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ARC-FLASH INCIDENT ENERGY DETERMINATION FOR ENERGIZED 11KV PANEL IN RUMUODOMAYA 33/11KV INJECTION SUBSTATION

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Abstract— Electricity distribution networks often require a change in configurations as a result of inclusion of new electrical loads and in some cases older loads being increased or expanded in terms of their capacity. The use of distribution equipment can occasionally cause a very dangerous incident known as an arc flash hazard, which could damage the equipment and cause greater harm to workers or operators of the equipment. Analysis is crucial in determining the level of arc flash hazard and improving worker's protection. The National Fire Protection Association (NFPA) 70E standard is used in this paper to perform an

boundaries, Personal protective equipment.	arc flash analysis on 11kV panels. Rumodomaya 33/11kV injection substation facility was investigated. The Electrical Transient and Analysis Program (ETAP) software is used to analyze the Arc Flash Hazard (AFH) of a 11kV distribution network. This research entails the use of bolted fault and arc fault currents, for the estimations of the incident energy, the permissible protection and restriction boundaries. It as well as determines the appropriate personal protective equipment (PPE) and warning label. The incident energy obtained for 18 – 36 inch working distance, range from 2.510 - 4.256 cal/cm^2. As the relay's clearing time increases or distance from the panel decreases, so does the risk increases. This work provides useful analytic technique for designers and engineers who engage in risk assessment of energized panels determine PPE for workers.

I. Introduction

Whenever an arc flash occurs in an electric panel, the energy extracted is referred to as "incidental energy"[1-2]. The heat produced during the event of an arc flash incidence could be up to 19,600◦C. The impact of this high level of heat energy could create hot air and vaporize explosive metals like copper, resulting in a large explosion or arc blast [3-5]. Workers whose work involves activities with energized panel and equipment are exposed to the dangers of this incident energy from equipment. In Nigeria, and many other developing and industrial countries, there are standards to which these panels are designed, installed, and operated.

Common standards in the area of arc flash protection include the Occupational Safety and Health Administration (OSHA) and the National Fire Protection Association (NFPA); these standards establish detailed guidance for employees who work in close proximity to electrical devices. Standard protection systems, such as relays and breakers, are thought to be ineffective at ensuring the safety of people near the point of failure [6-8]. Studies in [9-12], revealed that increasing arcing current increases pressure over a specific range of distances. The various steps for evaluating the seriousness of arc flashes in open air and in a box are discussed. In this paper, an injection substation panel used to control the Rumuodomaya 33/11kV network is modelled and simulated in ETAP for AFH analysis. Different safety boundaries were acquired for different paraments such as bolted fault (short circuit) current, arcing current, incident energy, flash protection boundary (FPB), and PPE risk category were considered. Simulation was used to analyze fault, working distance, and bolted short circuit current, which can help to reduce these hazards.

II. Literature Review

A. Arc-flash and Incident Energy

Arc-flash is a potentially dangerous discharge of electrical energy through several air in a closed switchgear panel. There are two types of arc flash: series and parallel. Arc flash in series with loads is referred to as series arc flash, whilst the parallel arc flash is referred to as parallel to the load [13]. The load limits the flowing current in a series arc flash. Although this current is significantly lower than the breaker or fuse settings, protection equipment does not recognize the fault as an error. As a result, the arc will continue to burn and either raise the ambient temperature or cause arc flash on other parts of the equipment, potentially resulting in arc-blast.

Since the parallel arc-flash occurs between the line and ground/neutral or line-line, the fault current is similar to a zero impedance short-circuit (bolted fault current) and is detectable by protection equipment. A resistive fault occurs when conductors come into contact, even though a short circuit current is the maximum current drawn from the supply. This study focuses on parallel arc-flash because it is unaffected by protection systems and thus more dangerous. Incident energy is the energy released by an electric arc (arc-flash) [14]. The arc-flash effect is determined by incident energy, the higher the incident energy, the significantly larger the implications.

The rate of incident energy is influenced by voltage, fault current, distance from the point of failure, and length of arcing time. The arc current or fault current caused by an arc flash must always be known in order to calculate incident energy [14-15].

