ELECTRICAL ARC FLASH SAFETY DETECTION IN POWER DISTRIBUTION NETWORK

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Abstract: This paper seeks to investigate the safety issues surrounding Federal University of Petroleum Resources Effurun (FUPRE) distribution network and the steps taken by the management to ensure that all employee' health and safety issues are protected. Using direct observation, data were collected while ETAP was used to analyze the system. According to our findings, the Admin Block has the highest total fault current with an arcing value of 11.197 A and a bolted fault of 15.490 A, followed by College of Science with an arcing value of 9.460 A and a bolted fault of 13.106 A. Bus 1 has the lowest arcing value of 0.735 A and a bolted fault of 0.735A but with the highest incident energy of 6.180 cal/cm^2, followed by Admin Block with incident energy of 2.868, while Health Center and Hostel had the lowest incident energy of 0.194 cal/cm^2 and 0.196 cal/cm^2, respectively. Arc-Flash Hazards are classified into five Hazard Risk Categories by NFPA 70E, Standard for Electrical Safety in the Workplace which range from category A-C from the findings. This has helped to shed more light on the safety detection and control practices in workplace. This work adopted the incident energy analysis method during the investigation of the FUPRE distribution network. This analysis also showed the effectiveness of FUPRE distribution network in terms of health and safety practices.

Keywords: safety detection, electrical arc flash, arc flash protection boundary

1. INTRODUCTION

Safety is a critical factor that must be put into consideration when it comes to the design and implementation of electrical systems. In the past, electrical hazards in the form of injuries and associated impacts were the major workplace health and safety concerns. These are still of immense concern today as experts are seeking ways to mitigate against such occurrences in workplaces. Electrical injuries and impacts when not mitigated against can cause serious related health problems such as sudden cardiac arrest, irregular heartbeat, hypoxia, sepsis and renal failure which if not attended to on time could lead to death. According to report that was published in industrial safety and Hygiene news, it basically estimated that on average 30,000 arc flash incidents is being witnessed every year. It further captured the estimates of annual totals of 7,000 burn injuries, 2,000 hospitalizations and 400 fatalities per year [1]. The high impact of electric hazards on one's quality of life justifies the reason for this work.

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The most noticeable direct effects of electric hazards are electric shock, arc flash and blast. Electric shock occurs when an electric current touch or flows through a human body. It also occurs whenever there is live electricity [2]. Electrical current could cause four types of injuries such as flash, flame, lightening and true. These types of injuries express their degree of impact on the human body.

Flash injuries causes superficial burns which occurs due to the heat of an arc flash. The current does not penetrate the skin. Flame can cause a person's clothes to ignite. Its current has probable chance of passing through the skin. Lightening is usually short but comes with high voltage electric energy with its current having the possibility of flowing through a person's body. In true injury effect of electrical current, the person becomes part of the circuit and electricity enters and exits the body.

The symptoms of electric shock differ from low voltage shocks to prolonged exposure. Low voltage symptoms are usually superficial, while prolonged exposure can cause deeper burns. The invention of electricity brought a consequent effect of electric shock which the world is yet to curtail for decades. Much emphasis has been placed on designing and regulating industry safety laws that will ensure that the impact of electric shock is reduced to the lowest minimum [3].

There are incidents where workers have been exposed to risks that are associated with working near electric assets. Organizations and individuals are told of their duty to ensure that no individual in the workplace comes within an unsafe distance at an electric line. This work, therefore, seeks to identify and establish the unsafe distance of an electric line at the Federal University of Petroleum Resources, Effurun distribution network. It also stated standards that can be used to protect against arc flash; which are NFPA, 70E, OSHA 1910, the National Electrical Code and IEEE 1584 [4].

