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Reliability Evaluation of 11kV/415V Power Distribution Substation using Failure Rate Approach (Case Study: A Business Unit in Lagos State, Nigeria)

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ABSTRACT

The world is becoming totally technology driven, one of the key driven factor is electricity, hence each country of the world continually improve on its reliability to enjoy the full benefit technology has to offer. Nigeria is not left out in this race considering the deregulation and privatization of its electricity sector and heavy investment continually committed to it. This paper attempt to determine the reliability of electric power distribution in Nigeria using one of the very active Business units of the Lagos state electricity distribution company (Disco), Lagos state is allotted 25% of the nation's grid energy. The 11kV/415V, 500kVA distribution substations was used for the exercise being the dominant substation in the distribution network. The annual average percentage failure of 3.8% was recorded for a forced (unplanned) outage as against the 1-2 % global average, but the true picture of poor reliability is evident when the percentage failure computed for both unplanned and planned outage (due to load shedding) produced an average of 56%. This evidently is an indication of ageing distribution substation equipment and poor reliability of the power supply at the distribution network section of the grid network.

Keywords: Distribution substations, Reliability, Failure rate, Electricity, power outage.

1. INTRODUCTION

Nigeria Electricity suffers several operations' irregularities and the deregulations of the sector which brings in private investors into the stream has not produced visible improvement as far as consumers are concerned, rather, it has increased unit cost of consumption without improvement in reliability. Nigeria, with the generating capacity of 12,522MW can only dispatch an average of 4,000MW [1]. Among the irregularities are: high rate of grid collapse or blackout [2], inadequacy of transmission capacity to evacuate available generating capacity, occasional gas shortage to fire the thermal generation plants [3], aged components in the grid network, poor maintenance culture (more pronounced at distribution substation level of the system), non-metered estimate billings, political interference, etc.

To minimize these irregularities requires system performance evaluation at different levels of the power system chain. However, improving any process requires identifying and measuring the performance of relevant parameters [4]. Among these numerous irregularities, this paper has chosen to focus on the distribution substation which is the interface between consumers and the grid network, and is handled by Distribution Companies (DISCOs). Further, one (1) of the two (2) distribution companies covering Lagos state has been chosen for this exercise and a business unit is used as a case study. For the purpose of criticism insinuation, which fosters blame game among the strata of Nigeria Power Sector [5], names of Disco and business units will be unanimous.

The lack of reliability associated with the power supply system in Nigeria still enlists electric power as one of the binding constraints on the pace of economic activities in the country [6].

2. 11KV/415V POWER DISTRIBUTION SUBSTATION NETWORK

Power distribution substation can be indoor or outdoor type. In Nigeria, while the small size industries and commercial premises do sometimes subscribe to indoor type, most residential environs use the outdoor type. The outdoor and indoor has virtually same components except that the indoor is within a building while the outdoor is exposed to natural elements. For safety and security reasons, the outdoor is usually fenced round. The major or primary purpose of a substation is to change electric power from one voltage level to another; other functions include switching operations, reactive power compensation, and protection. Further functions are performed at transmission and generating substations but are not part of this discussion.
Basically, in the Nigeria context, 11KV/415V power distribution substations consist of the following:

i. Incoming Feeder (11KV)
ii. Resistive elements (11KV Fuse)
iii. Surge (or lighting) Arrester
iv. Transformer (3-phase)
v. Bus Bars (Feeder pillar components)
vi. Grounding
vii. Outgoing Feeder

The list is just components peculiar to Nigeria 11KV/415V substations. Modern substations are enhanced with monitoring and intelligent components that introduces more sophistication. Though the power distribution substations, due to transformer sizes are not given adequate attention needed when compared with transmission and generation substations, yet without the distribution sub stations, the utility would not be able to supply the end users (consumers).

However, the increasing complexity of today’s electric power grid system, coupled with the pace of dynamic changing in its evolving technology has craved the need for strategic asset management that is also dynamic. This new wave does not leave the distribution sub stations behind, especially their transformers, due to their role in power reliability and efficient performance [7]. Any annual failure rate that exceed 2% calls for serious concern that should trigger an alarm bells to ring for an urgent counter measures [4].

3. RELIABILITY ASSESSMENT REVIEW

Reliability simply is a test of degree of trust and integrity of a component or system by technical term; hence, to be meaningful it must be measurable. Reliability is based on the probability that a component or system will perform satisfactorily for a given period when used under specified operating condition. Time aspect in reliability represents a measure for which a system degree of performance can be related. In essence, time is critical in reliability measurement as it provides the probability of a system or component surviving without failure for a designated period [8].

