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Improvement of 132/33KV Transmission Injection Substations Protection in Rivers State Using Short Circuit Analysis Technique

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ABSTRACT:
This paper presents the improvement of 132/33KV transmission injection substations protection, mainly short circuit fault on Port Harcourt Mains Zone-2 network and it seeks to correct the irregular tripping sequence, poor discrimination of relays, improper isolation action by the circuit breaker, poor current transformer ratio (CTR) calibration of the system. The 3x60MVA injection substation of the network was modeled. Short circuit analysis technique embedded in Electrical Transient Analyzer tool version 16.0 software was used to determine the tripping sequence of relay to circuit breaker coordination, using data from Transmission Company of Nigeria and Port Harcourt Electricity Distribution Company of Nigeria (PHED). The tripping sequence operation report showed that faults created at respective classified zones: A, B, C and D were analyzed and observed in accordance to the individual relay responsiveness to faults conditions. When a three (3) phase fault created at Zone-B, an irregular relay-tripping sequence was observed in the order of 1, 3, 2, and 4 with a tripping time of 11.5ms. This indicates violation in the relay response to fault conditions. Evidently, a new case of the study was re-modelled in order to satisfy the statutory conditions. The current transformer (CT-ratio) of the existing condition of (1200/1 = 1200:1) was modified through short-circuit calculation to (900/5 = 900:5) in order to enhance orderly coordinated sequential tripping of 1, 2, 3 and 4 with a tripping time of 7.1ms. The new case showed improved protection (i.e. the irregular relay tripping sequence in the order of 1, 3, 2 and 4 and tripping time of 11.ms of Zone B with a 3 phase fault was improved to have a regular relay tripping sequence in the order of 1, 2, 3 and 4 and tripping time reduced from 11.5ms to 7.1ms) using short circuit analysis technique through relay coordination of the 132/33KV Port Harcourt Mains Z2 injection Substation in Rivers State.

KEYWORDS*:* Protection, Relay Coordination, Short Circuit Analysis Technique, Tripping sequence, Transmission Injection Substation.

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1. INTRODUCTION

Electricity is a vital requirement needed for growth and advancement of every country's economy, infrastructure, and industry. So, the regular and constant availability of electric power is directly proportional to improved living condition of the people of such nation and consequently a positive change in all aspects of their lifestyle, hence the need for heavy investment in the power sector. (Anamika &Yajnaseni*,* 2014)

It is a good thing to revive the power sector so as to improve productivity in the commercial industries, and private establishments, which in turn will raise the standard of the living of the citizens (Akpojedje*et al*., 2016).

Electrical fault is an undesired short circuit situation or event that happens or arises either between two phases of wires or between a phase of wire and earth. Short circuit is the greatest and most dangerous fault type because it allows the flow of heavy currents in the network which can result to overheating or create mechanical forces which can mutilate or destroy equipment and other elements of power system. (Emmanuel *et al.,* 2016).

In the recent past, there have been several unreported and reported cases of electrocution in our electricity networks in Nigeria. Some of the reported cases include the Calabar electrocution resulting to the death of 7 persons and various degrees of injuries on 11 others in February, 2017. However, the report further revealed that a cut conductor of a certain 11KV feeder fell on a building where people were watching football and the feeder failed to trip (PHED, 2017).

In the same vein, report has it that a cut conductor on Cameroun 11KV feeder at Calabar rested on the roof of a building on the 31st December, 2017 claiming the life of 1 person and causing various degrees of injuries on 2 others due to relay failure. This was probably caused by poor relay coordination at the injection substation and lack of relay coordination between the injection substation and Calabar Transmission Station.

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A report from Port Harcourt Electricity Distribution Company Newsletter (PHED) (2016) stated that a sad incidence of electrical hazard that instantly claimed the lives of 13 persons trading under 11KV line at Slaughter market in Trans-Amadi 5 years ago resulting from high tension lines snap and yet the feeder failed to trip. In another development, it will be pertinent to state categorically that reports have it that at different occasions customers experience power outage due to the tripping of 33KV feeder connected to the substation that supplies them owing to the fact that the faulty 11KV feeder relay failed to operate.

The occurrence of fault is inevitable in power system operation. These faults could be poor relay response/coordination to circuit breaker which may seriously lead to transfer of the activities of faulty section(s) to the healthy part of the networks. In another development at different occasions customers experience power outage due to the fact that relays at Injection substation and Transmission station trip on same fault resulting to over-trip. This results to damage of equipment because the primary protection fails to trip while fault persisted. (Idoniboyeobu*et al.,*2017).

