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A Critical Analysis of Voltage Collapse in a Fragile Grid: The Nigeria Experience

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Abstract
Nigeria's power grid is a key area that requires urgent attention to revive the nation's economy which has continued to dwindle over the years. This paper seeks to analyze the grid's performance and proposes various ways to mitigate the fragile situation of the grid.This paper makes use of the historical data of the national grid operations under review, from 2015 to 2023. The data was analyzed using descriptive statistics (tables, frequency counts, charts, and graphical depictions) to extract the prominent elements required for the study's conclusion. In the period under study (2015-2023), the grid experienced a total number of 101 voltage collapses which is an average of about 11 times collapses in each year. Nigeria's grid installed capacity stands at about 14,000MW and has a generating peak value of about 5,200MW and an off-peak value of about 4,400MW. Furthermore, the results show that the grid generates an average of 4,800MW which translates to about 34.64% of the installed capacity. Also, from the results it can be seen that in 2016 the nation experienced the highest number of voltage collapses of 28 times, and in 2023 it had the lowest with 2 occurrences. Various reasons ranging from poor maintenance, vandalization, OEMs issues, spares, gas constraints, radial and non-redundancy nature of the grid, etc contributed to the major causes of the grid collapses. Training, revamping the power sector, decentralization of the national grid, and embracing renewable energy sources were proffered as solutions to the current problems facing Nigeria's grid network.
Keywords: *Causes of grid collapses, Grid capacity and generation, Grid performance analysis, Nigeria's power grid, Voltage collapses, Solutions for grid improvement*

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I. Introduction

An electrical grid is a network of connected power sources that connects the points of generation and consumption. Different sizes of electrical networks are available to cover wholecountries or continents. A sophisticated and vital system, the electrical grid is among the greatest engineering achievements of the modern period. It distributes power produced at various facilities to final customers by transmitting it, frequently across great distances. An electrical grid station is an essential component in the national transmission of power. An electrical power system's primary purpose is to supply sufficient power to all points of utilization at a pace that is both economically feasible and reasonably reliable; hence, with a decrease in or if possible, no collapse of the system while in operation. Therefore, every power system is expected to run optimally without experiencing any system collapse during its operations(O'Connor, 2002). Within the given limitations of variation about the system base levels, the power system network is expected to generate and transmit electricity to different load centres at different predetermined voltage and frequency levels. The voltage should be (330kV, 33kV, 11kV) ± 0.5%, and the typical nominal frequency should be 50Hz ± 0.5%. Any departure from these stability ranges may lead to a reduction in the quality of the power and, in extreme situations, to widespread power outages (NERC, 2019).

Nigeria as a nation has continued to struggle with challenges in its power sector, causing significant obstacles to the nation's economic development and its citizen's daily life. The negative impacts of its failure to provide its residents with consistent energy have been a serious issue for its industrial and household growth, especially given its constantly growing population. Recently, on September 13, 2023, at about 12:35 AM, the entire grid collapsed in the nation, causing power generation to drop from approximately 4355.20MW to 35 megawatts. This was caused by a fire outbreak and explosion sound that was heard on Kainji/Jebba 330kV line 2 (circuit K2J), a blue phase CVT, and a blue phase line isolator of Kainji/Jebba 330kV line 1(Global Transmission Report, 2023). The power sector has suffered significant setbacks because of recurrent grid collapses, even though the government has claimed to have allocated different sums to the sector. Despitemuch funds the government has claimed to allocate to the sector, the power sector has continued to suffer huge setbacks due to its frequent grid collapse. Looking at the frequency and trend of grid collapses in the country it gives great concern about its fragility and its associated adverse effects on the nation's development and sustainability (Akintayo, 2023).

Persistent power outages arising from the poor state of electricity infrastructure are hindering Nigeria's socio-economic growth (Amadi, 2015). Amidst daily increasesin the number of small and medium-scale enterprises, and the expansion of both urban and rural settlements which is associated with an unprecedented increase in the nation's energy demand,Nigeria's power system network has not witnessed an equal expansion in its power system infrastructure. The nation is still struggling to wheel power with the same power system network that is as old as the country itself, the lack of any meaningful modern upgrade of its infrastructure, the Nigeria power grid lack of capacity to embrace new SMART grid renewable architecture and many more has caused the continuous failure of its power grid. The country's power grid is in a state of fragility, the transmission lines are highly stressed,weak,and unlikely to be able to withstand or wheel their installed capacity. Furthermore, the long and radial nature of the Nigeria network makes it lack flexibility making it highly vulnerable to voltage collapses.This paper presents a criticalanalysisof voltagecollapse in a fragile grid- The Nigeria experience. The paper intends to provide and in-depth analysis of the voltage collapse thatwill enable policymakers and subject experts to make decisions and proffer solutions to Nigeria's dwindling power state.

