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INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

Article DOI:10.21474/IJAR01/21967

DOI URL: <http://dx.doi.org/10.21474/IJAR01/21967>



RESEARCH ARTICLE

QUALITY ANALYSIS OF HIGH-VOLTAGE NETWORK IN NIAMEY CITY

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Manuscript Info

Manuscript History

Received: 13 August 2025

Final Accepted: 15 September 2025

Published: October 2025

Key words:-

HTA network, Niamey, Reliability,
Harmonics

Abstract

The high-voltage distribution network in the city of Niamey has a tree structure, with some branches looped together, but it is operated radially. The river area, which includes the regions of Dosso, Niamey, and Tillabery, is mainly supplied by the 132 kV interconnection line from Berni Kebbi in Nigeria, covering around one-third of demand, with the remainder being met by local production. The high-voltage distribution network in the city of Niamey has 42 branches with a total length of 212,238 km, 94.3% of which are overhead and 5.7% underground. This network is used to supply HV/LV transformer stations to customers, numbering 288,924, 319,326, and 329,557 in 2022, 2023, and 2024, respectively, all power levels combined. Analysis of the high-voltage network in the city of Niamey shows that it fails 100% after only 240 hours of service, so its availability beyond that cannot be relied upon. Nevertheless, the study showed that the high-voltage/low-voltage transformer stations visited are not polluted by harmonics beyond the standard. Nevertheless, it is up to the distribution company to monitor harmonic rates in view of developments that introduce more static converters and other sources of pollution.

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Introduction:-

Power quality refers to the ability of the electrical grid to provide a high-quality power supply without disturbances that could affect industrial and domestic equipment [1, 2]. Rapid urbanization and population growth are placing considerable pressure on the distribution network in the city of Niamey. In this context, this study will not only identify the sources of disturbances, but also propose appropriate solutions to improve the reliability and efficiency of the electrical grid. The assessment of power quality on Niamey's HV/LV grid involves voltage and current measurements and the analysis of historical energy consumption data. This article examines the failure of Niamey's HV/LV network based on statistical operating data using quality index calculations. In addition, the study of harmonics at certain distribution stations provides insight into their contribution to the deterioration of electrical power quality.

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Methods and Materials:-

Statistics on disruptions to the Niamey distribution network:-

The data we present are the results of readings taken at the Niamey-III substation of all incidents on the high-voltage network in the city of Niamey that led to a power outage lasting more than five minutes. The data included in this study therefore covers the period from January 1, 2022, to August 31, 2024, for incidents, and from January 1 to **August 31, 2024, for quality index calculations. The following information is mainly included :**

- The various HTA feeders and their names ;
- Duration of power outages ;
- Energy not distributed .

Type of incidents:-

Disruptions detected on the HV network have a direct effect on power outages for customers and result in lost revenue and users. For each opening of the feeders, the type of incident is categorized according to whether the power outage is caused by :

- PD : Feeder Disruption ;
- AL : Power limitation on Nigeria's 132 KV line ;
- PP : Production disturbance ;
- PR : Network disturbances ;
- TR : Work or intervention.

Calculation of service quality indices:-

The need to calculate quality indices includes the exact numbers of customers affected by a power outage in the various feeders. Given that the digitization of the Niamey network is underway for low-voltage customers, for calculation purposes, we will consider that :

- Each subscriber station represents a single end customer;
- The number of customers is determined per station based on the installed power of the transformer in proportion to the total number of customers, except for subscriber or private stations ;
- The total number of customers for the feeder is the algebraic sum of the first two conditions above;
- DP and MX stations have the same customer density per km²;

The number of customers per transformer power is determined by equation (1).

$$NCT = ST \frac{(Ntc - NAB)}{\Sigma(SDP + SMX)} = ST.K \quad (1)$$

The number of customers per departure is determined by equation (2).

$$N_{cd} = \Sigma(NCT + NAB) \quad (2)$$

- Ntc: total end customers in Niamey;
- NCT: number of customers per type of transformer;
- SDP: installed capacity at public distribution substations;
- SMX: installed capacity at mixed substations;
- ST: transformer capacity;
- $\Sigma NCT = \Sigma ST.K$: represents the sum of DP and MX substation customers;
- ΣNAB : represents the sum of subscriber or private customers;
- Ncd: number of customers affected by an initial outage X

On a high-voltage distribution network, several quality indices can be used to assess the performance and reliability of the electricity supply. We will focus on calculating these indices for the high-voltage feeders in the city of Niamey. To do this, we will illustrate the calculation using an example from the Hamdalaye feeder for eight months of service from January to August for the year 2024. The calculation covers some of the main indices below:

The SAIDI index:-

This is an indicator used to assess the reliability and quality of the electricity supply. It measures the average duration of service interruptions affecting an end customer during a given period [2, 3, 4].

$$\text{SAIDI} = \frac{\sum(Ncd \times tc)}{Ntc} = \frac{\sum((NCT + NAB) \times tc)}{Ntc} \quad (3)$$