As a necessary consequence of the partnering between OSHA and NFPA, a benchmark known as NFPA 70E (Standard for Electrical Safety in the Workplace) was created [5]. The prerequisites for a safe workplace in the electrical installation industry were defined in this standard. It is primarily concerned with electric shock and arc flash. All employers are required by the OSHA act to provide workplace health and safety for their employees. Employers must also plan and execute missions within their organizations by establishing effective regulatory standards [6]. According to Stranks in his article titled" Manager's Reference to Health and Safety at Work", business owners and managers should implement a company mission that determines and enforces the necessary safety requirements by providing education, outreach programs, support, and education about their health and safety. Arc flash is basically a sudden release of electrical energy through the air when a high voltage gap exists and there is a breakdown of insulation between conductors that are in contact with each other or when an energized conductor makes direct contact with another energized conductor or ground. An arc flash belongs to a class of explosion that emits thermal radiation and heat, thereby creating huge burns, serious injuries and even death to workers that are within its zone of occurrence. Arc flash usually precedes arc blast. It can cause electrical equipment to explode and result to the creation of a plasma fireball. This effect leads to high temperature that can be as high as 35,000 ºF. This temperature is higher than the surface temperature of the sun with a typical value of 9,000 ºF. This high temperature has the capability of rapidly heating up the surrounding air and lead to extreme pressure that is capable of causing arc blast. When arc flash occurs it produces, fire, intense light, pressure waves and flying shrapnel [7].

An arc fault occurs when an unsafe condition of energetic electrical equipment causes an arc flash. Other factors that can as well cause arc flash are poor communication, lack of experts and poor human intervention [8].

Figure 1 captures a typical arc flash with its associated arc blast environment. If a worker is within the zone of its occurrence, which has been declared as unsafe distance, such a worker may sustain the impact of arc blast. When it happens, the worker may not show any extreme signs of electric shock but inner tissue or organ may have been damaged. Various standards have stated that workers who sustain various degrees of arc flash should seek immediate medical attention to further investigate its impact on such worker, and even those that have been shocked by electricity are not left out as they must also seek immediate medical attention. From the various impacts thus far, applying proper PPE and taking precautionary measures would minimize the risk of electrical shock hazards [9].

There are fundamental terms that have been designed to demonstrate the magnitude of an Arc-Flash and the hazards associated with it: incident energy is a source of instantaneous heat energy that is released by an Arc-Flash. It is usually measured in calories per square centimeter (cal/cm^2) and is thus defined as the amount of heat energy impressed on a one-square-centimeter area (cm^2). Other units of measure demonstrate heat energy in joules/cm^2, which can be converted to calories/cm^2 by dividing with 4.1868. If we place equipment to measures the level of incident energy at different distances from the arc, we can obtain the magnitude of the incident energy that can be used to analyze and establish the safe distance zone [10, 11]. The justification to this, is that the incident energy shrinks in proportional amount to the distance of the object in feet. Which is very much like walking through the door of a fireplace, the closer we are, the more heat energy that will be received. when test was carried out, incident energy of only 1.2 cal/cm^2 was found to be sufficient to stimulate a second-degree burn on unprotected skin. A second-degree burn is thought to be "merely" curable.

The concept of working distance is usually used to assess and understand the potential consequences of an arc flash. The various measurement techniques are done at 18-inch working distance but lesser inches might be considered as well but other tasks may be performed at greater distances. The working distance is then used to determine the level of risk and the type of personal protective equipment that may be suitable to protect against hazards [12]. The Table1 shows the incident energy levels in relation to their associated emitted energy at the point of occurrence.

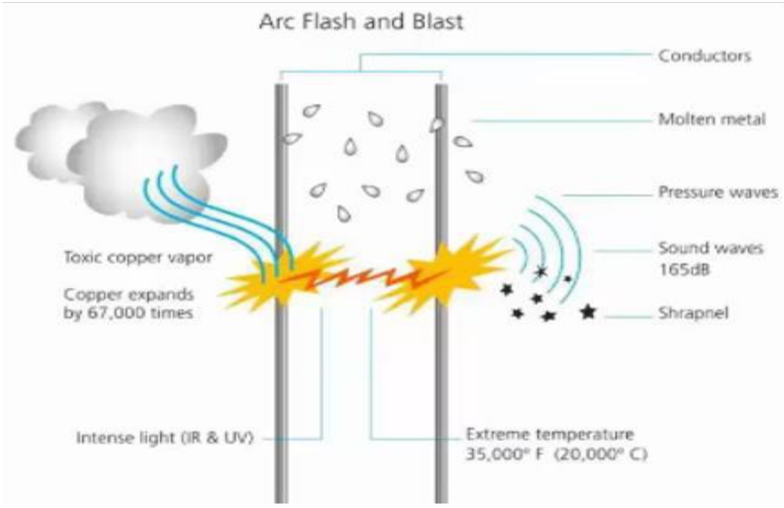

Fig. 1. Arc flash and blast (arc current >25 KA).