Voltage collapse is the partial or complete loss of end users' or customers' access to the electrical power grid. Natural, environmental, and meteorological factors, human mistakes, malfunctions, or defects such as overload, component malfunction, or issues with the distribution system's control and protection systems are the main causes. There are two types of voltage collapse on the grid: temporary and prolonged interruptions (Short, 2006).Voltage collapses are also occasionally referred to as power outages. The time it takes to restore the power supply distinguishes both voltage collapses. A momentary power outage occurs when there is a brief loss of power, typically lasting a few minutes. It is brought on by transient issues that raise the voltage supply level of less than 10% of the nominal for up to one-minute duration. Sustained voltage collapse is caused by permanent faults resulting in a decrease in the voltage supply to zero for more than one-minute duration. Customer facilities would be completely shut down for an extended period in the event of an electric power outage (IEEE 1159, 1995). As such, to repair the power supply, physical corrective maintenance is needed.

The national grid is an interconnecting system that comprises all generation stations, transmission substations, and distribution substations. If there is a technical issue with an interconnecting unit, it could hurt the system partially or totally. One of these adverse effects is the inability of electric power to be generated, transmitted, or distributed. In some cases, there is a partial or total blackout on the system. This is known as a grid collapse: which could be partial or total.One of the main reasons for the Nigerian grid's complete and partial collapse is extreme voltages at the system nodes. Samuel et al. (2012) described voltage collapse as the term used to describe the fragility of a fully loaded power system network that finally results in a blackout and diminishing voltage. This undermines the vital service of providing consumers with consistent, dependable power and has serious repercussions for the security of the system.

Ogbuefi et al. (2018) evaluated that voltage collapse is when a power system network loses itssecurity limits. It is, therefore, imperative for the system to maintain stability at all points to prevent its collapse. Hence, it becomes necessary to maintain a considerable security limit in both normal operating conditions and under contingency cases to ensure the reliable operation of a power system.

1.1 The Nigerian Power Grid

An electric grid is a system of synchronized power suppliers and consumers that is run by one or more control centres and connected by transmission and distribution lines. A network called the power grid is used to supply users with electricity. Generator stations, transmission towers, and separate consumer distribution lines are all part of the power system. Energy is produced by the generator. For distribution, transform energy into a high voltage.

The Transmission Company of Nigeria, generation companies, and distribution companies make up the Nigerian national electrical grid. Electricity production and distribution are permitted for private enterprises. Transmission of electricity generated by the producing business to the distribution firms at a standardized voltage of 330kV and 132kV is the exclusive responsibility of the Federal Government of Nigeria. Unfortunately, the nation only generates an average of 4,500MW per day on the Nigerian grid, which has a generating capacity of approximately 14,000MW, according to the transmission business. Additionally, the nation has an all-time peak generation of 5801.60MW, the highest daily energy ever attained of 119,471.55MWH, and a maximum peak generating capability of 7099MW(TCN, 2023).

The transmission lines in Nigeria have an installed transformation capacity of 11,660MVA and span a distance of roughly 7780 km. These transmission lines (132/33/11kV), which are brittle and can only generate a maximum of 8238MW of power, transport electricity not only throughout Nigeria but also to some regions of Niger and the Benin Republic (Okoye & Omolola, 2019).Of Nigeria's 210 million inhabitants, roughly 32 million live in grid-connected houses. Nigeria is heavily indebted. Globally, the consensus about electricity production states that one million people require 1,000 megawatts of power to have continuous access to electricity. Therefore, 32,000MW must be produced to meet the needs of the 32 million people who have access to energy, or who are connected to an electrical source. In Nigeria, we currently produce 4,500MW on average per day. Therefore, to guarantee a steady supply of power to every family connected to the grid, we require a minimum of 32,000MW (Nigeria Power Baseline Report, 2015). A one-line diagram of Nigeria's 330kV transmission network is presented in Figure 2.1.