Calculation of the number of customers affected by a power outage at the Hamdalaye substation

$$\sum NCT = \sum ST.K \text{ avec } K = \frac{(Nct - NAB)}{\sum(SDP + SMX)} = \frac{(329557 - 798)}{(231085 + 24730)} = 1,285$$

$$\sum NCT = \sum ST.K = (3 * 50 + 5 * 100 + 43 * 160 + 2 * 250 + 6 * 400 + 8 * 630) = 15470$$

$$\sum(ST.K + NAB) = \sum Ncd = 15470 * 1,285 + 44 = 19924, \text{ Soient } 19924 \text{ clients}$$

$$\text{SAIDI} = \frac{\sum(Ncd \times tc)}{Ntc} = \frac{19924 * 33375}{329557} = 2018, \text{ Corresponding to an average of 34 hours}$$

$\sum(Ncd \times tc)$: sum of customers affected by an outage $\times$ duration of the outage in minutes

Ntc = total number of customers affected by the outage

The SAIFI index:-

This index assesses the frequency of service interruptions by measuring the average number of interruptions per end customer in the same period of 2024.

$$\text{SAIFI} = \frac{\sum(Ncd)}{Ntc} = \frac{Nc * Ncd}{Ntc} \quad (4)$$

$$\text{SAIFI} = \frac{Nc * Ncd}{Ntc} = \frac{410 * 19924}{329557} = 25$$

A SAIFI of 25 means that, on average, each customer in the Hamdalaye area experienced 25 outages between January and August 2024.

Availability Rate:-

Availability makes it possible to assess the reliability of protection systems and network equipment and to plan preventive maintenance. It also helps guide training policy for those involved in the production and distribution chain.

$$D = \frac{MTBF}{MTBF + MTTR} \quad (5)$$

$$MTBF = \frac{TBF}{NP} = \frac{\text{Working time} - \text{Downtime}}{\text{number of breakdowns}} = \frac{365 * 24 * 60 - 33375}{410} = 1201$$

This means that between two power outages during the period covered by the Hamdalaye departure, there are 1,201 minutes or 20 hours of normal operation.

$$MTTR = \frac{tc}{Ntc} = \frac{\text{Downtime}}{\text{total number of outages}} = \frac{33375}{410} = 81$$

This means that in the event of a fault, the average repair time until the Hamdalaye departure resumes is 81 minutes..

$$D = MTBF / (MTBF + MTTR) = 1201 / (1201 + 81) = 0,94 \text{ soit } 94\%$$

Application of initial failure probability Hamdalaye:-

System failure is a direct response to poor system quality. Failure has now become a key parameter in quality measurement and decision support in the operation of an electrical network.

The failure $F(t)$ of a system at a given moment (t) can be defined as an estimate of the following probability:

$$F(t) = P(T > t) = 1 - e^{-\lambda t} \quad (6)$$

The failure can also be related to the reliability function $R(t)$, which is defined as:

$$R(t) = 1 - F(t) = e^{-\lambda t} \quad (7)$$

- ❖ $F(t)$ is the probability of failure at time t ;
- ❖ $R(t)$ is the probability of reliability at time t ;
- ❖ (P) represents probability;
- ❖ (T) is a random variable representing the time until system failure.

$$\text{Default rate: } \lambda = 1/MTBF. \quad (8)$$

$$\lambda = 1/MTBF = 1/20 = 0,05$$

- ❖ For a time $t = 1$ hour and $\lambda = 0.05$, the failure of the city departure is determined below :

$$F(t) = 1 - e^{-0,05 \times 1} = 0,04877 \text{ soit } 5 \%$$

- ❖ For seven days of operation of the Hamdalaye start, $t = 168\text{h}$ and $\lambda=0.05$, the failure of the start is determined below:

$$F(t) = 1 - e^{-0,05 \times 168} = 0,99977 \text{ soit } 100\%$$

a. Undistributed energy

Undistributed energy refers to the amount of energy that, although generated, is not actually delivered to consumers for various reasons. It represents a significant challenge for NIGELEC in terms of economic loss and its brand image.

This can include several aspects, among others:

- Failures and service interruptions ;
- Capacity restrictions ;
- Power limitations, etc.

It is therefore appropriate to quantify the losses due to energy not delivered to the Niamey distribution network. The average price set for a MWh is equal to $P_x = 97,250$ CFA francs, as decided by NIGELEC at its board meeting in December 2023. The amount of lost revenue is therefore calculated as follows :

$$M = E \times P_x \quad (9)$$

- P_x : average price per MWh;
- E : energy not delivered in MWh;
- M : amount of lost revenue.

a. Introduction to the CA 8220 network analyzer

The CA.8220 electrical network analyzer is a measuring instrument designed to evaluate the quality and performance of electrical networks. It is an essential tool for electrical engineers and technicians who want to optimize the performance of electrical networks and ensure good power quality.

The CA-8220 is a single-phase AC+DC 600 V category III (IEC 61010-1) power analyzer with a digital LCD display. By measuring the effective values, power, and disturbances of electrical distribution networks, it provides an instant snapshot of the main characteristics of a single-phase network (voltage, current, power, voltage/current harmonics, etc.) and allows you to monitor rotating machines (temperature, current and start-up time, winding resistance, rotation speed). Compact and shock-resistant, its ergonomic and simple user interface makes it pleasant and intuitive to use [5].