For efficiency, when primary protection fails to operate backup protection scheme must operate in order to divorce the fault, after tolerable time discrimination from the main zone. The faulty part should be removed from the healthy potion of the network when there is a short circuit, so that the healthy potion can be protected to ensure security of the equipment and personnel (Mohamed, 2016).

Considering the obvious challenges mentioned above, the aim of this research is to improve power protection of 132/33KV transmission injection substation in Rivers State Transmission Network (Case Study Port Harcourt Mains, Zone-2). This will be achieved by identifying and determining the method of relay coordination in the existing injection substation, collect numerical data to be implemented into formulated equations, represent and model the existing network in E-tap environment for purpose of investigation, formulate voltage equation, short-circuit-equation, current-voltage equation for purpose of analysis and investigation, to run a short-circuit test on the injection substation, to validate existing relay coordination of the protection scheme with modified or improved protection scheme (in line with IEE regulations).

Having identified the abnormal operation in the relay action of the circuit breaker for purpose of healthy condition of power system stability, this work will consider the improvement of injection substations protection through relay coordination in Port Harcourt Main – Zone 2 network, using short-circuit analysis technique. This will help us to improve the protection scheme of the transmission injection substation, increase the safety of lives, properties and equipment, reduce the down time associated with power outages on the lines, increase efficiency in operation of transmission lines, improve the system stability, increase power availability, reduce the cost of replacing damaged transmission lines and equipment and finally increase the revenue of Transmission Company of Nigeria (TCN).

2 MATERIALS AND METHODS

2.1 Materials

The data needed for investigating and analyzing the study case was collected from Port Harcourt Electricity Distribution Company (PHED) and Transmission Company of Nigeria (TCN). The method and procedure applied in this research work are presented.

2.2 Method of Analysis

The use of short circuit analysis was adopted as a method of investigation for purpose of power protection improvement of 132/33kV Port Harcourt Mains Injection Substation in Rivers State. The transformers considered on the network are at Port Harcourt Mains Z2 with 3 x 60MVA, 132/33kV Transmission Injection Substation. The data collected generally were used to calculate the distributed impedance, admittance and other parameters required for the short circuit analysis. Short circuit analysis was run on the network with the available data using ETAP software.

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Table 1: Data Consideration made in the Application Software

S/N	Parameters	Data
1	132kV transmission line route length	30.45km
2	T1A 60MVA impedance at PH mains transmission station	18.12%
3	T2A 60MVA impedance at PH mains Injection Substation	19.34%
4	T3A 60MVA impedance at PH mains injection substation	21.57%
5	Maximum load on 33kV line	20MW
6	Maximum load on Ref 1 33kV feeder	33kVA
7	Maximum load on Abuloma 33kV feeder	14kVA
8	Maximum load on Ref 2 33kV feeder	15kVA
9	Maximum load on Rainbow 33kV feeder	33kVA
10	Maximum load on RSPUB 2 33kV feeder	24kVA
11	Maximum load on Uniport 33kV feeder	14kVA
12	Maximum load on RSPUB 1 33kV feeder	23Kva
13	Maximum load on FDR3 33kV feeder	23kVA
14	Maximum load on FDR 2 33kV feeder	28Kva
15	Maximum load on Airport 33KV feeder	27Kva
16	Conductor type	ACSR
17	Conductor size	$150mm^2$
18	Cable size	$240mm^2$
19	System type	3-phase AC
20	CTRs	600/1, 1200/1, 800/1, 300/1 & 400/1
21	Base MVA	100
22	Relay type	IDMT Electromechanical Relay
23	Conductor resistivity at 20^0C	2.83×10^{-8}
24	33kV line spacing	1219.2mm

Source: PHED and TCN.

2.3 Short Circuit Analysis on Port Harcourt Mains Z2, transmission Sub-Station

Primary data collected using appropriate equations served as the input source to the short circuit analysis technique, which was analyzed on Electrical Transient and Analysis Program (ETAP) environment. The input data were used in the analysis to obtain expected result. Data collected include: route length to Transmission Station, CTRs, relay, Plug Set, transformer impedance, feeder full load currents, transformer ratings, conductor cross-section area, 132kV line spacing, base MVA, etc.