The primary and secondary distribution systems are the two halves of the distribution system network that are separated by the voltage level. The sub-transmission voltage of 132kV is stepped down to 33kV and 11kV for the principal distribution system network, which is a three-phase (three-wire) system. The 33kV or 11kV are known as feeders since they are linked to a certain region. The names of the areas the feeders serve are used to determine the feeders' names. The secondary distribution network, which runs at a lower voltage of 415V/230V stepped down from the primary distribution network voltage of 33kV or 11kV, is directly connected to the consumers. It is a three-phase, four-wire system.

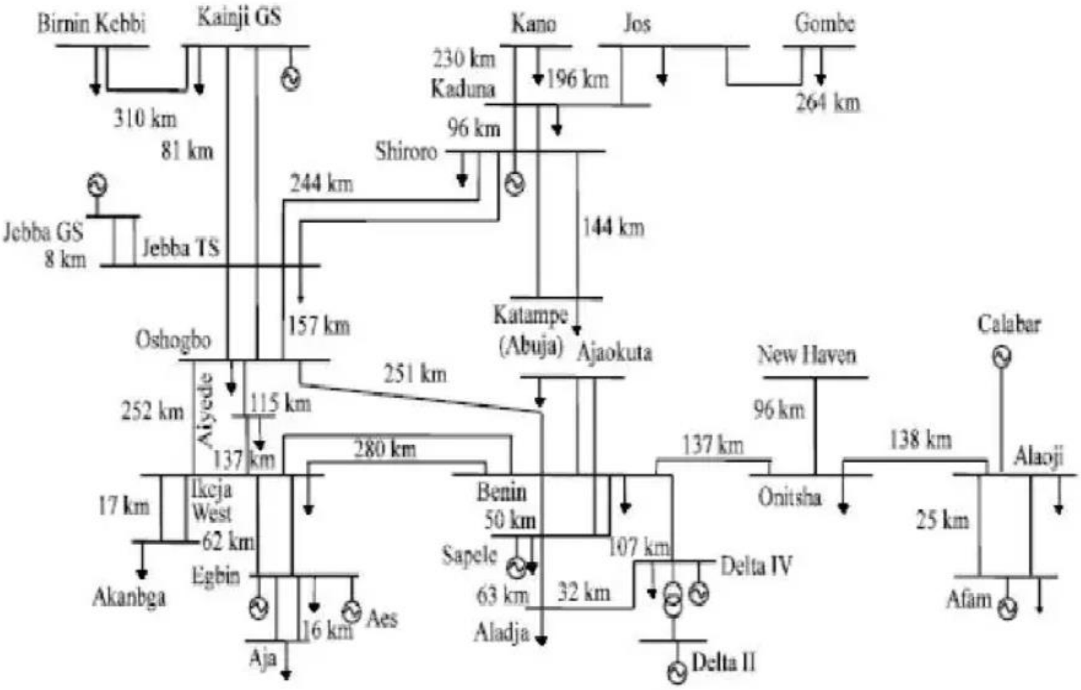

Fig. 2.1: One-line diagram of Nigeria's 330-kV transmission network (Ogbuefi et al. 2018)

1.2 Impact of the Nigeria Fragile Grid

The generation, transmission, and distribution phases of the electricity industry are all connected via the national grid. There have been multiple grid collapses in Nigeria as a result of the grid's incapacity to react quickly enough to different system dynamics. The Nigerian power infrastructure has not been able to produce enough electricity for home and industrial usage, despite the country's fast-expanding economy. The nation is endowed with the greatest reserves of coal, oil, gas, and uranium, making it the largest oil producer in Africa. Despite this abundance of resources, the survival of these businesses has been seriously hampered by the lack of power. Only 45% of Nigeria's population is connected to energy even with this below access to electricity by Nigerians, even the percentage of Nigerianswho have accessto power experiences power difficulties about 85% of the time, and in most cases, it is nonexistent in most areas(Aliyu et al., 2013). This has resulted in several negative outcomes, including the rapid loss of social amenities like drinkable drinking water and better health care services, among many others that will be covered in the next section, as well as the closure of industries and the collapse and deterioration of infrastructure.

Every country's GDP growth and overall energy usage are directly correlated (PwC Annual Power and Utilities Roundtable, 2016). Therefore, there is a chance that a nation with high energy consumption will also have a high GDP. According to the same survey, 90% of Nigerian businesses own generators; as a result, 60% of the country's population gets its energy from these sources. According to estimates, Nigeria has some of the lowest rates of energy access in the world, and it would cost the country $50 billion to guarantee a sufficient supply of electricity in Nigeria (DFID, 2016).

