Indonesian Journal of Electrical Engineering and Informatics (IJEEI)
Vol. 10, No. 1, March 2022, pp. 165~176
ISSN: 2089-3272, DOI: 10.52549/ijeei.v10i1.3688

Reliability Evaluation of 33/11kv Olunde Injection Substation for Improved Performance

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Article Info

Article history:

Received Jan 29, 2022
Revised Mar 2, 2022
Accepted Mar 19, 2022

Keyword:

Realiabiltiy
Substation
Transformer
Circuit Breaker

ABSTRACT

Electric power supply reliability (PSR) is crucial in the present economy to avoid huge economic loss and life discomfort. Thus, there is need to improve PSR. Reliability evaluation of power equipment was carried out on Olunde 33/11kV Injection Substation using extracted and available five years data of Fault Frequency and Downtime of associated power equipment for 2016 to 2020 from the Injection Substation's log books. Fault Tree Analysis (FTA) Technique was used in this research. The existing Injection Power Substation results shows that the overall injection substation unavailability of power supply was 0.00672; 33kV NBL Feeder alone has the highest percentage of failure contribution 72.97% of the unavailability of the injection substation. The reliability improvement of the Injection Power Substation using doubling maintenance activities method on the NBL 33kV feeder shows that the overall injection substation unavailability improved from 1:1.57; the NBL 33kV feeder failure contribution reduced to 15.63%. Using a redundant feeder, 33kV feeder, the overall unavailability of the injection substation improved from 1:3.6; the NBL 33kV failure contribution reduced to 1.31%. The redundant feeder approach in this work is highly significant since it is better than the doubling maintenance activities method.

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1. INTRODUCTION

Electrical energy supply is the process of transporting energy from generating point to consumption point through transmission and distribution networks [1, 2]. Electrical energy is essential to the development and economic growth of any country [3].

Electricity in Nigeria is generated at 16kV and stepped up to 330kV at the power station for transmission and feed to the grid [4]. Power grid is an electrical network transferring electricity from suppliers to consumers [5]. Transmission of electrical power is made efficient by transmitting at high voltage which is associated with reduced current for the purpose of reducing power loss along the transmission lines [1]. 330kV voltage which is transported along the primary transmission lines is stepped down to 132kV at the Transmission station by power transformers. 132kV flows through secondary transmission lines to sub-transmission substations where it is stepped down to 33kV and feeds the injection substations. The 33kV voltage is stepped down at the injection substation to 11kV which feeds the distribution transformers, stepping it down to 0.415kV (3 phase).

According to [6, 7] injection substation is a primary distribution substation where a higher voltage, like 33kV, is stepped down to 11kV for distribution, typically in a densely populated area. The creation of Olunde 33/11kV Injection Substation aimed at boosting the electric power supply in Olunde and Olomi communities, Ibadan, Oyo State, Nigeria. These two communities take power supply from the injection substation under consideration in this research and they host the headquarters of Akorede Local Council Development Area and the newly constructed National Correctional Centre (NCC) respectively. In recent times, the two communities suffer considerably from unreliable power supply which adversely affects commercial and residential activities. It is noteworthy that the purpose of establishing electric power stations is to meet upelectricaldemand of the end users and this is jeopardized when it fails to benefit these users as a result of incessant power outage. Reliability of electric power supply is crucial in the world of digital economy where a few minutes shortfall in the supply of electricity can result in huge economic loss and life discomfort. Unreliable electric power supplyreducestheinterestofinvestors in a country duetohigh costs of production which results in increase rate ofunemployment as well as broadening the poverty range of such a country [8]. Therefore, irregular supply of electricity is directly proportional to the inability of the end users to predict when it will be available for consumption [9]. Statistics of power supply showed that the distribution network makes the topmost contribution to the failure of electric power supply to customers [10]. The shortfalls in the supply of electricity can be minimized if not completely eradicated when the various types of equipment elements are performing their desired purposewhen needed. A failure or malfunctioning of power equipment can causepower failure toloads [11]. The benefits of power equipment are of great importance in satisfactory performance and long survival of the equipment. It is therefore pertinent to find means of determining the contribution of failure of power equipment in the injection substation to overall unavailability of the station as this will help in the criticality ranking of the power equipment and facilitate prioritization of maintenance of Olunde injection substation's power equipment for reliability improvement.

According to the [12] reliabilityis the adequate permance of a system designed function under required time without failure. According to [13] power system reliability is a measure of whether users have electricity at the required time. System reliability is the ability ofthe power system to provide adequate supply of electricalpoweratadesiredtimewithoutinterruption [8, 14]. Power system reliability can be grouped into two domains namely system adequacy and system security [15]. System Adequacy is the existence of sufficient facilities in the system to suit the consumer power demand with reference to continuous supply of electricity during or after a little interruption while System Security relates to the response of the power system to disturbances arising within the power system.

This research work determined the failure contribution of the various types of power equipment in Olunde 33/11kV injection substation, Figure 1, to the overall substation unavailability of power supply using a Fault Tree Analysis (FTA) Technique. The technique further provides reliability improvement measures [16].

