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RELIABILITY ASSESSMENT OF POWER EQUIPMENT IN A DISTRIBUTION SUBSTATION USING FAULT TREE ANALYSIS

A. J. Adelabu, Y. S. Haruna and U. O. Aliyu

Department of Electrical and Electronics Engineering
Abubakar Tafawa Balewa University, Bauchi-Nigeria.

Corresponding Author: getademola@yahoo.com

ASTRACT: This paper presents the reliability assessment of power equipment in a distribution substation using fault tree analysis (FTA) technique. The 33/11kVAnglo-Jos distribution substation of the Jos Electricity Distribution PLC was used as the case study for this research. The aim of the research is to analyze the reliability of power equipment in a distribution substation by using fault tree analysis. The data recorded in the substation's log book was used as the field data for this research work. The field data includes frequencies of failures of power equipment in the substation and their respective durations of failures. The single line diagram and the fault tree diagram of the power equipment in the distribution substation was constructed. The FTA model showed the logical arrangement of the basic events in hierarchical form leading to the desired top event. The qualitative fault tree analysis was done to determine the minimal cuts of the basic events that could lead to the top event by using Boolean algebra and probability expressions. The quantitative fault tree analysis was carried out to determine the mean time between failures (MTBF), mean time to repair (MTTR) and unavailability of each power equipment by using reliability expressions. The power equipment with the best MTBF and MTTR were also identified and discussed. This paper identified the power equipment that should be upgraded so as to achieve reliable distribution substation and guarantee improved electricity delivery to consumers.

Keywords: Power Equipment, Reliability, Fault tree Analysis and Distribution Substation.

I.

I. INTRODUCTION

Electricity is the hub of both economic and technological development. More important is the fact that every other sector of the economy depends on adequate supply of electricity. Poor state of electricity supply in Nigeria has imposed significant costs on the manufacturing sector. The bulk of these costs relate to the firms' acquisition of very expensive backup capacity to cushion them against the even larger losses arising from frequent and long power fluctuations. Small-scale operators are more heavily affected by the power outage as they are unable to finance the cost of backup power necessary to mitigate the impact of frequent outages [1].

Due to lack of efficiency in the power sector in Nigeria, the Nigerian Electricity Supply Industry (NESI) was unbundled into eighteen companies comprising of 6 generating companies (GENCOs), 1 transmission company (TRANSYSCO) and 11 distribution companies (DISCOs). The intention of this metamorphosis was to ensure improved system reliability, but this is very difficult to achieve because of the poor system maintainability that has been occurring for a very long time. The issue of maintenance of electric power equipment is of paramount national interest [2].

The electric power distribution substations are the most critical part of a power system because the power equipment in the distribution substation connects the consumers to the power grid. A substation reliability assessment evaluates the effect of these aspects on the service continuity of the main power system connected to the substation [3]. With increasing demand for electricity supply, the distribution companies have to achieve an acceptable level of reliability, quality and safety at an economic price in order to guarantee improved electricity delivery and maintain consumer's loyalty [4].

II. LITERATURE REVIEW

This paper focuses on the use of fault tree analysis (FTA) method to perform the reliability assessment of power equipment in a distribution substation. A fault tree translates the failure behavior of a physical system into a visual diagram and a logical model [5]. Fault Tree Analysis (FTA) was originally developed in 1962 at Bell Laboratories by H.A Watson, under a U.S Air Force Ballistics Systems Division contract to evaluate the Minuteman I Intercontinental Ballistic Missile (ICBM) Launch Control System [6]. The use of fault trees has since gained wide-spread support and is often used as a failure analysis tool by reliability experts. Following the first published use of FTA in the 1962 Minuteman I Launch Control Safety Study, Boeing and AVCO expanded use of FTA to the entire Minuteman II system in 1963-1964 [7]. The Boeing Company improved the technique and introduced computer programs for both qualitative and quantitative fault tree analysis. At the 1965 Safety Symposium, sponsored by the University of Washington and the Boeing Company, several papers were presented that expounded the virtues of fault tree analysis.

