTs in the control panels.

A Purview of Study

The deliverables or scope of this work centres on the coordination of relays in 33/11KV injection substation. For the purpose of this project, three 33/11KV injection substations were considered; at 3 x 15MVA 33/11KV injection sub-station Guzape, 2 x 15MVA 33/11KV injection sub-station Mitama and 2 x 15MVA 33/11KV injection sub-station Wuse. Relay model of these networks was created taking 2 x 15MVA 33/11KV injection sub-station Mitama,

network as the reference to other networks. The over current and earth fault data of the relays on 33KV, 11KV incomer and 11KV outgoing control panels were obtained through modelling.

B. *Relay Co-Ordination, Setting and Zone of Protection.*

Protection relays are devices that detect any changes in the incoming signal, which is mainly current or voltage [6]. The criteria for selecting current transformers are: maximum load current on the primary side, and rating of the associated relay. Performance of relays depends largely on healthiness of other elements such as circuit breaker, current transformers, pilot wires and the tripping units. Regular maintenance of these elements is very important [7].

Co-ordination of relays is an integral part of the overall system protection and is absolutely necessary to: a) Isolate only the faulty circuit or apparatus from the system. b) Prevent tripping of healthy circuits or apparatus adjoining the faulted circuit or apparatus. c) Prevent undesirable tripping of other healthy circuits or apparatus elsewhere in the system when a fault occurs somewhere else in the system. and, d) Protect other healthy circuits and apparatus in the adjoining system when a faulted circuit or apparatus is not cleared by its own protection system.

II. METHODS OF RELAY CO-ORDINATION

Relay co-ordination can be achieved by i) Current graded systems, ii) Time graded systems or discriminative fault

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protection, iii) A combination of time and current grading methods:

These methods are to give correct discrimination or selectivity of operation, and each protective system must select and isolate only the faulty section of the power system network, leaving the rest of the healthy system undisturbed. The selectivity and co-ordination is to choose the correct current and time settings or time delay settings of each of the relays in the system network [8].

(a) Time Graded Systems

Selectivity is achieved by introducing time intervals for the relays. The operating time of the relay is increased from the farthest side to the source towards the generating source and it is achieved with the help of definite time delay over current relays. As the number of relays in series increases, the operating time increases towards the source.

Fig. 3 represents the principle of a time graded over current system of protection for a radial feeder [9].

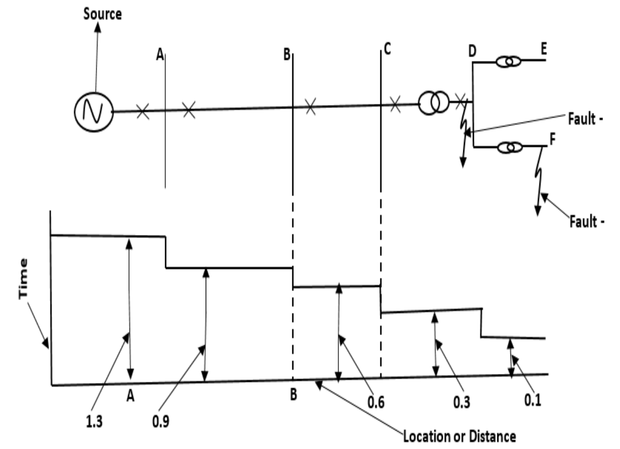

Fig. 3: Principle of a time graded over current system of protection

From Fig. (3), protection is provided at sections A, B, and C. Relay at C is set at the shortest time delay in order to allow the fuse to blow out for a fault in the secondary of the distribution Transformer D. If 0.3 seconds is the time delay for relay at C, then for a fault at F1, the relay will operate in 0.3 seconds.

Relays at A, B and S do not operate, but these relays only act as back up Protection relays. For a fault at F2, the fuses blow out in say 0.1 seconds and if they fail to blow out then the relay at C operates to clear the fault in 0.3 seconds.

(b) Current Graded Systems

This principle is based 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. The relays are set to pick up at progressively higher currents towards the source.