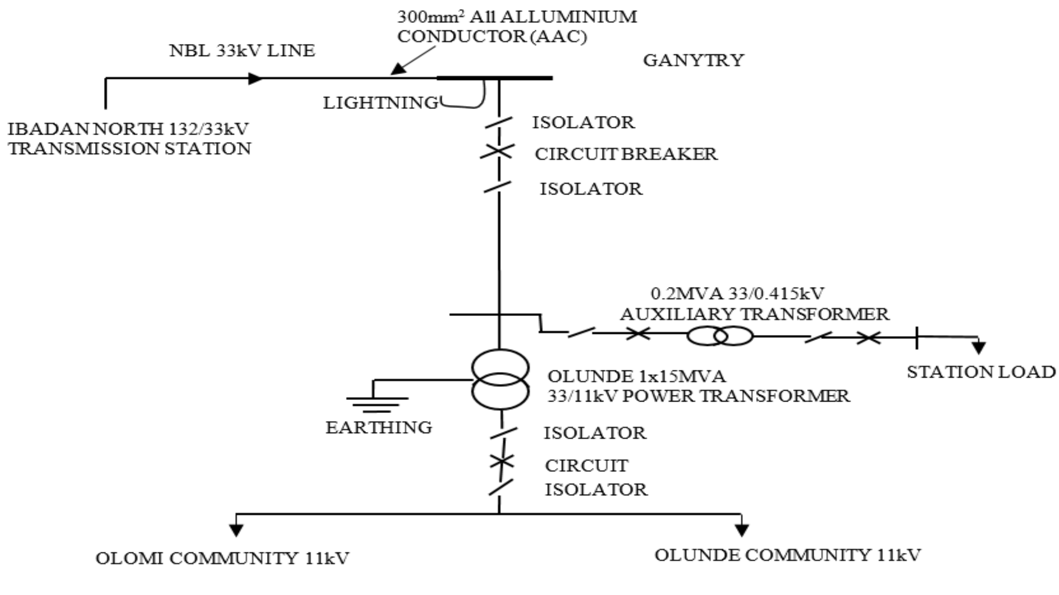

Figure 1. Single line diagram of Olunde 33/11kV injection substation

2. RESEARCH METHOD
2.1. Data Collection
Reliability evaluation of power equipment was carried out on Olunde 33kV Injection Substation. Available five years data of Fault Frequency and the Downtime of power equipment associated with the substation for 2016 to 2020 were extracted from the station's records [17, 18, 19, 20, 21] as is presented in Table 1.

Table 1**.** Power Equipment Fault Frequency and Down time for Five Years

S/N	POWER EQUIPMENT	FAULT FREQUENCY					DOWN TIME(HRS)				
		2016	2017	2018	2019	2020	2016	2017	2018	2019	2020
1	NBL 33kV Feeder	28	39	68	56	89	86	92	107	88	116
2	Power Transformer	1	3	2	4	2	4	7	12	21	7
3	Auxiliary Transformer	8	11	6	9	8	16	23	19	14	12
4	120V DC Supply	4	3	5	3	4	5	9	14	8	15
5	33kV Circuit Breaker	7	12	9	13	12	21	32	26	36	48
6	Current Transformer	1	2	0	3	2	1	4	0	2	3
7	Potential Transformer	1	2	3	2	2	1	5	4	3	2
8	Earthing System	3	2	5	1	2	7	5	12	1	6
9	Olomi 11kV Feeder	56	87	123	112	123	98	178	231	189	275
10	Olunde 11kV Feeder	47	96	82	106	126	82	134	190	187	216

2.2. Construction a Fault Tree Diagram
ReliotechTopEvent FTA Software [22] was used to construct the Fault Tree Diagram (FTD) for the major power equipment in the injection substation under consideration. Construction in the software was begun at the top level where the top unwanted event to be analyzed was defined as Olunde Injection Substation Unavailability of power supply (OISSU). The intermediate and Basic Events which caused the top event were connected using logic gates.

2.3. Assessment of the Fault Tree Diagram
2.3.1. Qualitative Fault Tree Diagram Assessment
Equations 1 and 2 were used to carry out qualitative Fault Tree Diagram Assessment and the Minimal Cutsets, MCS of the power equipment that lead to the Top Event were obtained.

$$\text{OISSU(Top Event)} = \sum_{i=1}^{K} MCS_i \qquad [23] \qquad (1)$$

where MCSi is*ith* minimal cut set and *k* is MCSnumber.

A minimal cut set comprises specific basic events.

Generally, *n*-equipment minimal cut set is given by equation (2).

$$MCS_i = \prod_{i=1}^{n} X_i \qquad [23] \qquad (2)$$

where *Xi* is *ith* basic event and *n* is number of basic events in a minimal cut set.