The presentation of these papers marked the beginning of the wide-spread interest in using fault tree analysis as a system safety and reliability tool for complex dynamic system such as nuclear reactors [8]. Since 1960, great efforts have been made in solving fault trees to obtain reliability information about complex systems. Following the lead of the aerospace industry, the nuclear power industry discovered the virtues and benefits of fault tree analysis, and began using the tool in the design and development of nuclear power plants [9]. Many key individuals in nuclear power industry contributed to advancing fault tree theory and fault tree software codes. In fact, the nuclear power industry may have contributed more to the development of fault tree analysis than any other single user group. Many new evaluation algorithms were developed, along with software using these algorithms.

Today fault tree analysis is by far the most commonly used technique of risk and reliability studies. Fault tree analysis has particularly been used with success to analyze system in nuclear power station [8].

A. Reliability Expressions in Fault Tree Analysis

Reliability expressions are used in fault tree analysis to determine the failure rate probability of the basic and overall top events. The expressions include;

$$Failure\ rate, \lambda = \frac{Number\ of\ times\ failure\ occurred}{Number\ of\ unit - hours\ of\ operation} \quad \ldots (1)$$

$$R_{(t)} = e^{-\lambda T} \quad \ldots (2)$$

$$R_{(t)} + Q_{(t)} = 1 \quad \ldots (3)$$

$$Q_{(t)} = 1 - R_{(t)} = 1 - e^{-\lambda T} \quad \ldots (4)$$

$$Q_{(t)} = \lambda T = \frac{T}{MTBF} \quad \ldots (5)$$

$$MTBF = \frac{Total\ system\ operating\ hrs}{Number\ of\ failures} \quad \ldots (6)$$

$$MTTR = \frac{Total\ duration\ of\ outages}{Freguency\ of\ outage} \quad \ldots (7)$$

$$Failure\ frequency, f = \frac{1}{MTBF + MTTR} \quad \ldots (8)$$

$$Availability, A = \frac{MTBF}{MTBF + MTTR} \quad \ldots (9)$$

$$Unavailability = \frac{MTTR}{MTBF + MTTR} = \frac{f \times MTTR}{8760} \quad \ldots (10)$$

Where, $R_{(t)}$= Reliability
$Q_{(t)} = Failure\ Probability$
λ = failure rate
T = Average down time per failure
MTBF= Mean time between failures
MTTR = Mean time to repair and
8760 = Total hours for a year

III. MATERIAL AND METHODS

The procedure in carrying out reliability assessment of power equipment in 33/11kV Anglo-Jos distribution substation using fault tree analysis technique is shown in Figure 1. The line diagram of the 33/11kV Anglo-Jos distribution substation shows the single-line schematic principle of breakdown of 33kV coming from Makeri transmission substation to 11kV been distributed to consumers within Anglo-Jos axis and its environs. The single line diagram of the 33/11kV Anglo-Jos distribution substation can be seen in Figure 2. The fault tree diagram of the 33/11kV Anglo-Jos distribution substation shows the logical arrangements of power equipment in the distribution substation. It represents the combination of the power equipment and their contribution to the overall system unavailability. The fault tree diagram is represented in Figure 3.

