*Journal of Engineering, Emerging Technologies and Applied Sciences -– Volume 1 Issue 2, Nov. 2023*

*Available at* ***https://www.ndu.edu.ng/journalofengineering/***

RESEARCH ARTICLE OPEN ACCESS

# Relay Coordination for Efficient Power Delivery and Equipment Protection at Station Road, Port-Harcourt

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## Abstract:

Incorrect operation of protective devices in a power system can result in massive equipment damage, human casualties, and even power supply disruption. This research is to address the problem of wrong sequence of operation of relays and circuit breakers at the Station Road network. Short circuit analysis was performed using ETAP 19.0 to study the behavior of the network in the event of fault. Additionally, Inverse Definite Minimum Time (IDMT) is used to ensure quick response of the protective devices. In this study, the response times of the four relays are investigated when a 3-phase fault is injected into the feeder network. The findings reveal that the tripping sequence response from feeder breaker to 33kV line breaker to 33kV control panel breaker and finally to 11kV incomer control panel, are abnormal. The result of the improved scenario shows the relays tripping sequence are in the proper order from the main feeder to the 11kV incomer control panel, 33kV control panel breaker, and 33kV line breaker, with proper time grading. It is crucial to achieve the right order of relay operation for efficient protection and service delivery.

*Keywords* — **Relay coordination, efficient power delivery, equipment protection**

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## I. INTRODUCTION

An electric power system is a network of electrical devices used for generation, transmission and distribution of electricity, with the objective to match customer expectations for the delivery of steady and reliable power supply free of unfavorable impacts from outages (A. Watson & A. Benjamin, 2022). This objective is constrained by the effectiveness and quality of the protections available to the various connecting networks of the power system. The security of a power network is the duty of a power system Engineer by using the right equipment for constant monitoring of the system to ensure maximum electrical supply continuity while avoiding equipment damage (M. H. Hussain, I. Musirin, S. R. Rahm, A. Abidin, A. F., & A. Azmi, 2013). Generally, relays are widely used for the protection of power systems, and are made to detect different currents during the same fault in different locations, and initiate the isolation of the faulted section.

When a fault in an electrical circuit is detected, a protective relay analyses operating conditions on the circuit and trips circuit breakers. The protection engineer evaluates the tripping characteristics of the different protective relays and design effective protective scheme (K. O. Uwho, H. N. Amadi, & P. Obire, 2022). Relays should be designed to detect abnormal or undesirable situations and deliver a tripping signal to the circuit breaker in order to separate the affected area without affecting adjacent sections. Statistics show that many relay trips are caused by wrong or poor settings rather than real failure (U. C. Ogbuefi, B. O. Anyaka, & M. J. Mbunwe, 2019). The primary devices nearest to the fault should be the first to respond, followed by backup devices further away to isolate the faulty section only. This is necessary to meet the basic statutory objective of every electrical energy provider for the provision of continuous, acceptable and reliable service to its customers. Therefore, if there is fault in the system, fault analysis process consisting of calculation of the maximum currents that components and switching devices must sustain and interrupt, and circuit protection coordination, is carried out.

Generally, relay coordination can be said to be determination of the sequence of relay operations for each potential fault location in order to quickly isolate the faulty section and to ensure adequate coordination margins (B, Dinesh, M. Rudra, P. Gupta, & H. Om 2005). Therefore, power system relay coordination is the tendency of the power system is remaining in operation after isolation of identified potential fault. Relay coordination problems have attracted a lot of attention in recent times with emphasis on control, planning and operation of the system. The issues of the power system are raising a lot of concern with increasing demand for power and loading of the transmission system.

In this paper, the relay coordination problem of relays and circuit breakers at the Station Road network is investigated. The investigation is centered on the response time of the relays, the tripping sequence response of the breakers and the order of the relay and breaker operation.

## II. OPERATION OF PROTECTIVE RELAY

Figure 1 shows the fundamental circuit breaker control network for opening action. The relay is attached to current transformer (CT) and the potential transformer (PT) to actuates and close the contacts when a fault occurs within the secured section. When the breaker trip coil is engaged, the breaker working mechanism will be on to activate opening action by allowing current to the trip circuit. The relay is responsible for the activation of the trip circuit, and the faulty section is removed by the circuit breaker.