2.3.2. Quantitative Fault Tree Diagram Assessment
Quantitative FTD assessment in this research work was carried out using equations 3-9.

$$\text{Mean time to repair (MTTR)} = \frac{\textbf{Total downtime (Hours)}}{\textbf{Fault frequency}} \qquad [24] \qquad (3)$$

Mean Time Between Failure (MTBF)= $\frac{\textbf{Total system operating hours}}{\textbf{Number of failures}}$ [25] (4)

Failure Rate (λ)= $\frac{\text{Fault frequency}}{\text{Total system operating hours}}$ [24] (5)

$$q(t) = \frac{\lambda}{\lambda+\mu}\left(1 - e^{-(\lambda+\mu)t}\right)$$ [22] (6)

$$\mu = \frac{1}{\text{MTTR}}$$ [22] (7)

$$\lambda = \frac{1}{\text{MTBF}}$$ [22] (8)

Q(t) = E1+ (E3. E4) + (E5+ E6+E7+ E8) +E2+ (E9.E10.E11) (9)

where: $q(t)$ is the Equipment unavailability, μ is the Equipment Repair Rate, E1 to E11 are the cut sets, Q(t) is the Overall Injection Substation Unavailability (OISU)
NB: results of equations 3, 4 and 5 were input into FT software.

2.3.3. Determination of failure contribution of the power equipment

The results of the power equipment unavailability were used in Reliotech FT software to determine the Minimal Cutset (MCS) failure contributions, and three Importance Measures (IM), for the power equipment using equations 10 -14.

2.3.3.1. Minimal CutSet

MCS Failure contribution = $\frac{\text{Unavailability of a MCS}}{\text{Sum of all MCS unavailabilities}}$ x 100% (10)

2.3.3.2. Importance Measures

Three Importance measures were obtained for the power equipment using equations 11-13.

i. Critical Important Measure, CIM,

CIM= $\frac{\Pr(\text{Any MCS Containing Event x})}{\Pr(\text{Top Event})} = \frac{Q(t) - Q(t)|qx=0}{Q(t)} = \frac{Q(t)|qx=1}{Q(t)}$ [22] (11)

ii. Marginal Important Measure, MIM,

MIM= $\frac{\textbf{Pr(Top Event)}}{\textbf{Pr(Event x present)}} - \frac{\textbf{Pr(Top Event)}}{\textbf{Pr(Event xNot Present)}} = Q(t)|qx = 1 - Q(t)|qx = 0$ [22] (12)

iii. Risk Reduction Worth, RRW

RRW= $\frac{Q(t)}{Q(t)|qx=0}$ [22] (13)

Percentage values of IM for the Power Equipment was obtained using equation 14

$$\frac{\text{IM of Power Equipment}}{\text{Sum of IM}} \text{ x } 100\%$$ (14)

Q(t) is the Overall injection substation Unavailability, qx(t) is the unavailability of the Power Equipment x, $Q(t)|qx = 1$ is the overall injection substation unavailability with the occurrence of unavailability of power equipment x,
$Q(t)|qx = 0$ is the overall injection substation unavailability without the occurrence of unavailability of the power equipment x.

3. RESULTS AND DISCUSSION

In this section, the results of research are explained and at the same time is given the comprehensive

3.1. Fault Tree Diagram construction

The result of FTD construction is shown in figure 2.

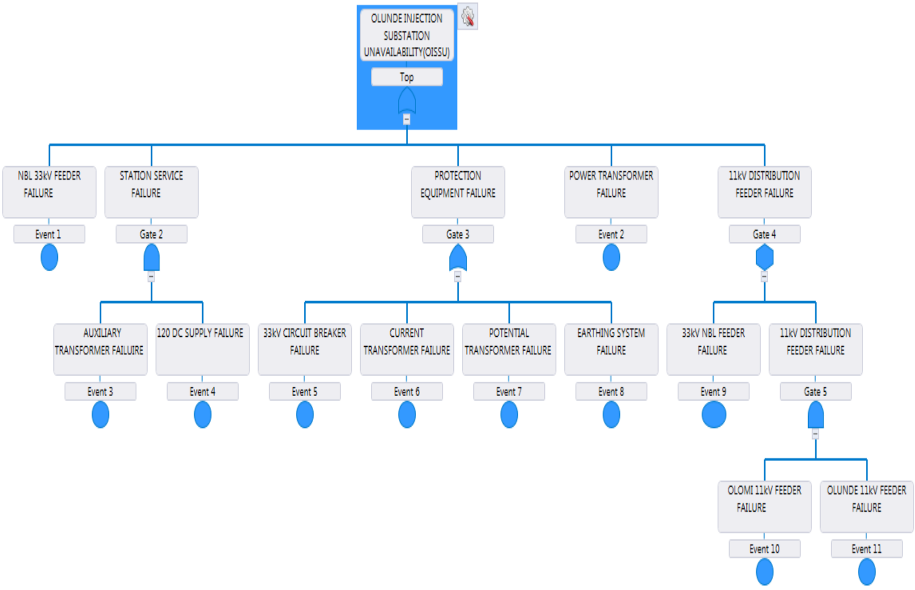

Figure 2: Logical Arrangement of the Substation Power Equipment

From Figure 2, the three intermediate events namely Station Service Failure (Gate 2), Protection Equipment Failure (Gate3), 11kV Distribution Feeder Failure (Gate4) and the two basic events, NBL33kV Feeder(Event1) and11kV Power Transformer Failure(Event2) each leads to the Unavailability of Olunde Injection Substation power supply. G2 will occur when both E3 and E4 occur, that is the Station Service fails when there are failures of the Auxiliary transformer and the !20V DC Supply. However, there is output of G3(Protection Equipment Failure) when any of E5, E6, E7 and E8 occurs, that is when there is failure of any of these four types of power equipment. There will be output in G4 when E9, E10 and E11 occur. E9 conditions event the output in gate G5.