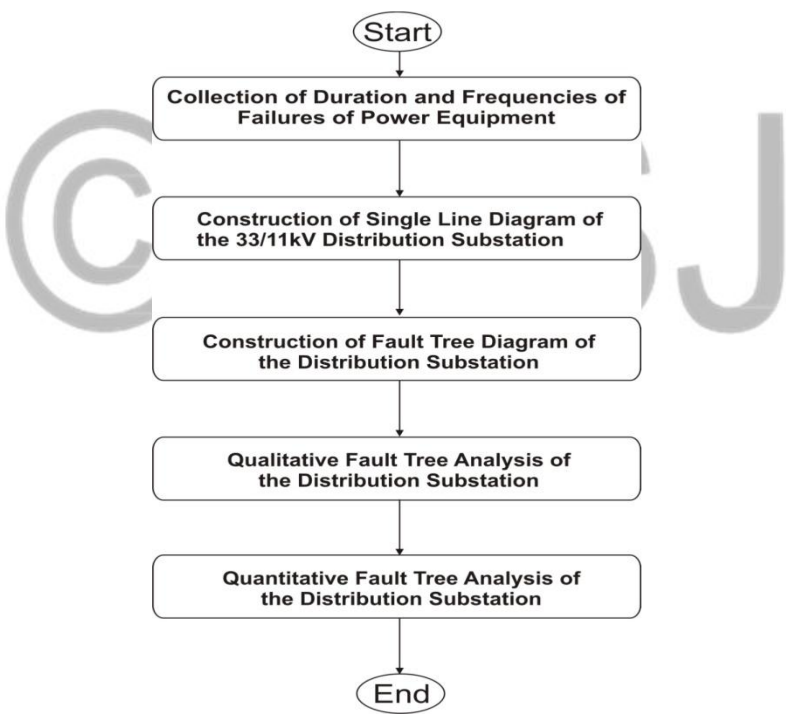

Figure 1: Outlined Procedure of Fault Tree Analysis of the 33/11kV Distribution Substation

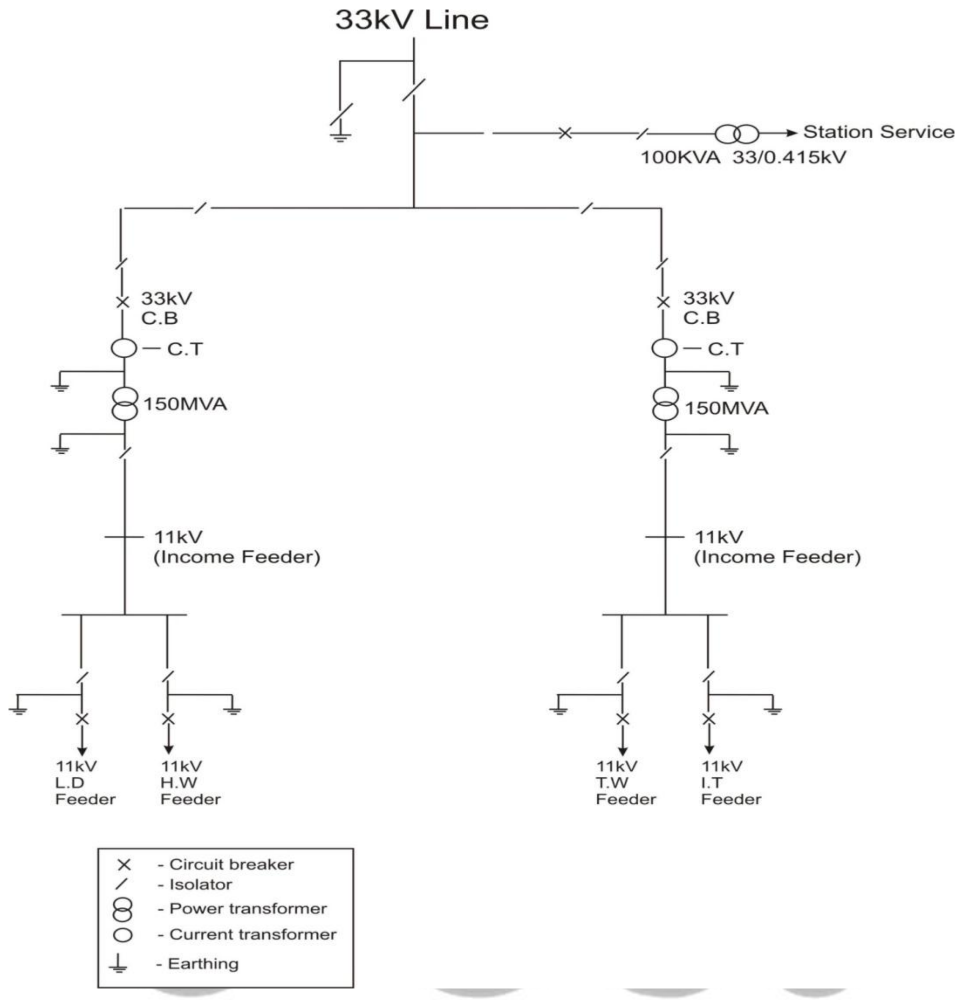

Figure 2: The Single Line Diagram of the 33/11kV Anglo-Jos Distribution Substation.