It also has the following features and functions:

- Harmonic analysis up to a certain order (generally up to the 50th) ;
- Ability to record data over an extended period of time, allowing for subsequent analysis.
- Ability to connect the device to a computer for data transfer and analysis using dedicated software.
- Allows potential problems in the network to be identified before they cause outages.
- Used to assess energy consumption and propose optimization solutions.



Figure 1 : Analyseur de réseau C.A 8220[5]

Results and Analyses:-

a. Analysis of disruptions on the Niamey distribution network:-

Figure 2 shows the histogram of disruptions by incident group affecting the Niamey HTA network during the years 2022, 2023, and from January 1 to August 31, 2024.

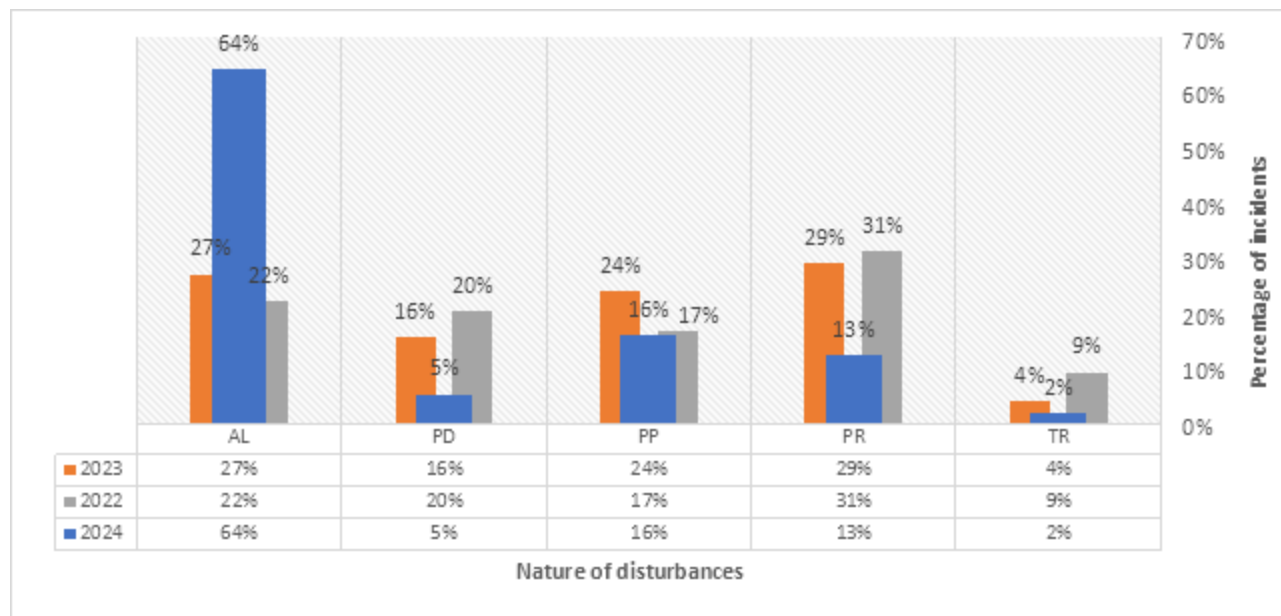


Figure 2: Histogram of disturbances

There is an asymmetrical distribution of incidents on the Niamey distribution network over the three years considered. There is a major peak due to the absence of the 132 kV interconnection line in 2024, which accounts for 64% of disruptions, indicating that this category is the most significant in terms of undistributed energy. Nevertheless, there has been an improvement in network-related disruptions over the same period. Overall, the limitation or absence of the 132 kV interconnection line is the most disruptive factor in the management of the electricity system in the river area and the Niamey distribution network in particular. It accounts for 38% of all disruptions over the three years, with a major impact on the delayed return on investment for manufacturers and small businesses, as well as social impacts.

Figure 3 shows the reliability and failure curve for the Hamdalaye feeder.