Another setback as a result of the nation's fragile grid has been on SMEs. Most SMEs have folded up and some existing ones are on the verge of shutting down due to poor power supply, most especially with the increase in fuel cost most small and medium companies can no longer meet up with the overhead operational costs, hence have resulted to most shutting down, laying off of workers and a reduction in quality of products or a rather high cost of products and services. This has led to a high unemployment rate, which has raised the nation's already high crime rates.

These effects of the national grid's fragility have a significant impact on the non-oil sector, impeding efforts to reduce poverty and create jobs. Due to the current power crisis, the majority of businesses in conflict supply their electricity at great financial risk to both themselves and the Nigerian economy. The estimated amount of self-generated power in Nigeria is 2,5000MW. As of April 5, 2017, the expected financial losses were NGN 1,337,000,000. As of April 11, 2017, the losses were NGN 1, 274,000,000 because of deficiencies in the country's gas supply and water management at various power plants (Alike, 2017).

There are also the negative consequences this has on the ecosystem. A 2009 survey reveals that over 196 hours of power outages occur each month for over 97% of Nigerian businesses. This indicates that because of the nation's electricity unreliability, these businesses experience an average of eight full days of lost output. The usage of alternative energy sources poses a significant environmental risk of carbon dioxide emissions, which harm humans, animals, and the ecosystem as a whole (Biu, 2016).

1.3Causesof the Nigeria Fragile Grid

In summary, the following are the main causes of voltage collapse:

- low water levels at the hydropower plants.
- Constraints on gas availability at gas power plants.
- The transmission firms' incapacity to distribute electricity from the generators
- Distribution firms' load rejection or demand.
- dated and feeble transmission networks.
- Inadequate utility performance and theft/damage of grid equipment.
- Not enough money to make the switch from an analog to a smart grid.
- Inadequate protection or control mechanisms that cause transmission lines to trip, or ineffective station-to-station relay coordination.
- Generation as a result of a bilateral deal.
- There are insufficient tools and procedures for predictive and preventive maintenance.

II. Materials and Methods

2.1 Materials

This paper makes use of the historical data of the national grid operations under review - from 2015 to 2023. These were derived from the daily dispatch and operational logbooks TCN National Control Centre O.F. 56, Dispatch and Operational Logbooks, under evaluation, which are held by the Transmission Company of Nigeria, from 2015 to 2023. In addition, information was also sought from some organizations and relevant literatureto make them suitable for the work at hand.

2.2 Method

The data was analyzed using descriptive statistics (tables, frequency counts, charts, and graphical depictions) to extract the prominent elements required for the study's conclusion.

Table 3.1: Nigerian National GridStatistical performanceshowing collapses from the year 2015 to 2023. **(**TCN National Control Centre, 2019-2023).

Year/ Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2015	1	0	2	0	4	0	1	0	0	1	1	0	10
2016	0	0	3	3	7	8	1	0	1	1	2	2	28
2017	6	3	1	3	1	1	1	0	4	4	0	0	24
2018	5	1	0	1	0	1	1	0	2	0	0	2	13
2019	4	1	0	1	1	1	0	1	0	0	1	0	10
2020	1	0	0	1	0	1	0	0	0	0	1	0	4

2021	**0**	**1**	**0**	**0**	**1**	**0**	**1**	**1**	**0**	**0**	**0**	**0**	**4**
2022	**0**	**0**	**2**	**1**	**0**	**1**	**1**	**0**	**1**	**0**	**0**	**0**	**6**
2023	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	[redacted]	**2**
SUM TOTAL	**17**	**6**	**8**	**10**	**14**	**13**	**6**	**2**	**10**	**6**	**5**	**4**	**101**

Table 3.1 shows the frequency at which the collapses occurred across various years. Also,table 3.2 shows the generation reports, the various generating stations' installed capacity, and their performances.

Table 3.2: Breakdown of peak and off-peak generation**(**TCN National Control Centre, 2019-2023).

