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Original Research Article

Comprehensive Evaluation of Harmonic Analysis and Mitigation Approaches for Distribution Networks: A Comparative Study Across Three Distinct Network Load Scenarios

Tom Wanjekeche*[1], Josephat NO. Simeon[2], Vilho N. Nguumbwa[3], Andreas T. Ndapuka[4]

[1] Department of Electrical and Computer Engineering, University of Namibia, Namibia
e-mail: twanjekeche@unam.na

[2] Department of Electrical and Computer Engineering, University of Namibia, Namibia
e-mail:simeonjosephat@gmail.com

[3] Department of Electrical and Computer Engineering, University of Namibia, Namibia
e-mail: nghuumbwav@gmail.com

[4] Department of Electrical and Computer Engineering, University of Namibia, Namibia
e-mail:ndapukant@gmail.com

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ABSTRACT

Distribution networks are essential components of modern power systems, catering to diverse consumer needs. However, the escalating demand for electricity has amplified concerns regarding harmonics stemming from non-linear loads. These harmonics pose significant threats to power quality and equipment integrity. This paper conducts a thorough examination of harmonic analysis and mitigation strategies within distribution networks, with a specific focus on three distinct load scenarios: low power factor, residential areas, and university campus. By evaluating harmonic levels, frequency components, and voltage distortions across these scenarios, it provides insights into their unique challenges. Moreover, the research explores mitigation techniques to address identified harmonic issues effectively. The findings not only enhance the understanding of harmonic problems in distribution networks but also offer practical solutions to enhance power quality and network reliability. This paper serves as a valuable resource for power system engineers, utility companies, and researchers involved in distribution network management.

KEYWORDS

Distribution network, Power factor, Harmonic analysis, Mitigation of power quality factors, Power quality.

INTRODUCTION

Distribution networks are a critical component of the modern electrical grid, responsible for delivering electricity to end-users efficiently and reliably. However, the proliferation of non-linear loads, such as power electronic devices and adjustable-speed drives, has led to an increasing concern about harmonic distortion in distribution networks. Harmonic distortion is characterized by non-sinusoidal waveforms in the electrical system, which can adversely affect power quality and lead to operational and reliability challenges. This literature review explores

* Corresponding author

the existing body of knowledge related to harmonic analysis and mitigation approaches in distribution networks, providing a foundation for the comparative study of the distinct network load scenarios. A study was conducted on a Namibian distribution network focusing on three scenarios.

Previous power quality analysis on distribution networks

To ensure reliable, efficient, and cost-effective operation of distribution networks as well as the continuous supply of power, there is a need to constantly monitor and maintain the networks' power quality parameters under the desired levels in accordance to the relevant electrical standards [1].

The authors in [2] proposed a methodology to investigate power quality problems of a power distribution network and rank different load sites' performance in order of mitigation measure requirement. A University campus grid of a school campus was modelled in MATLAB for power quality analysis using NP EN 50160; IES 61000-2-3 and IEEE Std 1159-2019 standards [3]. In [4], an energy audit was conducted for a university campus, it was discovered that Energy consumption was higher than normal due to voltage imbalance and low power factor. A modified IEEE 14 bus model was developed to simulate grid connected photovoltaic in a low voltage region of Liang, it was found that PV integration leads to positive impact on voltage distribution and reduced line losses to certain limit of PV integration [5]. Furthermore, the effect of decreasing power factor on electricity losses of rural low-voltage networks. It was discovered that as power factor decreases from 0.97 to 0.77 electricity losses increased tremendously [6].

The performance of different topologies of passive filters were evaluated for harmonic compensation, where double-tuned filter was identified as the suitable type for reduction of 5th and 7th harmonics [7]. In contrary, single-tuned passive filters proved efficient to mitigate individual harmonics and total harmonic distortion in distribution networks [8], as well as in a soap manufacturing industry that uses variable speed drives [9]. In [10], MATLAB was used to evaluate two fixed shunt capacitor banks (SCB) at a 33 kV busbar in a distribution substation for power factor correction, which showed substantial improvement on the bus.

Moreover, an optimization model was developed to analyze voltage quality improvement, several planning projects were ranked in certain area based on voltage improvement and results were promising [11]. In [12], a configuration method coordinated by series voltage regulator and reactive power compensation capacitor based on network admittance matrix was proposed for low voltage control of a rural distribution network.

In addition, a cost-effective algorithm was implemented to optimize the modulation parameters and minimize the total harmonics in an industrial power network [13]. A novel model was developed in [14] to reduce the number of N switching angles required to mitigate N-1 harmonics, and achieve both harmonic elimination and mitigation objectives. In addition, another model to overcome the poor accuracy and generality of traditional methods was also developed and tested [14]. In [15] further results were presented to improve estimation of the harmonic admittance.

In [16], authors used selective harmonic elimination technique was used to eliminate completely N number of harmonics with (N+1) number of switchings per quarter, harmonics up to 17th harmonic were mitigated with two switchings per quarter. In addition, a smart, efficient, and accurate techniques were developed to estimate harmonics on a distribution network, artificial intelligence was developed and its performance compared with traditional harmonic estimation techniques [17].

Moreover, countermeasure methods; revised JIS C 61000-3-2 (based on IEC 61000-3-2 standard) to suppress the harmonic current outflow of AHPs and installation of LC filters was designed and developed, it was revealed that both can effectively suppress the voltage distortion [18].

The performance of different methods was evaluated for harmonic mitigation, these included Active Power Filter (APF) and Static Synchronous Compensator (STATCOM) with different models of nonlinear loads. It was shown that all higher-order harmonics have been maintained within the standard with STATCOM giving a comparatively better performance [19]. In [20], a study presented the results of a comprehensive power quality analysis of an open-pit mine's electrical network utilizing the Electrical Transient Analyzer Program (ETAP), the findings indicated the presence of various power quality issues, including harmonic distortion, a power quality improvement plan was proposed.

