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ARC FLASH ASSESSMENT AND MITIGATION IN A 33/11KV PRIMARY DISTRIBUTION NETWORK

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Abstract. Arcing occurs when there is separation of energized contacts of switchgears which occurs when breakers are tripped due to a fault, thus, an arc flash is a spark of electrical current which leaves its intended path and travels through air from one conductor to another. This paper presents an approach for determining the nature and frequency of arcs in electrical power systems as well as adequate measures required to mitigate the effect of the arc initiated. This paper presents an approach for arc flash assessment and mitigation in a 33/11kV power system which was modelled and analyzed by Electrical Transient Analyzer Program (ETAP) software. A load flow study was carried out using Newton Raphson's method to verify the existing operating condition of equipment in the power system. Furthermore, a short-circuit analysis was performed to aid proper selection and sizing circuit breakers for relay coordination. Finally, an arc flash analysis was performed which determined the nature and frequency of the arc as well as methods required to mitigate its effect.

Keywords. Distribution Network, Load Flow, Short-Circuit, Arc Flash, Protection, Personal Protective Equipment (PPE).

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1. Introduction

A power system network is primarily segmented into three parts which are generation, transmission, and distribution systems. A distribution system is primarily concerned with the supply of power to the end-users; therefore, it is crucial to ensure an efficient and reliable magnitude of power supplied to the distribution system. In an electrical power system, it is practically impossible to have a system totally free from the occurrence of faults, however, the impact of these faults can be mitigated to ensure safety of personnel and equipment as well as reliability of power supply. During the occurrence of a fault in a section of the power system, a trip signal is issued by the protective relay to the circuit breaker nearest to the fault. The response of the circuit breaker is to isolate that section of the power system by opening its contacts. In the process of isolation, the circuit breaker's current carrying contacts initiate an arc which occurs for a short period of time; however, it is extremely destructive as a result of the magnitude of energy generated in form of heat. Arcing is a phenomenon which occurs when the energized contacts of a circuit breaker are de-energized [2]. Arc flash analysis is a study which is performed to discover the nature and frequency of the arc, thereby obtaining the magnitude of incident energy caused by separating the current-carrying contacts of the circuit breaker. The result obtained is then used to offer adequate selection of personal protective equipment for humans with respective boundaries (the personal protective equipment is selected based on the distance of the person from the point of arc initiation), thereby reducing the impact of an arc flash [9]. Thus, the closer you are to an arc, the more you feel the intensity of the arc. This paper presents an approach for performing an arc flash analysis on a 33kV primary distribution network, as well as an appropriate method for mitigating the impact of the arc flash using Amadi junction distribution network as a case study. Furthermore, circuit

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breakers in power systems are usually equipped with arc extinction mechanisms such as arc chute, SF6 gas and vacuum interrupter which is used for extinction of the arc using either high resistance or low resistance method, however, adequate protection is crucial especially for the adequate selection of personal protective equipment to prevent injuries or death. The objectives of the study are:

i Review of arc flash evaluation and mitigation techniques.
ii Collection of relevant network data from PHEDC.
iii Model the 33/11kV distribution network and perform a load flow analysis using ETAP software in order to verify the operating conditions of components in the network.
iv Perform a short-circuit analysis for proper sizing of circuit breakers.
v Perform a relay coordination study.
vi Perform an arc flash evaluation and proffer adequate mitigation techniques.

2. Literature Review

Tom and Marcia (2011) performed an analysis on medium-voltage arc flash in open air and pad mounted equipment[10]. The paper displays results obtained after an analysis on overhead arc flash scenarios as well as arc flash in pad mounted switch. Both scenarios generated more incident energy than anticipated. For overhead arc scenarios, longer arc lengths are considered when analyzing arc flash while the pad mounted switch utilizes the developed equation to help coordinate protective clothing with minimum approach distances and upstream protective relaying.

Jario et al. (2021) performed a study on the effect of means of grounding and asymmetrical current of arc flash[1]. From the results obtained, the magnitude of asymmetrical current will considerably generate an effect on the magnitude of incident energy during a fault, especially for systems with high X/R ratio. However, a comparative study was performed to observe arc flash in a power system using high resistance grounding and solid grounded systems.

Daniel et al. (2010) proposed an update of field analysis of arc flash incidents, PPE protective performance and related work injuries[3]. The paper provides a broad field analysis on the effectiveness of an arc flash personal protective equipment as well as personnel injuries in real world arc flash incidents, and an update on the ASTM test method employed in obtaining the arc rating of arc flash PPE. New discoveries and conclusions pertaining to the cause of arc flash consequences and personal protective equipment methods which can mitigate the injuries were also analyzed.

Ojuka et al. (2022) performed an arc flash analysis on a 132/33kv power system network to analyze, outline the main causes and impact of arc flash, enlightenment of boundaries during the period of arcing, and recommend adequate personal protective equipment (PPE), thereby mitigating the impact of an arc flash [4]. The results obtained after performing the analysis entails incident energy levels, safe working distance, magnitude of bolted fault current at various locations, and recommended PPE based on the working distances.

Weerawoot et al. (2016) performed an analysis to ascertain the effect of introducing Distributed Generations (DGs) on the magnitude of incident energy emanated by arcs due to faults[7]. It was observed that the magnitude of fault contribution from the DGs decreased the time of arcing, thereby decreasing the magnitude of incident energy emanating. The paper presented an arc flash hazard assessment in a distribution system with DGs incorporated.