A simple current graded scheme applied to the system as shown in Fig. (3) consist of high set over current relays at S, A, B and C such that the relay at S would operate for faults between S and A; the relay at A would operate for faults between A and B and so on. Thus discriminating by current grading alone is not a practical proposition for exact grading. As such current grading alone is not used, but may be used to advantage along with a Time Graded System [9, 10]. The relay should not be so expensive as to outweigh the benefit of using it to protect the associated equipment [11].

(c) Time and Current Graded System

The limitations imposed by the independent use of either time or current graded systems are avoided by using a combination of time and current graded systems. It is for this purpose that over current relays with inverse time characteristics are used. The time interval of operation between two adjacent relays depends upon a number of factors like: the fault current interrupting time of the circuit breaker, the overshoot time of the relay, Variation in measuring devices errors and Factor of Safety [9].

Factor of Safety

Some safety margin is intentionally introduced to account for errors and delays in breaker operating time. The Phase-to-Phase fault current should be considered for phase fault relays and the phase to earth fault current for earth fault relays. In the examples that follow, we shall limit ourselves to 100% setting and it is advisable that we don't exceed this value most especially for transformer protection [12].

A. Setting of Relay(S) In An Inter Connected System

The setting for over current fault (short circuit or phase to phase fault) relay is usually of the order of 120-200% of the full-load current. A protective relay will not operate at a current equal or less than its setting and minimum operating current of the relay must not exceed 130% of the setting.
For the earth fault (phase-to- ground fault) relay setting, the range of 20-80% of the over current fault is maintained. This is because, earth fault is more dangerous than the over current fault. An earth fault relay is subjected to maloperation if its setting is too low.

A time interval of 0.4 to 0.5 seconds may be allowed in the time setting of two adjacent protective relays for the selectivity shorter interval of 0.35 seconds, may be used with very inverse over current relays. Operating time of proactive relay is an important quantity to be determined before setting a protective relay. For relay setting and coordination, the following data are required: i) Time-plug setting multiplier curve (Time-PSM curve), ii) Current setting, iii) Time setting, iv) Fault Current, v) Current Transformer ratio, vi) Actual operating time of the relay.

The actual operating time of a relay is determined as follows:

i. Determination of relay current from fault current, I_f, and current transformer ratio x : y is given as:

Relay current, $$I_R = \frac{I_f \times y}{x} \quad (1)$$

Where x and y are the secondary and primary current of the CT respectively and I_f is the fault current.
ii. Determination of relay current plug setting multiplier (i.e P.S.M) is given by:

$$PSM = \frac{fault\,current\,in\ relay\,coil}{Pick-up\ value} \quad (2)$$

$$= \frac{I_R}{\text{Current setting} \times \text{retated secondary current of the CT}} \quad (3)$$

iii. Determination of operation time of relay corresponding to calculated PSM from Time-PSM curve. Determination of actual operating time of relay by multiplying the time obtained in step (iii) by the time setting multiplier in use [13].

A. Zones of Protection

For effective protection of the system with minimum part disconnected during fault, protection zones are mapped out. These zones are created in such a way that each overlap around an isolating device such as a circuit breaker. The method guarantees total protection of power system sub circuits. For such boundaries to be genuine there must be:

- Measuring devices such as Current Transformer or Voltage Transformer.
- Isolating devices such as breakers.

III. METHOD

The technique used in this work is the analytical approach. The technical data of 2X15MVA, 33/11KV Maitama injection substation was collected and used for modelling relay coordination. The data was used to model and coordinate IDMT Micom relay that monitor earth fault and over current fault of 33KV control panels, incomer control panels, and 11KV control panels in the injection sub-station. Table 3.1 shows the technical data of 2X15MVA, 33/11KV considered injection substation.