2.4 Case 1: Determination of Relay Operating Time

In the determination of actual operating time of a relay the data required are: Time – PSM curve, Current – Setting, Time – Setting, Fault – Current and CT ratio.

The installed relay type is Inverse Definite Minimum Time (IDMT) Relays. This type of relay is that which its operating time is inversely proportional to the fault current near Pick-up Value and becomes substantially constant slightly above one pick-up value of the relay.

2.5 Case 2: Determination of Relay Current from Fault Current (I_f) and CT

For us to determine the Relay Current, we will use the ratio of input current to output current, Ratio (x:y). (Glover *et al.*, 2008). Therefore, applying Equation (1), we have

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

where:

I_f = fault current

x = input current

y = output current

2.6 Case 3: Determination of Relay Current Setting Multiplier (PSM)

The Relay Current Setting Multiplier can be calculated by dividing the fault current in the relay coil by the pick-up value of the relay which is given as follows (Muthu &Vahab, 2016):

$$PSM = \frac{Fault\ current\ in\ relay\ coil}{Pick-up\ value} \quad \text{or}$$

$$\text{PSM} = \frac{I_R}{Current-setting \times rated\ secondary\ current\ of\ CT} \quad (2)$$

or

$$\text{PSM} = \frac{I_R}{\frac{I_P}{100} \times y} = \frac{I_R \times 100}{I_P \times y} \quad (3)$$

Similarly,

$$\frac{I_f \times 100 \times y}{x \times I_P \times y} = \frac{I_f \times 100}{x \times I_P} \quad (4)$$

where:
I_P = the percent current setting of the relay

2.7 New Case of Short-Circuit Analysis at Port Harcourt Mains Z-2 132/33kV Transmission Line Injection Substation

Some of the primary data collected e.g. cable size, system type, conductor size, maximum load on feeders, transmission route length, transformer impedance, etc., (see table 1) and data obtained using equations 1, 4, 5 to 20, 23, 24, 25, 26, 27, 30, 32, 33, 34 and 35 were considered (for the determination of relay current, relay current setting multiplier, fault current, time multiplier setting, plug setting multiplier, operating time of relay, tripping time of relay etc.) to generate and run a new short circuit analysis of relay coordination on Port Harcourt Mains Z2 Transmission Station using Electrical Transient and Analysis Program (ETAP) environment.

The data served as the input source to the short circuit analysis technique, which was also analyzed on Electrical Transient and Analysis Program (ETAP) environment (Hima*et al.,* 2015).

The input data was also used in the analysis to obtain result.

If DC is flowing around cylindrical conductor, the current is uniformly distributed over its cross-section area and its DC resistance is evaluated by Igbogidi*et al.* (2018), and Jayesh and Prajapati (2014).

$$R_D = \rho \frac{l}{A} (\Omega) \quad (5)$$

where:
ρ =conductor resistivity at a given temperature $(\Omega - \text{m})$
l =conductor length (m)
A=conductor cross-section area (m^2)

If cross-section area, A is $\pi \left(\frac{d}{2} \right)^2$ (6)

Then calculation of the diameter,
d = 2r (7)
Entering the cross – section A:

$$d = 2, \sqrt{\frac{A}{\pi}} = 2r \equiv 1.1284\sqrt{A} \quad (8)$$

From Equation (8), the radius r, can be evaluated using:

$$r = \frac{d}{2} \quad (9)$$

Per kilometer reactance x_0 of one phase can be evaluated using:

$$x_0 = 0.1445 \log_{10} \left(\frac{D_{GMD}}{r} \right) + 0.0157 \quad (10)$$

where:
D_{GMD}=the geometric mean distance between the line conductors
r = the radius of conductors

Determination of the line reactance X, is given as:

$$X = x_0 l_0 \quad (11)$$

The distributed series impedance Z_1 then becomes:

$$Z_1 = R + jX \quad (12)$$

The equivalent admittance Z_0 is given as:

$$Z_0 = Y = \frac{1}{z} = G + jB \quad (13)$$

From Equation (13), the conductance G, can be deduced as:

$$G = \frac{1}{R} \quad (14)$$

and the susceptance B, of the line becomes

$$jB = j\frac{1}{X} \quad (15)$$

If the source impedance Z, and Base MVA are known, then

$$\text{Source of impedance } Z = \frac{Base\ MVA}{Fault\ MVA} \quad (16)$$

If transmission line constants for the route length Z_1 and Z_0 are known, then transmission line constants on base MVA in p.u can be evaluated as