3.2. Assessment of the Fault Tree Diagram(FTD)

3.2.1. Qualitative Assessment

The result of the Minimal CutSets obtained from the qualitative assessment of Figure 2 is presented in Table 2.

Table 2. Minimal CutSets and their Equivalent Power Equipment

S/NO	CUT SETS	EQUIPMENT(S)
1	E1	NBL 33kV Feeder Failure
2	E2	Power Transformer Failure
3	E3 . E4	Auxiliary Transformer and 120V DC Supply Failures
4	E5	33kV Circuit Breaker Failure
5	E6	Current Transformer Failure
6	E7	Potential Transformer Failure
7	E8	Earthing System Failure
8	E9. E10 .E11	33kV CndFdr and Olomi 11kV Distr. Feeder Failure and Olunde 11kV Distri. Feeder Failure

Each of the Minimal Cutsets leads to the unavailability of the injection substation.

3.2.2. Quantitative Assessment

From the Fault Frequency (FF) and the Downtime (DT) data on Table 2, average values of FF and DT were calculated and the results are presented in Figure 3.

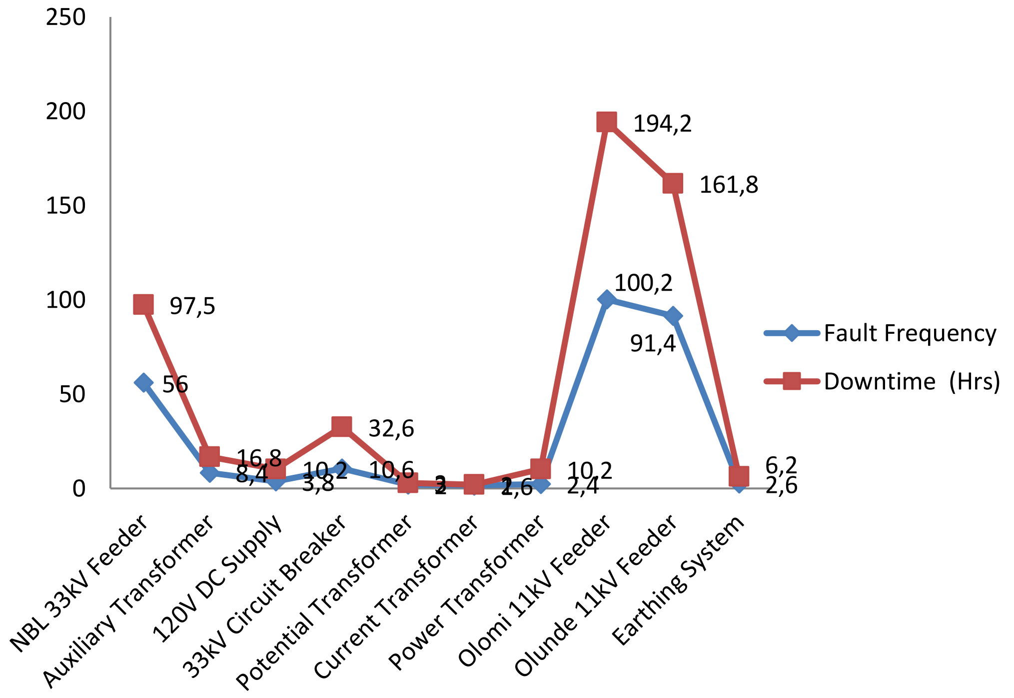

Figure 3. Average values of Fault Frequency and Downtime for the Power Equipment

From Figure 3, Olomi 11kV Feeder has the highest Fault frequency and the downtime; it is followed by Olunde 11kV Feeder; while the current Transformer has the least FF and DT. Also, from the same Figure 3, MTBF and MTTR values for the power equipment under review were calculated and the result is presented in Figures 4 and 5.