TABLE I
TECHNICAL DATA OF 2X15MVA, 33/11KV MAITAMA INJECTION SUBSTATION

Transformer Rating	2X15MVA
Voltage Rating	33/11KV
The C.T ratio of 33KV feeder control panel	300/600/1/1
The C.T ratio of the incomer panel	800/1200/1/1
The C.T ratio of the outgoing panel	400/800/1/1
Relay type	IDMT Micom relay
TMS value of the relay	0.025

Data in Table 1 was used to set and coordinate the IDMT Micom relay that monitors the earth fault and over current fault of the 33KV control panels, incomer control panels and 11KV control panels in the injection sub-station. The fault current and fault MVA of the line are obtained using Eqs. (4 & 5)

$$Fault\ Current = \frac{Fault\ MVA \times 10^3}{\sqrt{3} \times Base\ KV} \quad (4)$$

$$Fault\ MVA = \frac{Base\,MVA}{X_{P.U.eq.}} \quad (5)$$

Where: $X_{P.U.eq.}$ is the per unit reactant equivalent up to the point of fault, $Fault\ MVA$ is the fault apparent power of the station in Mega volt-ampere, $Base\,MVA$ is the base apparent power of the station in Mega volt-ampere, and $Base\ KV$ Is the base voltage of the station in Kilo-volt.

The technical data indicates that there are two 2 x 15MVA transformers in the injection substation; this implies that the 33KV feeder control panel will be two (2) plus the spear(s). The transformer incomer control panel will also be two (2) plus the spear(s). The number of 11KV outgoing feeder control panel depends on the CT ratio of the transformer incomer control panel. Per unit equivalent inductance of the feeder, $X_{P.U.eq.} = 80\%,$ fault MVA is calculated as 187.5.while the fault current associated with 33KV and 11kV control panel using Eq. 4 are approximately 3280.4A and 9841.2A respectively. Since same voltage flows through the 11KV control panel and the outgoing panel, same fault current will flow across the panel during the event of abnormal condition. Thus its fault is $9841.2\ A$.

As the rating of the transformers are the same, one transformer will be use to get the parameters needed to set the relay. While setting the Micom relay, the parameters used in the setting are: tying

$I_{>}$ = Over current or I - greater.,

$tI_{>}$ = Actual time of operation for over current.

$I_{>>}$ = Double over current or I - greater - greater.

$tI_{>>}$ = Actual time of operation for double over current.

$I_{>>>}$ = Triple over current or I - greater - greater - greater.

$tI_{>>>}$ = Actual time of operation for triple over current.

$I_{e>}$ = Earth fault or I_e - greater.

$tI_{e>}$ = Actual time of operation for earth fault.,

$I_{e>>}$ = Double Earth fault or Ie - greater - greater.

$tI_{e>>}$ = Actual time of operation for double earth fault.

$I_{e>>>}$ = Triple Earth fault or Ie - greater - greater - greater.

$tI_{e>>>}$ = Actual time of operation for triple earth fault.

TMS = Time Setting Multiplier.

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$PSM = \text{Plug Setting Multiplier.}$

The transformation ratio of the transformer is “a” and was calculated as 3. Likewise the primary current of the transformer ‘I_1’ is 262.2A and the secondary current I_2’ is 787.29A

From the above calculations, the maximum current of the primary and secondary sides of the transformer are approximately 262A and 787A respectively.

A. Modelling of parameters for 33KV relay control panel

Parameters to be used for the relay setting on the 33KV feeder control panels for over current and earth fault are calculated thus; from Eq. 1 that is $I_R = \frac{I_f \times y}{x}$ Where I_f = 3280.4 A, CT ratio = 600:1A , relay current I_R = 5.5A, relay Pick-up value is 1.25A, PSM is obtained as 4.4

The time that corresponds to the PSM of 4.4 is 1.2 seconds, relay operating time is 0.03 second.

Now,

$I_> \ is\ 0.44A$, $tI_>$ is 0.025seconds,

$I_{>>} = 2 \times I_> \ which\ is\ 0.88A,$

$tI_{>>>} equals\ 0.021\text{seconds}$

The earth fault is set to be 20% of the over current, and the operating time to be 20% of operation time of over current fault relay.