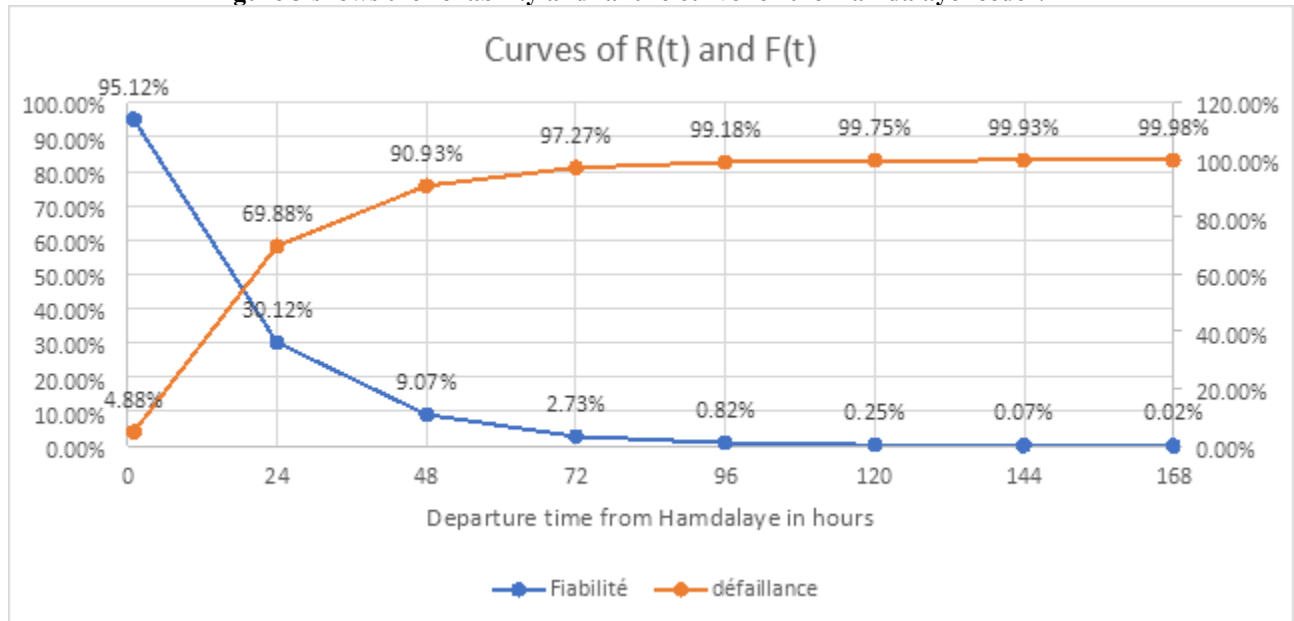


Figure 3: Reliability and Failure Curve

The reliability of the system ranges from 94% to 100% at one hour of service for all departures from Niamey. It begins to decline exponentially beyond one hour of service until it reaches a point $t = 168$ h where it no longer responds. Therefore, after one week of service, the distribution network can no longer be guaranteed to function properly and is no longer reliable.