Overcurrent relays (OCRs) which operates at a fixed fault current level are among the most used protective components in power system. To arrive at effective protection from these defensive tools, the pickup current and the time-dial setting of the relay must be regulated to ensure that the system perfectly coordinated. The relay operates when the fault current reaches a value equal to or greater than the pickup current. The overcurrent device's inverse characteristics are changed by modifying the time delay via the time dial setting.

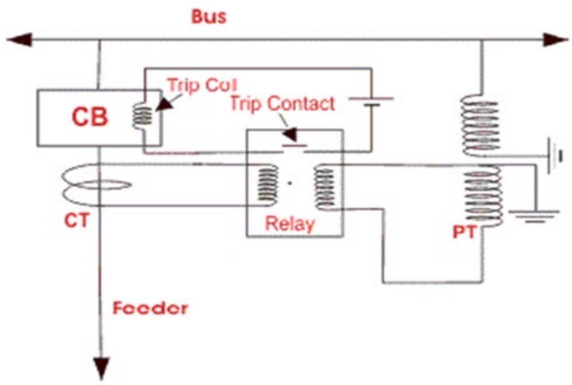


Figure 1: Basic Circuit Diagram of Protective Relay Scheme. Source: (Jayaprakash, J., Angelin, M., & Lakshmi, J. 2016).

Generally, during system design, the fault current calculation is used to determine the coordination of this protective relay (P. Obire, D. C. Idoniboyeobu, & S. L. Braide, 2022). The location and type of equipment to be secured are the most important selectivity criteria. Distance relays are usually applied for long-distance transmission lines, differential relays for transformer protection, directional overcurrent relays for meshed networks, OCRs for generators, motors, and feeders, and pilot relays for long-distance, switching in hazardous areas, cable, and power equipment protection.

### *A. Short Circuit Analysis*

When there is difference in potential between two points in a network, a low impedance connection can be made intentionally or accidentally which is abnormal (O.N. Igbogidi, D. C. Idoniboyeobu, & S. L. Braide, 2018). Its effect causes flow of excessive current through the power system, resulting in power outages. Even though the power system is built to defend against numerous problems, it is somehow harmed. The voltage and configuration of the power circuit, the method of neutral connections whether solidly grounded, resistance grounded, reactance grounded, and ungrounded, the presence of regulating devices such as shunt reactors, series reactors, shunt and series capacitors, and the speed with which the faulted circuit section is disconnected determine the fault current.

Short circuit analysis can be deployed to evaluate fault current in a power system for various faults. Apart from short circuit current, it can as well be used to assess the interrupting ratings of protective devices such as circuit breakers and fuses for assuring the protection of equipment installed in the power system, as well as protective device coordination (P. Obire, D. C. Idoniboyeobu, & S. L. Braide, 2022). If an electrical fault interrupts at a rate faster than the protective device's interrupting rate, the equipment will be severely damaged. As a result, no electrical equipment should be placed without first conducting a comprehensive short circuit analysis of the power distribution.

### *B. Grading of Over Current Relays*

The duration that must be allotted between the operations of two adjacent relays to achieve the right discrimination between them is called Grade Margin (S. Saini, 2014). Relay grading is actually a procedure in which the relay settings are such that when a fault occurs at any point, only the relay closest to the fault spot should respond to provide a selective operation. Relay grading scheme could be implemented via current grading, time grading and time-current grading.

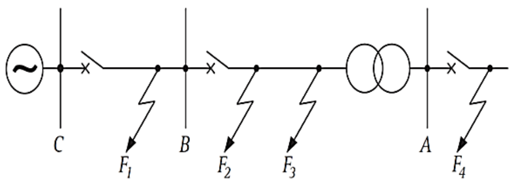


Figure 2: Discrimination by current

In current grading system, the fault current changes with the position of the fault due to variation in impedance value between the source and the fault. Thus, discrimination is achieved by reducing the current setting as we go closer to the source (E. Csanyi, 2018), therefore making the relay closest to the fault to trip the breaker.

The objectives of this study are to ensure that the right order of relay coordination is achieved and that the safety of personnel working in power system facility is secured thus, engendering efficient power delivery.

## III. MATERIALS AND METHOD

### *A. Research Materials*

Materials required for this research analysis and investigation are obtained from the Port Harcourt Electricity Distribution Company (PHEDC) and the Transmission Company of Nigeria (TCN).