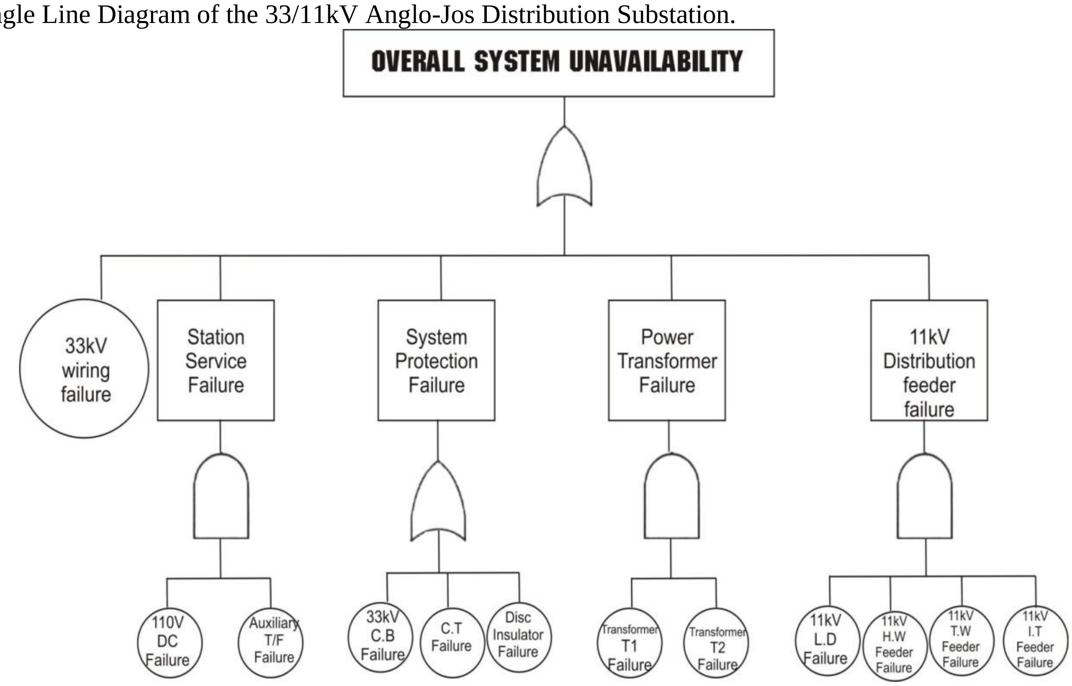

Figure 3: Fault Tree Diagram of the 33/11kV Anglo-Jos Distribution Substation.

IV. RESULTS AND DISCUSSIONS

The results of this paper showed the qualitative fault tree analysis and the quantitative fault tree analysis of the 33/11kV Anglo-Jos distribution substation. The log books were used as data received. The qualitative fault tree analysis was done using Boolean algebra and probability expressions. The quantitative fault tree analysis was done by using reliability expressions as shown in the literature review.

A. Qualitative Fault Tree Analysis Results

The purpose of performing the qualitative fault tree analysis is to determine the minimal cut sets that could easily lead to the overall system unavailability of power in the 33/11kV distribution substation.

Let:

F_a= 33kV wiring failure, F_b = Battery bank failure, F_c = Auxiliary transformer failure
F_d= 33kV circuit breaker failure, F_e = Current transformer failure, F_f= Disc insulator failure
F_g= Power Transformer T1 failure, F_h=Power Transformer T2 failure, F_i=11kV Liberty Dam feeder failure
F_j= 11kVHwolshefeeder failure, F_k= 11kVTudunwada feeder failure, F_l = 11kVIbrahim Taiwo feeder failure