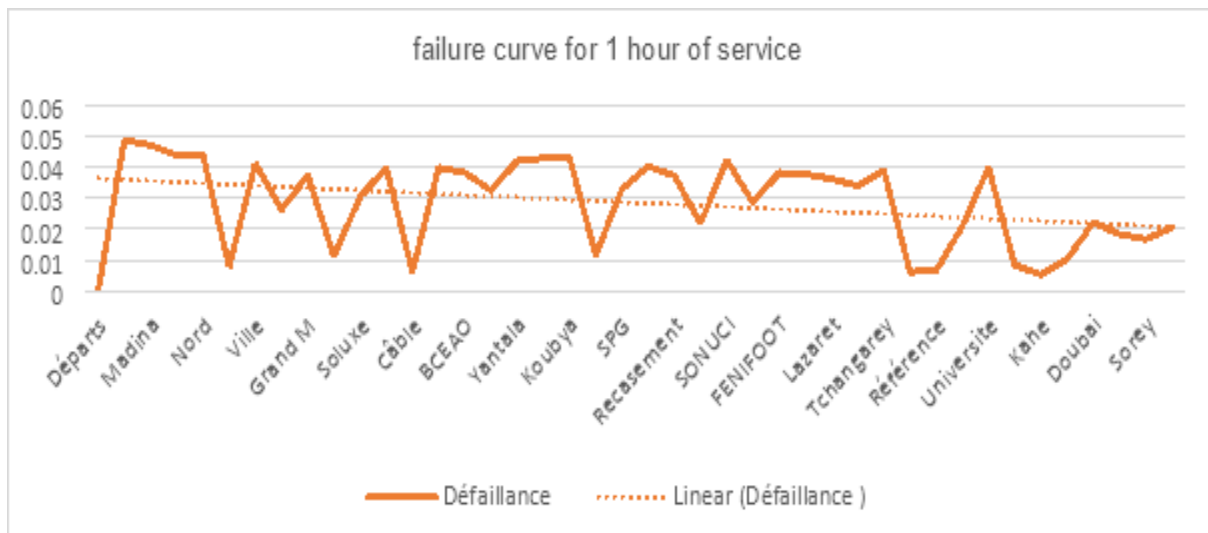


Figure 4: Failure and reliability of the Niamey network for one hour of service

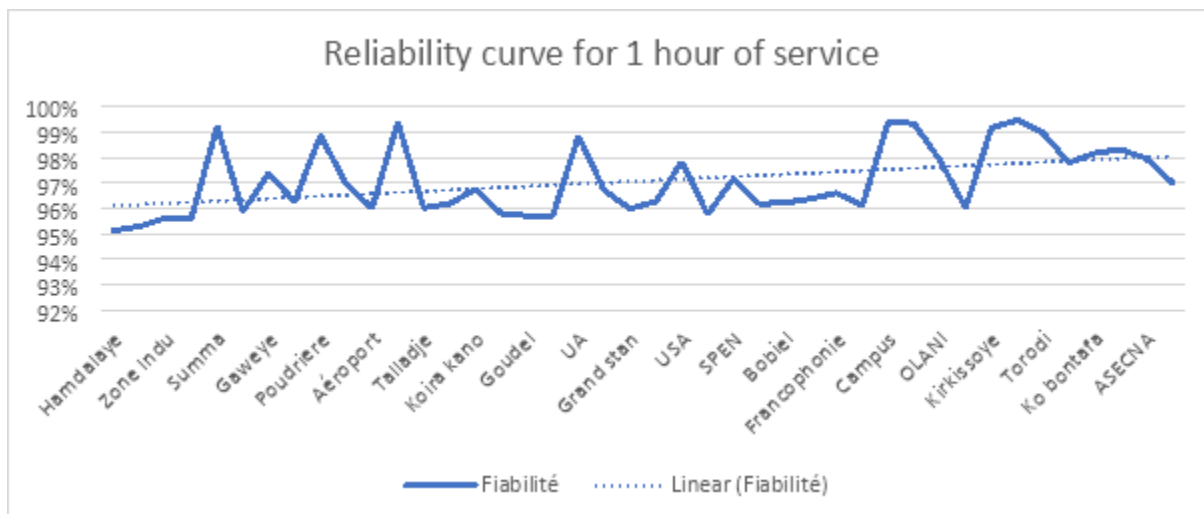


Figure 5: Niamey failure and reliability curve for 1 hour

b. Analysis of undistributed energy

Table 1 shows the energy not delivered due to high-voltage outages in Niamey over the last three years, as well as the amounts corresponding to lost revenue due to power outages lasting more than five minutes.

Table 1 : Energy not delivered due to high-voltage outages in Niamey

N°	Departs	E en MWh			Amount of lost revenue in CFA francs		
		2022	2023	2024	2022	2023	2024
1	Hamdalaye	200	6043	2749	19450000	587681750	267340250
2	Madina	209	4689	3334	20325250	456005250	324231500
3	Zone Indust	204	3281	2381	19839000	319077250	231552250
4	Nord	147	5360	129	14295750	521260000	12545250
5	Summa	9	1222	2987	875250	118839500	290485750
6	Ville	114	3164	1439	11086500	307699000	139942750
7	Gaweye	59	428	547	5737750	41623000	53195750
8	Grand March	82	2281	1613	7974500	221827250	156864250
9	Poudriere	40	3116	349	3890000	303031000	33940250
10	Soluxe	35	1721	1020	3403750	167367250	99195000
11	Aéroport	128	2822	2582	12448000	274439500	251099500
12	Câble	11	1086	75	1069750	105613500	7293750
13	Talladje	122	4926	3404	11864500	479053500	331039000
14	Bceao	91	2949	1608	8849750	286790250	156378000
15	Koira Kano	16	195	1022	1556000	18963750	99389500
16	Yantala	75	4219	2094	7293750	410297750	203641500
17	Goudel	110	5758	2733	10697500	559965500	265784250
18	Koubya	130	4504	2622	12642500	438014000	254989500
19	Ua	18	2626	177	1750500	255378500	17213250
20	Spg	96	4238	1509	9336000	412145500	146750250
21	Grand Stand	115	5014	2276	11183750	487611500	221341000
22	Recasement	105	5265	2271	10211250	512021250	220854750
23	Usa	12	165	208	1167000	16046250	20228000
24	Sonuci	118	5261	2612	11475500	511632250	254017000
25	Spen	55	1159	661	5348750	112712750	64282250

26	Fenifoot	143	3362	2063	13906750	326954500	200626750
27	Bobiel	192	4339	2890	18672000	421967750	281052500
28	Lazaret	72	5702	2680	7002000	554519500	260630000
29	Francophonie	121	3635	2208	11767250	353503750	214728000
30	Tchangarey	197	6135	3086	19158250	596628750	300113500
31	Campus	3	16	6	291750	1556000	583500
32	Référence	10	16	0	972500	1556000	0
33	Olani	26	2500	299	2528500	243125000	29077750
34	Universite	117	3793	3270	11378250	368869250	318007500
35	Kirkissoye	11	2659	69	1069750	258587750	6710250
36	Kahe	0	0,446	0,039	0	43373,5	3793
37	Torodi	8	109	59	778000	10600250	5737750
38	Doubai	99	3562	921	9627750	346404500	89567250
39	Ko Bontafa	43	1770	398	4181750	172132500	38705500
40	Sorey	43	363	224	4181750	35301750	21784000
41	Asecna	52	80	453	5057000	7780000	44054250
42	Fleuve	0	0	1258	0	0	122340500
		3438	119533	62286	334345500	11624627624	6057317293

The total shortfall for 2024 is as follows:

$$M = M_{2024} + M_{2024/2} = 6,057,317,293 + 3,028,658,647 = 9,085,975,940 \text{ CFA francs}$$

$M_{2024/2}$ represents the projected revenue shortfall for the last four months of the year, as Table 1 only takes into account data from January to August 2024.

Analysis of harmonics on the Niamey HV/LV network:-

Of all the disturbances, harmonics are unique in that they do not have a direct local influence in the same way as other disturbances such as transients, surges, micro-cuts, etc., whose direct or reciprocal effects between devices are both visible and identifiable. Harmonics refer to a global phenomenon where each user contributes only a small fraction of the disturbances degrading the network, but where the cumulative effects are increasingly significant.