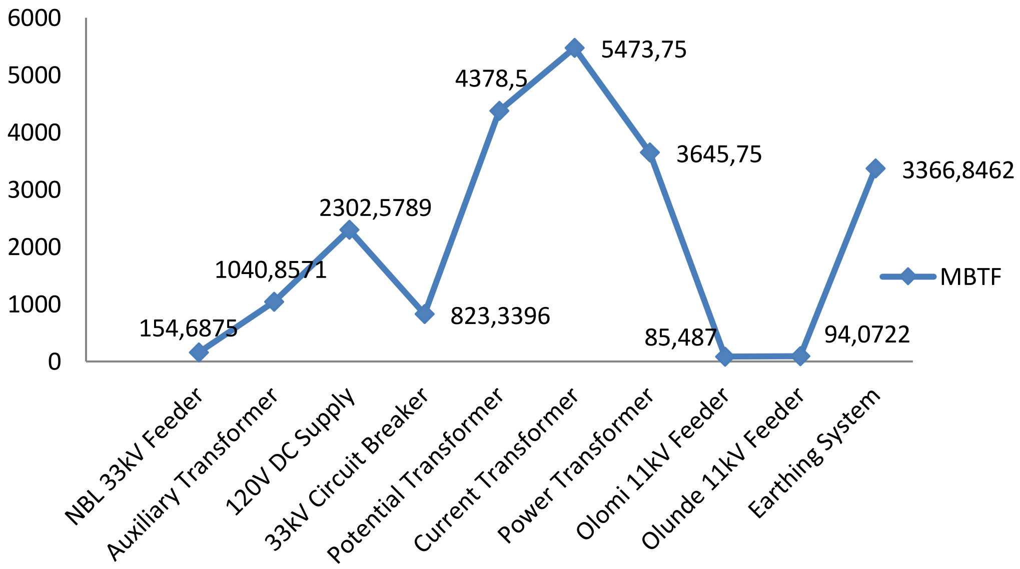

Figure 4. Mean Time Between Failure for The Power Equipment

From Figure 4, Current Transformer has the highest MBTF value, 5473.75. This means that the power equipment has the longest time of operation between failures. However, Olomi 11kV Feeder has the lowest value of MTBF.

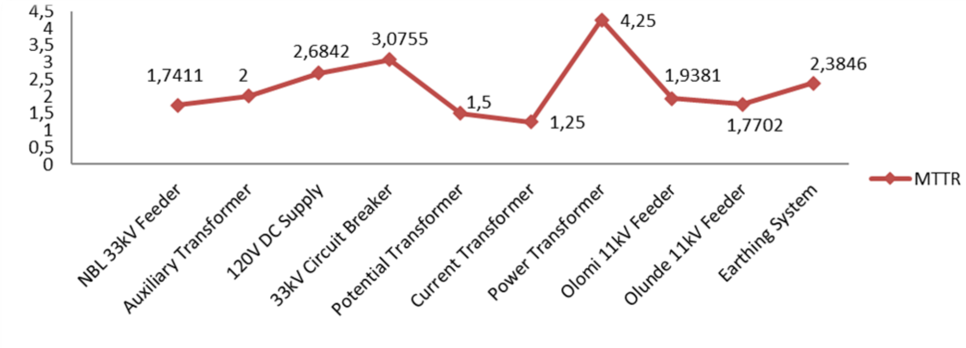

Figure 5. Mean Time to Repair for the Power equipment

From Figure 5, Power Transformer has the highest MTTR which indicates the longest period of time before the equipment operation restoration. The potential transformer has the fastest repair time.

From the values in Figures 4 and 5, unavailability of the power equipment was generated and the result is presented in Figure 6.

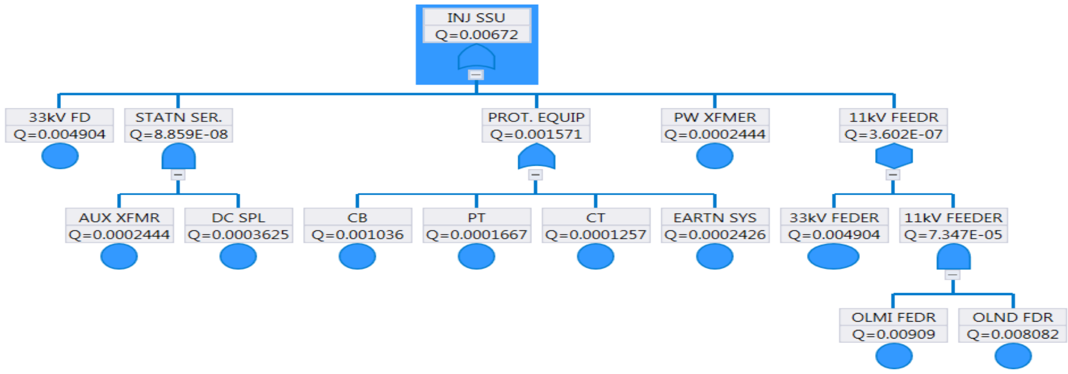

Figure 6. Fault Tree Diagram For Unavailability of The Power Equipment

From figure 6, the Overall injection substation unavailability of power supply is 0.00672.

3.2.3. Determination of Failure contribution of the power equipment

From Figure 6, the percentage failure contribution of the Minimal Cutsets for the power equipment were determined and presented in figure 7.