Amakiri et al. (2022) performed an arc flash analysis with a primary objective of identifying the safety issues surrounding FUPRE distribution network as well as the procedures taken by the management of the university to ensure adequate safety of personnel and equipment[6]. The results gave a detailed insight into the identification of risks as well as methods employed for mitigation of these risks.

Udhaya et al. (2021) performed a study on relay coordination with arc flash analysis based protective system[8]. The study proffers a valuable insight into the installation of electrical equipment and safe handling techniques against the arc flash voltage, thereby stating adequate measures required to improve safety management for electrical engineers. The result obtained after the analysis revealed that the characteristic curve of relays plays a crucial role in fault clearance, while system grounding mitigates the magnitude of incident energy emanating from an arc flash.

Terminologies Used in Arc Flash Analysis

i **Incident Energy**: This is the magnitude of energy focused on a surface, at a distance from the source, which is produced during arcing.
ii **Arc Flash Boundary**: This is the distance at which the magnitude of incident energy is equivalent to 1.2Cal/cm2.
iii **Working Distance**: This is the distance between the possible arc point and the head and body of a worker positioned in place to perform the task.
iv **Bolted Fault Current**: This is a short-circuit contact between two conductors at different potentials in which the impedance between the conductors is zero.
v **Available Fault Current**: This is the electrical current that can be provided by the serving utility and the facility-owned electrical generating devices and large electrical motors considering the magnitude of impedance in the current path.
vi **Arcing Fault Current**: This is a fault current flowing through an electrical arc-plasma.
vii **Limited Approach Boundary**: This is a shock protection boundary not to be crossed by unqualified persons unless escorted by qualified personnel.
viii **Restricted Approach Boundary**: This is a shock protection boundary to be crossed only by qualified people and shock protection is required.
ix **Prohibited Approach Boundary**: This is a shock protection boundary to be crossed only by qualified people trained in the use of techniques that may require direct contact with energized equipment.

3. Materials and Methods

The data used for this work were obtained from the office of the Port-Harcourt Electricity Distribution Company (PHEDC) in Nigeria and they are.

i Single line diagram of Amadi Junction injection substation.
ii Load data of Amadi Junction injection substation.
iii Bus bar and transformer ratings of Amadi Junction injection substation.

Method

A load flow analysis was performed on Amadi junction injection substation using Newton-Raphson (N-R) method to ascertain the existing state of the power system network. A short-circuit analysis was also performed which involved device duty calculations for adequate ratings of circuit breakers, and fault analysis using IEC 60909 to determine the fault magnitudes at various buses which will aid a protection study. Furthermore, an overcurrent protection scheme was designed to obtain the fault clearing time (FCT) at various locations. Finally, an arc flash analysis was performed using IEEE 1584-2002 standard.

Newton-Raphson (N-R) Method

Compared to other methods of load flow analysis, the N-R method is an iterative technique which makes use of Taylor's series expansion and partial derivatives in solving a set of non-linear equations with an equal number of unknowns. The time required for convergence is less compared to other methods, it is not sensitive to the slack bus chosen and the size of the system has no effect on the number of iterations. The Newton-Raphson method operates using equation (1) below:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix}$$

Where ΔP and ΔQ are the bus active and reactive power mismatch vectors between the specified value and the determined value, respectively; ΔV and $\Delta \delta$ represent the magnitude of bus voltages and angle vectors in an incremental form; and J1, J2, J3 & J4 are known as Jacobean matrices [5].

Short-Circuit Analysis

Short-circuit analysis is a power system study which is performed to determine the magnitude of fault current flowing through various buses in a power system network under various scenarios such as symmetrical and asymmetrical fault occurrence. Furthermore, the results obtained after performing a short-circuit analysis is used for adequate rating of protective devices as well as relay coordination.

Power System Protection

Power system protection is simply the art of employing mechanisms which will mitigate the impact of faults in the power system. In this research work, an overcurrent protection scheme was designed to determine the minimum time required for clearance of fault by the protective relay.

Arc Flash Assessment

The method employed to perform an arc flash analysis on the substation under study is the IEEE 1584-2002, and the procedures required are as follows.

Step 1; Obtain relevant data such as system and installation data.

Step 2; Ascertain the operating conditions of the power system. Furthermore, it is crucial to carry out short circuit analysis to obtain the maximum and minimum fault current flowing through various locations of the power system network.

Step 3; Determine the bolted fault current.

Step 4; Determine the arcing current.

For a nominal kV of 0.208 to 1.0kV:

$$l_g I_a = K + 0.662 \times l_g I_b f + 0.0966 \times V + 0.000526 \times G + 0.558 \times V \times l_g I_b f - 0.00304 \times G \times l_g I_b f$$

For a nominal kV of 1 to 15.0 kV:

$$l_g(I_a) = 0.0042 + 0.983 \times l_g(I_b f)$$

For a nominal kV greater than 15.0 kV:

$$I_a = I_b f$$

Where:

$G =$ gap distance between conductors (mm)

$I_a =$ Arcing current

$I_b f =$ Bolted fault current

$l_g = \log_{10}$

$K = -0.153$ for open configurations and -0.097 for box configurations

$V =$ System voltage

Step 5: Ascertain the characteristics of protection devices as well as duration of arcs.

Step 6: To select the typical bus gaps, ascertain the system voltages and class of equipment.