TABLE I
DATA REQUIRED FOR CALCULATIONS AND SIMULATION FROM PHEDC AND TCN

| S/N | Parameter | Assumptions |
|---|---|---|
| 1 | Route length of 33kV line | 4.5 km |
| 2 | Maximum load on 33kV line | 15.3 MW |
| 3 | T1B 30MVA Impedance at Transmission station | 12.50% |
| 4 | T1 15MVA Impedance at Marine Base Injection Substation | 10.52% |
| 5 | T2 15MVA Impedance at Marine Base Injection Substation | 10.60% |
| 6 | Peak load on Churchill 11kV Feeder | 2.8 MW (168 A) |
| 7 | Peak load on NPA 11kV Feeder | 2.7 MW (162 A) |
| 8 | Peak load on Station Road 11kV Feeder | 3.5 MW (210 A) |
| 9 | Peak load on Amadi North 11kV Feeder | 3.3 MW (198 A) |
| 10 | Conductor Size | 150 $mm^2$ |
| 11 | Conductor type | AAC |
| 12 | Cable size | 240 mm sq |
| 13 | CTRs Incomer | 1250-800/1 |
|  | CTRs Outgoing | 600-300/1 |
| 14 | Base MVA | 100 |
| 15 | Relay Type | Schneider O/C and E/F Relay |
| 16 | Conductor Resistivity at 32 °C Ωm | $2.83X10^{-8}$ |
| 17 | 33kv line spacing | 914.4 mm |

  

***B. Method of Analysis***

Short circuit current analysis and relay coordination with Standard Inverse and Definite Time are applied. Relay- Circuit Breaker reaction to fault current is examined using short circuit analysis technique, which is used to evaluate the performance of the existing network.

For a known source Impedance and Base MVA, total fault impedance at Marine Base 2×15MVA, 33/11kv injection substation in p.u can be evaluated starting from the Resistance, R of a conductor to the geometric mean distance between the line conductors, the per kilometre reactance of one phase, line reactance, X, the distributed series impedance, $Z_1$, the equivalent admittance which is a measure of how easily a circuit or device will allow the flow of electric current, $Z_0 = Y$ , then transmission line constants, $Z_1$P.U referred to base MVA in p.u from the data as provided in Table 1 as

$$Z_F = Z_s + Z_1 + Z_t \quad (1)$$

where $Z_t = Z_{pu} = \frac{\%\, Z \times (Base\ MVA)}{Transformer\ MVA}$ (2)

For a 3 phase 11kV line fault at the injection substation,

$$Fault\ MVA = \frac{Base\ MVA}{Total\ Fault\ Impedance\ at\ the\ sytationA} \quad (3)$$

Fault current, $\boldsymbol{I_F}$ at the station is:

$$I_F = \frac{Fault\ MVA}{\sqrt{3} \times V_{LL}} \quad (4)$$

where $V_{LL}$ is the Line-Line Voltage

Referring to Table 1, the conductor resistance, R is 0.849 Ω and the diameter, ***d*** and radius, ***r*** 13.82mm and 6.91mm respectively. The line reactance, $X_0$ for a 4.5 km line is 1.4503Ω., while the distributed series impedance, $\boldsymbol{Z_1}$ becomes 1.6805 Ω , and the Admittance, $Z_o$ = Y is 2.6971 Ω

For Source Impedance for base MVA of 100 MVA and Source % Impedance of 12.5%,

Source Impedance, $Z_{SP.U}$

$$Z_{s\ P.U} = \frac{12.5}{100} \times \frac{100}{30} = 0.417\ p.u \quad (5)$$

and

$$Z_{1P.U} = \frac{1.6805 \times 100}{(33)2} = 0.1543 p.u \quad (6)$$

**i) <u>Relay Calculation Setting:</u>**

**Relay 8: Station Road Feeder Protective Relay**

Maximum load of Station Road 11kV feeder = 210Amps.

TMS = 0.08 (Simulated Set Value)

Time difference between two Relays as 100ms

CT Ratio = 600/1A (7)

PS = 50%

Curve Type: Standard Inverse

Fault current (ETAP) on Station Road Feeder = 4.561kA

$$PSM = \frac{I_f}{PS\ \times CT\ Ratio} = \frac{4.561 \times 1000}{0.5 \times 600} = 15.2 \quad (8)$$

$$T = \frac{0.14}{PSM^{\ 0.02} - 1} \times TMS \quad (9)$$

$$T = \frac{0.14}{15.2^{0.02} - 1} \times 0.08 = 200ms \quad (10)$$

**RELAY 5: $T_2$ 11KV Incomer Relay**

Time of operation of Relay 5= 100 + 200 = 300ms

  