The following failures can be calculated as;

$$\text{Station service failure} = (F_b \cap F_c) \quad \dots (11)$$

$$\text{System protection failure} = (F_d \cup F_e \cup F_f) \quad \dots (12)$$

$$\text{Power transformer failure} = (F_g \cap F_h) \quad \dots (13)$$

$$\text{11kV distribution feeder failure} = (F_i \cap F_j \cap F_k \cap F_l) \quad \dots (14)$$

$$\text{Overall system unavailability} = F_a \cup (F_b \cap F_c) \cup (F_d \cup F_e \cup F_f) \cup (F_g \cap F_h) \cup (F_i \cap F_j \cap F_k \cap F_l)$$
$$= F_a + (F_bF_c) + (F_d+F_e + F_f) + (F_gF_h) + (F_iF_jF_kF_l) \quad \dots (15)$$

The minimal cut sets are F_a, (F_bF_c), F_d, F_e , F_f, (F_gF_h) and $(F_iF_jF_kF_l)$. The list of the minimal cut sets can be seen in Table 1.

Table 1: List of minimal cut sets and their corresponding power equipment

S/No.	Cut Sets	Power Equipment
1	F_a	33kV wiring failure
2	F_bF_c	Battery bank failure and Auxilliary transformer failure
3	F_d	33kV circuit breaker failure
4	F_e	Current transformer failure
5	F_f	Disc insulator failure
6	F_gF_h	Power transformer T1 failure and Power transformer T2 failure
7	$F_iF_jF_kF_l$	11kV distribution feeders

B. Quantitative Fault Tree Analysis of the 33/11kV Anglo-Jos Distribution Substation

The data received were analyzed based on the power equipment used in the Anglo-Jos distribution substation. Durations of failure of each power equipment were extracted. Similarly, frequency of failure of each power equipment were extracted. These data were extracted for a period of one year (January 2016 to December2016). The tabulated results are analyzed in Table 2.The comparison of the failure frequencies (F), duration of failures (T), mean time between failures (MTBF), mean time to repair (MTTR) and unavailability of power equipment were done as listed in Figures 4 to 8.

Table 2: Analysis of the Power Equipment in Anglo-Jos Distribution Substation in 2016

S/No.	Power Equipment	Frequency (F)	Duration (Hrs)	MTBF (Hrs)	MTTR (Hrs)	Unavailability 10^{-4}
1	33 kV Line	29	70	299.6551	2.4137	7990
2	Auxiliary Transformer	22	45	396.1363	2.0454	5136
3	110 V DC Battery Bank	5	36	1744.8000	7.2000	4109
4	33 kV Circuit Breaker	2	2	4379.0000	1.0000	228
5	Current Transformer	1	1	8759.0000	1.0000	114
6	Disc Insulators	10	12	874.8000	1.2000	1369
7	Power Transformer T1	11	40	792.7272	3.6363	4566
8	Power Transformer T2	3	11	2916.3333	3.6666	1255
9	11 kV Liberty Dam Feeder	86	264	98.7906	3.0697	30136
10	11 kV Hwolshe Feeder	40	84	216.9000	2.1000	9589
11	11 kV Tudun Wada Feeder	48	117	180.0625	2.4375	13356
12	11 kV Ibrahim Taiwo Feeder	53	94	163.5094	1.7735	10730

