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Power System Protection and Relay Coordination in NTA 33/11KV Injection Substation

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Abstract
This study presents the modelling and simulation of coordinating's of protective relays at the Nigerian Television Authority (NTA) 33/11 KV injection substation. The injection substation is located at Mgbuoba, in Obio/Akpor Local Government Area of Rivers State. This research analyzes the poor order of operation of relays in Nigerian Television Authority NTA 33/11kv Injection substation. The substation consists of four 11kv feeders namely Ohakwe, Location, Mgbouba and Ozuoba feeders. Power Supply to NTA 33/11kv Injection substation is through 33kv distribution line duly linked to Rumousi 132/33kv transmission station. When a fault occurs and the main protection fails, the backup protection must intervene to isolate the fault, the defective part must be quarantined when a short circuit is identified to avoid destruction and ensure the safety of personnel and equipment. Programmed relays observe and control the circuit breakers. The circuit breaker is switched off by the relay in the event of a fault. Relays are designed to distinguish between fault and normal conditions and provide protection. The main research objectives were to model NTA 33/11kv injection substation network using ETAP 19.0.1 to analyze the network, and using Newton Raphsons method of load flow analysis to determine the operating voltages at the various bus levels and impedance based method of short circuit analysis to determine the short circuit impedance and the magnitude of the short circuit using ohm's law.

Keywords: *Relays, Circuit Breakers, Buses, Feeders, Current Transformers.*

1. INTRODUCTION

System disturbances in recent times has become a major challenge in power system operation. The power distribution network is often faced with system disturbances as a result of network overload, Poor var support, high transmission loss which in most cases leads to cascaded tripping. Consequently, efficient operation of the existing 33kV network becomes a major challenge for systems and operation engineers.

The necessity to address power quality issues has led power system engineers, equipment makers, and researchers to focus on the development of various techniques to solve power challenges. Currently, several techniques have been devised to enhance the quality of electricity transmission.

Gafari *et al*. (2013) improved the performances and coordination of relay in a 28-bus 330kV transmission system using load flow study and short circuit study to determine the pre-fault condition on the network and also to determine the current magnitude on the system.
Amakiri *et al.* (2019) examined the cause of frequent outage on Effurun 3 x 60MVA, 132/33KV transmission substation network. ETAP software was used to analyse the network. The relay scheme coordinated properly from downstream to upstream. Kanikwu *et al*. (2019) in their work noted that the relay protecting a distribution transformer failed to operate during fault on the line close to them. It was further reviewed that when the relay setting were properly relay selected the circuit breakers associated to the respective transformers tripped thereby protecting the rest of the network from damage and collapse. Idoniboyeobu *et al*. (2018) noted in their work also that relay coordination is a means by which the protective relays closest to the point of fault operates first, thus providing primary protection but in the event of failure the backup protection operates. Hari *et al.* (2019), examined the time characteristics of overcurrent relay. The focus was on the coordination and operating time of overcurrent relay (OCR) protecting a 60MVA 132/33KV substation transformer and four (4) feeders. It is more cost-effective to increase the voltage at the point of generation, transmit it over the long distance, and then decrease the voltage at the point of usage (Ezekiel & Engla, 2019).

The limitations of using either time or current for grading purposes are addressed (Sandesh et al., 2016). The relay types utilized for overcurrent protection strategy include instantaneous, definite time, and inverse time overcurrent relays (Abouzar & Mahmoud, 2014). Relays should only activate if the fault occurs within the protected area (Razzaghi *et al*., 2013). Also, it is necessary to synchronize the functioning of backup relays with that of the primary relays (Kamal, 2014).

The protection scheme is only used when necessary because of the high cost of directional protection units and also the need of power transformers for its actualization. (Abdur, 2022). Li-Kyoung *et al.* (2017) stated that it is preferable for configuration to be done on a factory test-set before installation. Additional protective devices, such as Buchholz protection and oil temperature monitoring, are often connected to the transformer (Ahmed *et al*., 2013).