$I_F$ = 3.397kA

$$\text{PSM} = \frac{I_F}{PS\ \times CT\ Ratio} = \frac{3.397\times1000}{0.7\times800} = 6.07 \qquad (11)$$

$$0.300 = \frac{0.14}{6.07^{0.02}-1} \times TMS \qquad (12)$$

TMS = 0.08

**RELAY 3: $T_2$ 33KV Control Panel Relay**

Time of Operation of Relay 3 = 100 + 300= 400ms

$I_F$ = 1.168kA

$$\text{PSM} = \frac{I_F}{PS\ \times CT\ Ratio} = \frac{1.132\times1000}{0.6\times300} = 6.29 \qquad (13)$$

$$0.400 = \frac{0.14}{6.29^{0.02}-1} \times TMS \qquad (14)$$

TMS = 0.1

## IV. RESULTS AND DISCUSSION

### *A. Relay coordination of Station Road 15MVA, 33/11kV Substation (Existing Case)*

Figure 3 depicts the order of tripping sequence for a 3-phase fault in the existing network injected on Station Road feeder. The tripping sequence is in the order of: Feeder circuit breaker (CB8) → 33kV line Breaker (CB1) → 33kV Control Panel Breaker(CB3) → 11kV Incomer Breaker(CB5). This response violates the right order of operation.

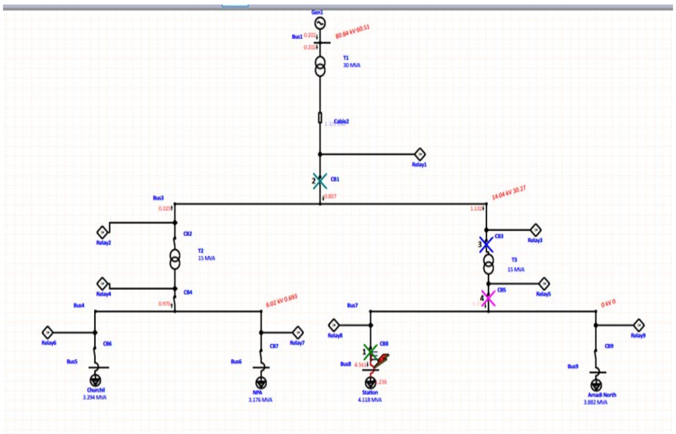

Figure 3: Circuit Breaker Tripping Sequence for Fault on Station Road Feeder (Existing case)

TABLE II
RELAY RESPONSE SEQUENCE WITH TIME OF OPERATIONS

Sequence-of-Operation Events - Output Report: Untitled

3-Phase (Symmetrical) fault on connector between CB8 & Station. Adjacent bus: Bus7

Data Rev.: Base    Config: Normal    Date: 08-01-2022

| Time (ms) | ID | If (kA) | T1 (ms) | T2 (ms) | Condition |
|---|---|---|---|---|---|
| 24.3 | Relay8 | 4.561 | 24.3 | | Phase - OC1 - 51 |
| 30.0 | Relay1 | 0.807 | 30.0 | | Phase - OC1 - 51 |
| 84.3 | CB8 | | 60.0 | | Tripped by Relay8 Phase - OC1 - 51 |
| 110 | CB1 | | 80.0 | | Tripped by Relay1 Phase - OC1 - 51 |
| 145 | Relay3 | 1.132 | 145 | | Phase - OC1 - 51 |
| 165 | CB3 | | 20.0 | | Tripped by Relay3 Phase - OC1 - 51 |
| 224 | Relay5 | 3.397 | 224 | | Phase - OC1 - 51 |
| 244 | CB5 | | 20.0 | | Tripped by Relay5 Phase - OC1 - 51 |

Table II represents the operation of relays with their adjoining circuit breakers and the corresponding tripping time (ms) for 3-phase fault on Station Road feeder of the existing network.

There is a clear violation of relay response to fault when compared with the proper sequence.