Step 7: Select the working distance.
Step 8: Determine the magnitude of incident energy at various locations.
Using the Empirical method (1.0 to 15.0 kV):

$$E = 4.184 \times C_f \times E_n \times \left(\frac{t}{0.2}\right) \times \left(\frac{610^x}{D^x}\right)$$

Using Lee Method (greater than 15.0 kV):

$$E = 2.142 \times 10^6 \times V \times I_{bf} \times \left(\frac{t}{D^2}\right)$$

Where:

$E =$ Incident energy (J/cm^2)
$t =$ Arcing time (seconds)
$D =$ Distance from a possible arc point to the person (mm)
$V =$ System voltage (kV)
$I_{bf} =$ Bolted fault current
$E_n =$ Normalized incident energy
$C_f =$ Calculation factor

Step 9: Calculation of arc flash boundary.
Using Empirical method (1.0 to 15.0 kV):

$$D_B = \left[4.184 C_f E_n \left(\frac{t}{0.2}\right)\left(\frac{610^x}{E_B}\right)\right]^{\frac{1}{x}}$$

Using Lee method (greater than 15.0 kV):

$$D_B = \sqrt{2.142 \times 10^6 V I_{bf} \left(\frac{t}{E_B}\right)}$$

Where:

$D_B =$ Boundary distance from the arcing point (mm)
$E_B =$ Incident energy at the boundary distance (J/cm^2)
$X =$ Distance exponent

Step 10: Determine energy levels and PPE

Arc Flash Mitigation

Arc flash mitigation refers to the processes involved in ensuring reduction in the impact of an arc flash occurrence. The following methods are adopted for the mitigation of arc flashes in electrical power systems:

i Reduction of fault clearing time by improving the coordination setting of protective devices.
ii Increase in working distance using hot sticks or remote switching.
iii Decrease in the short-circuit current using currently limiting reactors and circuit breakers.
iv Decrease in energy exposure using arc-resistant switchgears.
v Proper selection and utilization of personal protective equipment.

Software

Electrical Transient Analyzer Program (ETAP) 21.0 was used for the modelling and analysis by simulation of the Amadi Junction injection substation.

Description of Existing Network

The power system under investigation which is Amadi junction injection substation is in Port Harcourt, Nigeria and it is made up of three (3) buses, 2x15MVA 33/11kV power transformers and five (5) outgoing feeders. Figure 1 displays the single line diagram of Amadi Junction injection substation while Table 1 displays the transformer and load data respectively.

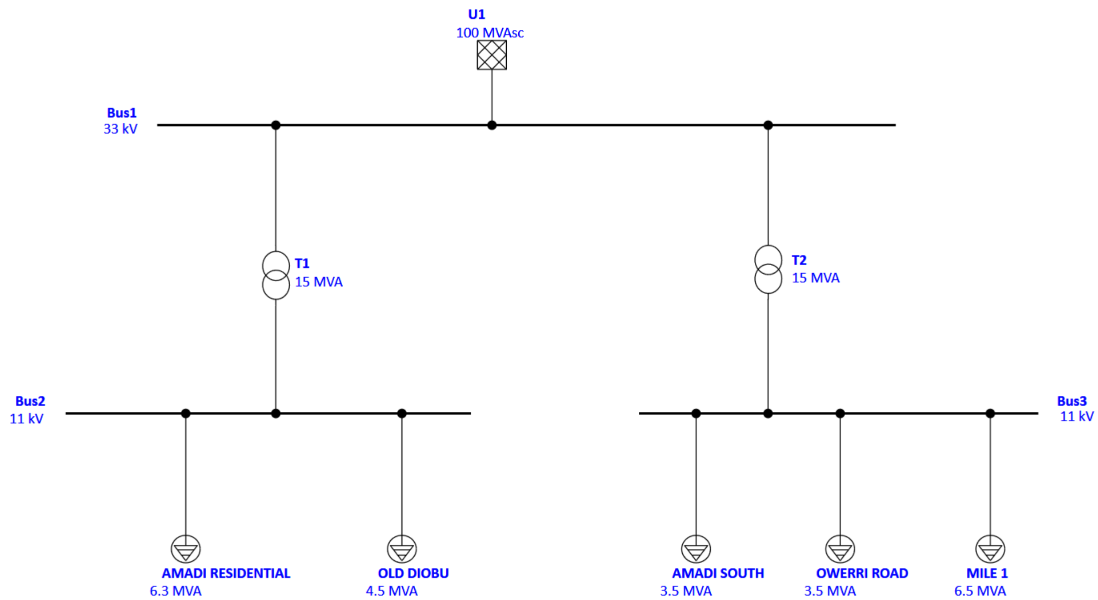

FIGURE 1. ETAP Representation of Amadi Junction Injection Substation

TABLE 1. Equipment Data (Source: Port Harcourt Electricity Distribution Company)

S/N	$EquipmentID$	$VoltageRating(kV)$	Capacity (MVA)
1.	T1	33/11	15
2.	T2	33/11	15
3.	Amadi Residential	11	6.3
4.	Old Diobu	11	4.5
5.	Amadi South	11	3.5
6.	Owerri Road	11	3.5
7.	Mile 1	11	3.5

4. RESULTS

This section provides a detailed explanation on the results obtained after performing a load flow analysis, short circuit analysis, relay coordination, arc flash analysis and mitigation on Amadi Junction injection substation.