Power supply that is stable and reliable is a priority to nations' technological and economic growth. The incessant power interruptions in Nigeria have been traced to failure in the distribution network [9].

Recently, 50KVA pole mounted distributed substations was incorporated in Lagos state power distribution network to reduce the impact of incessant power interruptions and improve reliability at distribution level of the Nigeria grid system. The battle for reliability in Nigeria grid network is an ongoing one with uncertain ending, hence, continuous reliability evaluation is inevitable for optimum utilization of the available generation capacity.

3.1 RELIABILITY EVALUATION PARAMETERS

All the evaluation methods of determining system or components reliability are based on concepts of measure in time space. These concepts include: failure rate, probability function, reliability models, meantime time between maintenance (MTBM), meantime between failure (MTBF), availability, system effectiveness and life cycle cost [10]. Some of these terms are expressed mathematically as follows;

a) Failure rate F_r (t) or λ is the rate of failure within specified time interval. For failure rate per hour,

F_r (t) or $\lambda = \frac{\text{Number of Failures}}{\text{Total operating hours}}$ (per hour) …………………… (1)

b) Mean time between Failure

$MTBF = \frac{1}{\lambda}$ (hours) …………………… (2)

c) Reliability function,

R (t) = 1 – F(t) ……………………… (3)

Where F(t) is the probability of a component failing by time t

d) System effectiveness is expressed as
Effectiveness = Performance **x** Reliability **x** Availability …....... (4)

System effectiveness measures the probability of a system successfully meeting an operational requirement as the need arises.

e) Mean time between Maintenance (MTBM): is a reliability measure that takes into account the maintenance policy of a system and expressed mathematically as

$$MTBM = \frac{\text{Up time}}{\text{No. of maintenance}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

It is the ratio of total number of life units expended to the total number of maintenance event.

3.2 SUBSTATION FAILURE

Substation failure is inclusive of all the components constituting the substation network but among these the transformer is given more attention because of its core operation within the substation network. Transformer is the single largest substation asset and almost 60 percent of the substation costs are attributed to transformer [11].

Most evaluation of utility failure registers and fault statistics shows that the distribution networks section of the power system contribute the most to customer interruptions and failure events to which the transformer is the dominant [12]

In essence, attention will be given to transformer failure analysis. The reported distribution transformers failure rate reported to be at 12-17% in India is a confirmation of dominant role of transformers in a distribution network [13]

Data from different parts of the world shows a wide range of different causes of distribution transformer failure that can be broadly grouped into five (5) categories listed in table 1

Table 1. Typical failure causes for distribution transformers

External	End-user	Manufacturer	Procurement	Ageing
1. Unauthorized tapping 2. Arson, vandalism 3. Oil leaks 4. LV system faults 5. Weather: lightning strike, storm, extreme ambient, etc. 6. External short circuit: cables connected 7. Animals 8. Vegetation 9. Ground tilting	1. Improper pre-check and installation 2. Improper terminations 3. Faulty earth connections 4. Bypassing of protection systems 5. Protection malfunction 6. Inadequate maintenance 7. Prolonged overloading or unbalancing	1. Faulty design 2. Quality of raw material 3. Poor workmanship 4. Improper manufacturing process 5. Improper transportation 6. Underrated connectors	1. Improper technical specifications 2. Improper inspection process 3. Choice of lowest price first before proper evaluation	1. Insulation property deterioration 2. Moisture ingress 3. Natural wear out

Source: Transformer magazine vol. 8, issue 3, 2021

4. DATA AND ANALYSIS

Data for substation were collected from the selected business unit. 500KVA, 11KV/415V substations was chosen since they are dominants (over 14,000) within the system and over 90% of them are over 15 years in operation (Disco data, 2020). Substation with mean average of number of faults was chosen at random from the data log book for fair representation. The data for consecutive 3 years of operation was then collected for this exercise. The collected data are shown in Table 2.

TABLE 2: Substation Transformer number of outages data

Month	Number of outage									Hours of outage (HRS)						
	Planned (Load shedding)			UnPlanned			Total			Planned				Unplanned or fault case		
	YR1	YR2	YR3	YR1	YR2	YR3	YR1	YR2	YR3	Maintenance	Load shedding					
											YR1	YR2	YR3	YR1	YR2	YR3
January	31	36	27	1	3	4	32	39	31	NIL	240	270	216	28	71	132
February	27	38	36	2	0	2	29	38	38	NIL	154	266	252	82	0	21
March	30	27	42	1	0	3	31	27	45	NIL	210	189	294	17	0	142
April	40	25	32	2	1	0	42	26	32	NIL	260	200	208	31	7	0
May	25	36	33	0	2	0	25	38	33	NIL	175	252	231	0	24	0
June	38	29	35	0	1	3	38	30	38	NIL	228	203	245	0	35	228
July	27	32	38	3	0	2	30	32	40	NIL	140	240	247	74	0	18
vAugust	47	24	30	2	4	0	49	28	30	NIL	275	192	210	62	128	0
September	32	30	24	0	1	3	32	31	27	NIL	192	240	168	0	9	47
October	26	38	30	1	0	4	27	38	34	NIL	208	247	210	26	0	197
November	42	26	37	2	5	0	44	31	37	NIL	252	182	259	35	203	0
December	28	42	25	4	2	0	32	44	25	NIL	196	252	200	197	13	0