  

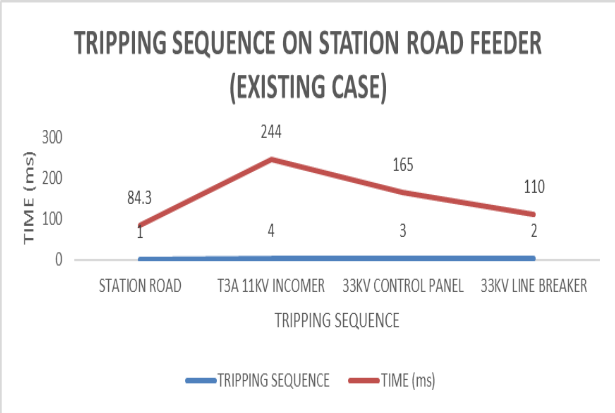


Figure 4: Breaker Operation Sequence for Fault on Station Road Feeder (Existing Case)

Figure 4 represents a graph of the various circuit breakers tripping sequence with their corresponding time of operation in response to a 3-phase fault on Station Road feeder for the existing case.

***B. Relay coordination of Station Road 15MVA, 33/11kV Substation (Improved Case)***

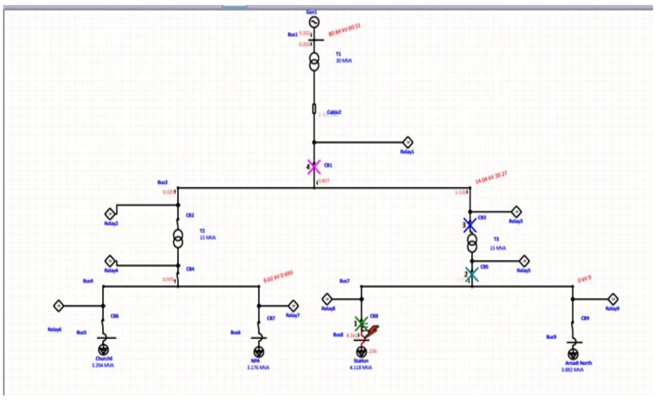

Figure 5: Circuit Breaker Tripping Sequence for Fault on Station Road Feeder

Figure 5 explains the sequence of tripping for a 3-phase fault on Station Road 11kV outgoing feeder for the improved network. This mode of operation shows the right order, which is:

Feeder Circuit Breaker (CB8) → 11kV Incomer Breaker(CB5) → 33kV Control Panel Breaker(CB3) → 33kV line Breaker(CB1).

TABLE III
RELAY RESPONSE SEQUENCE WITH TIME OF OPERATION FOR MODIFIED CASE

Sequence-of-Operation Events - Output Report: Untitled

3-Phase (Symmetrical) fault on connector between CB8 & Station. Adjacent bus: Bus7

Data Rev.: Base Config: Normal Date: 15-01-2022

| Time (ms) | ID | If (kA) | T1 (ms) | T2 (ms) | Condition |
|---|---|---|---|---|---|
| 200 | Relay8 | 4.561 | 200 | | Phase - OC1 - 51 |
| 240 | CB8 | | 40.0 | | Tripped by Relay8 Phase - OC1 - 51 |
| 313 | Relay5 | 3.397 | 313 | | Phase - OC1 - 51 |
| 336 | Relay3 | 1.132 | 336 | | Phase - OC1 - 51 |
| 340 | Relay1 | 0.807 | 340 | | Phase - OC1 - 51 |
| 373 | CB5 | | 60.0 | | Tripped by Relay5 Phase - OC1 - 51 |
| 407 | Relay9 | 1.166 | 407 | | Phase - OC1 - 51 |
| 416 | CB3 | | 80.0 | | Tripped by Relay3 Phase - OC1 - 51 |
| 420 | CB1 | | 80.0 | | Tripped by Relay1 Phase - OC1 - 51 |

Table III represents the operation of relays with its associated circuit breakers and the corresponding tripping time (ms) for the modified case or new case for a 3-phase fault on Station Road feeder.

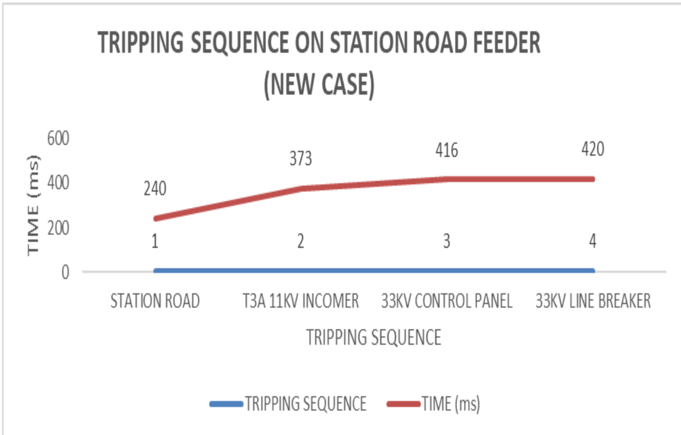


Figure 6: Sequence of Circuit Breaker operation for fault on Station Road feeder (Improved Case)

Figure 6 shows a graph representation of the various circuit breaker tripping sequence with its associated time of operation in response to a 3-phase fault on Station Road feeder for a modified case.