Load Flow Analysis of Amadi Junction Injection Substation

Figure 2 displays the result obtained after performing a load flow analysis on the injection substation under study, and it is observed that the active and reactive power flow are displayed in kW and

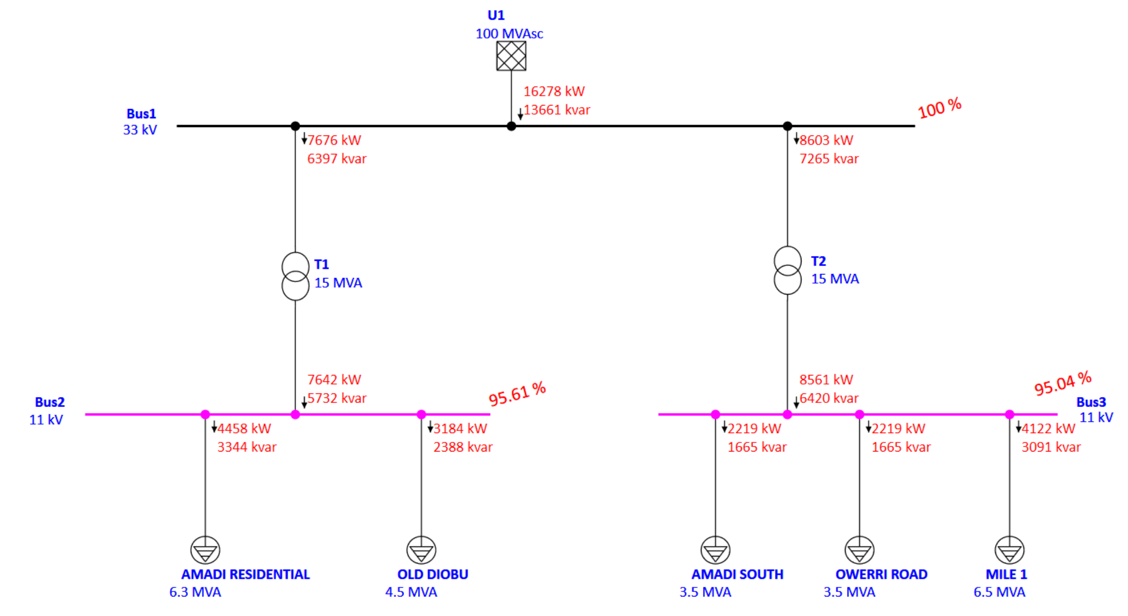

FIGURE 2. Existing Load Flow Analysis of Amadi Junction Injection Substation

kvar respectively, while the direction of power flow is indicated by an arrow. Furthermore, the operating voltage magnitude of each busbar is displayed in percentage (%). The buses which are displayed black (Bus1) means that they are operating within healthy voltage limits, while the buses displayed pink (Buses 2 and 3) are experiencing a slight magnitude of undervoltage, however, it can be managed. Critical examination of the results obtained from the analysis reveals that the total active and reactive power loss generated by branch elements in the power system network are 75.4kW and 1508.9kvar respectively.

Short-Circuit Analysis of Amadi Junction Injection Substation

Figure 3 displays the result obtained after performing a three-phase short-circuit analysis on Amadi Junction injection substation. From the results displayed, all the buses are flagged red, and this is because all the buses were faulted before performing the analysis. Furthermore, it is also observed that the voltage magnitude at each busbar is 0kV which is also because of faulting the buses and performing a three-phase short-circuit analysis. The magnitude of fault current flowing through various busbars are displayed in kA while the voltages and phase angles are displayed in kV and degrees respectively. The results obtained will be used in conjunction with device duty calculations embedded in short-circuit analysis to aid proper selection and ratings of circuit breakers.

Design of an Over-Current Protection Scheme for Amadi Junction Injection Substation
An over-current protection scheme was designed for the power system network under study which involved circuit breakers in conjunction with current transformers and over-current relays. The primary objective of this protective scheme was to determine the fault clearing time which is a relevant parameter for performing an arc flash analysis. Figures 4 and 5 below display the results obtained after performing the coordination study.