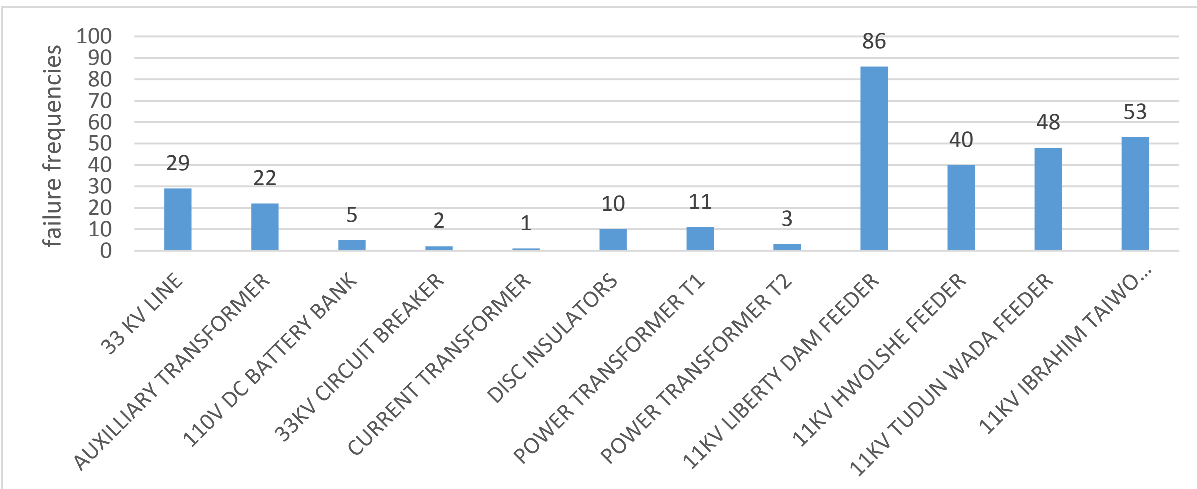

Figure 4: Comparison of Frequencies of Failures of Power Equipment in 33/11kV Anglo-Jos Distribution Substation in Year 2016

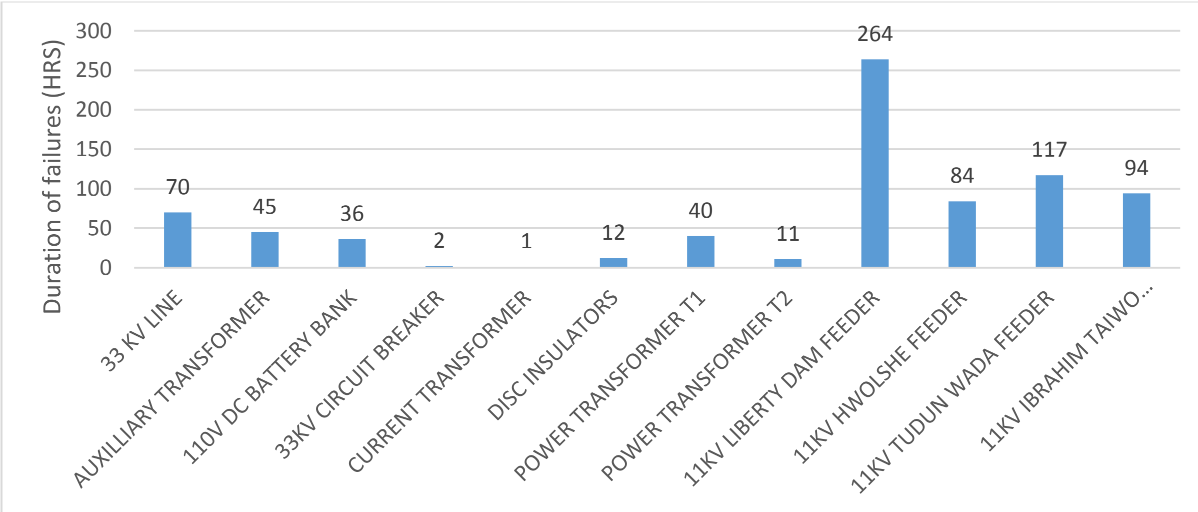

Figure 5: Comparison of Duration of Failures of Power Equipment in 33/11kV Anglo-Jos Distribution Substation in Year 2016