POSSIBLE CAUSES OF POOR POWER QUALITY IN THREE NETWORK LOAD SCENARIOS

Power quality issues on Network 1

Possible causes of harmonics in the University campus' power network which has Solar PV plant of 100 kW include solar inverters, computers, welding machines and aircons. Just like any other electronic equipment, photovoltaic inverters inject harmonics into the electrical installation which leads to overheating. Moreover, personal computers draw non-sinusoidal current causing considerable distortion in voltage and current in the network. Distortion causes variation in voltages which might go beyond acceptable limits of ±10%, resulting in reduction in equipment lifespan and hence malfunctioning. These effects were noticed at the campus that necessitated further investigation.

Power quality issues on Network 2

Top priority of Utility companies is to ensure that power supplied to consumer is of good quality, but Northern Regions Distribution Company (NORED), a distribution company in northern Namibia, has been experiencing a low power factor (PF) averaging 0.2 lagging on its Okangwati distribution network. This falls below minimum acceptable limit of 0.85 Power factor lagging as set by the Electricity Control Board (ECB) of Namibia. Table 1 shows the PF data obtained from the Okangwati Auto-Recloser.

Table 1. Auto-recloser electrical data on Okangwati network

RECORDER ID	DATE	HOUR	KW	KVAR	PF	KVA
OKANGWATI	10121	30	301.5	1245	0.235	1280.99
OKANGWATI	10121	100	298.5	1243.5	0.233	1278.83
OKANGWATI	10121	130	292.5	1249.5	0.228	1283.28
OKANGWATI	10121	200	283.5	1255.5	0.220	1287.11
OKANGWATI	10121	230	276	1258.5	0.214	1288.41
OKANGWATI	10121	300	264	1248	0.207	1275.62
OKANGWATI	10121	330	259.5	1248	0.204	1274.69
OKANGWATI	10121	400	256.5	1246.5	0.202	1272.62
OKANGWATI	10121	430	258	1237.5	0.204	1264.11
OKANGWATI	10121	500	253.5	1248	0.199	1273.49
OKANGWATI	10121	530	252	1258.5	0.196	1283.48
OKANGWATI	10121	600	250.5	1261.5	0.195	1286.13
OKANGWATI	10121	630	262.5	1245	0.206	1272.37
OKANGWATI	10121	700	246	1252.5	0.193	1276.43
OKANGWATI	10121	730	223.5	1261.5	0.174	1281.15
OKANGWATI	10121	800	241.5	1252.5	0.189	1275.57

Preliminary investigations showed that- the network was lightly loaded with only 15%, resulting reactive power generation by shunt capacitance thus lowering the line's efficiency. This also leads to higher receiving end voltage compared to sending end voltage a condition known as Ferranti effect.

The effect of Ferranti on distribution lines (80 km < l > 250 km) and can be explained in detail using the π (pi) model as represented in Figure 1 and eqs. (1-5) [21], [22]. In this paper, an investigation was carried out to determine the optimal loading of the line as will be discussed in IV. Using the pi model, the sending end voltage is determined using eqs. (1-5) [22]:

$$V_s = \left(1 + \frac{ZY}{2}\right) V_r + ZI_r \tag{1}$$

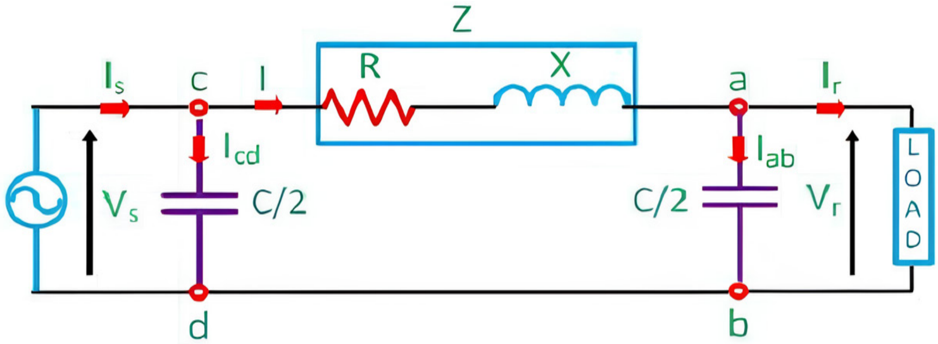

Figure 1. Pi model presentation of Ferranti effect

Eq. (1) shows the simplified KVL, however, at no load or lightly loaded, Ir is equivalent to zero reducing the equation to eq. (2):

$$V_s = \left(1 + \frac{ZY}{2}\right) V_r \tag{2}$$

$$V_s - V_r = \left(1 + \frac{ZY}{2}\right) V_r - V_r \tag{3}$$

$$V_s - V_r = \left(1 + \frac{ZY}{2} - 1\right) V_r \tag{4}$$

$$V_s - V_r = \left(\frac{ZY}{2}\right) V_r \tag{5}$$

where $Z = (r + j\omega L)\, S$ and $Y = j\omega C$.

Resistance is neglected when modelling the Ferranti effect in medium and long transmission lines, hence equation is simplified as in eq. (6):

$$V_s - V_r = -\frac{1}{2}(w^2 S^2) lcV_r \tag{6}$$

Eq. (6) is further sampled to:

$$V_s - V_r = -\frac{1}{2}(w^2 S^2)\left(\frac{1}{(3 \times 10^8)^2}\right) V_r \tag{7}$$

Since, $\omega = 2\pi f$ hence eq. (7) is simplified to:

$$V_s - V_r = -\left(\frac{4\pi}{18} \times 10^{-16}\right)(f^2 S^2 V_r) \tag{8}$$

Eq. (8) confirms Ferranti effect, where sending end voltage is higher that receiving end voltage.

Power quality issues on Network 3

NORED is also grappling with elevated levels of power quality issues within its Eheke residential bulk supply network. In a network incorporating hammer mills with power ratings ranging from 15 to 40 kW equipped with variable speed drives (VSDs) and star/delta starters, several power quality challenges may emerge. The utilization of VSDs introduces harmonics into the electrical system due to their nonlinear characteristics, potentially causing increased heating in components and efficiency reduction.

