Quality analysis of high-voltage network in Niamey city

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Abtract
The high-voltage distribution network in the city of Niamey has a tree structure, withsome branches loopedtogether, but itisoperatedradially. The river area, whichincludes the regions of Dosso, Niamey, and Tillabery, ismainlysupplied by the 132 kV interconnection line from Berni Kebbi in Nigeria, coveringaround one-third of demand, with the remainderbeing 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 isused to supply HV/LV transformer stations to customers, numbering 288,924, 319,326, and 329,557 in 2022, 2023, and 2024, respectively, all power levelscombined. Analysis of the high-voltage network in the city of Niamey shows thatit fails 100% afteronly 240 hours of service, soitsavailabilitybeyondthatcannotbereliedupon. Nevertheless, the studyshowedthat the high-voltage/low-voltage transformer stations visited are not polluted by harmonicsbeyond the standard. Nevertheless, itis up to the distribution company to monitor harmonic rates in view of developmentsthatintroduce more staticconverters and other sources of pollution.

Keywords : HTA network, Niamey, Reliability, Harmonics

1. Introduction

Power qualityrefers to the ability of the electricalgrid to provide a high-quality power supplywithoutdisturbancesthatcould affect industrial and domesticequipment [2].
Rapid urbanization and population growth are placingconsiderable pressure on the distribution network in the city of Niamey. In thiscontext, thisstudywill not onlyidentify the sources of disturbances, but also propose appropriate solutions to improve the reliability and efficiency of the electricalgrid.
The assessment of power quality on Niamey's HV/LV gridinvolves voltage and currentmeasurements and the analysis of historicalenergyconsumption data. This article examines the failure of Niamey's HV/LV network based on statistical operating data usingquality index calculations. In addition, the study of harmonics at certain distribution stations provides insight intotheir contribution to the deterioration of electrical power quality.

2. Methods and materials

2.1 Statistics on disruptions to the Niamey distribution network

The data wepresent are the results of readingstaken at the Niamey-III substation of all incidents on the high-voltage network in the city of Niamey thatled to a power outage lasting more than five minutes. The data included in thisstudythereforecovers the periodfromJanuary 1, 2022, to August 31, 2024, for incidents, and fromJanuary 1 to August 31, 2024, for quality index calculations. The following information ismainlyincluded:

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

2.2. 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 eachopening of the feeders, the type of incident iscategorizedaccording to whether the power outageiscaused by:

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

2.3. Calculation of service quality indices

The need to calculatequality indices includes the exact numbers of customersaffected by a power outage in the various feeders. Giventhat the digitization of the Niamey network isunderway for low-voltage customers, for calculationpurposes, wewillconsiderthat:

- Eachsubscriber station represents a single end customer;
- The number of customersisdetermined 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 algebraicsum of the first two conditions above;
- DP and MX stations have the samecustomerdensity per km^2;

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

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

The number of customers per departureisdetermined by equation (2).

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

- *Ntc: total end customers in Niamey;*
- *NCT:number of customers per type of transformer;*
- *SDP:installedcapacity at public distribution substations;*
- *SMX:installedcapacity at mixed substations;*
- *ST: transformer capacity;*
- *ΣNCT=ΣST.K: represents the sum of DP and MX substationcustomers;*
- *ΣNAB:represents the sum of subscriber or privatecustomers;*
- *Ncd:number of customersaffected by an initial outage X*

On a high-voltage distribution network, severalquality indices can beused to assess the performance and reliability of the electricitysupply. Wewill focus on calculatingthese indices for the high-voltage feeders in the city of Niamey. To do this, wewillillustrate the calculationusing an examplefrom the Hamdalaye feeder for eightmonths of service fromJanuary to August for the year 2024. The calculationcoverssome of the main indices below:

The SAIDI index

This is an indicatorused to assess the reliability and quality of the electricitysupply. It measures the average duration of service interruptions affecting an end customerduring a givenperiod [2, 3, 4].