$$Z_{1P.U} = \frac{Z_1 \times Base\ MVA}{(KV)^2} \quad (17)$$

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Impedance of transformer at Port Harcourt Mains, Z2 Transmission Station on the base MVA can be evaluated using Equation (19).
The Total Fault Impedance at Port Harcourt Mains Injection Substation in p.u. can be evaluated thus:

$$Z_f = Z_0 + Z_1 + Z_t \qquad (18)$$

where:

$$Z_t = Z_{P.U} = \frac{\%Z \times (Base\ MVA)}{Transformer\ MVA}$$

Assuming that a 3-phase fault occurs on Port Harcourt Mains, Z2 Transmission Station, then Fault MVA becomes

$$\text{MVA} = \frac{Base\ MVA}{Total\ Fault\ Impedance\ at\ P/H\ Mains\ Injection\ Substation} \qquad (19)$$

Hence Port Harcourt Mains, Z2 Transmission Station, fault current can be determined thus:

$$\text{Fault current} = \frac{Fault\ MVA}{\sqrt{3}.V_L} \qquad (20)$$

where: V_L = Line voltage
(Igbogidiet *al.,* 2018)

2.8 Case 5: Data collection for system analysis existing operating conditions

Short circuit analysis was carried out in the existing relay coordination of 3 x 60MVA transformers, 132/33kV Transmission Injection Substation. The system networks were modeled in electrical transient analyzer tool (Etap-Version-16.0), in order to observe the tripping sequence and violations occurrences. The sequence of operation and coordination are captured in letters A, B, C and D respectively.

2.9 Design Equation

The circuit analysis and design equations used to determine relevant parameters for a protection scheme are as follows (Mehta &Mehta*,* 2006):

Case 1:
Fault MVA is given as

$$MVA = base\frac{MVA}{Z_{P.U}}(MVA) \qquad (21)$$

The fault current (I_f) is given as

$$I_f = \frac{Fault\ MVA \times (10)^3}{\sqrt{3} \times KV} \qquad (22)$$

Case 2:
Similarly;
Load current (I_{f_L}) is given as
Case 3:

$$I_{f_L} = \frac{KVA \times 1000}{\sqrt{3} \times V} \qquad (23)$$

Also, for relay settings conditions, the time multiplier setting is given as: Time Multiplier Setting (TMS)

$$TMS = OTR + \frac{PSM^{0.02} - 1}{0.14} \qquad (24)$$

Where
TMS = Time Multiplier Setting
OTR = Operating Time of Relay
PSM = Plug Setting Multiplier

Case 4:
Evidently, plug-setting multiplier **is** given as

$$(PSM) = \frac{I_{F_R}}{I_P} \qquad (25)$$

Case 5:
The fault current (I_f) referred to primary of CT **is** given as:

$$I_F = \frac{I_F}{CT_P} \qquad (26)$$

Where, CT_P is primary sides of current transformer, the total operating time of relay (TOTR) **is** given as:
TOTR = OTR + OTCR + OVTR
Circuit breaker (OTCB) = 0.5secs

Case 6:
The Operating Time of Relay (OTR) **is** given as:

$$t_{op}\ \text{(operating time)} = \frac{0.14 \times TMS}{[PMS^{0.02} - 1]} \qquad (27)$$

Case 7:
Determination of overshoot time of relay **is given as**
(OVTR) = 10% x OTR (28)

2.10 Choosing Relay Parameters:

According to Audih (2017), and Gupta (2012), we can calculate for the load current, Time Multiplier setting and tripping time of relay using the Equations (29), (30), and (35).
Scenario – 1: Load Current

$$\text{Load current } (L_{F_L}) = \frac{KV_A \times 1000}{\sqrt{3} \times V} \qquad (29)$$

Scenario – 2: Relay Settings

Time Multiplier Setting (TMS)

$$\text{TMS} = \frac{OTR*[PSM^{0.02}-1]}{0.14} \quad (30)$$

$$\text{CT} = F_{C_P} = \frac{I_F}{CT_P} \quad (31)$$

CT = Current Transformer

F_{C_P}= Fault current referred to primary

$$(CT) = {}^{I_F}/_{CT_P} \quad (32)$$

CT_P = Primary side of current transformer

Total Operating Time of Relay (TOTR)

TOTR = OTR + OTCB + OVTR (33)

The Operating Time of Relay (OTR) is given as:

$$t = \frac{0.14\times TMS}{[PSM^{0.02}-1]} \text{ seconds} \quad (34)$$

or

$$t = \frac{0.14\times TMS}{\left(\frac{I_F}{I_S}\right)^{0.02}-1} \quad (35)$$

where,

t = Tripping time of relay

TMS =Time Multiplier Setting

PSM = Plug Setting Multiplier

PSM = Function $\left({}^{I_F}/_{I_S}\right)$

Where

I_F= Fault current

I_S= Set pick-up current.