In addition, star/delta starters, employed for motor starting, can lead to current peaks during transition phases, impacting electrical components and possibly inducing voltage sags. Furthermore, the variable speed drives may cause abrupt load changes, resulting in voltage fluctuations that could affect the performance of sensitive equipment. These power quality issues may collectively contribute to mechanical stress on the hammer mills, potentially reducing equipment lifespan leading to consistent failures. The nature of power quality issues caused by hammer mills on Eheke residential supply network and mitigation measures are discussed in IV.

POWER QUALITY MONITORING AND MITIGATION MEASURES

Power monitoring and results analysis on Network 1

For further analysis on University campus network, power quality analyzer was installed, where electric parameters such as power frequency, THD, individual harmonics, supply voltage limits, voltage unbalance, flicker severity, supply voltage compatibility, and instances of sags, swells, and interruptions were captured. Preliminary investigation was to determine if those parameters fell within acceptable ranges. Additionally, the University campus distribution system was modelled using the ETAP software as shown in **Figure 2** for a more detailed analysis of power quality factors. The simulation results on bus 6 connecting Solar PV inverter to the grid is given in **Figure 3**. The waveform is distorted with high percentage of harmonics.

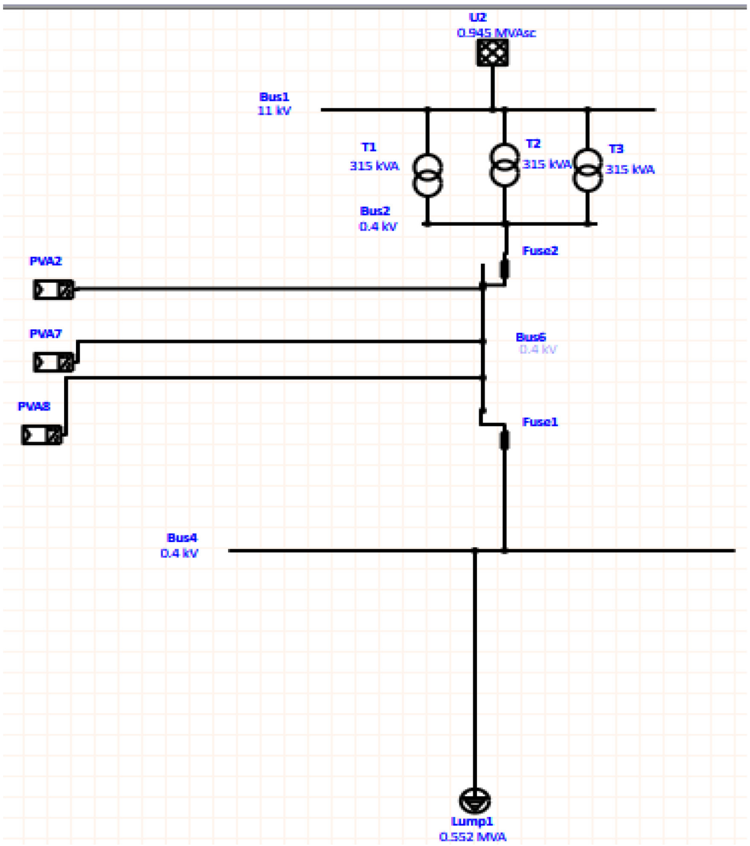

Figure 2. The single line diagram for the Engineering campus

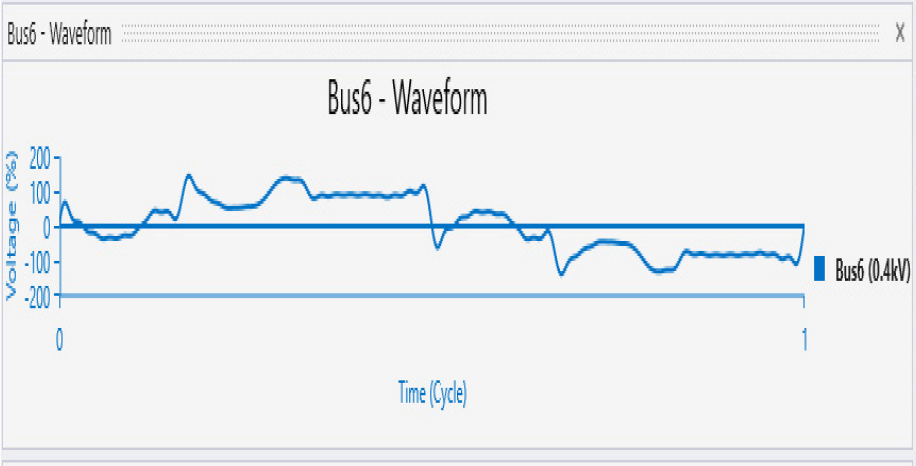

Figure 3. Output voltage waveform at bus 6 before mitigation measures

With further analysis of the system in ETAP and using NRS 048-2:2 017 analyser, it was discovered 5th harmonics and over voltages in the network as shown in **Table 2** were the main cause of power quality problems. 5th harmonics failed the test by overshooting to 0.46%. This is validated in **Figure 4** where is clearly illustrated that 5th harmonic order is the highest contributor to the harmonic content.