Table 1. Arc-flash hazards standard for electrical safety in the workplace (NFPA 70E, standard for electrical safety in the workplace for arc-flash hazards).

Incident energy (cal/cm^2)	Results/Example
0.0033	Amount of energy, the sun produces in 0.1sec on the ground's surface at the equator.
1	Equivalent to a fingertip exposed to a cigarette lighter flame for one second
1.2	Amount of energy that will instantly cause 2^{nd} degree burns to bare skin
4	Amount of energy that will instantly ignite a cotton shirt
8	Amount of energy that will instantly cause incurable 3^{rd} degree burns to bare skin

1.1. Categories of arc flash safety detection and energy levels

Based on the categories of arc flash, workers are advised to wear suitable clothing and personal protective equipment (PPE) that are rated for the estimated incident energy in order to protect them when working on electrical equipment. The selected personal protective equipment (PPE) should have a higher rating than just the maximum incident energy possible.

The IEEE 1584 and NFPA 70E standard published the required specifications that categorizes incident energy levels into five (0-4), with each category indicating the level of danger that is associated with it. The category 0 level indicates no danger, while category 4 level indicates dangerous zone. The incident energy levels connected with each category can be seen in Table 2 [13].

Table 2. The level of incident energy associated with each category (NFPA70E, the level of incident energy associated with each PPE category NFPA70E 2012 – 2018).

Hazard classification as per NFPA 70E 2012 – 2018	
PPE Category	Energy Level
A	< 2 cal/cm^2
B	4 cal/cm^2
C	8 cal/cm^2
D	25 cal/cm^2
E	40 cal/cm^2
F	100 cal/cm^2
G	120 cal/cm^2

1.2. Protection boundaries set by NFPA 70E - flash protection boundary

Major burns induced by arc flash can (Figure 2) occur somewhere in this boundary if proper PPE is not used. Employees within the same boundary should always wear appropriate PPE irrespective of their task, in order to avoid second-degree burn when some distance from the arc source. A second degree burn threshold of 1.2 cal/cm^2 > 0.1 sec. is considered [14].

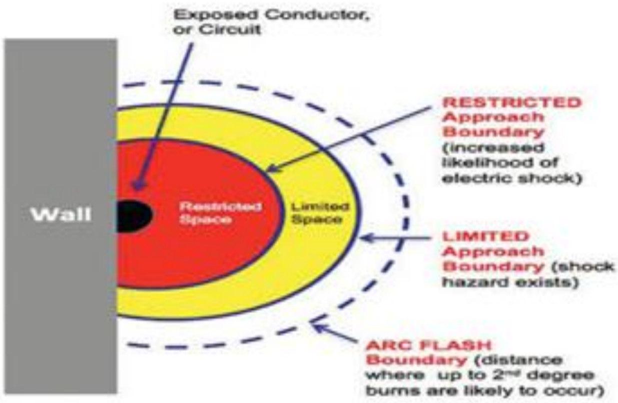

Fig. 2. 2015 arc flash boundaries.

1.3. Concept of arc flash boundary

The concept of arc flash boundary helps to establish safety guide in workplace. It is the minimum safe distance from exposed energized conductors or circuit parts that can cause arc flash. It serves to help the workers know where the arc flash boundaries are and be conscious of them when at workplace. There are three boundaries that have been recommended by national fire protection association (NFPA) in order to minimize risk of electrical injuries. Each boundary defines its zone of safety as established by (NPFA). These regions of boundaries are as explained below.

1.3.1. Limited approach boundary

This region exists when one moves toward the energized and exposed equipment. In this zone, one can still sustain minor shock within this region. Non- qualified workers are not permitted within the boundary without wearing proper PPE and being escorted by qualified personnel.

1.3.2. Restricted boundary

This is the region/zone closest to the live, energized or exposed equipment. To pass this boundary, one must be a qualified worker with the proper training and PPE. For one to work on any equipment in this zone, permit must be obtained from the appropriate authority.

1.3.3. Prohibited approach boundary

This is a shock protection boundary that can be violated only by "qualified" staff using the same protection as if direct contact with live part is projected. It is determined exclusively on the system nominal voltage.

1.3.4. Justification of arc flash safety detection

Arc flash safety detection is performed for a variety of reasons, most of which are as follows:

1. To avoid workplace injury or death.
2. To reduce equipment damage.
3. To reduce system downtime.
4. Adherence to codes and safety regulations.
5. To ensure that insurance requirements are fulfilled.
6. To save cost on legal fees.