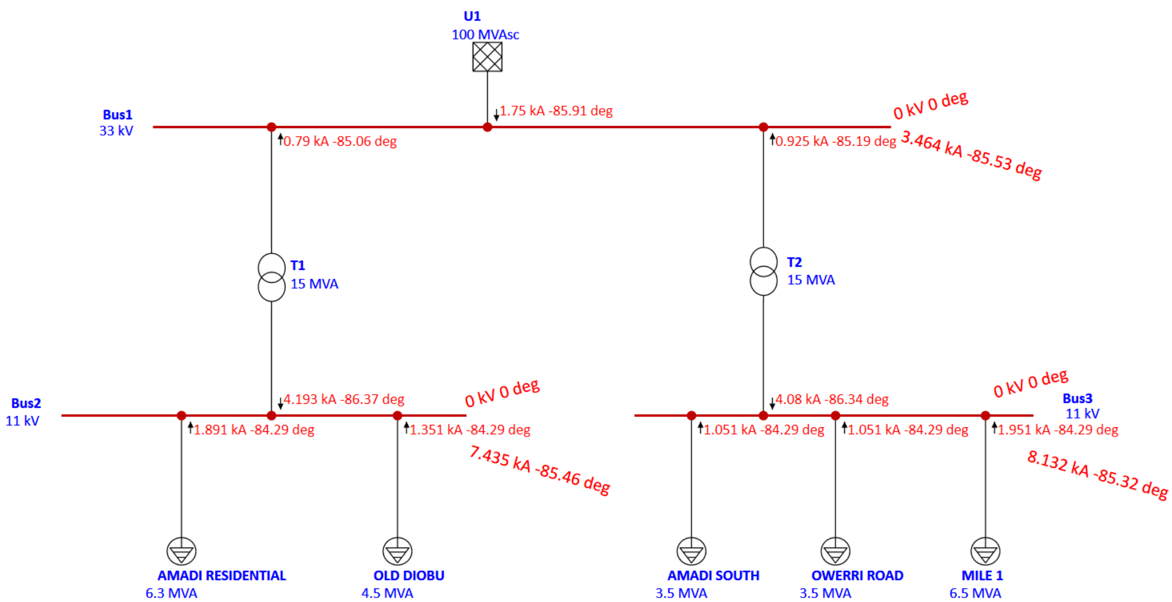

FIGURE 3. Short-Circuit Analysis of Amadi Junction Injection Substation

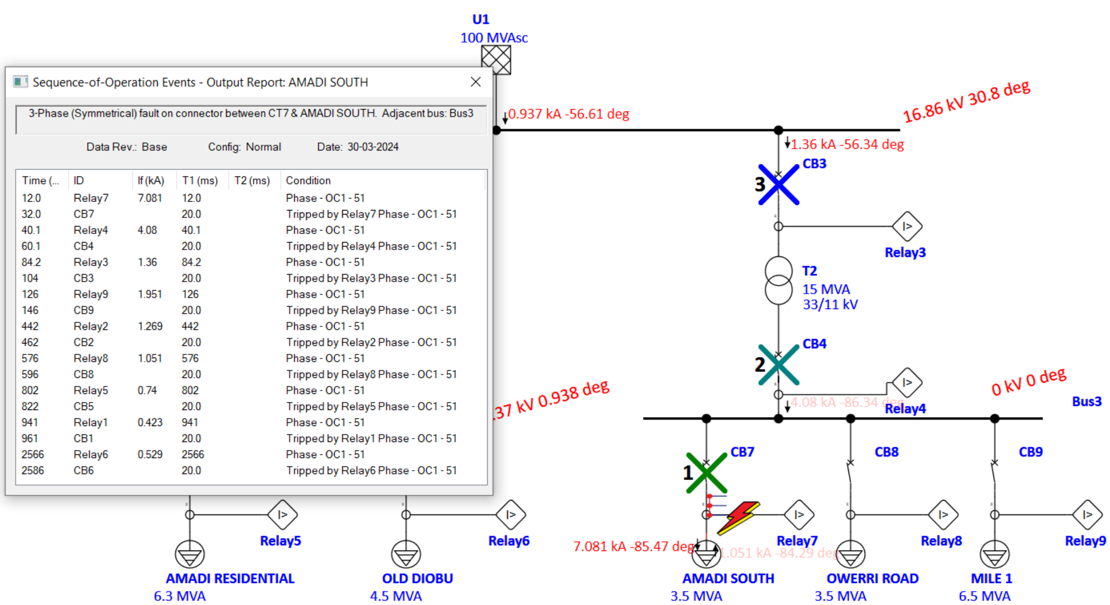

FIGURE 4. Insertion of a Fault on Amadi South Feeder

Figure 4 displays the action of the protective devices after inserting a symmetrical fault on Amadi South feeder in order to validate the protection scheme designed. A detailed study of the results obtained and displayed reveals that upon insertion of a symmetrical fault at Amadi South feeder, Relay 7 was the first line of defense which operated by issuing a trip signal to CB7 at a total time of 32.0ms (relay operating time + circuit breaker operating time). Furthermore, if the fault is not cleared after the tripping of CB7, Relay 4 then issues a trip signal to CB4 at a total time of 60.1ms thereby giving enough clearance in order to ensure proper selectivity between protective devices. The voltage magnitudes at

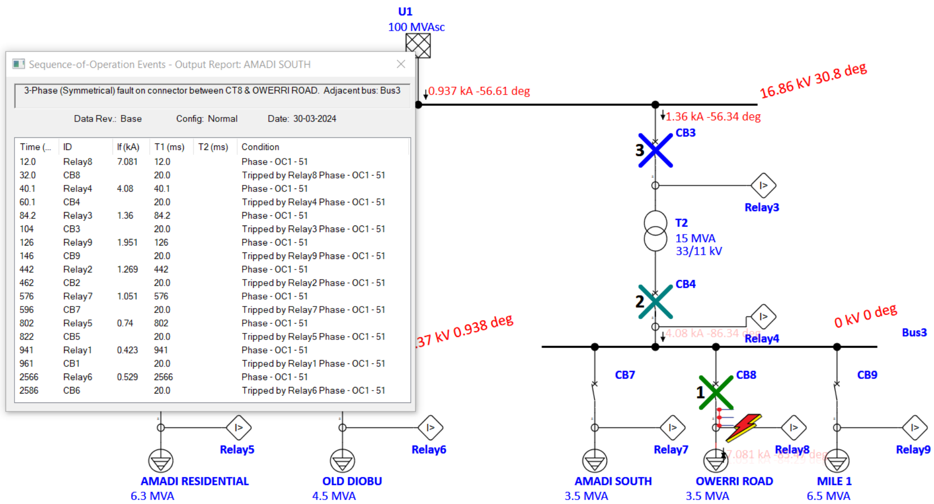

FIGURE 5. Insertion of a Fault on Owerri Road Feeder

various busbars are displayed in kv while the phase angles are displayed in degrees. The sequence of operation of the protective devices are also shown in the dialogue box at the left.

Figure 5 displays the action of the protective devices when a symmetrical fault was inserted at Owerri Road feeder in order to verify the action of the protective devices under such a scenario. The results obtained are displayed and the sequence of operation of protective devices are seen, thus, validating the proposed design of an overcurrent protection scheme.