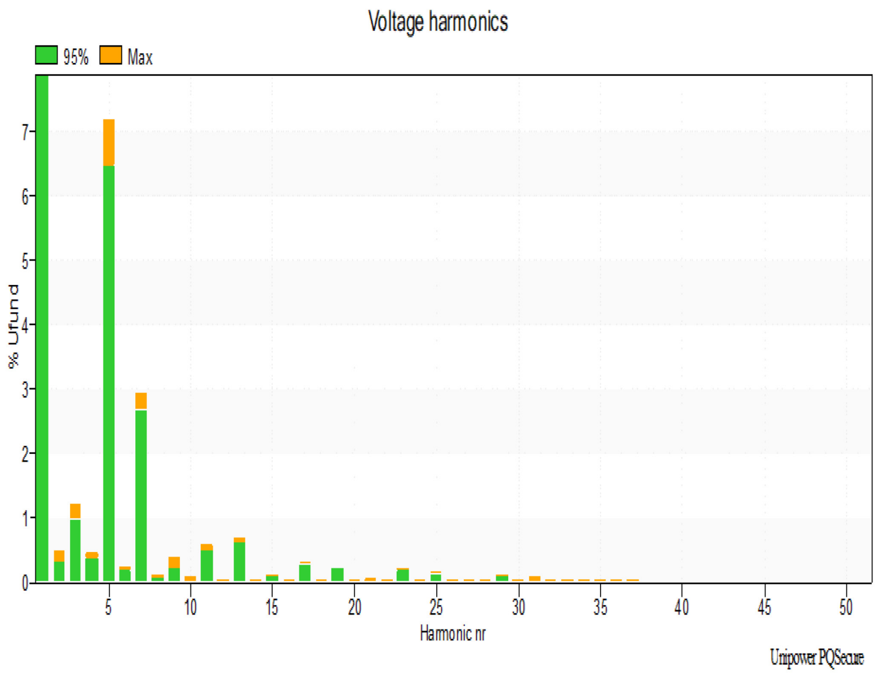

Figure 4. Voltage harmonics for the Campus

Further analysis was on 3 harmonics. In **Figure 5** it can be observed that all the recorded 3rd harmonics were within the compatibility limits of 5% for the 3rd week. **Figure 6** clearly shows that all the recorded 4th harmonics order data are within the compatibility limits of 1% for the 4th week. From **Figure 7** it can be observed that for some of the days, the recorded 5th harmonic data have violated the compatibility limits of 6%, and thus failed the compatibility test.

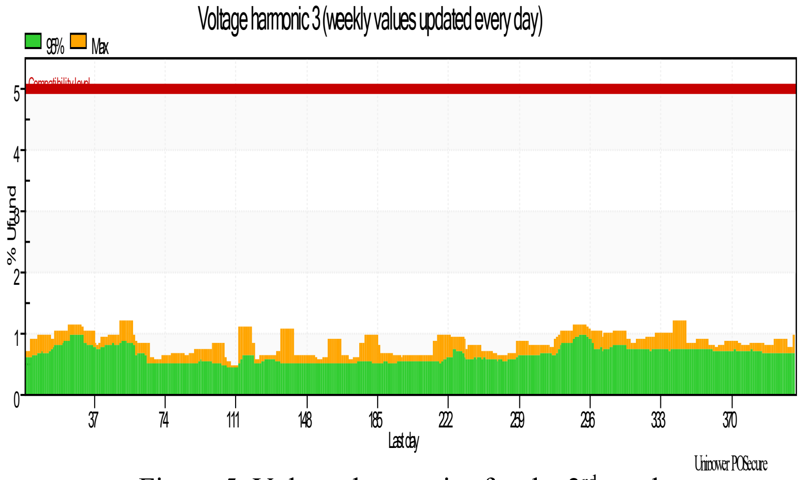

Figure 5. Voltage harmonics for the 3[rd] week

Table 2. Individual voltage harmonics

#	Compatibility level [%]	Max [%]	95% highest [%]	Compliance
2	2.00	0.46	0.28	Passed
3	5.00	1.19	0.95	Passed
4	1.00	0.44	0.36	Passed
5	6.00	7.19	**6.46**	**Failed (0.4%)**
6	0.50	0.24	0.16	Passed
7	5.00	2.94	2.67	Passed
8	0.50	0.11	0.06	Passed
9	1.50	0.37	0.20	Passed
10	0.50	0.09	0.00	Passed
11	3.50	0.56	0.46	Passed
12	0.46	0.01	0.00	Passed
13	3.00	0.70	0.58	Passed
14	0.43	0.01	0.00	Passed
15	0.50	0.10	0.07	Passed
16	0.41	0.01	0.00	Passed
17	2.00	0.30	0.27	Passed
18	0.39	0.00	0.00	Passed
19	1.76	0.21	0.19	Passed
20	0.38	0.00	0.00	Passed
21	1.57	0.05	0.00	Passed
22	0.36	0.00	0.00	Passed
23	1.41	0.19	0.17	Passed
24	0.35	0.00	0.00	Passed
25	1.27	0.13	0.12	Passed
26	0.35	0.00	0.00	Passed
27	1.16	0.02	0.00	Passed
28	0.34	0.00	0.00	Passed
29	1.06	0.09	0.08	Passed
30	0.33	0.00	0.00	Passed
31	0.97	0.07	0.00	Passed
32	0.33	0.00	0.00	Passed
33	0.90	0.02	0.00	Passed
34	0.32	0.00	0.00	Passed
35	0.83	0.03	0.00	Passed
36	0.32	0.00	0.00	Passed
37	0.77	0.03	0.00	Passed