The detection of arc flashes is a critical component of what OSHA require in terms of electrical hazards. Arc flash safety detection is required by NFPA 70E in order for employers to determine the amount of thermal energy that could be generated in the event of an arc flash incident. This information is used to classify flash protection boundary around the source of potential hazard and to measure the effects of arc-rated clothing and other PPE put in place to protect employees. This work basically used ETAP to perform the arc flash safety detection calculations in accordance with IEEE calculations procedures. The result of this research was based on the assumption that protective devices were operating perfectly and will clear the fault as designed by the manufacturer. If devices fail to operate effectively, an arc fault can exist longer than expected and result in hazard that is far greater than the result obtained from the various calculations. Based on this, it was necessary to ensure that all overcurrent protective devices operate in accordance with the manufacturer's recommendations. The most observed way of Arc flash protection is by working on equipment that is not energized. The arc flash software program was also used to calculate the available arcing fault current for a fault through each bus in the system. The resulting arc flash boundary depending on the applicable protective device running times, and the incident energy that workers may indeed be given access to at the specified working distances were obtained [15, 16].

2.MATERIALS AND METHOD

2.1. Materials

The materials included in this work were the available data from the six (6) distribution injection substations within the Federal University of Petroleum Resources Effurun network under assessment, which was gotten from the institution's public work department.

2.2. Description of the network

The proposed 2.5 MVA, 33/11 kV network is situated at the Federal University of Petroleum Resources Effurun. The university is located in Warri, Delta State, Nigeria. It is powered by the 33 kV feeder from the Effurun Transmission Substation. The feeder from the Effurun transmission substation runs through Ugbumoro to the university's 2.5 MVA transformer. Figure 3 depicts the entire FUPRE network on a single line diagram using Electrical Transient Analyzer Program (ETAP). There are Six (6) substations on the university's campus that are powered by this 2.5 MVA transformer. There is One (1) MVA transformer behind the administration building, and five (5) 500 kVA, 11 / 0.415 kV transformers at the hostel, health center, college of science, college of engineering, and Tetfund Classroom Building.

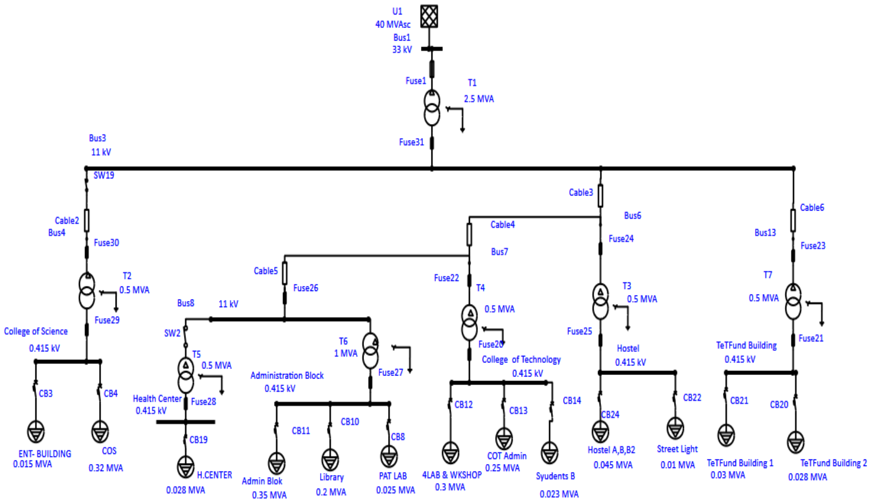

Fig. 3. Single line network diagram of the Fupre 33/11kV distribution station in Effurun, Delta State.

2.3. Method of analysis

To resolve the issue of arc flash, using the incident energy analysis method, the following six steps were taken:
- Identification of the electrical system and installation data.
- Calculation of the impedance of individual components and networks in relation to the point of failure.
- Determination of bolted fault current (short circuit).
- Calculation of the arc fault current
- Determination of incident energy.
- Determination of the Protection Boundary of the appropriate PPE category.

2.4. Mathematical modelling of ETAP 19.0.1

This model provides information on the incident energy calculation method. This method is considered the more accurate and is configured as the default method.