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

(3)

Calculation of the number of customersaffected by a power outage at the Hamdalayesubstation

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

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

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

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

∑(Ncd×tc):sum of customersaffected by an outage × duration of the outage in minutes

Ntc= total number of customersaffected by the outage

The SAIFI index

This index assesses the frequency of service interruptions by measuring the averagenumber of interruptions per end customer in the sameperiod of 2024.

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

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

A SAIFI of 25 meansthat, on average, eachcustomer in the Hamdalaye area experienced 25 outagesbetweenJanuary and August 2024.

Availability Rate

Availabilitymakesit possible to assess the reliability of protection systems and network equipment and to plan preventive maintenance. It alsohelps guide training policy for thoseinvolved in the production and distribution chain.

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

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

This meansthatbetweentwo power outagesduring the periodcovered by the Hamdalayedeparture, there are 1,201 minutes or 20 hours of normal operation.

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

This meansthat in the event of a fault, the averagerepair time until the Hamdalayedepartureresumesis 81 minutes..

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

Application of initial failureprobability Hamdalaye

System failureis a direct response to poor system quality. Failure has nowbecome a key parameter in qualitymeasurement and decision support in the operation of an electrical network.

The failure F(t) of a system at a given moment (t) can bedefined as an estimate of the followingprobability:

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

The failure can alsoberelated to the reliabilityfunction R(t), whichisdefinedas:

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

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

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

$\lambda = 1/\text{MTBF} = 1/20 = 0{,}05$

- **For a time t = 1 hour and λ = 0.05,** the failure of the city departureisdeterminedbelow :

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

- **For sevendays of operation**of the Hamdalaye start, t = 168h and λ=0.05, the failure of the start isdeterminedbelow:

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

a. Undistributedenergy

Undistributedenergyrefers to the amount of energythat, althoughgenerated, is not actuallydelivered to consumers for variousreasons. It represents a significant challenge for NIGELEC in terms of economicloss and its brand image.

This can includeseveral aspects, amongothers:

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

It isthereforeappropriate to quantify the losses due to energy not delivered to the Niamey distribution network. The averageprice set for a MWh isequal to Px = 97,250 CFA francs, as decided by NIGELEC at itsboard meeting in December 2023. The amount of lost revenue isthereforecalculated as follows:

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

- P_x : averageprice 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 analyzeris a measuring instrument designed to evaluate the quality and performance of electrical networks. It is an essential tool for electricalengineers and technicianswhowant 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 analyzerwith a digital LCD display. By measuring the effective values, power, and disturbances of electrical distribution networks, itprovides an instant snapshot of the main characteristics of a single-phase network (voltage, current, power, voltage/currentharmonics, etc.) and allowsyou to monitor rotating machines (temperature, current and start-up time, windingresistance, rotation speed). Compact and shock-resistant, itsergonomic and simple user interface makesitpleasant and intuitive to use [5].

It also has the followingfeatures and functions:

- Harmonicanalysis up to a certain order (generally up to the 50th) ;
- Ability to record data over an extendedperiod of time, allowing for subsequentanalysis.
- Ability to connect the device to a computer for data transfer and analysisusingdedicated software.
- Allowspotentialproblems in the network to beidentifiedbeforethey cause outages.
- Used to assessenergyconsumption and propose optimization solutions.

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

3. 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 fromJanuary 1 to August 31, 2024.