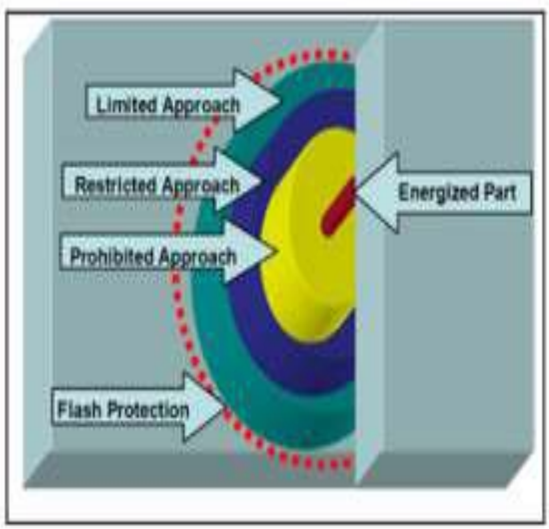

Figure 1: Approach Boundary

- Flash Protection Boundary: Safe distance from exposed live parts, where one can get a second degree burn if arc-flash occur.
- Limited Approach Boundary: A distance from exposed live

part within which a shock hazard exists.

- Restricted Approach Boundary: A distance from an exposed live part within which there is an increased risk of shock for personnel working in close proximity to the live part.
- Prohibited Approach Boundary: A distance from an exposed live part within which work is considered the same as contacting the live parts [15].

B. Labelling of Arc Flashes

The NEC® and NFPA 70E both necessitate equipment labelling to warn of potential Arc Flash Hazards. Each panel must always be labelled with an IEC-approved Arc Flash Hazard Warning Label that comprises the following details to warn and advise workers about the Arc Flash Hazard:

1. System Voltage Nominal
2. Arc Flash Boundary (3) At least one of the following:
   i. The readily accessible incident energy and matching working distance, OR b) The Arc Flash PPE category in Table 1 fortifying the equipment, and not both.
   ii. Clothing with a minimal level arc rating.
   iii. Site-specific PPE level

Table 1: The level of incident energy associated with each category NFPA70E

Hazard classification as per NFPA 70E 2012 – 2018		
PPE Category	Energy Level	Clothing's
A	0 - 2cal/cm^2	Non-melting or untreated natural fiber long-sleeve shirt and long pant Trousers.
B	2.01 - 4cal/cm^2	Flame retardant (FR) long-sleeve shirt (minimum arc rating of 4), worn over untreated cotton T-shirt with FR pant Trousers (minimum arc rating of 8)
C	4.01 - 8cal/cm^2	FR long-sleeve shirt (minimum arc rating of 4), worn over untreated cotton T-shirt with FR pants (minimum arc rating of 8)

D	8.01 - 25cal/cm^2	Multilayer FR flash jacket and FR bib overalls (minimum arc rating of 4) or FR long-sleeve shirt and FR pants (minimum arc rating of 4) worn over untreated natural fiber long-sleeve shirt and pants, worn over an untreated cotton T-shirt
E	25.01 - 40cal/cm^2	Multilayer FR flash jacket and FR bib overalls (minimum arc rating of 4) or FR long-sleeve shirt and FR pants (minimum arc rating of 4) worn over untreated natural fiber long-sleeve shirt and pants, worn over an untreated cotton T-shirt
F	40.01 - 100cal/cm^2	"Non available based on NFPA 70E"
G	100.01 - 120cal/cm^2	"Non available based on NFPA 70E"

Source: [16]

C. ETAP Hazard/Risk Categories Levels of Personnel Protection Equipment (PPE) Clothing

Wear suitable clothing and personal protective equipment (PPE) grouped for the estimated incident energy to protect the individual working on electrical equipment. Personal protective equipment (PPE) should always be rated higher than the maximum incident energy that can occur. Furthermore, both the IEEE 1584 standard and the NFPA 70E standard have made public specific requirements that divide incident energy levels into five categories (0-4) or PPE categories (A-G), with each category indicating the level of threat that is strongly dependent on the incident energy level. Category 0 or A connotes no danger, whereas category 4 or C connotes an extremely dangerous situation. The incident energy levels associated with each category are shown in Table 1 [17-20].