Arc Flash Analysis of Amadi Junction Injection Substation

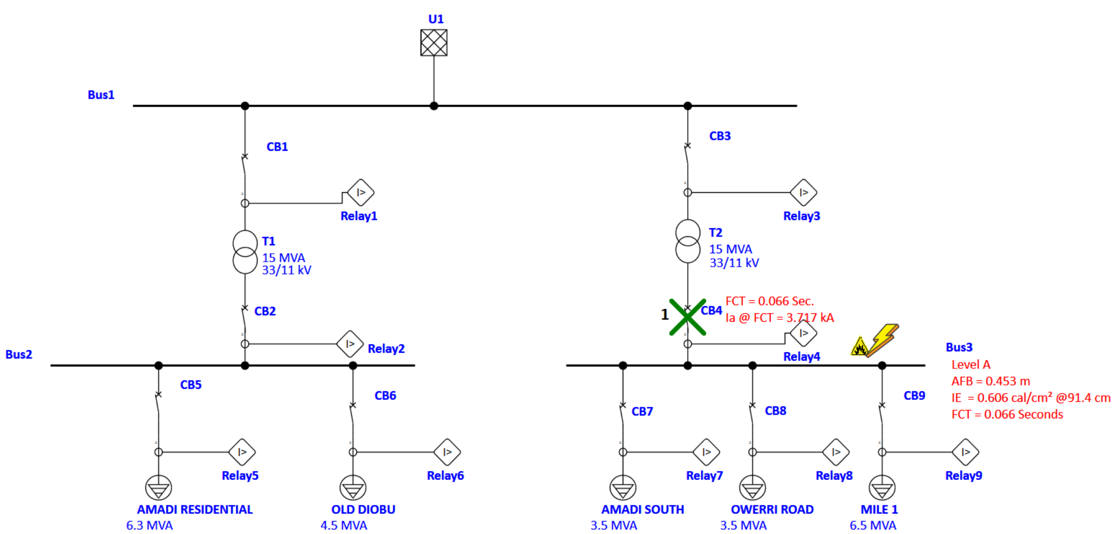

FIGURE 6. Insertion of an Arc Fault on Bus 3

Figure 6 above displays the result obtained after inserting an arc fault on Bus 3, and a critical examination of the resuts reveals the fault clearing time (FCT) to be at 0.066secs with a corresponding arcing current of 3.717kA. Furthermore, the results obtained also displays the arc flash boundary distance to be 0.453m, while the magnitude of incident energy at a working distance of 91.4cm is 0.606cal/cm2. It was also observed that the voltage magnitude at Bus 3 is 0kv and this is as a result of the insertion of an arc fault. The result also displays the required personal protective equipment to be used as Level A.

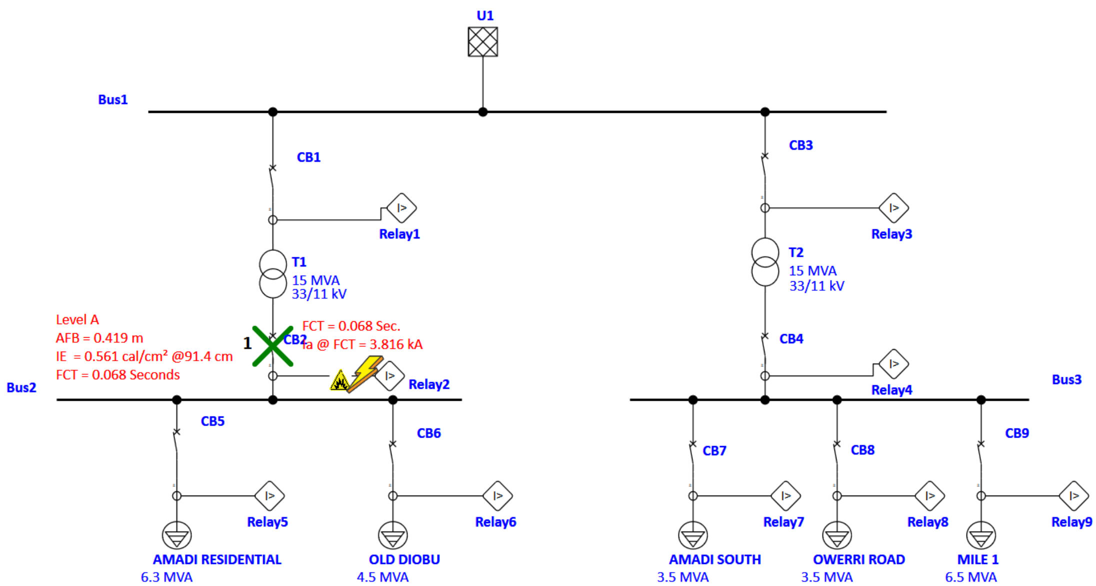

Figure 7. Insertion of an Arc Fault on Bus 2

Similar to Figure 6, Figure 7 displays the effect of an arc fault on Bus 2 which reveals the FCT to be 0.068secs at an arcing current of 3.816kA. The results obtained reveal the arc flash boundary, incident energy, working distance, and recommended level of personal proetective equipment to be 0.419m, 0.561cal/cm2, 91.4cm, and Level A respectively. Furthermore, customized arc flash labels are provided by the software indicating relevant information on the arc flash rating of equipment.