So, $I_{e>}$ = 20% of $I_>$ $gives\ 0.088A$, $tI_{e>}$ = 20% of $tI_>$ $which\ gives\ 0.005\text{seconds}$, $I_{e>>}$ = 2 x $I_{e>}$ gives 0.176A, $tI_{e>>}$ $yields\ 0.0025\text{seconds}$

$I_{e>>>}$= 3 x $I_{e>}$= 3 x 0.088 = 0.264A, $tI_{e>>>}$ $equals\ 0.00167\text{seconds}$. The results are as shown in Table 2

B Modelling of parameters for 33KV relay control panel

From Eq. (1), $I_R = \frac{I_f \times y}{x}$ Where I_f = 10000A, CT ratio = 1200:1A

Therefore, relay current, $I_R = \frac{I_f \times y}{x}$ gives 8.33A. Pick-up value of relay = current setting x rated secondary current of the CT given 1.25A

Plug setting multiplier of the relay, PSM is:

$$PSM = \frac{\text{Fault current in the relay coil, } I_R}{\text{Pick-up value of the relay}}$$

$$is\ 6.664$$

Suppose the time that corresponds to the PSM of 6.664 is 2.5seconds, the actual operating time of the relay is = 2.5 x Time Setting Multiplier (TSM) which gives 0.0625seconds. the parameters that will be use in the relay setting are calculated and the values as presented in Tables 3 & 4.

The earth fault is set to be 20% of the over current fault and the operating time to be 20% of operation time of over current fault.

Then, $I_{e>}$ = 20% of $I_>$ = 0.132A, $tI_{e>}$ = 20% of $tI_>$ = 0.005secoonds, $I_{e>>}$ = 2 x $I_{e>}$= 2 x 0.132 = 0.264A, $tI_{e>>}$= 0.0025seconds, $I_{e>>>}$= 3 x $I_{e>}$ = 0.396A, $tI_{e>>}$ = 0.00167 seconds

C Modelling of parameters for outgoing relay control panel

Relay current, $I_R = \frac{I_f \times y}{x}$ = 5.83A,

Pick-up value of relay = current setting x rated secondary current of the CT which is 1.25A, and PSM was calculated as 5.

Note, the outgoing feeders will share the current on the incomer control panel. Assuming that we have three (3) outgoing feeders, the load on each feeder will be: 787:3A equals 262A

Since these outgoing feeders have the same type of relay, one of them will be used to calculate the parameter for setting of the relays. The relay setting parameters are calculated as: $I_> = 0.44A$, TSM = 0.025seconds, $I_{>>} = 1.5 \times I_> = 0.66A$, $tI_{>>}$ = o.0167seconds

$I_{>>>} = 2 \times I_> = 0.88A$, $tI_{>>>} = 0.0125\text{seconds}$.

We set earth fault to be 20% of the over current fault and the operating time to be 20% of operation time of over current fault. Then, $I_{e>}$ = 20% of $I_>$ which gives 0.088A $tI_{e>}$ = 20% of $tI_>$ equals 0.005seconds, $I_{e>>}$ = 2 x $I_{e>}$ = 0.18A, $tI_{e>>}$ 0.0024seconds.

$I_{e>>>}$= 3 x $I_{e>}$ = 0.264A, and $tI_{e>>}$= 0.00164seconds.

D Maintenance of Relays

Maintaining protective relays will ensure the maximum degree of protection for the power system network. After protective relay has been installed, deterioration may take place, such as rough or burnt contacts owing to frequent operation, or contacts may become tarnished because of atmospheric contamination. Defects may have developed unnoticed until it is revealed by the failure of the protection device to respond to a power system fault. For these reasons, all relays must be checked periodically.

IV. RELAY COORDINATION RESULTS AND DISCUSSION

a) The parameters for the 33KV relay setting

Since there are two (2) numbers 15 MVA transformers, there will be two (2) numbers 33KV feeder control panels and a spare. The parameters for the 33KV relay setting are summarized in the Table

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TABLE II
PARAMETERS FOR MICOM RELAY SETTING ON 33KV CONTROL PANELS.