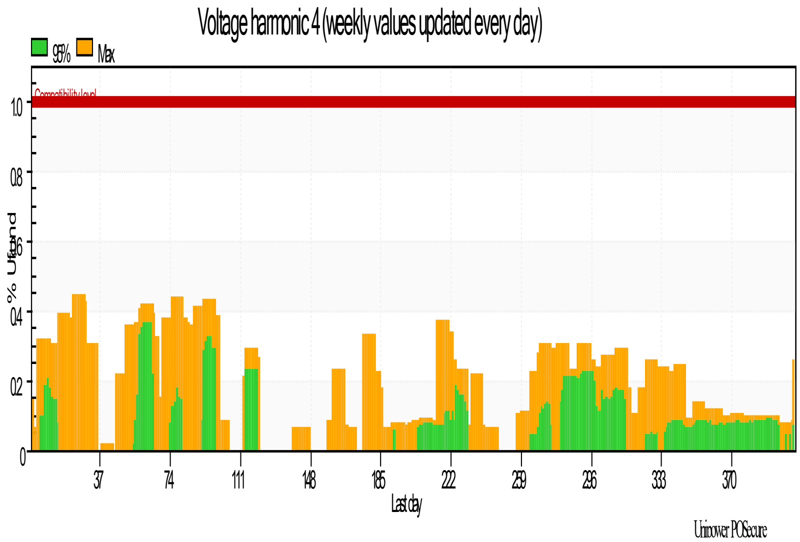

Figure 6. Voltage harmonics for the 4th week

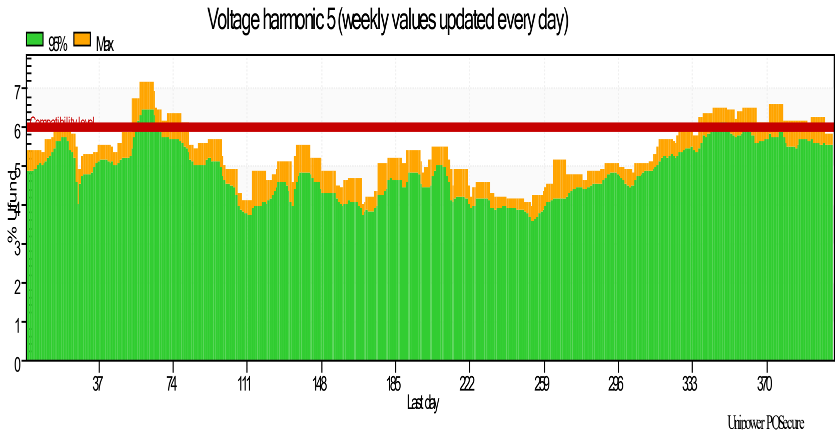

Figure 7. Voltage harmonics for the 5th week

Table 3 shows summary of power quality assessment from power analyzer, while **Table 4** shows a sustained overvoltage for more than 3 seconds on the specified days. Most severe one was in August 16, and recorded an overvoltage of 209%, for 363,058 seconds on phase 1 and 2 upstream direction. A sustained overvoltage of 209% for 363.058 seconds can have severe and potentially catastrophic consequences on electrical equipment and systems. The prolonged exposure to a voltage twice the designed or rated level may lead to extensive damage to electronic components, therefore their causes should always be identified and appropriate measures taken to mitigate these kind of network problems.

Table 3. Power quality parameter status for the Engineering campus

Power quality parameters	Status
Power frequency	Passed
Unbalance	Passed
Supply voltage limit	Passed
Supply voltage compatibility	Passed
Flicker severity	Passed
THD	Passed
Individual harmonics	Failed
Number of sags	0
Number of swells	7
Number of interruptions	2

Table 4. The different categories of voltage dips

Time	Duration [s]	Residual voltage [%]	Category	Phases	Direction
2021-08-13 16:09:38.027	1445.492	195.7	Over Voltage	1,2	Upstream *
2021-08-14 16:36:55.035	61680.957	121.1	Over Voltage	2	Upstream *
2021-08-15 09:44:56.273	31658.328	121.0	Over Voltage	2	Upstream *
2021-08-16 18:32:35.991	363.058	209.0	Over Voltage	1,2	Upstream *
2021-08-17 18:39:58.045	84102.094	122.9	Over Voltage	2	Upstream *
2021-08-18 07:47:10.852	36776.875	122.6	Over Voltage	2	Upstream *
2021-08-19 13:37:56.510	74651.703	121.9	Over Voltage	2	Upstream *

Proposed quality mitigation measures for Network 1. For mitigating power quality disturbances caused by harmonics, a single tuned filter was designed and installed at bus 6 as shown **Figure 8**.

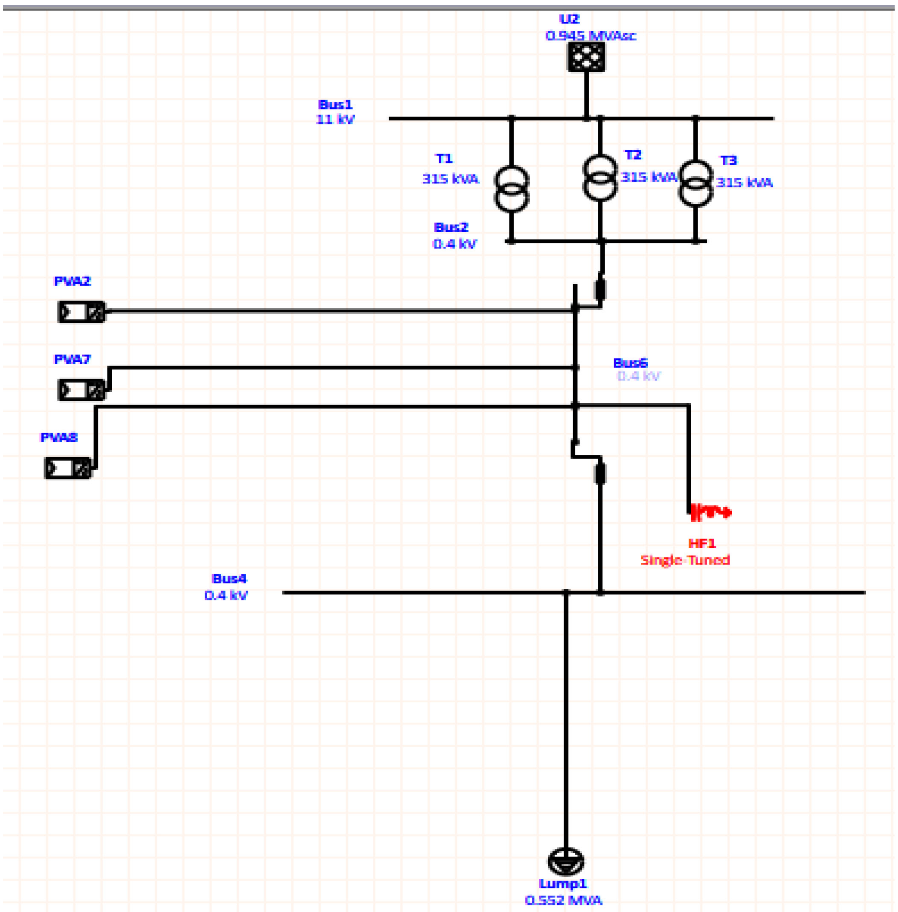

Figure 8. A single line diagram with an embedded single tuned harmonic filter at busbar 6

Design of filter component values

A single tuned filter consists of RLC components connected in series. To determine the values for these RLC components, eqs. (1)) - (4) were utilized, while also adhering to the IEEE 519-1992 harmonic standard to ensure compliance with the permissible limits [23]. The design of the filter was limited to 5^{th} order harmonic which was dominant.