Rao *et al.* (2013) observed that the current/time tripping characteristics of IDMT relays may need to be adjusted based on the desired tripping time and the characteristics of other protection devices employed in the network. According to Akintola *et al.* (2017) the performance of relays can be classified as Correct, incorrect and inconclusive. The secondary defensive mechanism that isolates the defective portion only in the event that the first safeguard fails to function (Bunty & Dakshata, 2017). Circuit breakers should be able to open when instructed by monitoring devices such as relays (Muthu & Vahab, 2016).
Load flow analysis helps in assessing power losses in the system and managing power generation and consumption in the bus bar load (Zaid *et al*., 2018). According to Sadaat (2016), Gauss-Seidel techniques is a commonly used technique for computing load flow solution. In addition, Gupta (2016) asserted that the N-R technique involves less iterative process before convergence is reach. Similarly, it is insensitive to slack bus. Fault is often described by the amount of the fault current and power factor or phase angle of the fault current (Aguilera 2016).

Idoniboyeobu *et al*. (2018) noted in their work also that relay coordination is a means by which the protective relays closest to the point of fault operates first, thus providing primary protection, but in the event of failure the backup protection operates. This was demonstrated in this study by improving the relay coordination of the NTA 2 x 15MVA, 33/11KV injection substation.

Transmission is responsible for conveying and transferring the generated electricity to the distributions system (Fayomi, 2020). Over current relays are often employed in distribution and sub-transmission network for protection purposes (Al-Nasseri *et al*., 2016). The element of power system are the sources, branches, buses, loads, protective and switching devise (Festus, 2019). Fuses are mostly used for parts of distribution systems where they are capable of both sensing and isolating faults (Mehta and Mehta, 2018). The duration of operation can be decreased by employing a field effect transistor to activate the relays contacts (Magnus, 2013).

The elements of a power system are the sources, branches, buses, loads, protective and switching devices (Festus, 2019).
All electrical power systems must have one or more source of supply of power energy. These sources may be external to the system or they may be part of the system. Examples of power sources are the generators, alternative and batteries.
Discrimination by current is not a feasible method for accurately distinguishing between the circuit breakers at two specific locations (Sandesh *et al*., 2016). Onyeanya (2013) in her study proposed the deployment of STATCOM FACTS devices in the NTA 33/11KV injection substation to enhance maximum power transfer.

2.0 MATERIALS AND METHODS

2.1 Materials

Single Line Diagram (SLD) of the NTA Injection Substation, existing data of the relays settings and network components obtained from the NTA Injection substation.
Electrical Transient Analyzer Program (ETAP 19.0.1) was used for the simulation.

2.2 Methods Adopted for the Study.

i. Load flow analysis:
ii. Short circuit analysis:
iii. Star protection and coordination**:**

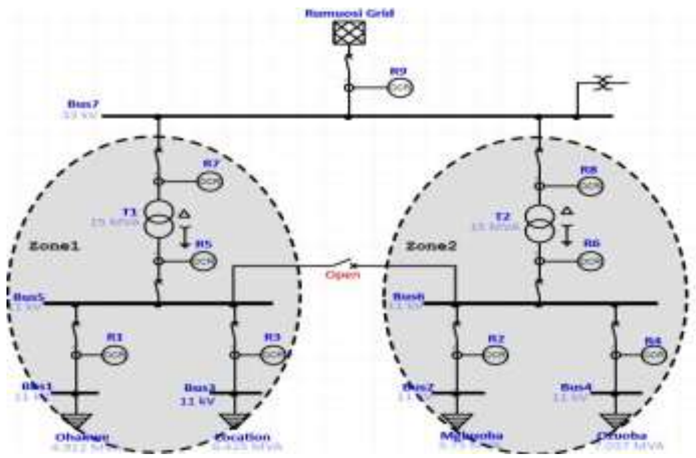


Figure 1: Single Line Diagram of NTA Injection Substation

2.3 Short Circuit Analysis; The impedance based method of short circuit analysis was employed to ascertain the short circuit impedance and short circuit current. The following are the model equations.

2.4 Load Flow Analysis

Load flow analysis was used for determining the operating condition of the network and also check for bus voltage violation. The Newton-Raphson Power Flow Techniques was used for this analysis.