Source: DISCO Business unit Distribution substation data log (2020)

Things that are clearly visible from table 2 data are;

i. The planned outage for maintenance column which is reflecting nil, meaning no planned maintenance; the substation outage can either be due to fault or load shedding.

ii. Also, has seen in table 1 of typical failure causes for distribution transformers, failure categories peculiar to the Disco reflected in the data of table 2 is that of End-user and Ageing.

iii. It can also be deduce that the strategy for sustaining the transformers in the distribution network is high number of monthly planned outage (or load shedding) and the durations, considering the number of annual unplanned outages (or failure)

The annual and monthly average number of outages for both planned and unplanned outages as well as for the duration of outages in hours for further evaluation or performance assessment are shown in table 3.

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TABLE 3: Distribution Substation Transformer outages data evaluation

Month	Number of outage									Hours of outage (HRS)						
	Planned (load shedding)			Unplanned			Total			Planned				Unplanned or fault cases		
	YR1	YR2	YR3	YR1	YR2	YR3	YR1	YR2	YR3	Maintenance	Load shedding					
											YR1	YR2	YR3	YR1	YR2	YR3
January	31	36	27	1	3	4	32	39	31	NIL	240	270	216	28	71	132
February	27	38	36	2	0	2	29	38	38	NIL	154	266	252	82	0	21
March	30	27	42	1	0	3	31	27	45	NIL	210	189	294	17	0	142
April	40	25	32	2	1	0	42	26	32	NIL	260	200	208	31	7	0
May	25	36	33	0	2	0	25	38	33	NIL	175	252	231	0	24	0
June	38	29	35	0	1	3	38	30	38	NIL	228	203	245	0	35	228
July	27	32	38	3	0	2	30	32	40	NIL	140	240	247	74	0	18
August	47	24	30	2	4	0	49	28	30	NIL	275	192	210	62	128	0
September	32	30	24	0	1	3	32	31	27	NIL	192	240	168	0	9	47
October	26	38	30	1	0	4	27	38	34	NIL	208	247	210	26	0	197
November	42	26	37	2	5	0	44	31	37	NIL	252	182	259	35	203	0
December	28	42	25	4	2	0	32	44	25	NIL	196	252	200	197	13	0
Total	393	383	389	18	19	21	411	402	410	NIL	2530	2733	2740	552	490	785
Average	32.75	31.92	32.42	1.50	1.58	1.75	34.25	33.50	34.17	NIL	210.83	227.75	228.33	46.00	40.83	65.42

A better look at table 3 showing the computation of number of annual and monthly average of outages and the durations (in hours) shows a ratio of 2:32 of monthly unplanned outage to planned outage, likewise the outage hours show a monthly average ratio 1:5 of monthly unplanned outage to planned outage. These indicators reflect unreliable supply to consumers and an alternative supply to meet this shortfall is inevitable.

The failure rates as represented by equation (1) and further expanded in equations (6) to (11) are computed and recorded in table 4 to establish the reliability status of the distribution substation using transformer outages as indicator for measurement [14].

Considering the number of failure as number of unavailability of the distribution substation in operation, we have the following equations;
Monthly failure rate, excluding planned outages;

$$\lambda_U = \frac{montyly\ number\ of\ unplanned\ outage}{monthly\ unplanned\ outage\ total\ hours\ of operation} \quad \ldots\ldots\ldots..(6)$$

Annual failure rate, excluding planned outages;

$$\lambda_{U(annual)} = \sum_{i=1}^{n} \lambda_{U(i)} \quad \ldots\ldots\ldots. \ (7)$$

Percentage annual failure rate, excluding planned outages;

$$\%\ \lambda_{U(annual)} = \lambda_{U(annual)} \times 100\ \% \quad \ldots\ldots\ldots\ldots. \ (8)$$

Monthly failure rate, including planned outages;

$$\lambda_P = \frac{montyly\ total\ number\ of\ \ outage}{monthly\ total\ hours\ of operation} \quad \ldots\ldots\ldots\ldots. \ (9)$$