2.4.1. Determine the arcing current

For low voltage electrical systems (<1 kV), the arc current is determined using equation (1).

$$I_a = 10^{[K + 0.662 \log(I_{bf}) + 0.0966V + 0.000526G + 0.5588V + \log(I_{bf}) - 0.00304G + \log(I_{bf})]} \quad (1)$$

where Log is to base 10 ($\log_{10}$), $I_a = arcing\ Current\ (kA)$, $K = -0.153$ open configuration and -0.097 box configuration, I_{bf}= bolted fault current for three phase faults (symmetrical RMS in kA), V = system voltage (kV), G = gap between conductors (mm).

2.4.2. Determine the normalized incident energy

The normalized incident energy, which is derived from 0.2 second arc duration and 610 mm arc distance, is determined using formula (2).

$$E_n = 10^{[K_1 + K_2 + 1.081 * \log(I_a) + 0.0011G]} \quad (2)$$

where E_n are incident energy normalized for time and distance (J/cm^2), $I_a =$ arcing Current (kA), $K_1 = -0.792$ open configuration and -0.555 box configuration, $K_2 = 0$ ungrounded and high resistance grounded systems and -0.113 grounded systems, G = gap between conductors (mm).

2.4.3. Evaluation of incident energy

The normalized incident energy is used to calculate the incident energy at a normal surface at a specific distance and arcing time using the formula (3).

$$E = 4.184\, C_f E_n \left(\frac{t}{0.2}\right)\left(\frac{610}{D}\right)^x \quad (3)$$

where $E$are incident energy (J/cm^2), C_f = Calculation factor = 1.0 voltage $>$ 1 kV and 1.5 voltage $<$ 1 kV, t = arcing time (seconds), D = working distance from arc (mm), x = distance exponent as shown in Table 3.

Table 3. Distance factor (x) for different voltages and enclosure models.

Enclosure Model	0.208 to 1 kV	$>$ **1** to 15kV
Open air	**2**	**2**
Switchgear	**1.473**	**0.973**
MCC and Panels	**1.641**	**-**
Cable	**2**	**2**

2.4.4. Arc flash protection boundary

The flash protection boundary is the distance at which staff without personal protective equipment (PPE) may suffer second-degree injuries that can be cured. It is expressed as:

$$D_B = 610 + \left[4.18 C_f E_n \left(\frac{t}{0.2}\right)\left(\frac{1}{E_B}\right)\right]^{\frac{1}{X}} \quad (4)$$

where: D_B are distance of the boundary from the arcing point (mm), C_f = calculation factor = 1.0 voltage > 1 kV and 1.5 voltage < 1 kV, E_n = normalized incident energy, E_B = incident energy at the boundary distance (J/cm²); can be set at 5.0 J/cm² (1.2 cal/cm²) for bare skin, t = arcing time (seconds), D = working distance from arc (mm), x = distance factor from Table 3, I_{bf} = bolted fault current (kA).

3. RESULTS AND DISCUSSION

The various results obtained from the simulation serves to describe the expected arc boundaries within the university community. It captures the zones with high and low arc alert that workers must be conscious of when working in them. The bus incident energy summary obtained is shown in Figure 4, Table 4 and Figure 5.