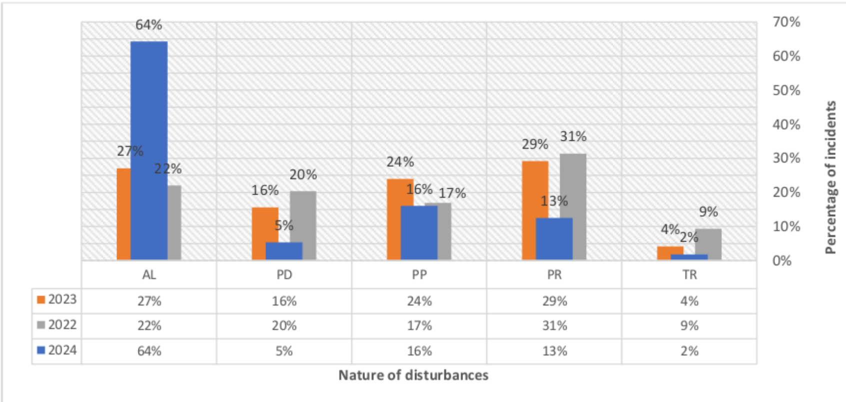

Figure 2:Histogram of disturbances

There is an asymmetrical distribution of incidents on the Niamey distribution network over the threeyearsconsidered. There is a major peak due to the absence of the 132 kV interconnection line in 2024, whichaccounts for 64% of disruptions, indicatingthatthiscategoryis the mostsignificant in terms of undistributedenergy. Nevertheless, there has been an improvement in network-related disruptions over the sameperiod.

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 threeyears, 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 failurecurve for the Hamdalaye feeder.

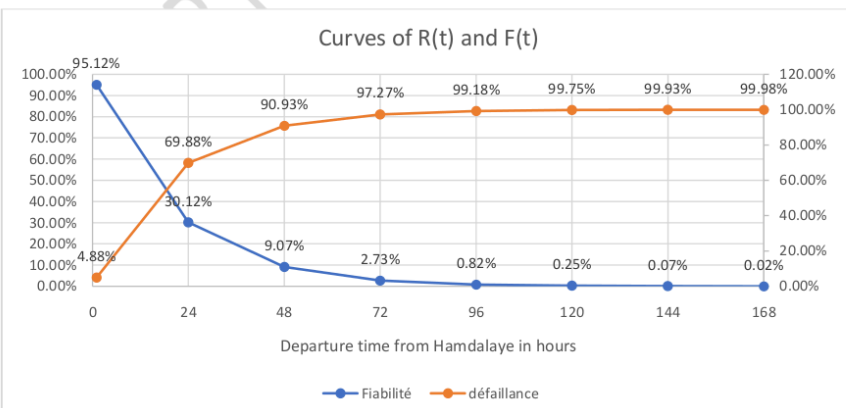

Figure 3:Reliability and Failure Curve

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.

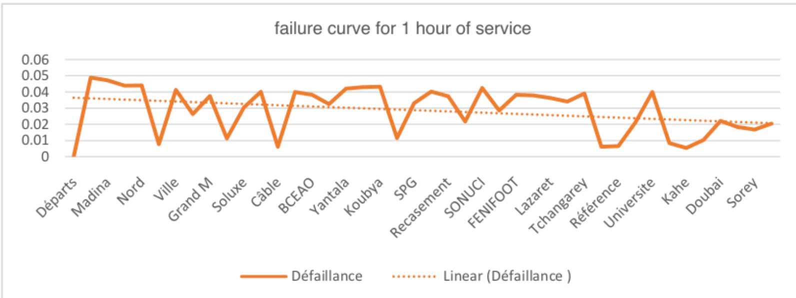

Figure 4: Failure and reliability of the Niamey network for one hour of service

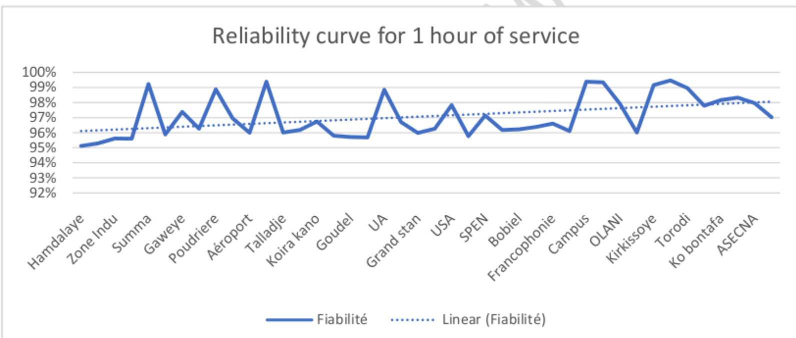

Figure 5: Niamey failure and reliabilitycurve for 1 hour

b. Analysis of undistributedenergy

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

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

		E en MWh			**Amount of lost revenue in CFA francs**		
N°	Departs	**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 = M2024 + M2024/2 = 6,057,317,293 + 3,028,658,647 = 9,085,975,940 CFA francs