In fact, as part of this study, we took measurements to analyze harmonics at two HV/LV substations in Niamey with distinct load characteristics, as shown below:

- the HV/LV substation, 400 kVA secondary, at the National Hospital in Niamey;
- the 3 HV/LV substation, 1000 KVA, which supplies an administrative area of Niamey.

The data was measured using the CA.8220 multifunction electrical network analyzer and Power Pad software, which enabled us to analyze the data and visualize the waves and spectra of the harmonics.

Table 2: Data measured at stations 3 and Hospital

Poste Hospital National de Niamey																	
Mesures de tension U(V) et courant I(A)												Mesures de puissances KW					
Position 1			Position 2			Position 3			Position 4			Position 1			Position 2		
Ueff	Ieff	f	Ueff	UDC	Ucf	Ueff, T/2 max	Ueff	Ueff, T/2 min	Umax	Umax	K	P	Q	S	Ueff	Ieff	f
404	486	50,44	405	0,4	1,4	415	406	0	580	580-	1,03	320	105	337	0	0,94	0,94
Poste 3 de Niamey																	
Mesures de tension U(V) et couran I(A)												Mesures de puissances KW					
Position 1			Position 2			Position 3			Position 4			Position 1			Position 2		
Ueff	Ieff	f	Ueff	UDC	Ucf	Ueff, T/2 max	Ueff	Ueff, T/2 min	Umax	Umax	K	P	Q	S	PDC	PF	DPF
420	579	50,4	420	0,5	1,42	423	420	0	600	600-	1,08	379	76	393	0	0,97	0,98

Figures 6 and 8 shows the current analyses for the Hospital and Station 3 respectively during one phase of their load. It can be seen that the signal from Station 3 is more distorted than that from the Hospital. The spectra in Figures 7 and 9 highlight this distortion, where the respective THD values are 4.7% and 6.5%. For

the Hospital substation, the dominant harmonics are of rank 3 and 5, while for substation 3, those of rank 3, 5, and 7 dominate.

We will illustrate the calculations with the data revealed for substation 3 below:

Distorting power D

$$S = \sqrt{P^2 + Q^2 + D^2} \Rightarrow D = \sqrt{S^2 - P^2 - Q^2} \quad (10)$$

$$D = \sqrt{393^2 - 379^2 - 76^2} = 70,93 \Rightarrow D = 70,93 \text{ KW}$$

Power factor PF

$$FP = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2 + D^2}} = \frac{379}{393} = 0,96 \quad (11)$$

$$FP = \frac{P}{S} = K \cos \varphi_1 \Rightarrow \cos \varphi_1 = \frac{PF}{K} = \frac{0,96}{1,08} = 0,89 \Rightarrow \cos \varphi_1 = 0,89$$

K represents the distortion factor and φ_1 is the phase shift between the fundamental current and the voltage.

Effective value of the fundamental current: I_1

$$I_{eff} = \sqrt{I_1^2 + I_3^2 + I_5^2 + I_7^2} \quad (12)$$

$$\Rightarrow I_{eff}^2 = I_1^2 + I_3^2 + I_5^2 + I_7^2$$

$$\Rightarrow 579^2 = I_1^2 (1 + 0,05 + 0,04 + 0,03) \Rightarrow I_1 = \frac{3579}{\sqrt{1,12}} = 547$$

Table 3: Emission of harmonic currents in Niamey's high-voltage/low-voltage network

Harmonics	Rank	Frequency Hz	% H	Effective value
Niamey Post Office 3 (THD = 6,5 %, $\cos \phi = 0,89$ et $D = 70,93$ KW)				
H ₁	1	50	100%	547 A
H ₃	3	150	5%	27 A
H ₅	5	250	4%	22 A
H ₇	7	350	3%	16 A
Niamey Hospital secondary station (THD = 4,7% $\cos \phi = 0,92$ et $D = 12$ KW)				
H ₁	1	50	100%	452 A
H ₃	3	150	2,5%	11 A
H ₅	5	250	4%	18 A
H ₇	7	350	1%	5 A

1KV < U ≤ 30KV with TDH = 8% of ranks below :

Rank 3 $\Rightarrow H = 5\%$, Rank 5 $\Rightarrow H = 6\%$ et Rank 7 $\Rightarrow H = 5\%$

It is clear that the voltage harmonics for the measured stations are well below the standard limit.