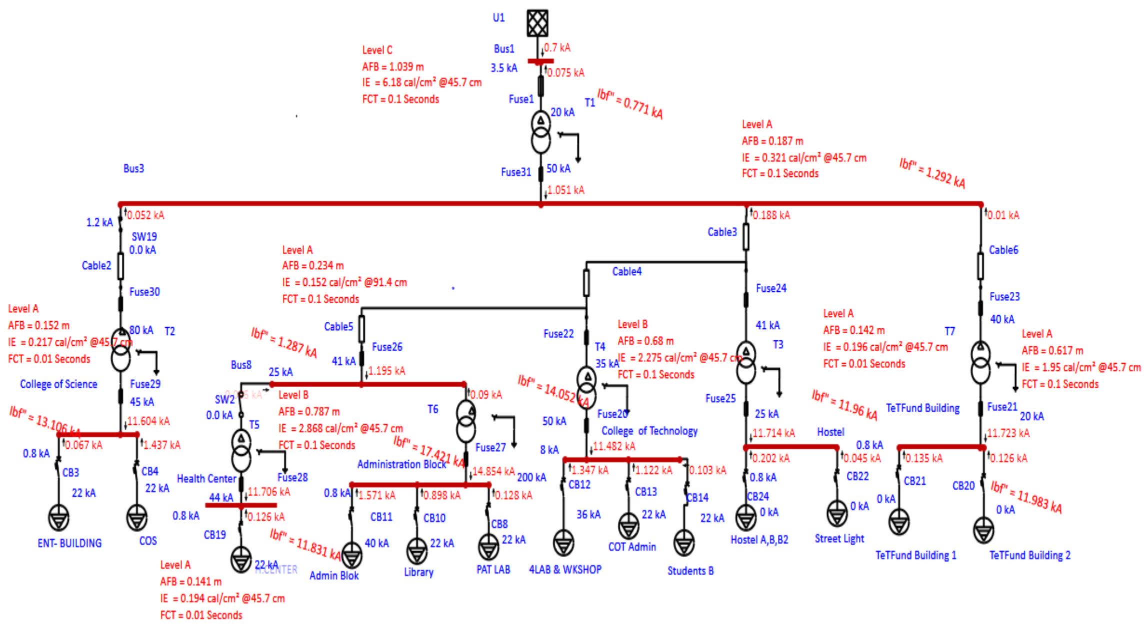

Fig. 4. Simulation of FUPRE distribution network in ETAP 19.0.1 environment.

Table 4. Bus incident energy summary.

Bus			Total fault current (kA)		Arc fault analysis results			Energy level
ID	Nom. kV	Types	Bolted	Arcing	Fault Clearing Time (FCT) (cycle)	Incident Energy (cal/cm²)	Arc fault boundary (AFB) (m)	
Bus 1	33.00	Open Air	0.735	0.735	5.000	6.180	1.04	**C**
Admin Block	0.415	Panel Board	15.490	11.197	5.000	2.868	0.79	**B**
College of Technology	0.415	Panel Board	12.289	8.858	5.000	2.275	0.68	**B**
College of Science	0.415	Panel Board	13.106	9.460	0.500	0.217	0.19	**A**
Health Centre	0.415	Panel Board	11.831	5.519	0.500	0.194	0.14	**A**
Hostel	0.415	Panel Board	11.960	8.614	0.500	0.196	0.14	**A**
Tetfund Building	**0.415**	Panel Board	11.484	8.261	5.000	1.950	**0.62**	**A**

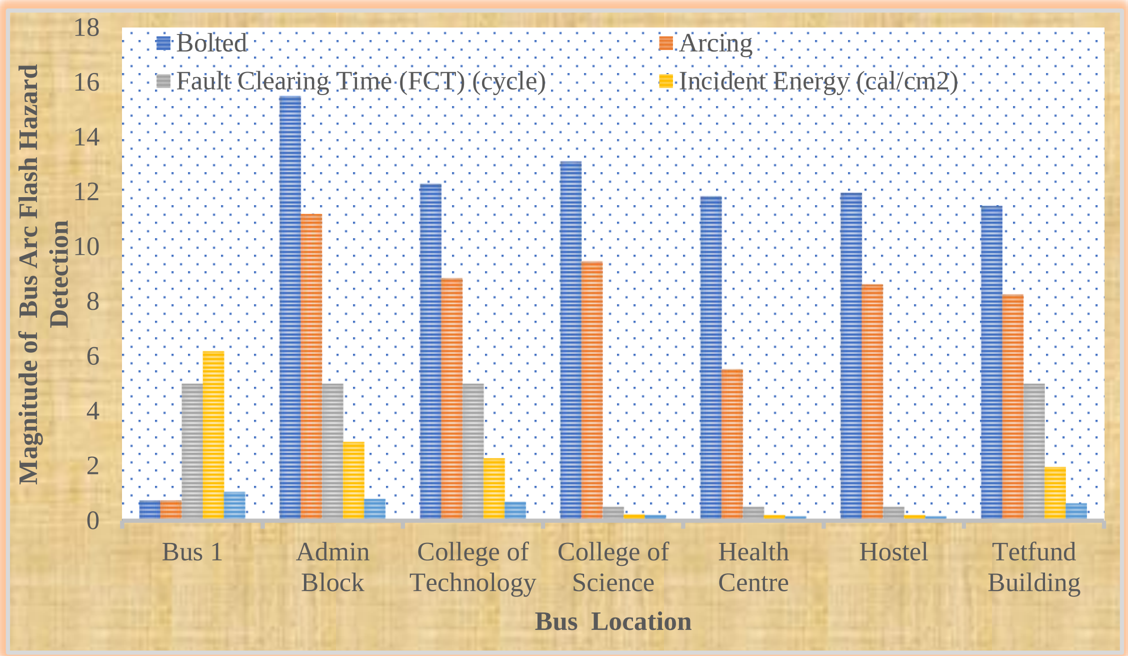

Fig. 5. Bus incident energy summary of total fault current and arc fault analysis results with respect to bus location.