M2024/2 represents the projected revenue shortfall for the last four months of the year, as Table 1 onlytakesintoaccount data fromJanuary to August 2024.

c. Analysis of harmonics on the Niamey HV/LV network

Of all the disturbances, harmonics are unique in thatthey do not have a direct local influence in the sameway as otherdisturbancessuch as transients, surges, micro-cuts, etc., whose direct or reciprocaleffectsbetweendevices are both visible and identifiable. Harmonicsrefer to a global phenomenonwhereeach user contributesonly a small fraction of the disturbancesdegrading the network, but where the cumulative effects are increasinglysignificant. In fact, as part of thisstudy, wetookmeasurements to analyzeharmonics at two HV/LV substations in Niamey with distinct loadcharacteristics, as shownbelow:

- 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 wasmeasuredusing the CA.8220 multifunctionelectrical network analyzer and Power Pad software, whichenabled us to analyze the data and visualize the waves and spectra of the harmonics.

Table 2: Data measured at stations 3 and Hospital

Poste Hopital 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 respectivelyduring one phase of theirload. It can beseenthat the signal from Station 3 is more distortedthanthatfrom the Hospital. The spectra in Figures 7 and 9 highlight thisdistortion, 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.

Wewillillustrate the calculationswith the data revealed for substation 3 below:

Distorting power D

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

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

Power factor PF

$FP = \frac{P}{S} = \frac{P}{\sqrt{P^2+Q^2+D^2}} = \frac{379}{393} = 0{,}96$ (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 φ1 is the phase shift between the fundamentalcurrent and the voltage.

Effective value of the fundamentalcurrent: I_1

$I_{eff} = \sqrt{I_1^2 + I_3^2 + I_5^2 + I_7^2}$ (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 harmoniccurrents in Niamey's high-voltage/low-voltage network

Harmoncs	Rank	Frequency Hz	% H	Effective value
Niamey Post Office 3(THD = 6,5 %, cosϕ = 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% cosϕ = 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% ofranksbelow :

Rank 3 ⇒ H = 5%, Rank 5 ⇒ H = 6% et Rank 7 ⇒ H = 5%

It isclearthat the voltage harmonics for the measured stations are wellbelow the standard limit.