	STATION	TURBINE	INSTALLED CAPACITY MW	AT PEAK MW	OFF-PEAK MW	AVERAGE MW
1	KAINJI	HYDRO	960	372	266	319
2	JEBBA	HYDRO	578	450	405	427.5
3	SHIRORO	HYDRO	600	435.63	331.1	383.365
4	DADIN KOWA	HYDRO	40	39.9	39.9	39.9
5	ZUNGERU	HYDRO	750	0	0	0
6	EGBIN ST1 - 6	STEAM	1320	532	529	530.5
7	SAPELE	STEAM	720	58.6	68.4	63.5
8	DELTA	GAS	915	478	394	436
9	AFAM IV-V	GAS	300	76	0	38
10	GEREGU GAS	GAS	435	140	128	134
11	OMOTOSHO GAS	GAS	336.8	98.1	99.3	98.7
12	OLORUNSOGO GAS	GAS	336	94.2	93.7	93.95
13	GEREGU NIPP	GAS	435	80	65	72.5
14	SAPELE NIPP	GAS	500	180	115	147.5
15	ALAOJI NIPP	GAS	504	125	98	111.5
16	OLORUNSOGO NIPP	GAS	750	112	90	101
17	OMOTOSHO NIPP	GAS	500	110.7	99.7	105.2
18	ODUKPANI NIPP	GAS	625	220	205	212.5
19	IHOVBOR NIPP	GAS	337.5	80	60	70
20	Taopex ENERGY	GAS	15	13	12.8	12.9
21	OKPAI	GAS/STEAM	480	268	232	250
22	AZURA - EDO IPP	GAS	460	438	377	407.5
23	AFAM VI	GAS	650	377	327	352
24	IBOM	GAS	198	90.2	59.7	74.95
25	A.E.S	GAS	270	0	0	0
26	ASCO	GAS	110	0	0	0
27	OMOKU	GAS	150	77.3	75.8	76.55
28	TRANS AMADI	GAS	100	41.2	20.1	30.65
29	RIVERS IPP	GAS	180	158	161	159.5

30	PARAS ENERGY	GAS	132	70.3	75	72.65
31	GBARAIN NIPP	GAS	230	0	0	0
TOTAL			**13,917.30**	**5,215.13**	**4,427.50**	**4821.32**

III. Results and Discussion

Table 3.1 shows that over the research period, there were 101 voltage collapses on the grid, or an average of almost 11 collapses annually. Also, in Fig 4.1, the installed capacity of each generating station connected to the grid provides the average at-peak and off-peak values in the period under review. Nigeria's grid installed capacity stands at about 14,000MW and has a generating peak value of about 5,200MW and an off-peak value of about 4,400MW. Furthermore, this means that the grid is generating an average of 4,800MW which translates to about 34.64% of the installed capacity as shown in table 4.1. This average is very poor for a country with so much enormous potential and resources both human and natural. Also, it can be seen (in Figure 4.2) that in 2016 the nation experienced the highest number of voltage collapses 28 times and in 2023 it had the lowest with 2. Figure 3 shows that in the period under review, more collapses occurred in January, May, and June with the frequency of occurrence of 17, 14, and 13 respectively. We can also see that Zungeru although newly commissioned is yet to contribute to the grid, others include AES, ASCO, Trans- Amadi and Gbarain NIPP have not been contributing recently to the grid due to various reasons ranging from poor maintenance, vandalization, OEMs issues, spares, gas constraints, etc.