5. Conclusion

In electrical power systems, arc flash assessment plays a crucial role in identifying the magnitude of incident energy during an arc fault as well as determining the fault clearing time of switchgears which required the design of an overcurrent protection scheme using overcurrent relays in conjunction with current transformers and circuit breakers. This provides an edge to the safety of equipment and personnel by providing a safe working distance as well as adequate personal protective equipment thereby mitigating the effect of the arc flash.

APPENDIX I

LOAD FLOW RESULT

LOAD FLOW REPORT

Bus		Voltage		Generation		Load		Load Flow					XFMR
ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF	%Tap
* Bus1	33.000	100.000	0.0	16.279	13.661	0.000	0.000	Bus2	7.676	6.397	174.8	76.8	
								Bus3	8.603	7.265	197.0	76.4	
Bus2	11.000	95.611	-2.9	0.000	0.000	7.642	5.732	Bus1	-7.642	-5.732	524.4	80.0	
Bus3	11.000	95.035	-3.3	0.000	0.000	8.561	6.420	Bus1	-8.561	-6.420	591.0	80.0	

* Indicates a voltage regulated bus (voltage controlled or swing type machine connected to it)

# Indicates a bus with a load mismatch of more than 0.1 MVA

FIGURE 8. Load Flow Analysis Report

APPENDIX II

SHORT-CIRCUIT RESULT

Short-Circuit Summary Report

3-Phase, LG, LL, LLG Fault Currents

Bus		3-Phase Fault			Line-to-Ground Fault				Line-to-Line Fault				*Line-to-Line-to-Ground			
ID	kV	I"k	ip	Ik	I"k	ip	Ib	Ik	I"k	ip	Ib	Ik	I"k	ip	Ib	Ik
Bus1	33.000	3.464	8.793	1.750	2.611	6.628	2.611	2.611	3.000	7.615	3.000	3.000	3.183	8.079	3.183	3.183
Bus2	11.000	7.435	18.851	3.286	7.836	19.870	7.836	7.836	6.439	16.326	6.439	6.439	7.719	19.574	7.719	7.719
Bus3	11.000	8.132	20.552	3.286	8.339	21.076	8.339	8.339	7.042	17.798	7.042	7.042	8.315	21.015	8.315	8.315

All fault currents are in rms kA. Current ip is calculated using Method C.

* LLG fault current is the larger of the two faulted line currents.