Annual failure rate, including planned outages;

$$\lambda_{P(annual)} = \sum_{i=1}^{n} \lambda_{P(i)} \quad \ldots\ldots\ldots. \quad (10)$$

Percentage annual failure rate, excluding planned outages;

$$\%\ \lambda_{P(annual)} = \lambda_{P(annual)} \times 100\ \% \quad \ldots\ldots\ldots\ldots. \quad (11)$$

Table 4: DISCO Distribution substation transformer monthly and annual failure rate

Month	Planned outages duration (HRS)			Total Hours of operation (HRS) Excluding planned outage			Total Hours of operation (HRS) Including planned outage	Total Number of Outages			Failure rate (λ_U) Excluding planned outage			Failure rate (λ_P) Including planned outage		
	YR1	YR2	YR3	YR1	YR2	YR3	YR1, YR2&YR3	YR1	YR2	YR3	YR1	YR2	YR3	YR1	YR2	YR3
January	240	270	216	504	474	528	744	32	39	31	0.0020	0.0063	0.0076	0.0430	0.0524	0.0417
February	154	266	252	542	430	444	696	29	38	38	0.0037	0.0000	0.0045	0.0417	0.0546	0.0546
March	210	189	294	534	555	450	744	31	27	45	0.0019	0.0000	0.0067	0.0417	0.0363	0.0605
April	260	200	208	460	520	512	720	42	26	32	0.0043	0.0019	0.0000	0.0583	0.0361	0.0444
May	175	252	231	569	492	513	744	25	38	33	0.0000	0.0041	0.0000	0.0336	0.0511	0.0444
June	228	203	245	492	517	475	720	38	30	38	0.0000	0.0019	0.0063	0.0528	0.0417	0.0528
July	140	240	247	604	504	497	744	30	32	40	0.0050	0.0000	0.0040	0.0403	0.0430	0.0538
August	275	192	210	469	552	534	744	49	28	30	0.0043	0.0072	0.0000	0.0659	0.0376	0.0403
September	192	240	168	528	480	552	720	32	31	27	0.0000	0.0021	0.0054	0.0444	0.0431	0.0375
October	208	247	210	536	497	534	744	27	38	34	0.0019	0.0000	0.0075	0.0363	0.0511	0.0457
November	252	182	259	468	538	461	720	44	31	37	0.0043	0.0093	0.0000	0.0611	0.0431	0.0514
December	196	252	200	548	497	544	744	32	44	25	0.0073	0.0040	0.0000	0.0430	0.0591	0.0336
Annual	2530	2733	2740	6,254	6,056	6,044	8,760	411	402	410	0.0347	0.0368	0.0420	0.5621	0.5492	0.5607
Average	210.83	227.75	228.33	521.2	504.2	503.7	730	34.25	33.5	34.17	0.0029	0.0031	0.0035	0.0468	0.0458	0.0467

The annual percentage failure extracted from table 4 is shown in table 5 for a clearer view and better evaluation of the reliability status of the distribution substation.

Table 5: Annual Percentage failure, planned and unplanned

Year	$\lambda_{U(annual)}$	$\%\ \lambda_{U(annual)}$	$\lambda_{P(annual)}$	$\%\ \lambda_{P(annual)}$
Year 1	0.0347	3.47	0.5621	56.21
Year 2	0.0368	3.68	0.5492	54.95
Year 3	0.0420	4.20	0.5607	56.07

5. CONCLUSSION AND SUGGESTIONS

5.1 CONCLUSSION

From the data gathered and analysis carried out the following conclusion can be drawn;

1. The over 30 number of times of planned monthly outages is unhealthy for the substation life cycle as switching cycle has direct impact on the life cycle of electrical components. Same goes for Nil planned maintenance, if not for the pronounce planned outage for load shedding, the transformers life cycle would have expired.

2. An average of 2 number of failure per month due to fault, considering number of monthly load shedding outages is an indication of poor reliability in terms of substation operations. (table 4)

3. The planned percentage failure for each of the 3 years considered (table 5) exceed the global average of 1-2%, even in the face of conspicuous load shedding outages which is over 30 times that of forced outages.

4. The annual percentage failure rate of over 50% (with planned outage inclusion) show that the distribution substation reliability is very poor and, on a normal day, replacement plan should be given consideration.

5.2 SUGGESTIONS

The distribution substations suffer planned maintenance outage negligence and have consequently increased the failure rate. Scheduled maintenance plan should be incorporated into distribution substations operations. Secondly, to reduce switching cycle and increase equipment life span within the distribution network, it is advisable to shift hours load shedding to days load shedding. Load shedding is inspired by inadequate grid generating capacity which cannot be resolved soon.

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