III. Materials and Method

Materials

The data available from the Rumuodomaya 1x15MVA, 33/11kV substations network under evaluation, derived from the Port Harcourt Distribution Company, was used in this work (PHDC).

A. Research Methodology

The single diagram shows the data impedances of the major components (transformers and busbars), as well as the load and cable impedances. All impedances must be carefully and precisely observed because they will influence the outcome of the analysis. Most of the short circuit currents are from the utility, though some are from lump loads as well. As shown in Figure 2, the switchgear panel and open air are being used as research objects.

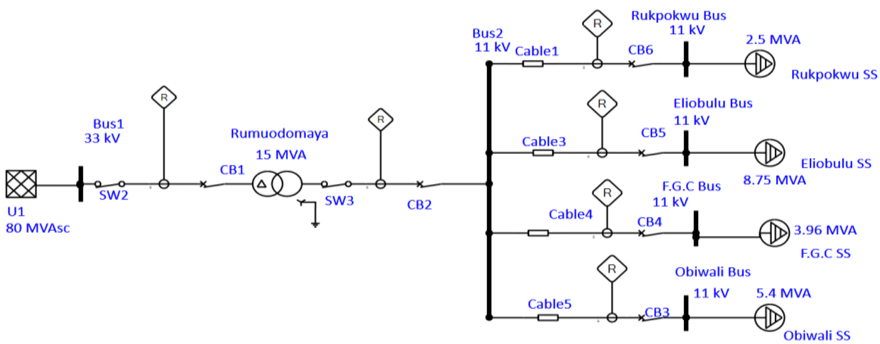

Figure 2: Single-line diagram and components' specification

B. Methodology Method of Analysis

The following are the five (5) steps required to determine the incident energy and afterwards level of personnel protection equipment (PPE) to limit the harm to personnel caused by electric using ETAP 19.0.1 software:

1. Calculation of the bolted fault (short circuit) current.
2. Arcing current determination
3. Assessment of incident energy
4. Calculation of the bolted fault (short circuit) current.
5. Arcing current determination
6. Assessment of incident energy
7. Establishing the Flash protection boundary (FPB).

8. Determining the PPE Risk Category

C. ETAP Arc- Flash Calculation

The following equations are used to calculate arcing current, incident energy, and flash protection boundary use in ETAP software.

1. Bolted fault current calculation

Because the type of arc flash acknowledged in this study is parallel arc flash, calculation of bolted current as used for short circuit current in this network is required, using Equation (1):

$$I_{f3\emptyset} = \frac{V_{L-N}}{Z_1} \qquad (1)$$

where:

$I_{f3\emptyset}$ = 3ph short circuit current (Amps)

V_{L-N} = Line to neutral voltage (Volts)

Z_1 = Positive sequence impedance (Ω)

2. Arc-fault current calculation

There are two methods to calculate arcing fault current as shown in Equations (2) and (3), i.e., for low voltage (V < 1000 V) and high voltage (V > 1000 V) system [21].

For Low voltage:

$$\log(I_a) = K + .662.\log\left(I_{bf}\right) + 0.000526.G + 0.5588.V.\left(\log\left(I_{bf}\right)\right) - 0.00304.G.\left(logI_{bf}\right) \qquad (2)$$

For high voltage:

$$\log(I_a) = 0.00402 + 0.983.\log(I_{bf}) \qquad (3)$$

where:

I_a = arcing current (KA)

K = 0.153 for open configuration: 0.097 for closed configuration panel

I_{bf} = 3-ph symmetrical bolted fault current (KA)

V = Voltage (KV)

G = distance between conductors (mm)

From this equation it is obvious that the arc-fault current is determined by the bolted fault current.