According to our findings, the Admin Block has the highest total fault current with an arcing value of 11.197 and a bolted fault of 15.490, followed by College of Science with an arcing value of 9.460 and a bolted fault of 13.106. Bus 1 has the lowest arcing value of 0.735 and a bolted fault of 0.735 but with the highest incident energy of 6.180, followed by Admin Block with incident energy of 2.868, while Health Center and Hostel had the lowest incident energy of 0.194 and 0.196, respectively. Arc-Flash Hazards are classified into five Hazard Risk Categories by NFPA 70E, Standard for Electrical Safety in the Workplace.

Bus 1 seems to have a hazard risk category of 2 with an energy level of C, Admin Block has a hazard risk category of 1 with an energy level of B, and the Health Center and Hostel both have a hazard risk category of 0 with an energy level of A.

When such an arc fault occurs, the bolted fault accompanies it, indicating a short circuit with no electrical resistance at the point of the fault. The bus arc flash hazard detection summary is shown in Table 5.

Table 5. Bus arc flash hazard detection summary.

Faulted Bus				FCT (cycle)	Arc Flash Boundary (m)	Incident Energy (cal/cm^2)	Working Distance (cm)	Energy Level
ID	Nominal kV	Equipment Types	Gap					
Bus 1	33.000	Open Air		5.000	**1.0**	6.2	46	C
Bus 2	11.000	Open Air	152	5.000	0.8	0.3	46	**A**
Admin Block	0.415	Panel Board	25	5.000	**0.2**	2.9	46	**B**
College of Technology	0.415	Panel Board	25	5.000	**0.7**	2.3	46	**B**
College of Science	0.415	Panel Board	25	0.500	0.2	0.2	46	**A**
Health Centre	0.415	Panel Board	25	0.500	0.1	0.2	46	**A**
Hostel	0.415	Panel Board	25	0.500	0.1	0.2	46	**A**
Tetfund Building	0.415	Panel Board	25	5.000	**0.6**	1.9	46	**A**

Figure 6 depicts the Bus Arc Flash Hazard Detection Summary in relation to Bus Location. According to our findings, Bus 1 has the highest Arch Flash boundary and Incident energy of 1.0m and 6.2 cal/cm^2 with a working distance of 46 cm, preceded by Admin Block with Arch Flash boundary and Incident energy of 0.2 m and 2.9 cal/cm^2 with a working distance of 46 cm, and College of Science, Health Center, and Hostel with the lowest Highest Arc Flash boundary and Incident energy of 0.1meter and 0.2 cal/cm^2 with a working distance of 46 centimeter, respectively. For clarity, Figure 7 is only utilized to display the lowest incidence energy, arc flash boundary, and fault current time of the college of science, health center, and hostel. Strict safety measures must be adhered to when working in those zones with higher alert bearing in mind their impact when ignored.