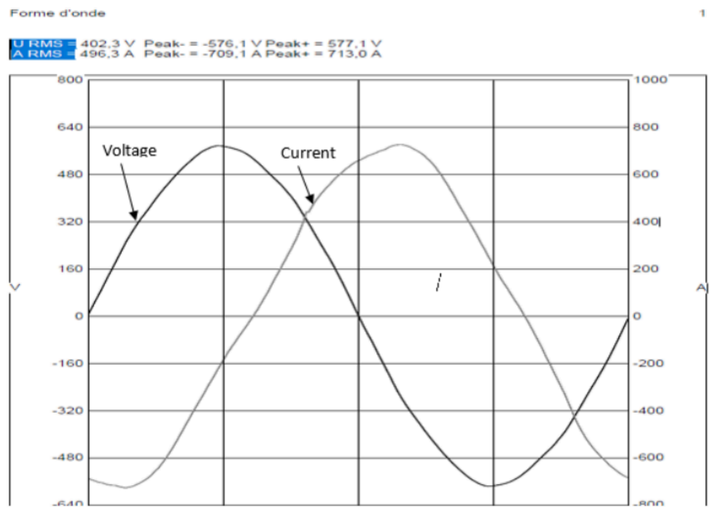

Figure 6 : Voltage and currentwavesmeasured at the hospitalsubstation

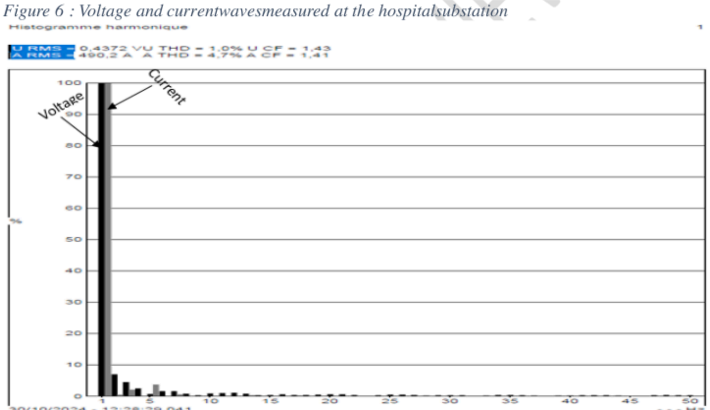

Figure 7 : Spectra of voltage/currentharmonicsfromhospitalload

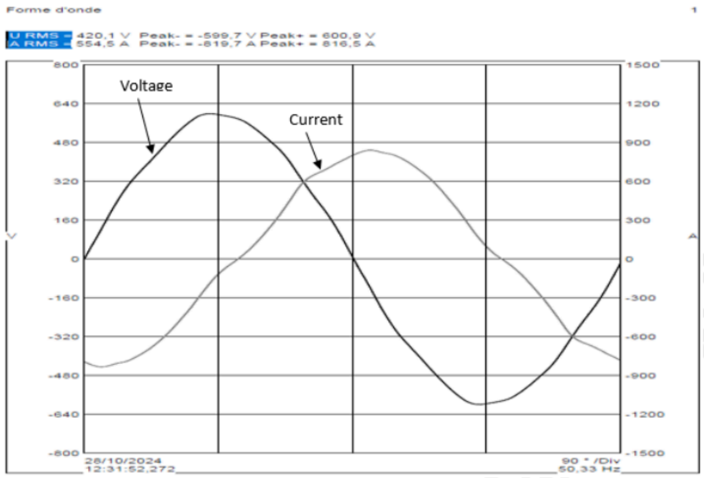

Figure 8 :Voltage and currentwavesmeasured at station 3

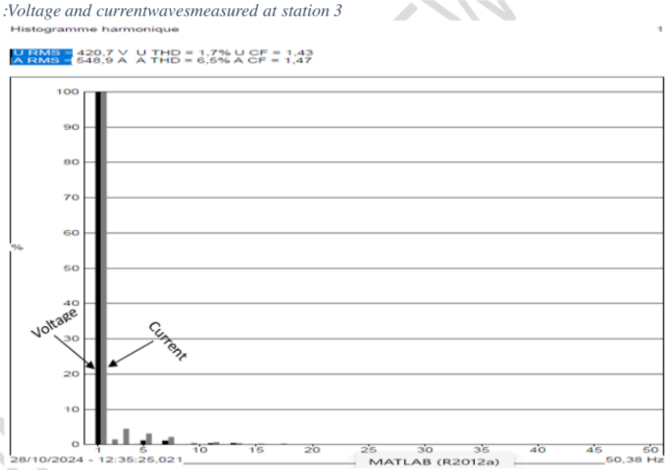

Figure 9 :Spectra of voltage/currentharmonics of the load at station 3

3. Conclusion

The analysis of electrical power quality on Niamey's high-voltage network is a subject of crucial importance in the currentcontext of rapideconomicdevelopment and urbanization. The resultsobtainedthroughharmonicmeasurements and analysis of power quality indices have highlightedseveral major challenges facing the network. It appearsthatsignificantdisturbancesrelated to the absence of the 132 kV interconnection line, the intervention of the SRMERD, and system synchronizationproblems and otherhazards impact not only the reliability of the grid but also user satisfaction. In addition, thesedisturbances can have adverse effects on electricalequipment, therebyincreasing operating costs and reducing the service life of installations.

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