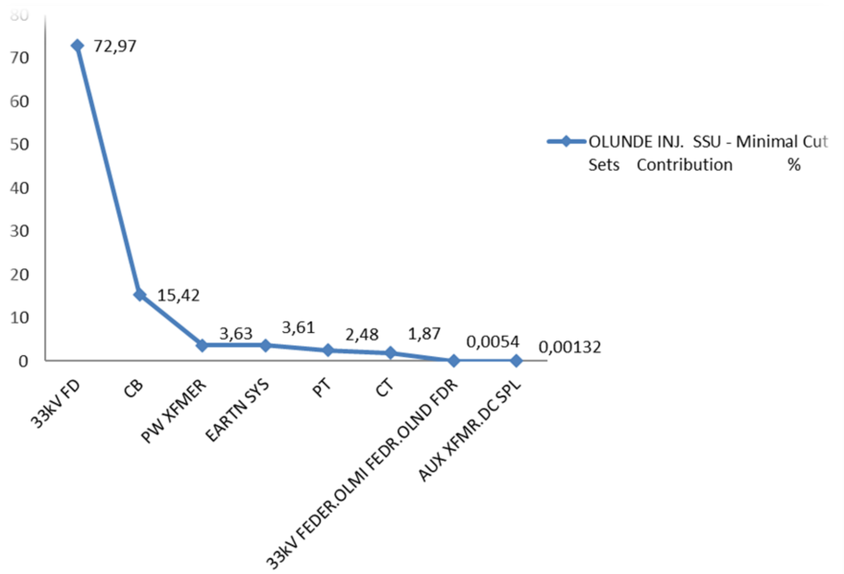

Figure 7. Percentage Failure Contribution of The Minimal CutSets for Olunde Injection Substation

From Figure 7, 33kV NBL Feeder has the highest percentage (72.97%) of failure contribution to the unavailability of the injection substation while AUX XFMR and120V DC SUPPLY has the least failure contribution of 0.00132%. Also from Figure 6, the percentage values of the Importance Measures were calculated and the result is presented in figure 8.

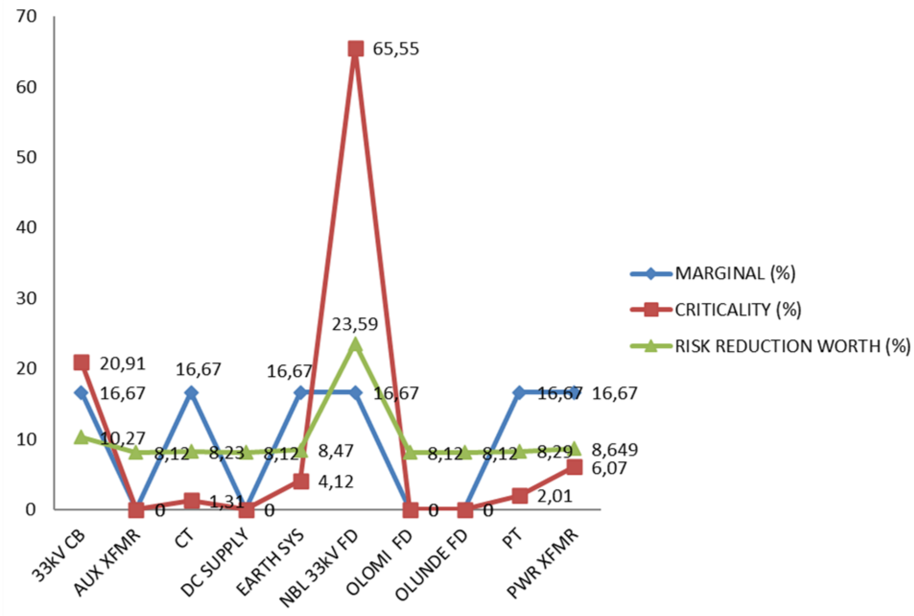

Figure 8. Three Important Measures

In Figure 8, 33kV CB, Current transformer, Earthing System, 33kV NBL Feeder, Power Transformer and Potential Transformer have Marginal Importance value of 16.67% each. This is an indication that each failure is significant in the overall injection substation unavailability. However, 33kV NBL Feeder again has the highest values for Criticality and Risk Reduction Worth of **65.55%** and **23.59%** respectively. This corresponds to the highest risk in the overall injection substation unavailability of power supply

3.3. Reliability Improvement

3.3.1. Doubling maintenance activities on the substation power equipment

Table 3 presents the values of MBTF, MTTR and the Failure rate of power equipment when the Fault Frequency (FF) and the Downtime (DT) for NBL 33kV Feeder were halved by doubling the maintenance efforts on the feeder due to its highest risk and the highest failure contribution.

Table 3. MBTF and MTTR with doubled maintenance activities method on NBL 33kV Feeder

S/N	POWER EQUIPMENT	Fault Frequency	Downtime (Hrs)	MBTF (Hrs)	MTTR (Hrs)	Failure Rate/Yr
1	NBL 33kV Feeder	28	48.75	311.1161	1.7411	0.00321
2	Auxiliary Transformer	8.4	16.8	1040.8571	2.0000	0.00096
3	120V DC Supply	3.8	10.2	2302.5789	2.6842	0.00043
4	33kV Circuit Breaker	10.6	32.6	823.3396	3.0755	0.00121
5	Potential Transformer	2	3	4378.5000	1.5000	0.00023
6	Current Transformer	1.6	2	5473.7500	1.2500	0.00018
7	Earthing System	2.6	6.2	3366.8462	2.3846	0.00030
8	Power Transformer	2.4	10.2	3645.7500	4.2500	0.00027
9	Olomi 11kV Feeder	100.2	194.2	85.4870	1.9381	0.01170
10	Olunde 11kV Feeder	91.4	161.8	94.0722	1.7702	0.01063

Considering half values of FF and DT for NBL 33kV Feeder, unavailability of the power equipment was geenerated using the Fault Tree Software and the result is presenred in Figure 9.