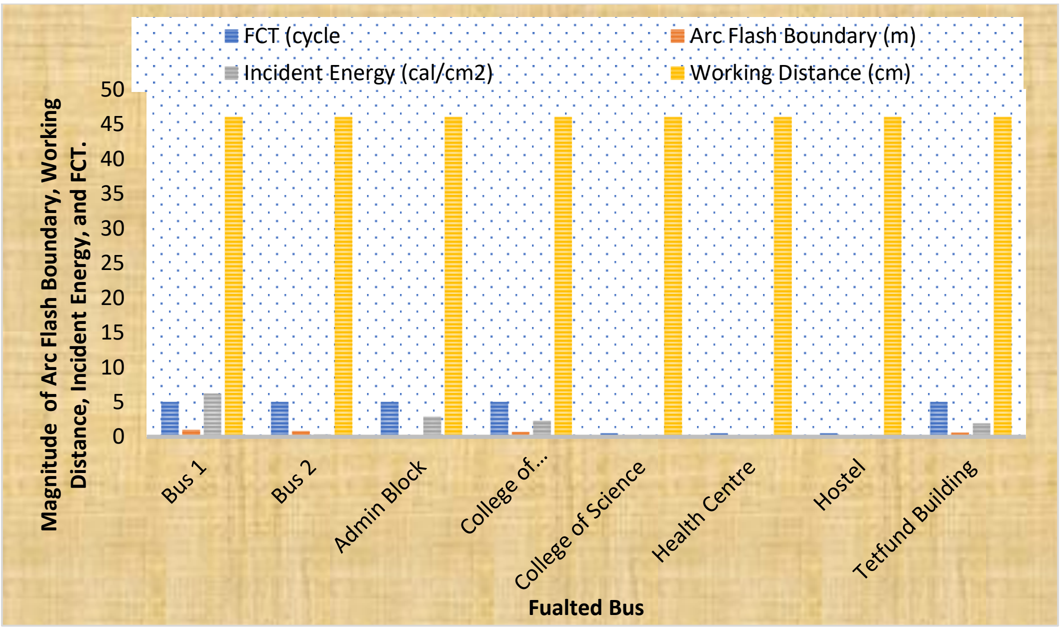

Fig. 6. Bus arc flash hazard detection summary with respect to bus location.

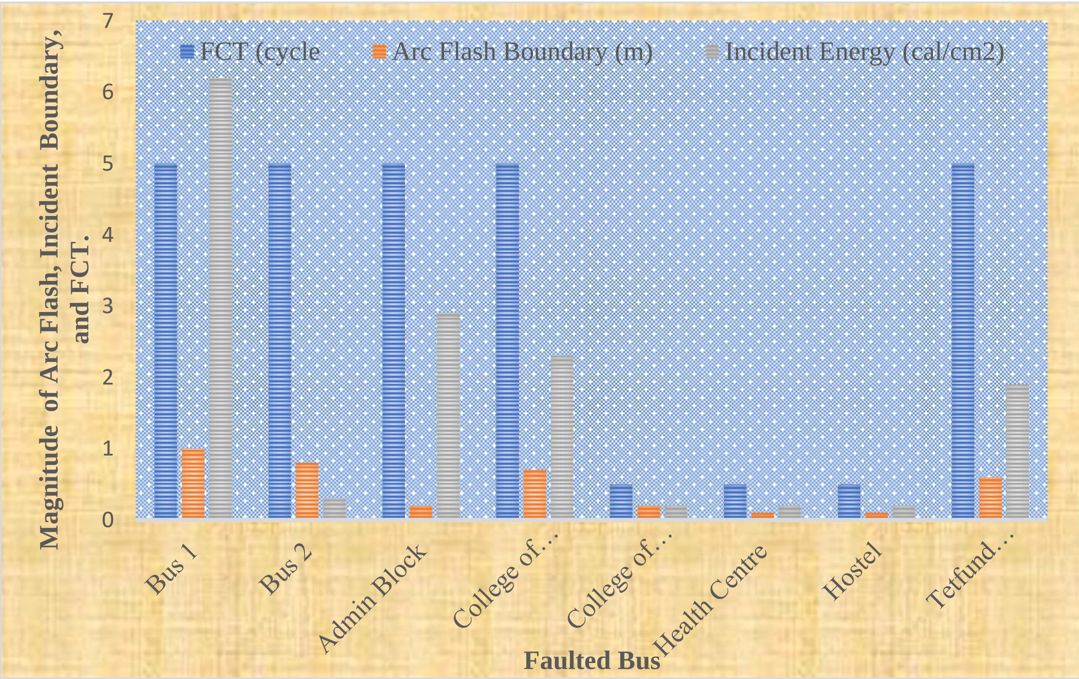

Fig. 7. Bus arc flash hazard detection summary with respect to bus location.

4. CONCLUSIONS

The purpose of this paper is to look into the safety issues surrounding the FUPRE distribution network, as well as the steps that are being taken by the management of the university to ensure that all employees' health and safety practices are strongly adhered to. Data were collected from the appropriate authority while ETAP software was used to analyse the system to validate our findings. This has helped to shed light on the risk detection, control methods and mechanisms used in the FUPRE distribution network. This analysis also demonstrated the efficacy of the FUPRE distribution network's safety practices. When implemented, it will further improve the various existing safety measures in the university community.

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