Scenario 3: Time and Current Grading:

The relay operations in this case functions with the inverse time to current principle. That is the tripping time is inversely proportional to the current magnitude. This paper identified the use of Inverse Definite Minimum Time (IDMT) relay with normal inverse time to current characteristics as shown in Equation (36).

$$t = \frac{0.14\times TMS}{\left(\frac{I_F}{I_S}\right)^{0.02}-1} \quad (36)$$

Where

t =Tripping time of relay

TMS=Time Multiplier Setting

I_F= Fault current

I_S= Set pick-up current.

3. RESULTS AND DISCUSSION

Case A: Faults Created at Zone-A

From Figure. 1 and Table. 2, we observe that when a 3-phase fault was created at Zone-A, in order to observe the level of sensitivity and discriminations. The relay at Zone-A took longest time to discriminate the fault condition followed by relay-B, C and D in the tripping sequence order of 4, 3, 2 and 1. This shows a poor sensitivity of relay to circuit breaker action as indicated in Figure. 1 and Table 2.

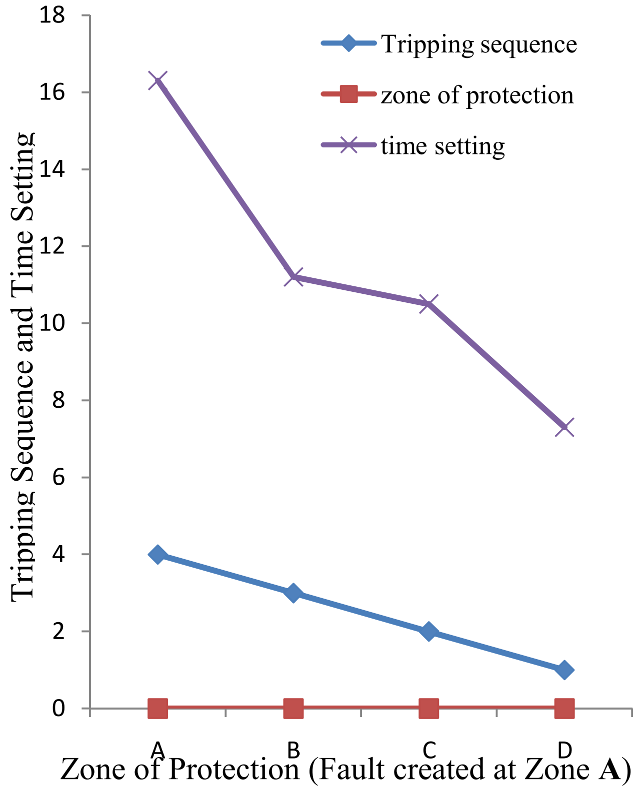

Figure 1 Tripping Sequence, Time Setting Versus Zone of Protection

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Table 2: Tripping Sequence of Relay with Respect to Zone of Protection, Time Setting

Tripping Sequence	Zone of Protection	Time Setting
4	A	16.3
3	B	11.2
2	C	10.5
1	D	7.3

Case B: Faults Created at Zone-B

Similarly, 3-phase faults were also created at Zone-B, as seen in Figure 2, the expected relay and CBs to that zone (Zone B) are overtaken by other associated relays and circuit breakers (CB) for discrimination and isolation of the faulted case at Zone-B. From Figure 2 and Table 3, it will be observed that Relay-D takes the longest time to trip followed by Relay-B, C and A respectively, in the relay sequential tripping-order of 1, 3, 2 and 4. It can be seen that relay on Zone

A tripping time was 7.6ms, while Zone B tripping time was 11.5ms. Also, it is seen that Zone C and Zone D had a tripping time of 9.6 and 16.5 respectively. This shows a poor tripping sequence of the expected relay and thereby shows poor relay to circuit breaker coordination.