Reactive power of the capacitor is calculated using eq. (9). The power factor of the network varies between 0.85 and 0.95 due to load changes over an 11-month period. A power quality assessment was conducted at the JEDS Campus in Ongwediva, Namibia. The lowest recorded power factor was 0.85. It is assumed that the power factor (*pfn*) can be improved from 0.85 to 0.95 using the filter:

$$Q_c = pfn(\tan(\cos - 1(pf1) - \tan(\cos - 1(pf2)) \quad (9)$$

Eq. (10) is used in calculating capacitive reactance (X_c):

$$X_c = V \times 2 \times Q_c \quad (10)$$

Using eq. (10) capacitance of the capacitor (C) is determined as given in eq. (11):

$$C = \frac{1}{2\pi Q_c} \quad (11)$$

At resonance, the quality factor of the single tuned passive filter is expected to be 100 according to the ETAP modelling tools. The inductance value was determined at resonance, as well as resistance of the filter as given in eq. (12). The values of the RLC filter components used are listed in Table 5. A fine-tuned sinusoidal waveform, Figure 9, shows that harmonics were significantly reduced.

$$R = Xn \quad (12)$$

Table 5. Filter component values

Filter component	Value
Resistance	0.0052 Ω
Inductance	0.319 mH
Capacitance	1029.7 µF

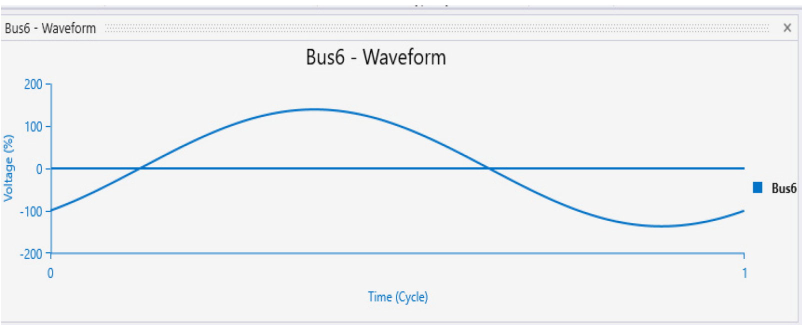

Figure 9. Output voltage waveform at bus 6 after mitigation measures

Power monitoring and results analysis on Network 2. To investigate the cause of low power factor on Okangwati distribution system, a simulation model was built in ETAP including all relevant components such as generators, transformers, motors, and any reactive power compensation system. Load flow analysis was performed for each scenario to determine the loading percentage that gave the lowest power factor. This was compared with actual power factor from the distribution company. The voltages, reactive power, real power, and percentage power factor outcomes for all the four cases obtained from the ETAP were used in the analysis.

The maximum feeder requirements were obtained from NORED and also used in the model development. During the simulation, the known maximum demand value of the bulk supply point is maintained and the load of the remaining transformer supply points is scaled according to the configured scenario parameters. Load scaling was used to adjust all unknown transformer loads to the set percentage load value of 15%, 30%, 70%, and 100%, defined as scenario D-A respectively.

Scenario A. **Table 6** illustrates portions of the network's Load Flow Analysis (LFA) data for scenario A. As can be seen, power factor falls within the permissible range of at least 0.85 at most of the buses. However, there is a dominant negative reactive power, resulting in a leading power factor. In addition, **Table 7** shows a voltage drop at the receiving end. The purple colour was used to indicate the continuous voltage drop and also warn that the buses are about to experience under voltage (< 95%). Power factor is almost unity.

Table 6. Load flow analysis results for scenario A

Load Flow				
ID	MW	Mvar	Amp	%PF
Bus2-33kV OUTGOING	2.525	1.190	24.2	90.5
Bus3-OKANG RECLOSER IN	0.836	-0.037	15.2	-99.9
Bus1-INCOMING 66kV	-2.491	-0.988	48.8	93.0
Bus2-33kV OUTGOING	-0.836	0.037	15.2	-99.9
Bus4-OKAN RECLOSER OUT	0.836	-0.037	15.2	-99.9
Bus5-OROTJITOMBO T-OFF	0.836	-0.037	15.2	-99.9
Bus3-OKANG RECLOSER IN	-0.836	0.037	15.2	-99.9
Bus4-OKAN RECLOSER OUT	-0.835	0.030	15.2	-99.9

Table 7. Bus voltage profile and loading for scenario A

Bus ID	Nominal kV	Voltage	kW Loading	kVAR Loading
Bus1	66	100	2524.7	1190
Bus2	33	96.02	2491.1	1025.7
Bus3	33	96.01	836	36.99
Bus4	33	96.01	836	36.99
Bus5	33	95.94	835.4	60.99
Bus6	33	95.94	78.24	79.14
Bus7	33	95.94	39.12	24.24
Bus8	33	95.9	39.09	24.22
Bus9	33	95.83	756.2	43.19
Bus10	33	95.83	19.51	12.09

Scenario B. For line loaded at 70% as given in **Table 8**, voltage drop is less than in Scenario A as given in **Table 9**. This is because for line loaded at 70% voltage drop in a 70% loaded distribution line is proportional to the square of the current.