3. Incident energy normalized

According to the standard, to calculate the incident energy, the incident energy must first be measured [21]. Incident Energy to be measured is an empirical formula based on statistical analysis of the released energy during an arc-flash event with a duration of 200 ms and a distance of 610 mm between the arc-flash and the calorimeter. The Equation (4) is used to calculate this energy.

$$\log(E_n) = K_1 + K_2 + 1.081.\log(I_a) + 0.0011.G \quad (4)$$

4. Incident energy

Incident energy is obtained by converting the incident energy normalized. In this conversion it involves some factors, namely: calculation factor, distance factor between the point of fault and human and distance exponent using Equation (5):

$$E = 4.184.C_f.E_n.\frac{tt}{0.2}.\frac{610^x}{D^x} \quad (5)$$

where:

E = incident energy (J/cm^2)

C_f = calculation factor

- 1.5 for low voltage ($< 1kV$)

- 1.0 for medium voltage and higher

D = distance from faulty point to human (mm)

X = distance exponent

5. Flash protection boundary

Flash protection boundary is calculated by equation as introduced by [ibid] that refers to the magnitude of the incident energy:

$$D_B = \left[4.184.C_f.E_n.\frac{t}{0.2}.\frac{610^x}{E_n}\right]\frac{1}{X} \quad (6)$$

where:

D_B = safe distance from arcing point (mm)

IV. Result and Discussion

A. Bolted fault current analysis

As per the standard, the bolted fault current (I_{bf}) is the same as the previously stated three-phase, symmetrical short circuit current at the point of fault. Suggested model can be used to perform calculations. Figure 3 depicts a short circuit analysis performed by ETAP software.

With the addition of the bus transformer, the utility (1.4 kA), Bus 2 (2.739 kA), and the lump loads bus, the total short circuit current rises to 15.077kA. (10.938kA). Following a short circuit analysis, the ETAP IEC Arc-Flash tool is used to obtain bolted fault current (I_{bf}), arcing current (I_a), incident energy (E), and arc flash boundary data (AFB). The findings of the arc flash study are shown in Table 2. The required label can be generated using the print option, providing all necessary data to anyone working near energized equipment. Figures 4, 5, 6 and 7 depict the labels for the Eliobulu, F.G.C, Obiwali, and Rupkokwu buses.

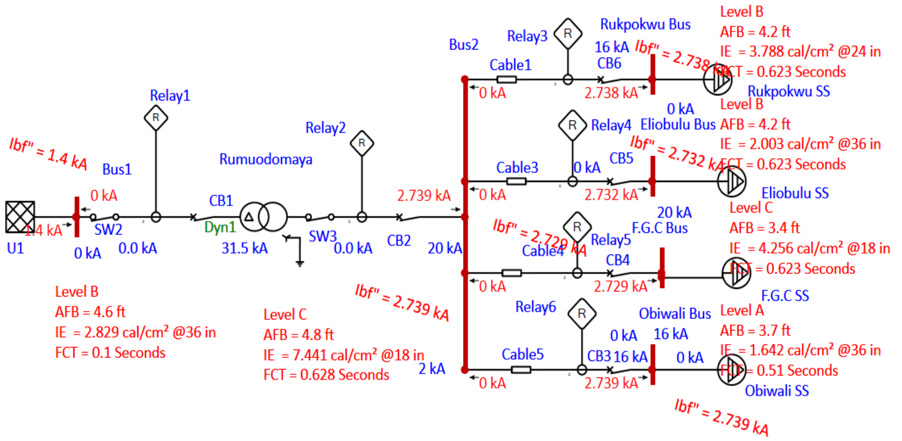

Figure 3: The point of fault position (bus 1-6)

On the label, all required documents such as arc flash boundary, incident energy, working distance, category, and different shock protection boundaries are indicated, assisting workers in taking safety actions and protecting individuals with appropriate Personnel protective equipment (PPE). ETAP provides a variety of label generation options from which to create proper labels that also indicate required PPEs, incident energy, arc flash boundaries, and various shock protection boundaries. As a result, it can provide immediate assistance to the operator.