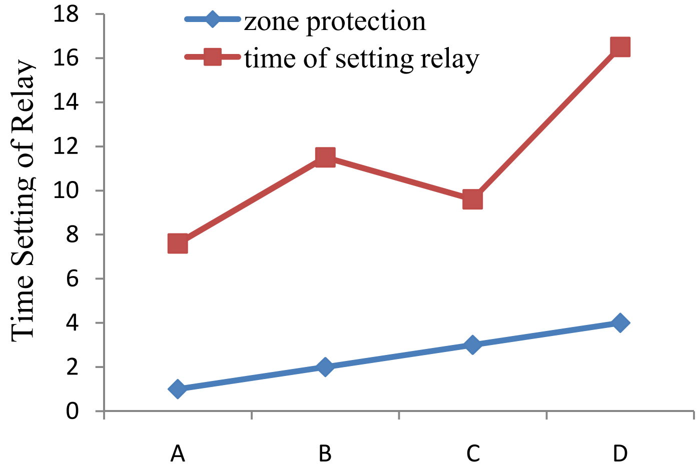


Figure 2 Time of Setting of Relay Versus Zone of Protection

Table 3: Tripping Sequence of Relay with Respect to Zone of Protection, Time Setting

Tripping Sequence of Relay	Zone Protection	Time Setting of Relay
1	A	7.6
3	**B**	**11.5**
2	C	9.6
4	D	16.5

Case D: Fault Created at Zone-D

The expected relay to circuit breaker (CB) at Zone-D to be responsive to 3-phase faults occurrence, was seen to be overtaken by other relays and associated circuit-breaker (CBs) action at Zone A, B and C respectively for purpose of discrimination and isolations. The tripping sequential orders are 1, 2, 3 and 4 respectively as seen in Figure 3 and Table 4.

From Table 4, it was observed that relay in Zone A tripped at 8.1ms, relay in Zone B tripped at 9.2ms, relay in Zone C tripped at 10.3ms and relay in Zone D tripped at 17.4ms. This tripping

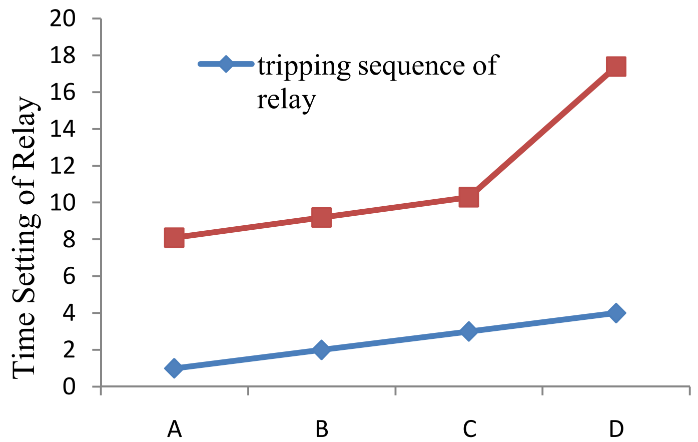


Figure 3 Time Setting of Relay versus Tripping Sequence of Relay

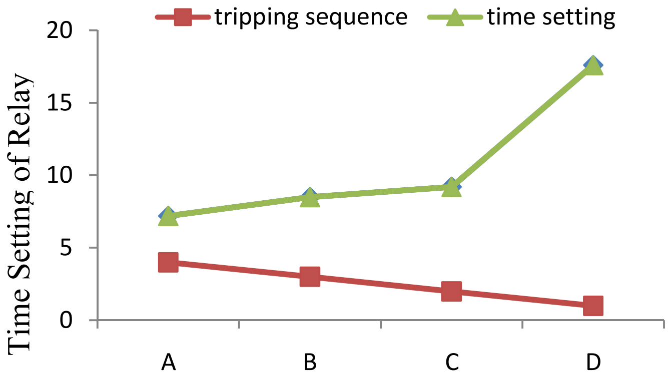
Table 4: Tripping Sequence of Relay with Respect to Zone of Protection, Time Setting

Zone Location	Tripping Sequence of Relay	Time Setting of Relay
A	1	8.1
B	2	9.2
C	3	10.3
D	4	17.4

Case C: Faults Created at Zone-C

Evidently, 3-phase fault was created at Zone-C. The relay sensitivity shows poor coordination in the pre-designed setting of the relay time and there was a tripping sequence violation that occurred. It was observed that Relay A was the first to trip at 7.2ms, followed by Relay B at 8.5ms, Relay C at 9.2ms and Relay D at 17.6ms with sequential tripping sequence order of 1, 2, 3 and 4 respectively as shown in Figure 4, Table 5.