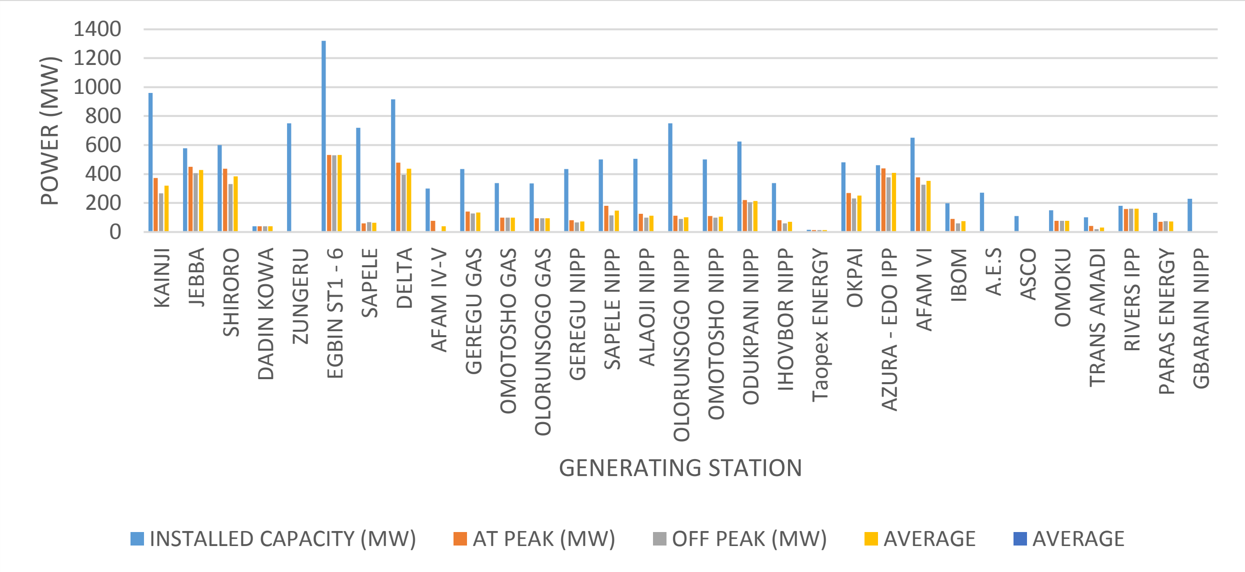

Fig. 4.1: Generating Station Capacity

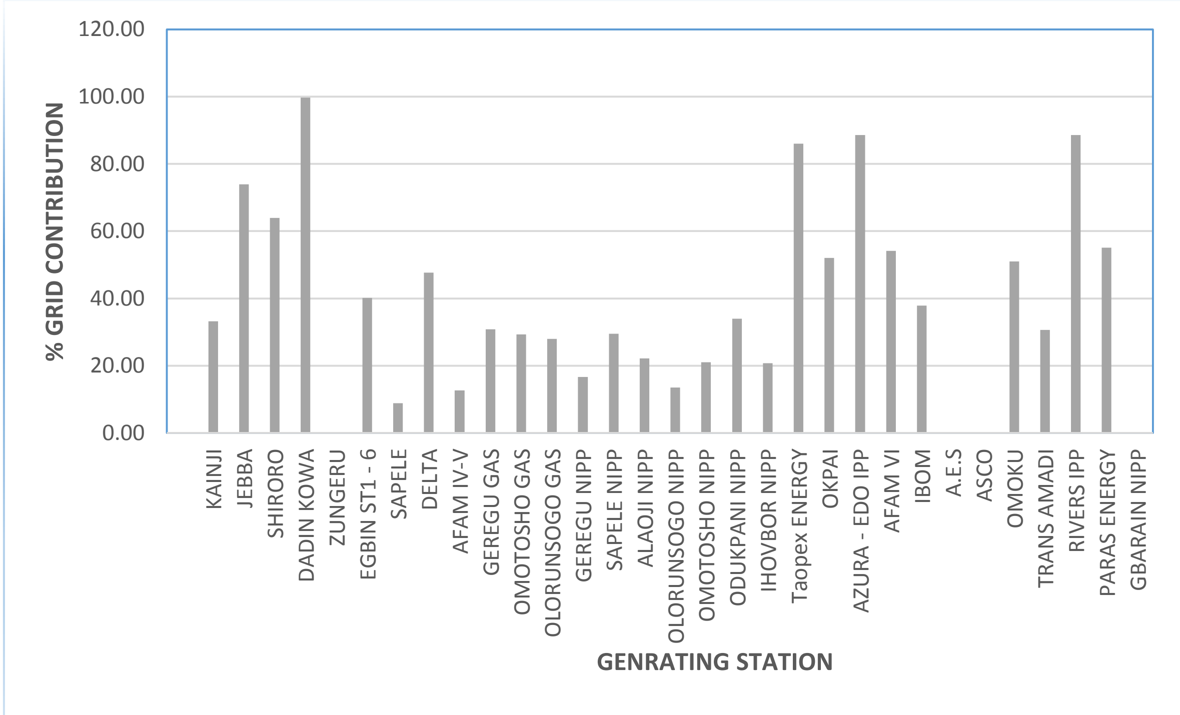

Fig. 4.2: Generating Station Percentage Grid Contribution

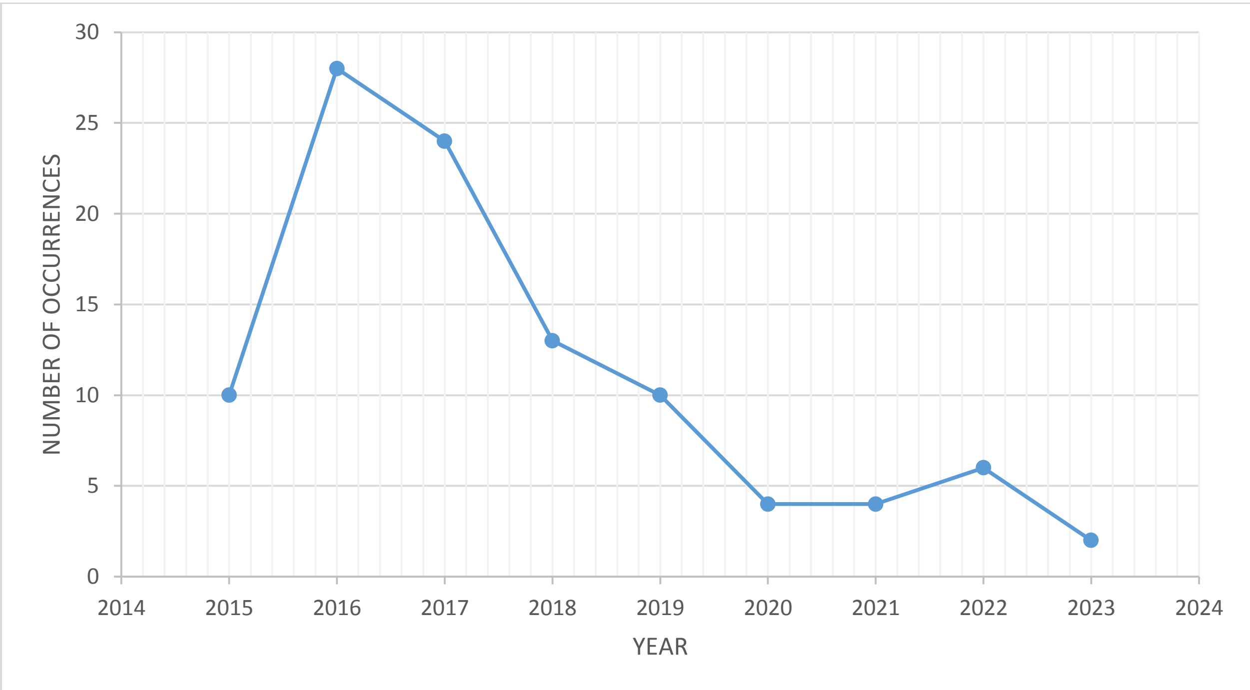

Fig. 4.3: Voltage collapses from 2015 – 2023

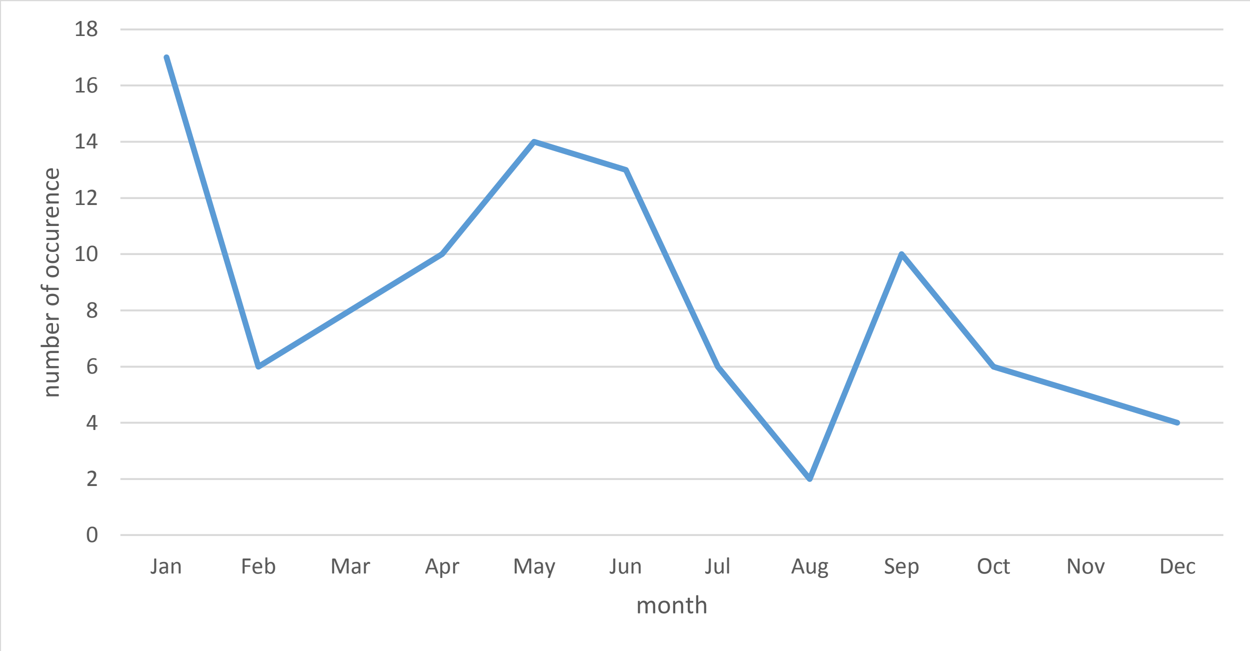

Fig. 4.2: Frequency of voltage collapses every month (2015 – 2023)

Table 4.1: Grid Generation(TCN National Control Centre, 2023).

GENERATING STATION	INSTALLED CAPACITY (MW)	AVERAGE (MW)	% GRID CONTRIBUTION
KAINJI	960	319	33.23
JEBBA	578	427.5	73.96
SHIRORO	600	383.365	63.89
DADIN KOWA	40	39.9	99.75
ZUNGERU	750	0	0.00
EGBIN ST1 - 6	1320	530.5	40.19
SAPELE	720	63.5	8.82
DELTA	915	436	47.65
AFAM IV-V	300	38	12.67
GEREGU GAS	435	134	30.80
OMOTOSHO GAS	336.8	98.7	29.31
OLORUNSOGO GAS	336	93.95	27.96
GEREGU NIPP	435	72.5	16.67
SAPELE NIPP	500	147.5	29.50
ALAOJI NIPP	504	111.5	22.12
OLORUNSOGO NIPP	750	101	13.47
OMOTOSHO NIPP	500	105.2	21.04
ODUKPANI NIPP	625	212.5	34.00
IHOVBOR NIPP	337.5	70	20.74
Taopex ENERGY	15	12.9	86.00
OKPAI	480	250	52.08

AZURA - EDO IPP	460	407.5	88.59
AFAM VI	650	352	54.15
IBOM	198	74.95	37.85
A.E.S	270	0	0.00
ASCO	110	0	0.00
OMOKU	150	76.55	51.03
TRANS AMADI	100	30.65	30.65
RIVERS IPP	180	159.5	88.61
PARAS ENERGY	132	72.65	55.04
GBARAIN NIPP	230	0	0.00
TOTAL	13917.3	4821.315	34.64