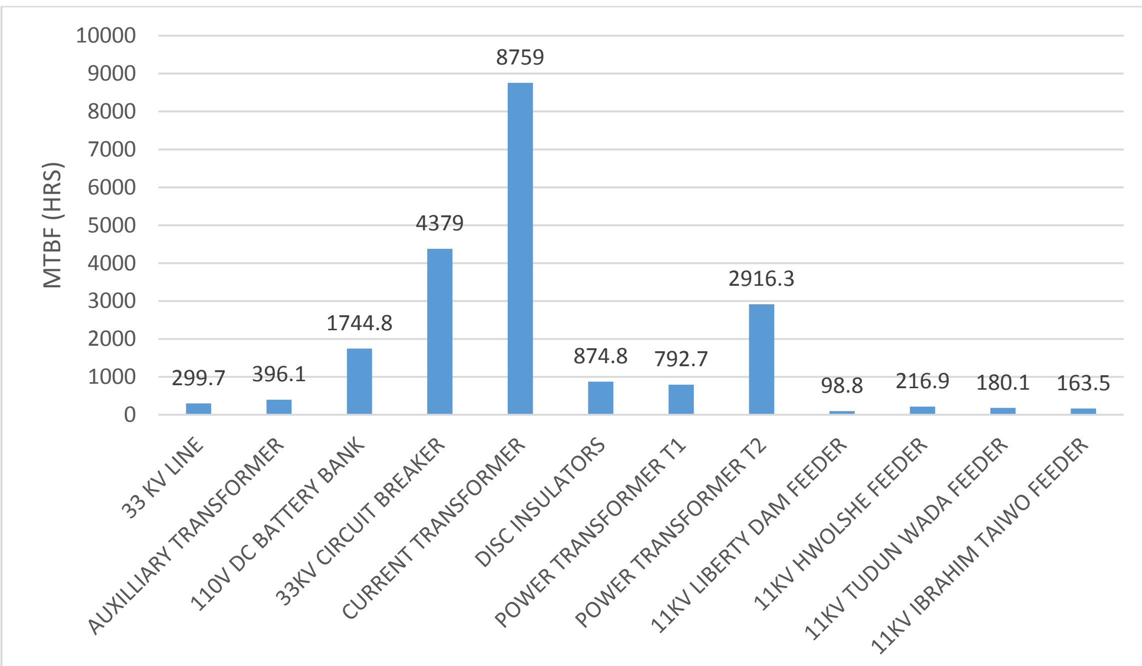

Figure 6**:** Comparison of Mean Time Between Failures (MTBF) of Power Equipment in 33/11kV Anglo-Jos Distribution Substation in Year 2016

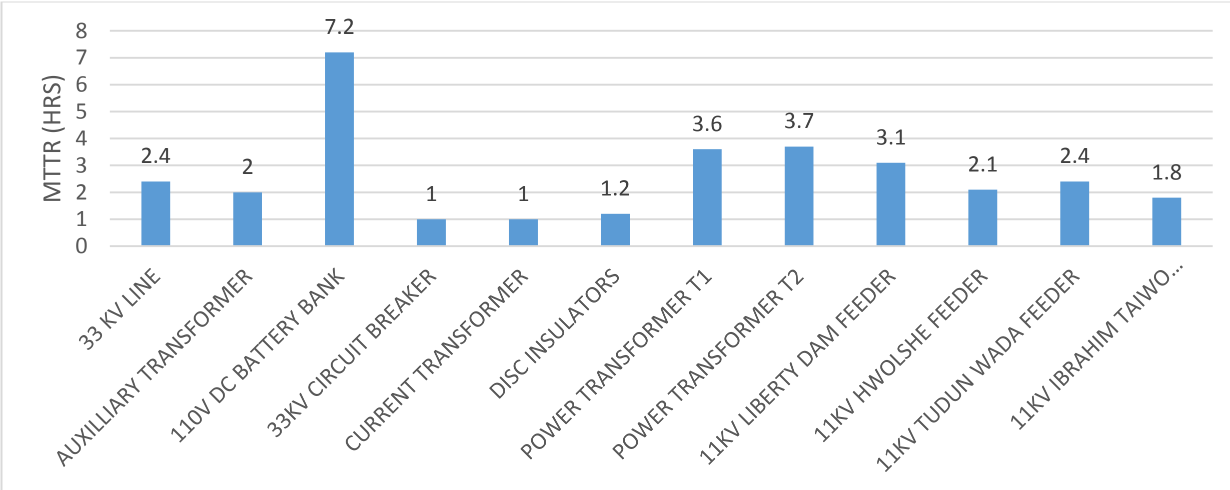

Figure 7: Comparison of Mean Time to Repair (MTTR) of Power Equipment in 33/11kV Anglo-Jos Distribution Substation in Year 2016