Table 8. Load flow analysis results for scenario B

Load Flow				
ID	MW	Mvar	Amp	%PF
Bus2-33kV OUTGOING	1.665	0.508	15.2	95.6
Bus3-OKANG RECLOSER IN	0.608	-0.217	11.5	-94.1
Bus1-INCOMING 66kV	-1.652	-0.430	30.5	96.8
Bus2-33kV OUTGOING	-0.608	0.217	11.5	-94.2
Bus4-OKAN RECLOSER OUT	0.608	-0.217	11.5	-94.2
Bus5-OROTJITOMBO T-OFF	0.608	-0.217	11.5	-94.2
Bus3-OKANG RECLOSER IN	-0.608	0.217	11.5	-94.2
Bus4-OKAN RECLOSER OUT	-0.607	0.210	11.5	-94.5

Table 9. Bus voltage profile and loading for scenario B

Bus ID	Nominal kV	Voltage	kW Loading	kVAR Loading
Bus1	66	100	1665.3	508.5
Bus2	33	98.05	1652.2	647.4
Bus3	33	98.05	607.5	217
Bus4	33	98.05	607.5	217
Bus5	33	98.01	607.2	209.6
Bus6	33	98.01	57.18	90.19
Bus7	33	98.01	28.58	17.71
Bus8	33	97.99	28.57	17.7
Bus9	33	97.95	549.5	125.2
Bus10	33	97.95	14.27	8.84

Scenario C. **Table 10** for scenario C shows that when the distribution line is 30% loaded, the power factor is around 56%, which is below limit of 85%., hence Power quality problem. **Table 11** for scenario C shows voltage increase along the buses, indicating that when the distribution line is loaded at 30%, the voltage at the receiving end keeps increasing and this because of the Ferranti effect. Voltage profile is however still within the maximum limit of 105%, thus no threats posed on the distribution network.

Table 10. Load flow analysis results for scenario C

Load Flow				
ID	MW	Mvar	Amp	%PF
Bus2-33kV OUTGOING	0.308	-0.449	4.8	-56.6
Bus3-OKANG RECLOSER IN	0.307	-0.456	9.5	-55.8
Bus1-INCOMING 66kV	-0.307	0.456	9.5	-55.8
Bus2-33kV OUTGOING	-0.307	0.456	9.5	-55.8
Bus4-OKAN RECLOSER OUT	-0.307	0.456	9.5	-55.8
Bus5-OROTJITOMBO T-OFF	0.307	0.456	9.5	-55.8
Bus3-OKANG RECLOSER IN	0.307	-0.456	9.5	-55.8
Bus4-OKAN RECLOSER OUT	-0.307	0.456	9.5	-55.8

Scenario D. **Table 12** is for scenario D, where the distribution line is 15% loaded, the power factor drops below 30%, this is too low compared to allowed limit of 85% and required mitigation measures. **Table 13** for scenario D shows that voltage increases further exceeding the limit range of 33kV at the receiving end of the distribution line. This was due to lightly load line (15% loading) that leads to generation excessive reactive power. Ferranti effect that leads to development of shunt capacitance between the ground and the line comes into play leading to line losses and low efficient system

Table 11. Bus voltage profile and loading for scenario C

Bus ID	Nominal kV	Voltage	kW Loading	kVAR Loading
Bus42	11	100.54	51.55	31.27
Bus43	11	100.54	19.33	11.8
Bus44	11	100.54	12.89	7.99
Bus45	11	100.54	6.44	3.99
Bus46	11	100.54	32.22	19.75
Bus47	11	100.54	6.44	3.99
Bus48	11	100.53	25.77	15.97
Bus49	33	100.98	19.5	2.65
Bus50	33	100.98	6.5	4.03
Bus51	33	100.98	13	8.06
Bus52	33	101.05	64.37	132.7
Bus53	19.1	102.56	62	136.3
Bus54	19.1	102.27	60.85	120.5
Bus55	19.1	102.27	4.27	2.65

Table 12. Load flow analysis results for scenario D

Load Flow				
ID	MW	Mvar	Amp	%PF
Bus2-33kV OUTGOING	0.171	-0.558	5.1	-29.3
Bus3-OKANG RECLOSER IN	0.168	-0.578	10.2	-27.8
Bus1-INCOMING 66kV	-0.168	0.578	10.2	-27.8
Bus2-33kV OUTGOING	-0.168	0.577	10.2	-27.9
Bus4-OKAN RECLOSER OUT	0.168	-0.577	10.2	-27.9
Bus5-OROTJITOMBO T-OFF	0.168	-0.577	10.2	-27.9
Bus3-OKANG RECLOSER IN	-0.168	0.577	10.2	-27.9
Bus4-OKAN RECLOSER OUT	-0.167	0.569	10.1	-28.2

Table 13. Bus voltage profile and loading for scenario D

Bus ID	Nominal kV	Voltage	kW Loading	kVAR Loading
Bus46	11	103.26	16.99	10.3
Bus47	11	103.26	3.4	2.11
Bus48	11	103.25	13.59	8.42
Bus49	33	103.48	10.24	4.72
Bus50	33	103.48	3.41	2.12
Bus51	33	103.48	6.83	4.23
Bus52	33	103.48	38.83	161.7
Bus53	33	105.69	35.94	166
Bus54	33	105.58	35.54	147.8
Bus55	33	105.58	2.27	1.41
Bus56	33	105.15	29.41	77.36
Bus57	33	105.06	13.51	2.51
Bus58	33	105.06	4.5	2.79
Bus59	33	105.05	9	1.63
Bus60	33	105.05	4.5	2.79
Bus61	33	105.04	4.5	2.79

Proposed quality mitigation measures for Network 2. To mitigate the low power factor problem in Network 2, Static Var compensators (SVC) and Shunt reactors (SR) were selected as possible suitable mitigation methods based on the reviewed literature. The simulation results for SVC and SC connected to the ETAP model are as shown in **Table 14** and **Table 15** respectively.