Forme d'onde

1

U RMS = 402,3 V Peak- = -576,1 V Peak+ = 577,1 V
 A RMS = 496,3 A Peak- = -709,1 A Peak+ = 713,0 A

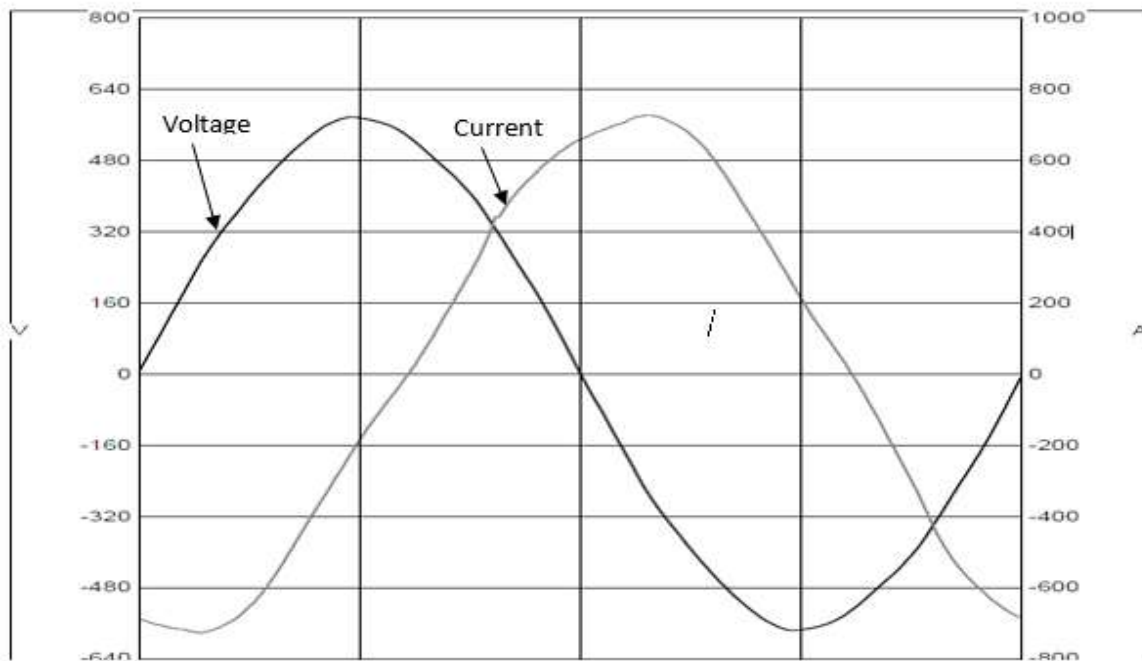


Figure 6 : Voltage and current waves measured at the hospital substation

Histogramme harmonique

1

U RMS = 0,4372 VU THD = 1,0% U CF = 1,43
 A RMS = 490,2 A A THD = 4,7% A CF = 1,41

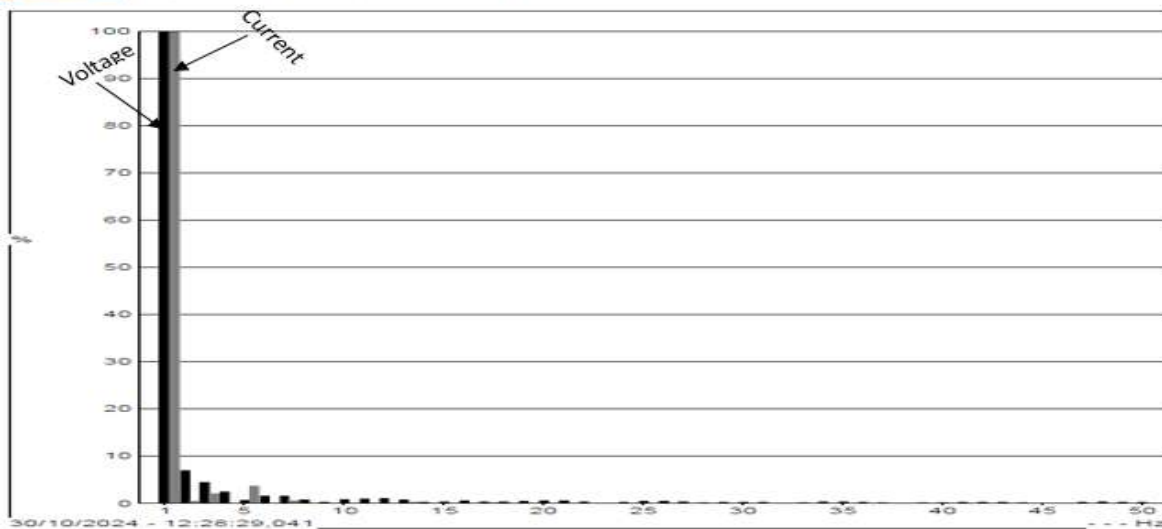
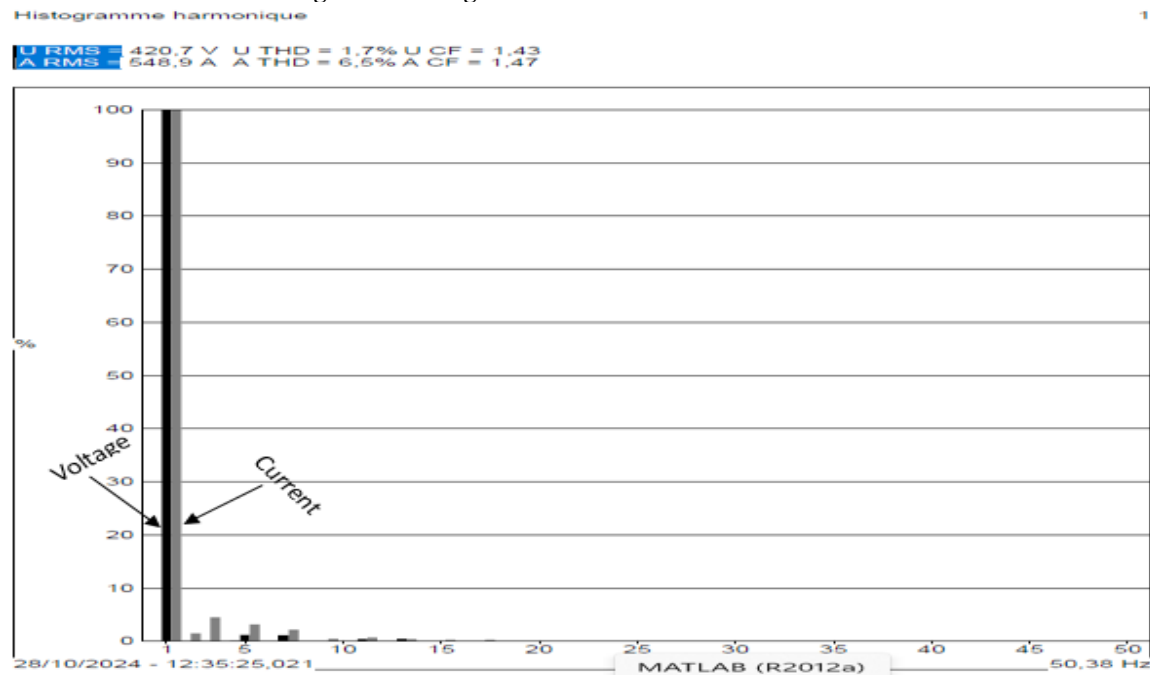
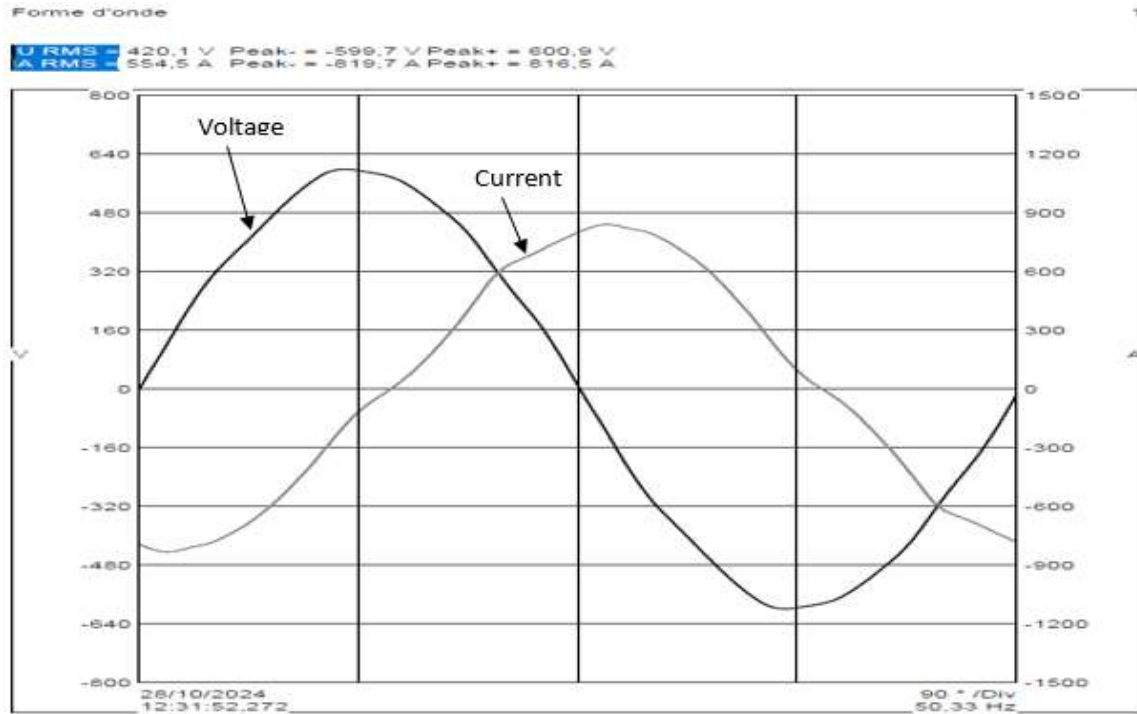


Figure 7 : Spectra of voltage/current harmonics from hospital load



Conclusion:-

The analysis of electrical power quality on Niamey's high-voltage network is a subject of crucial importance in the current context of rapid economic development and urbanization. The results obtained through harmonic measurements and analysis of power quality indices have highlighted several major challenges facing the network. It appears that significant disturbances related to the absence of the 132 kV interconnection line, the intervention of the SRMERD, and system synchronization problems and other hazards impact not only the reliability of the grid but

also user satisfaction. In addition, these disturbances can have adverse effects on electrical equipment, thereby increasing operating costs and reducing the service life of installations.

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