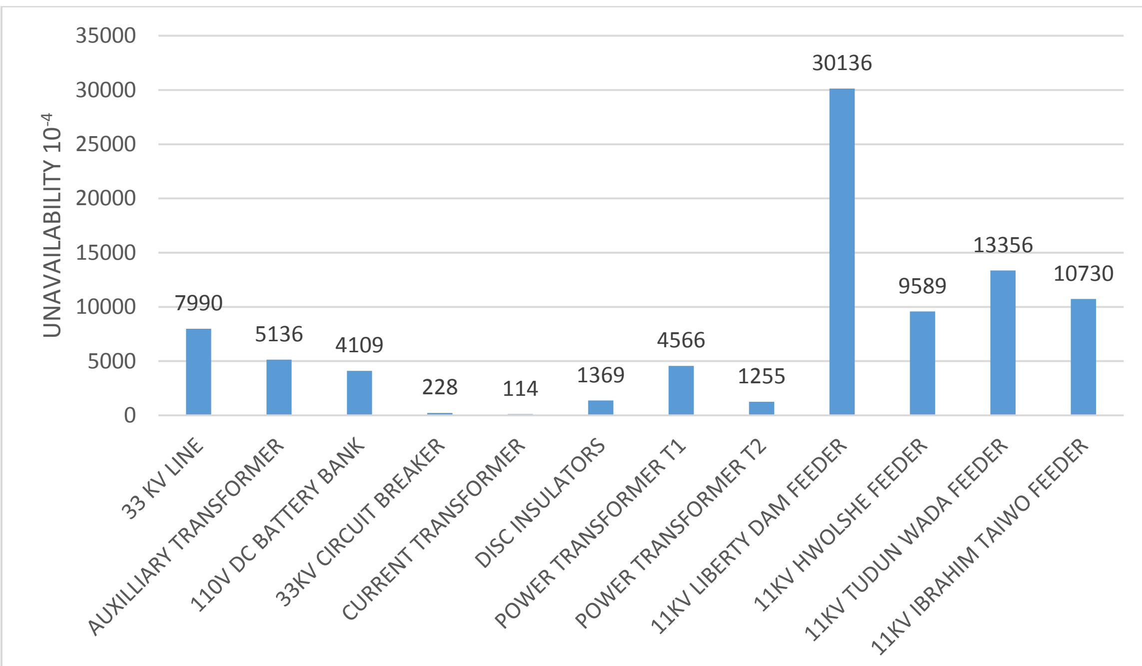

Figure 8: Comparison of Unavailability of Power Equipment in 33/11kV Anglo-Jos Distribution Substation in Year 2016

C. Discussions of Results

Figure 4 showed that 11kV liberty dam feeder had the highest number of failure in the year 2016. Figure 5 showed that 11kv liberty dam feeder had the highest duration of failures in the year 2016. In general, 11kV liberty dam feeder had the highest number of failures and duration of failures within the period. It is therefore necessary to work on the causes of failures of the 11kV liberty dam feeder in order to improve the reliability of the distribution substation.

Figure 6 showed that the current transformers had the highest mean time between failures (i.e above 8759 hours) within the period reviewed. This means that the current transformers can work for an average of 8759 hours before it fails. The 11kV liberty dam feeder had the least mean time between failures (i.e below 99 hours) within the period reviewed. This means that 11kV liberty dam feeder cannot efficiently work for 99 hours without developing a fault.

Figure 7 showed that the 110V DC battery bank had the highest mean time to repair within the period reviewed. This means that the 110V DC battery bank is not been repaired or fixed for a long period of hours (i.e 7.2 hours) whenever it fails. Figure 8 showed that 11kV liberty dam feeder had the highest probability of unavailability among the power equipment used in the distribution substation. The results also showed that 33kV circuit breaker and the current transformer had the least probability of system unavailability.

V. CONCLUSION

The aim of this paper is to perform a reliability assessment of power equipment in a 33/11kVdistribution substation using fault tree analysis technique. The single line diagram of the distribution substation showed the power equipment in the substation and their arrangement in breaking down the 33kV to 11kV for the purpose of delivering power to consumers. The fault tree diagram showed the logical arrangement of the power equipment and their contribution towards overall system unavailability.

The qualitative fault tree analysis showed the minimal cut sets that could easily lead to the overall system unavailability and the quantitative fault tree analysis has helped to identify the power equipment that are contributing majorly to system unavailability and these power equipment should be upgraded to obtain a better reliability of the system.

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