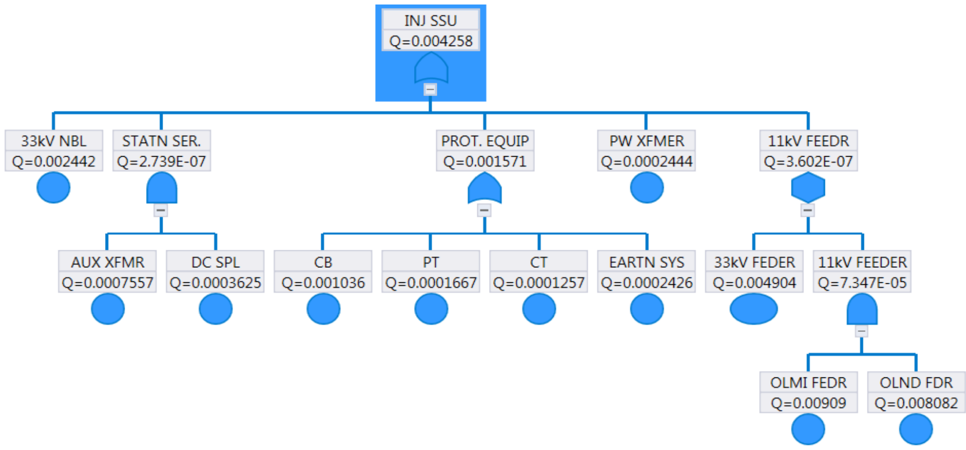

Figure 9. FTD with Doubling Maintenance Activities Method

From Figure 9, the overall unavailability of the injection substation reduced from **0.00672** to **0.004258** which correspond to **36.63%** reliability improvement in the overall injection substation.

From Figure 9, MCS failure contribution for doubling maintenance activities method is computed and result presented in Figure 10.

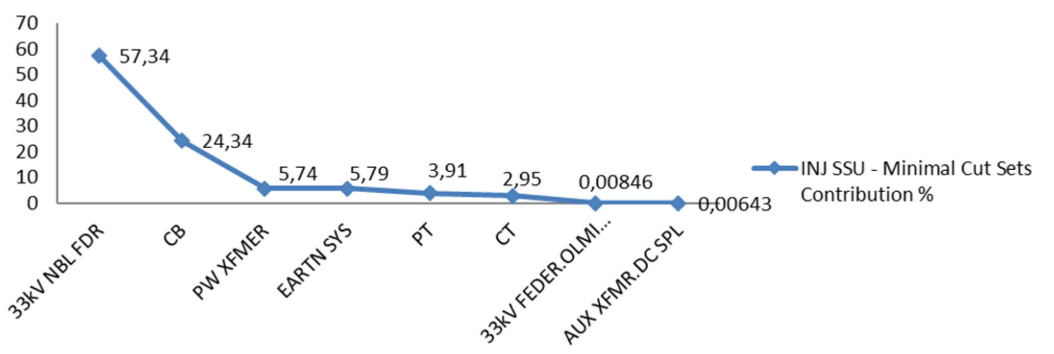

Figure 10. MCS Failure Contribution for Doubling Maintenance Activities Method On NBL 33kV Feeder

From Figure 10, the minimum CutSet failure contribution for the NBL 33kV Feeder reduced from **72.97%** to **57.34%** when the maintenance effort on the feeder was doubled. This indicates a little reduction **(15.63%)** in the failure contribution of the power equipment.

3.3.2. Introduction of a new basic event (33kV Redundant Feeder) for Reliability Improvement of the injection Substation

The unavailability of the power equipment was computed and the result is presented in Figure 11.