Table 2: Simulated Results of Arc-flash Incident Energy Analysis

Bus ID	Non kV	Equipment Type	Ibf (kA)	Ia (kA)	E (cal/cm^2)	AFB (ft)	Working Distance	Cate-gory
Eliobulu Bus	11	Switchgear	2.732	2.510	2.003	4.16	36	B
F.G.C Bus	11	Open Air	2.729	2.314	4.256	3.40	18	C
Obiwali Bus	11	Switchgear	2.739	2.517	1.642	3.66	36	A
Rupkokwu Bus	11	Switchgear	2.738	2.516	3.788	4.16	24	B

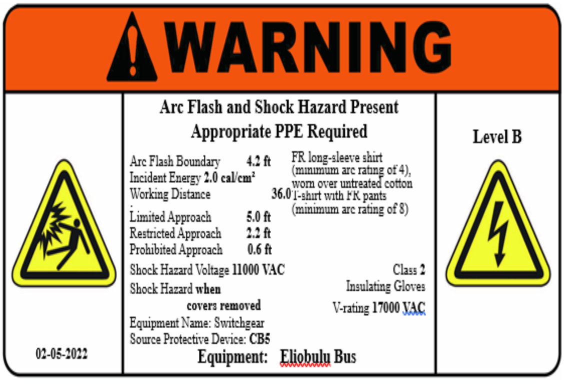

Figure 4: Arc Flash Warning label of Eliobulu Bus (Switchgear) with PPE category of level B

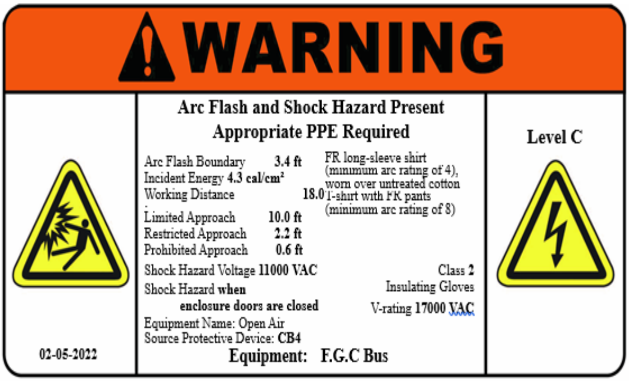

Figure 5: Arc Flash Warning label of F.G. Bus (open air) with PPE category of level C

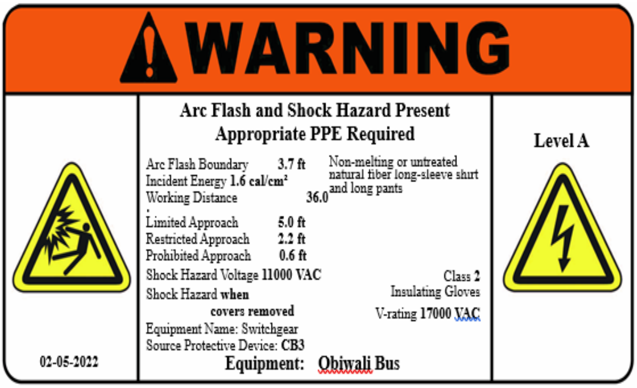

Figure 6: Arc Flash Warning label of Obiwali Bus (Switchgear) with PPE category of level A

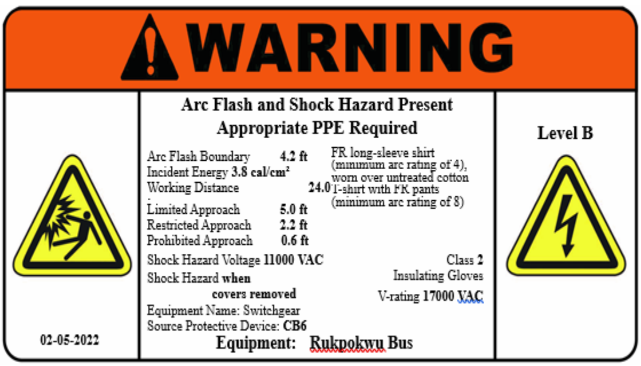

Figure 7: Arc-Flash Warning label of Rupkokwu Bus (Switchgear) with PPE category of level B

V. Conclusion

This work provides a helpful analytic process for designers and engineers who are in charge of evaluating the risk associated with electrical - energized panels and deciding on PPE for workers. In this work, an arc flash risk assessment on an energized panel was used to determine the arc flash energy level. According to the result, the 11kV panel under consideration emits incident energy at a working distance of 18-36 inches that ranges from 2.510-4.256 cal/cm^2. Arc-flash Labels for the energized panel were made with the proper class indicators based on the results.

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