  

TABLE IV
COMPARING SEQUENCE OF OPERATION OF CIRCUIT BREAKERS

| **Comparison Of Existing Case With New Case On Station Road Feeder** | | | |
|---|---|---|---|
| **Feeder** | **Tripping Sequence** | **Time (ms)** | |
| | | **Existing** | **New** |
| Station road | 1 | 84.5 | 240 |
| T3a 11kv incomer | 2 | 244 | 373 |
| 33kv control panel | 3 | 165 | 416 |
| 33kv line breaker | 4 | 110 | 420 |

Table IV clearly shows the distinctive difference between the existing and modified case regarding sequence of operation of various circuit breakers to fault on Station Road 11kv outgoing feeder.

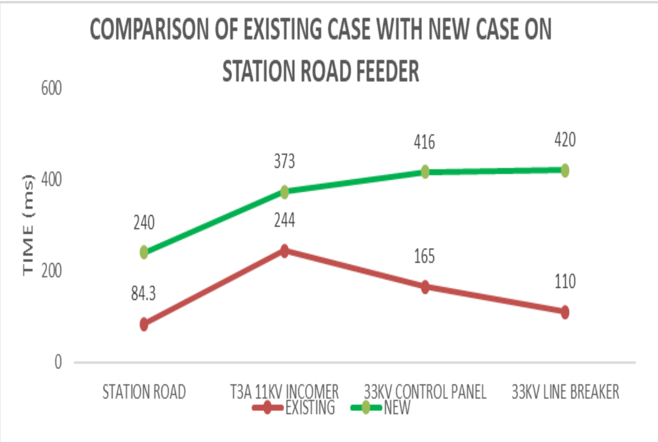


Fig 7 Comparison of Sequence of Circuit Breaker Operation for Fault on Station Road Feeder (Existing case vs New Case)

Figure 7 represents the different graphical behaviour of circuit breakers in response to a 3-phase fault on Station Road feeder when comparing existing with modified case

TABLE V
RELAY OPERATING TIME FOR FAULT ON STATION ROAD FEEDER

| **Relay** | **Theoretical Calculations / (SOP)** | **ETAP Modified Network/ (SOP)** | **ETAP Existing Network/ (SOP)** | **Curve Type** |
|---|---|---|---|---|
| | **Relay Time Operations (Sec)** | | | |
| **Relay 8** | 0.08 **(1)** | 0.08 **(1)** | 0.083 **(1)** | **SIT** |
| **Relay 5** | 0.081 **(2)** | 0.082 **(2)** | 0.1 **(4)** | **SIT** |
| **Relay 3** | 0.1 **(3)** | 0.09 **(3)** | 0.09 **(3)** | **SIT** |
| **Relay 1** | 0.34 **(4)** | 0.34 **(4)** | 0.19 **(2)** | **Definite Time** |

## V. CONCLUSION

Protection scheme is very essential in power engineering for safety and quality power delivery. To arrive at appropriate coordination, the parameters of the relay should be correctly examined. Power systems relays should be adequately coordinated to provide primary and back up security.

The result of the existing network in ETAP 19.0.1 when a 3-Phase fault is introduced at the Station Road feeder shows a wrong order of relay coordination and its adjoining protective devices. Thus, an adjustment on Time current curve (TCC) is done to solve the inappropriate operation leading to an improved case.

Manual computation and comparison of relay settings with simulated figures for both existing and improved cases reveal a slight difference between the existing case and improved case coordination. This means that the result obtained by both methods i.e., manual calculation and simulation are almost the same on improved case.

Lastly, a thorough comparison was carried out to justify result based on sensitivity, security and selectivity. The result shows that the improved case validates the attributes of a sound protective relay in response to fault.

## VI. RECOMMENDATIONS

PHEDC should consider incorporation of numerical or digital relays in its networks for fast response time; and to also carry out regular routine test on the various protective devices in order to ascertain their functionality.

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