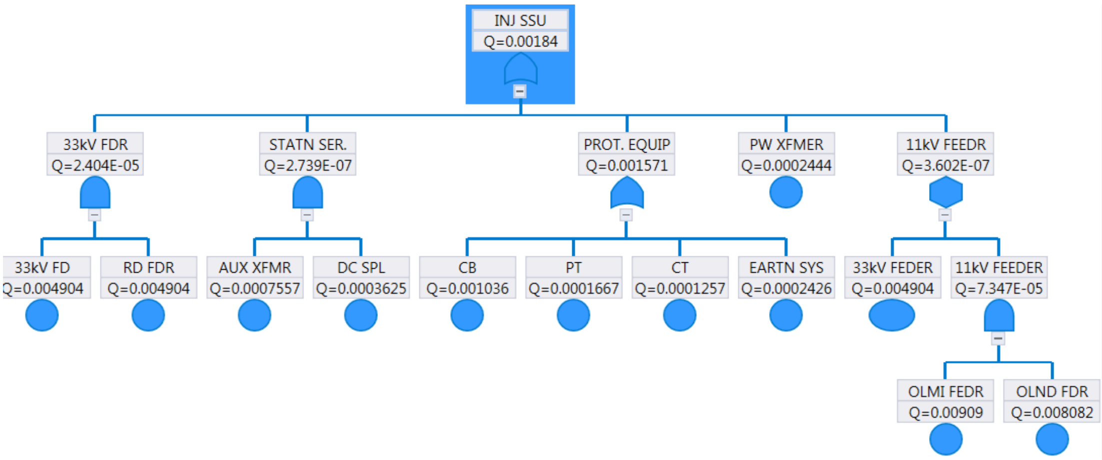

Figure 11. Fault Tree Diagram with 33kV Redundant Feeder

From Figure 11, the overall unavailability of the injection substation reduced from its initial value of **0.00672** to **0.001849** which corresponds to **72.48%** overall reliability improvement of the injection substation. From Figure 11, Figure 12 is produced.

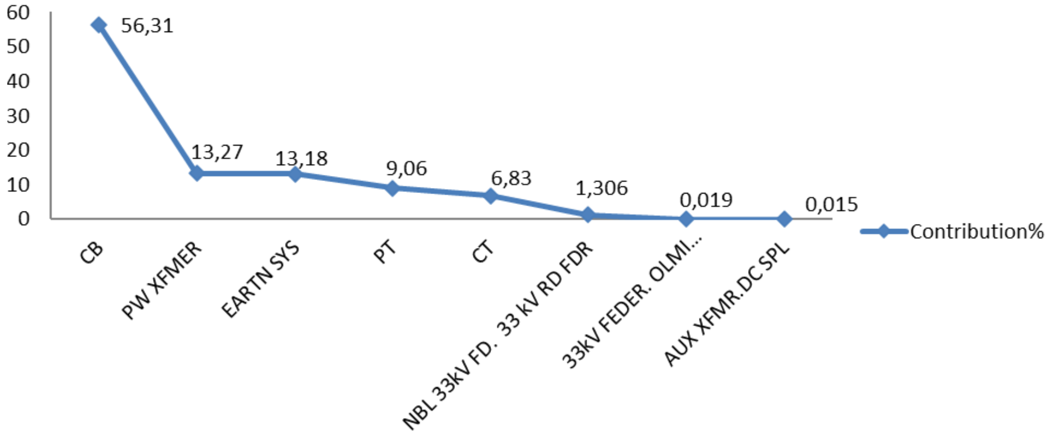

Figure 12. Minimum CutSet Results with a 33kV Redundant Feeder

From Figure 12, the MCS percentage failure contribution of NBL 33kV Feeder and the Redundant Feeder reduced from initial value of **72.97%** to **1.31%.** This indicates a high reduction **(71.59%)** in the failure contribution of the power equipment MCS.

4. CONCLUSION

A Fault Tree Analysis (FTA) Technique forreliability evaluation is tool in establishing the working state of power equipment associated with Olunde injection substation. The *existing* Injection Power Substation results showed that each of the Minimal Cutsets lead to the unavailability of the injection substation; the overall injection substation unavailability of power supply was **0.00672;** 33kV NBL Feeder has the highest percentage **(72.97%)** of failure contribution to the unavailability of the injection substation while AUX XFMR and120V DC SUPPLY as a Cutset has the least failure contribution of **0.00132%;** critical and marginal Importance Measure of NBL 33kV feeder are **65.55%** and **23.59%**respectively. However, 33kV Circuit Breaker, Current transformer, Earthing System, Power Transformer and Potential Transformer have the Marginal Importance Measure of **16.67%** each which indicates that their failure though minimal have impact in the unavailability of the injection substation. The reliability improvement of Injection Power Substation when doubling *the maintenance activities method* was used **on the NBL 33kV feeder** shows that the overall injection substation unavailability reduced from **0.00672** to **0.004258(36.63%** improvement**);** the failure contribution of NBL 33kV feeder reduced from **72.97%** to **57.34%** (**15.63%** reduction). Withthe introduction of a redundant feeder, the failure contribution of NBL 33kV feeder and the 33kV redundant feeder as a Cutset reduced from **72.97% to 1.306 %(71.66% reduction)** and the overall unavailability of the injection substation reduced from **0.00672 to 0.001849 (72.48% improvement).** The introduction of a redundant feeder approach in the reliability evaluation and improvement of the injection substation is highly significant. ***It is better than doubling the maintenance activities method.*** *FTA* is a veritable tool for design and operation of complex systems is recommended to identify the weakest area of any injection power substation as this will help identify the power equipment improvement that would maximize the reliability of the whole injection substation for optimum performance. The introduction of a redundant feeder approach in the reliability evaluation and improvement of the injection substation should be preferred to doubling maintenance activities method.

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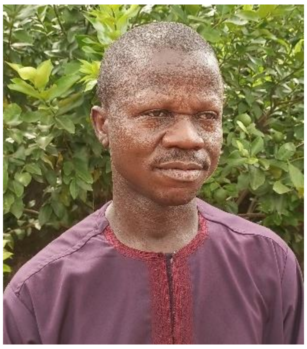

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