For any ith bus,

Let $V_i = V_{\text{i}}\angle\delta_i$ and $V_i^* = V_{\text{i}}\angle-\delta_i$, (2.1)

For kth bus,

$V_k = V_{\text{k}}\angle\delta_k$ and $Y_{ik} = Y_{\text{ik}}\angle\theta_{ik}$ (2.2)

The real and reactive power injected in the network is given by

$$S_i = V_i I_i^* = P_i + jQ_i \quad (2.3)$$

$$I_i = \left(\frac{S_i}{V_i}\right)^* = \frac{P_i - jQ_i}{V_i^*} \quad (2.4)$$

$$I_i = \frac{P_i - jQ_i}{V_i^*} = \sum_{k=1}^{n} Y_{ik} V_k \quad (2.5)$$

$$P_i - jQ_i = V_i^*\left(\sum_{k=1}^{n} Y_{ik} V_k\right) \quad (2.6)$$

$$P_i - jQ_i = V_i^*\left(\sum_{k=1}^{n} Y_{ik} V_k\angle\delta_k + \theta_{ik} - \delta_i\right) \quad (2.7)$$

$$P_i - jQ_i = \sum_{k=1}^{n} |Y_{ik}||V_{\text{i}}||V_{\text{k}}|\left[\cos(\delta_k + \theta_{ik} - \delta_i) + j\sin(\delta_k + \theta_{ik} - \delta_i)\right] \quad (2.8)$$

Separating (3.8) into real and imaginary parts we have,

$$P_i = \sum_{k=1}^{n} |Y_{ik}||V_{\text{i}}||V_{\text{k}}|\cos(\delta_k + \theta_{ik} - \delta_i) \quad (2.9)$$

$$Q_i = -\sum_{k=1}^{n} |Y_{ik}||V_{\text{i}}||V_{\text{k}}|\sin(\delta_k + \theta_{ik} - \delta_i) \quad (2.10)$$

Where

Y_{ik}= the admittance matrix

P_i= the injected real power

Q_i= the injected reactive power

δ_i= phase angle

Expanding (2.9) and (2.10) in Taylors series neglecting higher order terms we have

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \frac{\Delta P_n^{(k)}}{\Delta Q_2^{(k)}} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \begin{bmatrix} \begin{vmatrix} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} \end{vmatrix} \begin{vmatrix} \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \end{vmatrix} \\ \begin{vmatrix} \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} \end{vmatrix} \begin{vmatrix} \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{vmatrix} \end{bmatrix} \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \frac{\Delta \delta_n^{(k)}}{\Delta \left|V_2^{(k)}\right|} \\ \vdots \\ \Delta \left|V_n^{(k)}\right| \end{bmatrix} \quad (2.11)$$

The Jacobian matrix gives the linearized relationship between mall changes in voltage angle $\Delta\delta_i^{(k)}$ and magnitude $\Delta\left|V_i^{(k)}\right|$ with small change in real $\Delta P_i^{(k)}$ and reactive power $\Delta Q_i^{(k)}$ respectively.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_3 \\ J_2 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \quad (2.12)$$

Where

$J_1,\ J_2, J_3, J_4$ are the elements of the Jacobian matrix

The off-diagonal and diagonal elements of J_1 are

$$\frac{\partial P_i}{\partial \delta_k} = |Y_{ik}||V_{\mathrm{i}}||V_{\mathrm{k}}|\sin(\delta_i + \theta_{ik} - \delta_k) \quad (2.13)$$

$$\frac{\partial P_i}{\partial \delta_i} = -\sum_{\substack{k=1 \\ k\neq i}} |Y_{ik}||V_{\mathrm{i}}||V_{\mathrm{k}}| \sin(\delta_i + \theta_{ik} - \delta_k) \quad (2.14)$$

The off-diagonal and diagonal elements of J_2 are

$$\frac{\partial P_i}{\partial V_k} = |Y_{ik}||V_{\mathrm{i}}|\cos(\delta_i + \theta_{ik} - \delta_k) \quad (2.15)$$

$$\frac{\partial P_i}{\partial V_i} = 2|Y_{ii}||V_{\mathrm{i}}|cos\theta_{ii} + \sum_{\substack{k=1 \\ k\neq i}}^{n} |Y_{ik}||V_{\mathrm{k}}|\cos(\delta_i + \theta_{ik} - \delta_k) \quad (2.16)$$

The off-diagonal and diagonal elements of J_3 are

$$\frac{\partial Q_i}{\partial \delta_k} = -|Y_{ik}||V_{\mathrm{i}}||V_{\mathrm{k}}|\cos\begin{pmatrix} \delta_i + \theta_{ik} \\ -\delta_k \end{pmatrix} \quad (2.17)$$

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{\substack{k=1 \\ k\neq i}} |Y_{ik}||V_{\mathrm{i}}||V_{\mathrm{k}}| \cos\begin{pmatrix} \delta_i + \theta_{ik} \\ -\delta_k \end{pmatrix} (2.18)$$