The tripping time of the Relays in Zones A, B, C and D show poor relay to circuit breaker coordination, improper and tripping sequence.



Tripping Sequence of Relay (Fault created at Zone **C**)

Figure 4 Time Setting Versus Tripping Sequence

Table 5: Tripping Sequence of Relay with Respect to Zone of Protection, Time Setting

Zone of protection	Tripping Sequence	Time Setting
Zone-A	1	7.2
Zone –B	2	8.5
Zone-C	3	9.2
Zone-D	4	17.6

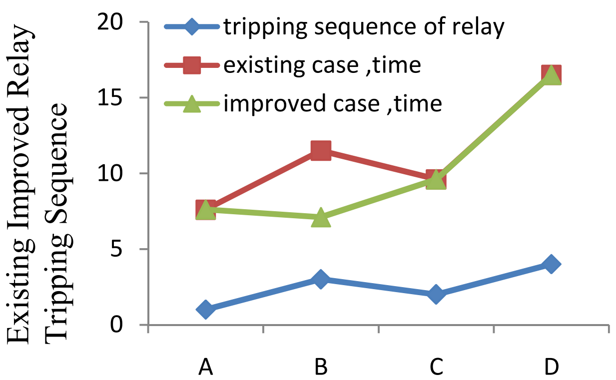
Case E: Improved and Existing Condition of Relay Tripping Sequence and Setting

Fault created at zone B, required expected orderly tripping sequence in that zone B, but it was observed through the modeled simulated study case that there is a tripping sequence violation in the order of 11.5ms as existing operating time as against 7.1ms improved operating time as shown in Table 6 and Figure 5

Evidently the tripping sequence is in the order of 1, 3, 2 and 4 respectively in the existing case. While Zone A tripping sequence of existing to improved case is 7.6ms as against 7.6ms. Zone C engages a tripping sequence of 9.6ms existing operating tripping time setting to 9.6ms as improved operating tripping time setting.

Similarly, Zone D engages the same tripping sequence of 16.5ms for existing and improved case, which is presented in Figure 5.

Therefore, it can be seen that the tripping sequence for the improved case is 1, 2, 3 and 4 as against 1, 3, 2 and 4 as it is in the existing case.



Tripping Sequence of Relay (Fault created at Zone B)

Figure 5: Existing, Improved Relay Zone of Coordination versus Tripping of Time

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Table 6: Tripping Sequence of Relay with Respect to Zone of Protection, Time Setting

Zone of Protection	Tripping Sequence Relay Existing Case	Existing Case Time	Zone of Protection	Tripping Sequence Relay Improved Case	Improved Case Time
A	1	7.6	B	1	7.1
B	3	11.5	A	2	7.6
C	2	9.6	C	3	9.6
D	4	16.5	D	4	16.5

CONCLUSION

The simulation of the existing model (Port Harcourt Mains Z-2, 132/33KV Transmission injection substation) revealed strongly mismatches, violations of tripping sequence of existing case, poor sensitivity of relay actions, poor discrimination/ for purpose of selectivity action, improper isolation , improper calibration of CTR ratio's for primary and secondary transformers. The existing current transformer ratio's setting (CTR) was 1200/1 which was modified to new CTR ratio of 900/5 in line with designed requisite calculation, based on IEE regulations and IEC declared standard. The adjustment in the CTR setting ratio from 1200/1 to 900/5 has seriously eliminated the irregular tripping sequence violations occurrence.

Also, it was observed that the time grading of the relay is unequally time graded but this research work has achieved equal time grading of the relay setting, which has resulted in proper and correct discrimination of the tripping sequence of the relays/circuit breakers in their respective zones. Evidently, this research has shown that other possible variables that could constitute abnormal operation of the protective relay action are the mechanical malfunctioning of the spring due to ageing/strength of the component, irregular tripping sequence over times resulting to clearances, wear and tear of component parts that required regular maintenance and replacement where necessary in order to engage regular, efficient and reliable operations of the system. This research has also provided an improved power protection scheme for injection substations and has revealed that, using different types and make of relays on a substation, affect proper relay coordination and operation of any protection scheme.

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