FIGURE 9. Summary of Short-Circuit Analysis

APPENDIX III

OVER-CURRENT PROTECTION RESULTS

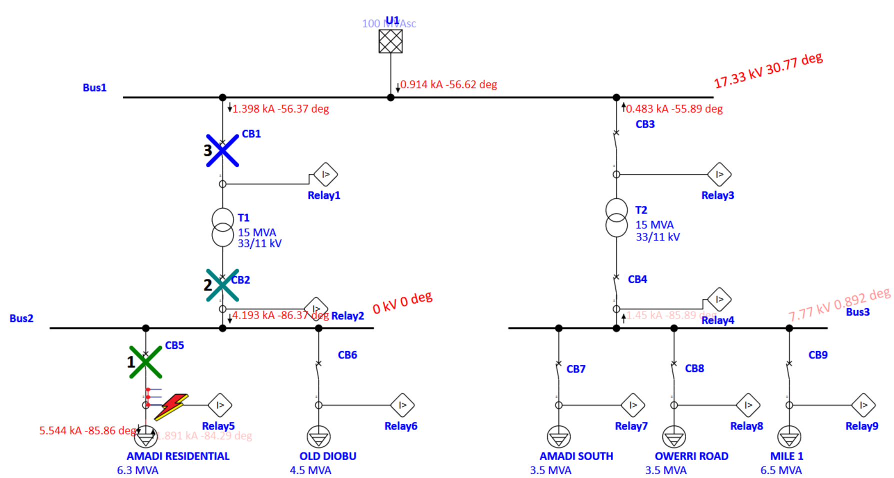

FIGURE 10. Fault Insertion at Amadi Residential

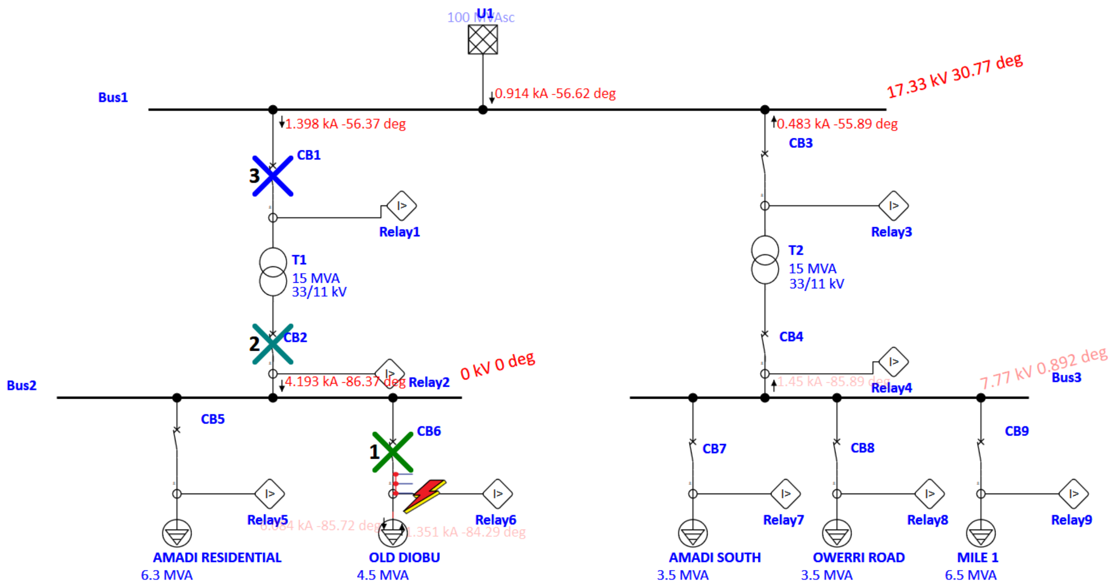

FIGURE 11. Fault Insertion at Old Diobu

APPENDIX IV

ARC FLASH RESULTS

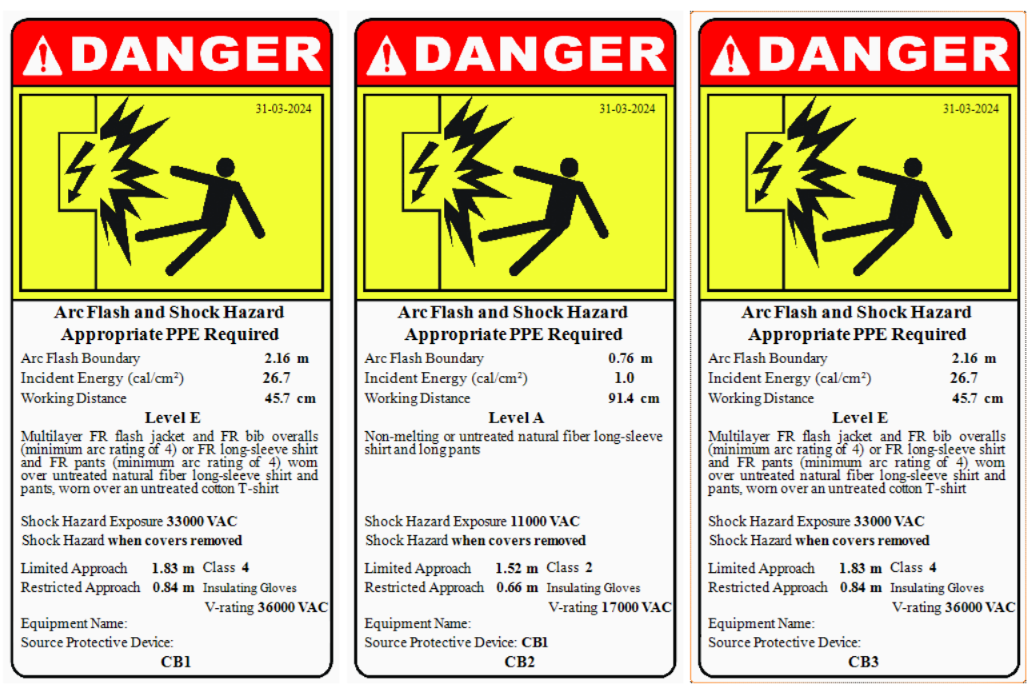

FIGURE 12. Customized Arc Flash Label for Circuit Breakers

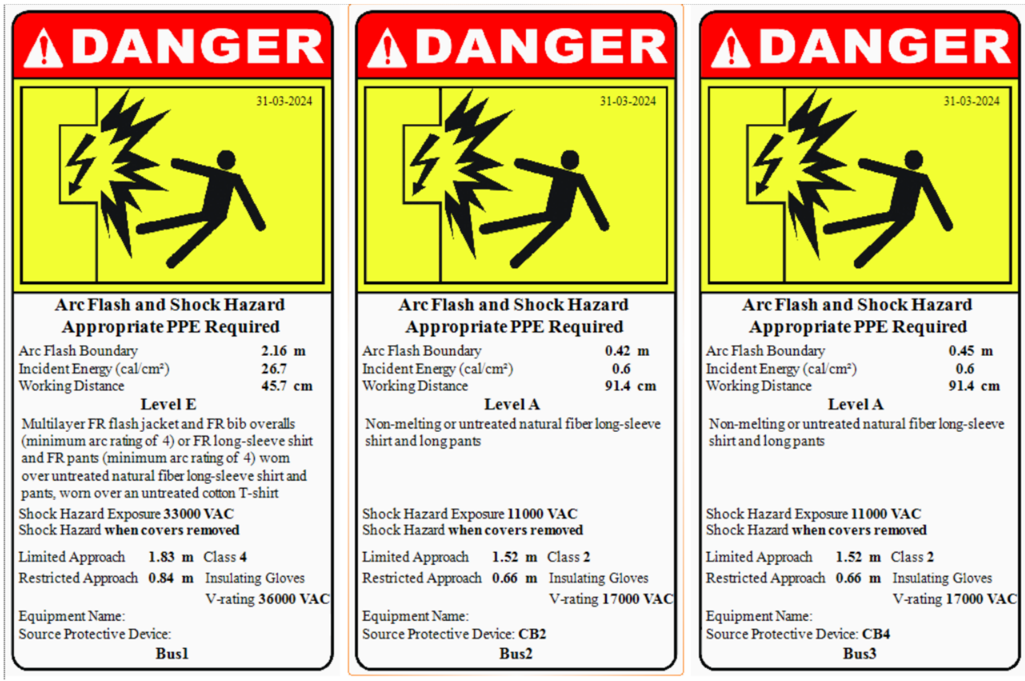

FIGURE 13. Customized Arc Flash Label for Buses

Statements and Declarations

The authors declare that they have no conflict of interest, and the manuscript has no associated data.

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