The off-diagonal and diagonal elements of J_2 are

$$\frac{\partial Q_i}{\partial V_k} = |Y_{ik}||V_{\mathrm{i}}|\sin(\delta_i + \theta_{ik} - \delta_k) \quad (2.19)$$

$$\frac{\partial Q_i}{\partial V_i} = 2|Y_{ii}||V_{\mathrm{i}}|sin\theta_{ii} + \sum_{\substack{k=1 \\ k\neq i}}^{n} |Y_{ik}||V_{\mathrm{k}}|\sin(\delta_i + \theta_{ik} - \delta_k) \quad (2.20)$$

Compute the scheduled error ΔP_i and ΔQ_i for each load

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)} \quad (2.21)$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)} \quad (2.22)$$

2.5 Relay Sizing

An easy way to determine the limit of a relay is to multiply the rated volts times the rated Amps. Every relay will have two ratings.

2.6 Relay Pickup Current (Ipu)

$$I_{pu} = \frac{Relay\ Current\ setting}{CT\ ratio} \qquad (2.27)$$

2.6.1 Fault in Relay Primary Coil

$$Fault\ in\ Relay\ coil\ = \frac{Short\ Circit\ Fault\ Current\ (kA)}{CT\ ratio} \qquad (2.28)$$

2.6.2 Plug Setting Multiplier (PSM)

$$PSM = \frac{Fault\ in\ Relay\ Coil}{Pickup\ Current} \qquad (2.29)$$

2.6.3 Relay Time Dial Multiplier

Curve type: Standard Inverse

Type of operation = time multiplier sittings x $\left(\frac{k}{(PSM)^{\alpha}-1}\right)$ (2.30)

Where:
T: Operating Time
PMS: Plug Setting Multiplier
Where k=0.14, α= 0.02 from IEC Standard inverse operating curve shown in table 3.3 below.

3. RESULTS AND DISCUSSION

3.1 Star Protection and Coordination Analysis

The existing protection settings were uploaded in ETAP 19.0.1 software environment and two (2) scenarios were considered for this study to analyze the relay and circuit breaker operation, and coordination.

i. Base Case: When a three-phase fault was simulated on the two (2) 11kV outgoing feeders
ii. Improved Case: When a three-phase fault was simulated on the two (2) 11kV feeders

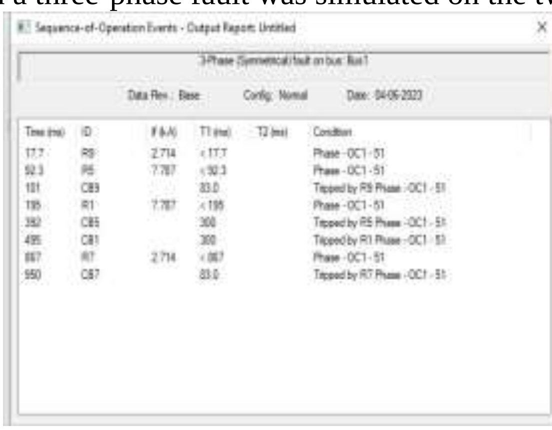


Figure 2: Base Case Sequence of Operation for Fault on 11kV Outgoing Feeder Section 1.

Figure 2 shows the base case sequence of operation for fault on 11kV outgoing feeder on section 1 of the injection substation. The protection scheme of the substation is said to be miss-coordinated as the relays upstream from the point of fault trips before the relay downstream of the substation feeders. The correct sequence of operation is for any fault occurrence at the 11kV feeder, the feeder relay (R1) or (R3) must trip first then after at least 150 ms delay bus section relay (R5) at the secondary side of transformer T1 trips. In a similar sequence (R7) at the primary side of transformer T1 after 150 ms delay then the relay at the bus section 33 kV incomers (R9).