IV. Conclusion And Recommendations

4.1 Conclusion

Nigeria's power grid is a key area that requires urgent attention in other to revive the nation's economy which has continued to dwindle over the years. This has led to a lot of companies folding due to the inability to meet with demands of operations, lack of business activities, and high rates of unemployment. From the analysis, it's obvious that a country with so much potential is struggling to meet 50% of its population demand. Currently, Nigeria is not even able to generate at half its installed capacity, which is still far from the minimum of 50,000MW required from it to sustain its energy demand.

Therefore, now is the ideal moment for this country's leaders to implement the appropriate strategic frameworks and make wise investments in the Nigerian power sector, which would spur the needed expansion of the Nigerian economy. According to expert estimations, Nigeria's power output has to reach 30,000 megawatts by 2020 and 78,000 megawatts by 2030 for the country's economy to grow at a pace of 10% annually.

V. Recommendations

Voltage collapses can be prevented or eliminated in the following ways:

1. New technology and approaches need to be utilized in fault prevention, finding, and clearing**.**
2. The fuel source feed for generation stations should put modalities in place to make sure that the gas supply is not broken during operation.
3. System operators should make sure the right equipment for operations, protection, monitoring, metering, and control are installed and maintained.
4. Employing and training the right personnel to operate and maintain the system.
5. Constant expansion and adequate investmentinto transmission and distribution capacity.
6. Adequate security be provided to protect power infrastructure from theft and sabotage.
7. Decentralizing the grids to have smaller integrated grids. This will go a long way to prevent nationwide blackouts because of total grid collapses.
8. Optimally integrate distributed generation (DGs) units either micro or small distribution networks (feeders) at strategic locations.
9. The nation needs to employ a more effective security network for surveillance of its gas lines against vandalism.
10. The decentralization of Nigeria's national grid should be accelerated by the government. One way to achieve this is by using mini-grids powered by renewable energy sources, such as wind and solar power.
11. Lastly, the majority of transmission lines and substations are outdated and in need of quick repair. Due to their inability to handle the demands of modern demand, they necessitate the use of two circuits.

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