Relay Parameters	Feeder one (1)	Feeder two (2)	Feeder three (3) (Spare feeder)
$I_{>}$	0.44A	0.44A	0.44A
TSM	0.025	0.025	0.025
PSM	4.4	4.4	4.4
$I_{>>}$	0.88A	0.88A	0.88A
$t\ I_{>>}$	0.032s	0.032s	0.032s
$I_{>>>}$	1.32A	1.32A	1.32A
$t\ I_{>>>}$	0.021s	0.021s	0.021s
$I_{e>}$	0.088A	0.088A	0.088A
TSM	0.025	0.025	0.025
PSM	15	15	15
$I_{e>>}$	0.176A	0.176A	0.176A
$t\ I_{e>>}$	0.0025s	0.0025s	0.0025s
$I_{e>>>}$	0.264A	0.264A	0.264A
$t\ I_{e>>>}$	0.00167s	0.00167s	0.00167s
CT ratio	600:1A	600:1A	600:1A
Make	Micom	Micom	Micom

TABLE III
PARAMETERS FOR MICOM RELAY SETTING ON INCOMER CONTROL PANELS

Relay Parameters	Incomer one (1)	Incomer two (2)	Spare
$I_{>}$	0.66A	0.66A	0.66A
TSM	0.025	0.025	0.025
PSM	6.664	6.664	6.664
$I_{>>}$	0.99A	0.99A	0.99A
$t\ I_{>>}$	0.0167s	0.0167s	0.0167s
$I_{>>>}$	1.3A	1.3A	1.3A
$t\ I_{>>>}$	0.0127s	0.0127s	0.0127s
$I_{e>}$	0.132A	0.132A	0.132A
TSM	0.025	0.025	0.025
PSM	6.664	6.664	6.664
$I_{e>>}$	0.132A	0.132A	0.132A
$t\ I_{e>>}$	0.0025s	0.0025s	0.0025s
$I_{e>>>}$	0.396A	0.396A	0.396A
$t\ I_{e>>>}$	0.00167s	0.00167s	0.00167s
CT ratio	1200:1A	1200:1A	1200:1A
Make	Micom	Micom	Micom

From Table 2, when over current fault occurs in the 33KV feeder, relay on the control panel will send tripping command to the circuit breaker if the secondary current exceeds 1.32A and the time for the relay to send this command is 0.021s. Similarly, when earth fault occurs in the 33KV feeder, relay on the control panel will send tripping command to the circuit breaker if the secondary current exceeds 0.264A and the time for the relay to send this command is 0.00167s.

b) The parameters for the 11KV incomer relay setting

Since there are two (2) transformers, there will be two incomer control panels and a spare. The relay setting parameters are summarized In Table III.

From Table 3, when over current fault occurs in the 11KV incomer feeder, relay on the control panel will send tripping command to the circuit breaker if the secondary current exceeds 1.3A and the time for the relay to send this command is 0.0127s. Similarly, when earth fault occurs in the 11KV feeder, relay on the control panel will send tripping command to the circuit breaker if the secondary current exceeds 0.396A and the time for the relay to send this command is 0.00167s. The reason for the relay to trip at lower value of earth fault current is that earth fault is very dangerous in interconnected systems.

V CONCLUSION

Protective relay is a very important electrical device that must be installed in every power system control panel. In this work, the technical data of 2X15MVA, 33/11KV Maitama injection substation was collected and used for modelling relay coordination for the station. After the coordination, the result shows that 33KV feeder will trip on over current and earth faults if the secondary current of the CT exceeds 1.32A and 0.264A within 0.021s and 0.00167 respectively. The 11KV incomer feeder will trip on overcurrent and earth faults if the secondary current of the CT exceeds 1.3A and 0.396A within 0.0127s and 0.00167s respectively. From these results, it can be seen that earth faults trip faster than overcurrent fault; this is because of the harmful nature of earth.

VI RECOMMENDATIONS

We recommend the following:

a) Periodic maintenance of the protective relays should be done monthly to ascertain its functionality.
b) Checks on the operational status of the associated circuit breakers to confirm its tripping status should be done monthly.

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