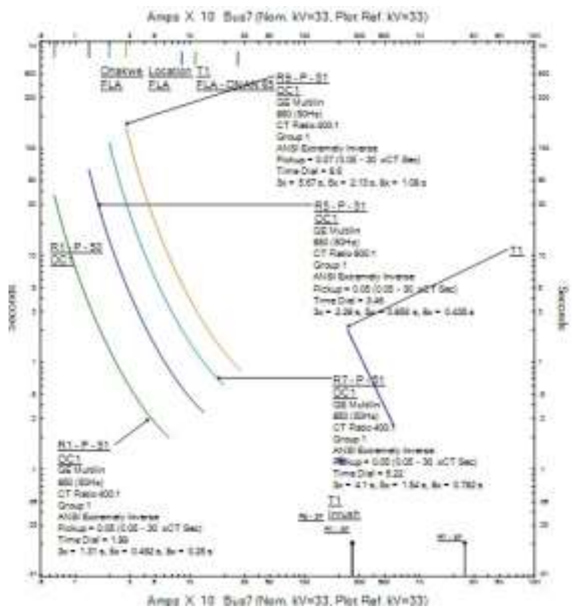
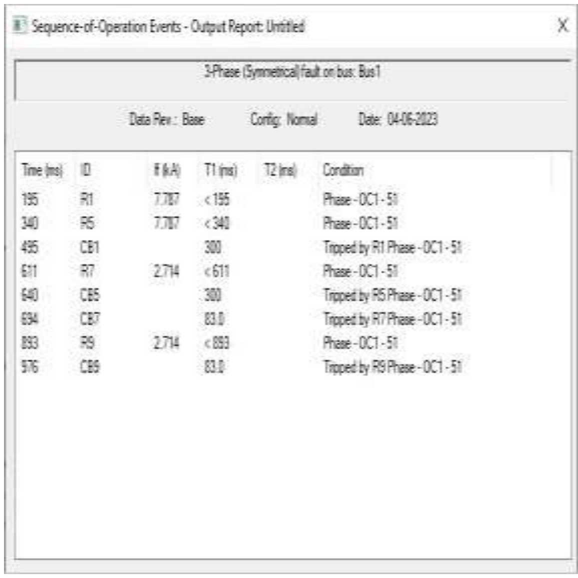


Figure 3: TCC Plot for Section 1

Figure 3. depict the time current curve (TCC) plot of the protective relays for section 1, at the NTA 33/11kv Injection substation. The TCC curve plays a crucial role in ensuring effective coordination amongst protection devices in the network by visually representing the device's reaction to different degrees of overcurrent. The TCC curve depicted in Figures 3 guarantees that the coordination begins from the fault site at bus 1 (downstream) in the 11kV feeder, and extends up to the fault level at the 33kV bus-bar.



Sequence-of-Operation Events - Output Report: Untitled

3-Phase (Symmetrical) fault on bus: Bus1

Data Rev.: Base Config: Normal Date: 04-06-2023

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
195	R1	7.787	< 195		Phase - OC1 - 51
340	R5	7.787	< 340		Phase - OC1 - 51
495	CB1		300		Tripped by R1 Phase - OC1 - 51
611	R7	2.714	< 611		Phase - OC1 - 51
640	CB5		300		Tripped by R5 Phase - OC1 - 51
694	CB7		83.0		Tripped by R7 Phase - OC1 - 51
893	R9	2.714	< 893		Phase - OC1 - 51
976	CB9		83.0		Tripped by R9 Phase - OC1 - 51

Figure 4: Improved Case: Simulation of Three-Phase Fault on 11kV Outgoing Feeders of section 1.

Upon examining figure 4, it is evident that the feeder relay (R1) was the first to trip, occurring at 195 milliseconds due to the instantaneous element. Subsequently, the bus section relay (R5) on the secondary side of transformer T1 also tripped. Following a 150 ms delay, relay R7 is activated at the main side of transformer T1. Subsequently, relay R9 is triggered at the bus section for the 33 kV incomers. The current operational sequence has been corrected, and the grading gap between relays is consistently maintained at a minimum of 150 milliseconds.

The discrimination was accurately performed based on the sequence of operations described above. Therefore, there will be no occurrence of coordination errors, which were not resolved in the basic scenario.

4. CONCLUSION.

The main research objectives were to model NTA 33/11kv injection substation network using ETAP 19.0.1 to analyze the network, and using Newton Raphsons method of load flow analysis to determine the operating voltages at the various bus levels and impedance based method of short circuit analysis to determine the short circuit impedance and the magnitude of the short circuit using ohm's law.

This study analyzed the poor order of operation of relays in Nigerian Television Authority NTA 33/11kv Injection substation. When a fault occured and the main protection fails, the backup protection must intervene to isolate the fault.

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Author's Contributions
B. Akujuru conceptualization, methodology, writing-reviewing and editing.

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