Table 14 shows that SVC improved power factor from 0.2 to 0.864, while SR improved it to 0.972 in **Table 15** making it the most effective. In addition, **Table 16** shows that variation of voltage was within acceptable limit with SVC, this was improved further with SR as a mitigation measure as seen in **Table 17**.

Table 14. Load flow analysis with SVC

Load Flow				
ID	MW	Mvar	Amp	%PF
Bus2-33kV OUTGOING	0.156	-0.091	1.6	-86.4
Bus3-OKANG RECLOSER IN	0.156	-0.093	3.2	-85.8
Bus1-INCOMING 66kV	-0.156	0.093	3.2	-85.8
Bus2-33kV OUTGOING	-0.156	0.093	3.2	-86.0
Bus4-OKAN RECLOSER OUT	0.156	-0.093	3.2	-86.0
Bus5-OROTJITOMBO T-OFF	0.156	-0.093	3.2	-86.0
Bus3-OKANG RECLOSER IN	-0.156	0.093	3.2	-86.0
Bus4-OKAN RECLOSER OUT	-0.156	0.085	3.1	-87.9

Table 15. Load flow analysis with SR

Load Flow				
ID	MW	Mvar	Amp	%PF
Bus2-33kV OUTGOING	0.179	-0.043	1.6	-97.2
Bus3-OKANG RECLOSER IN	0.179	-0.045	3.2	-97.0
Bus1-INCOMING 66kV	-0.179	0.045	3.2	-97.0
Bus2-33kV OUTGOING	-0.179	0.044	3.2	-97.1
Bus4-OKAN RECLOSER OUT	0.179	-0.044	3.2	-97.1
Bus5-OROTJITOMBO T-OF	0.179	-0.044	3.2	-97.1
Bus3-OKANG RECLOSER IN	-0.179	0.044	3.2	-97.1
Bus4-OKAN RECLOSER OUT	-0.179	0.036	3.2	-98.0

Table 16. Voltage profile and loading with SVC

Bus ID	Nominal Voltage (kV)	Voltage (kV)	Active Power Loading (kW)	Reactive Power Loading (kVar)	Current Loading (A)
Bus12	33	100.36	3.21	1.99	0.066
Bus13	33	100.24	136.5	97.37	2.927
Bus14	33	100.24	3.2	1.99	0.066
Bus15	33	100.23	133.3	102.2	2.932
Bus16	33	100.23	6.4	1.68	0.116
Bus17	33	100.23	3.2	1.98	0.066
Bus18	33	100.23	3.2	1.98	0.066
Bus19	33	100.2	126.9	117	3.013
Bus20	33	100.2	6.4	3.97	0.131
Bus21	33	100.2	120.4	117.8	2.942

Table 17. Voltage profile and loadings with SR

Bus ID	Nominal Voltage (kV)	Voltage (kV)	Active Power Loading (kW)	Reactive Power Loading (kVar)
Bus31	33	99.54	106.9	494.8
Bus32	33	99.54	46.17	35.74
Bus33	33	99.54	2.02	1.25
Bus34	33	99.54	44.14	14.68
Bus35	33	99.54	9.47	1.14
Bus36	33	99.54	3.16	1.96
Bus37	33	99.54	6.32	3.91
Bus38	33	99.54	34.67	14.2
Bus39	33	99.54	25.19	14.88
Bus40	11	99.32	25.15	14.82

Power monitoring and results analysis on Network 3

For Network 3, investigation of power quality issues on Eheke distribution network with numerous hammer mills utilizing star/delta starters and Variable Speed Drives (VSDs) was done using a portable Unipower UP-2210 logger, the data logger was strategically installed at key locations within the distribution network, particularly near the hammer mills, ensuring secure connections to relevant electrical panels. The logger was then configured to record both voltage and current waveforms over a period of 8 months in 2021.

From THD of individual harmonics, it can be shown that 3rd, 4th and 5th harmonics were above threshold harmonic levels of 4%, 2.5% and 3% respectively, except for March when the THD was 3.900%. This is illustrated in **Figure 10**, **Figure 11** and **Figure 12** respectively. It is also noted that harmonic level was low in January, February and March, and this is attributed to the fact that hammer mills are hardly used during this period since it is rainy season and not yet harvesting season.

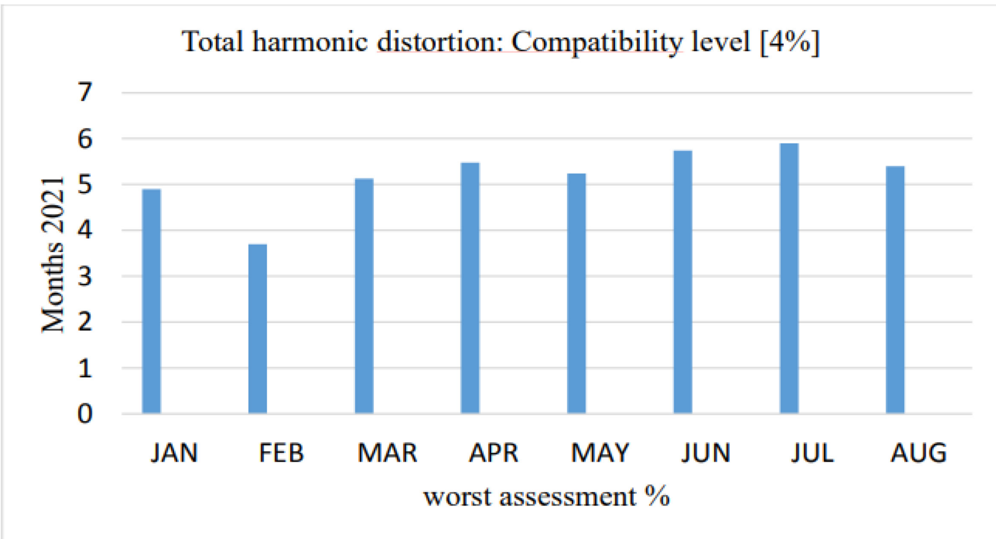

Figure 10. Voltage total harmonic distortion

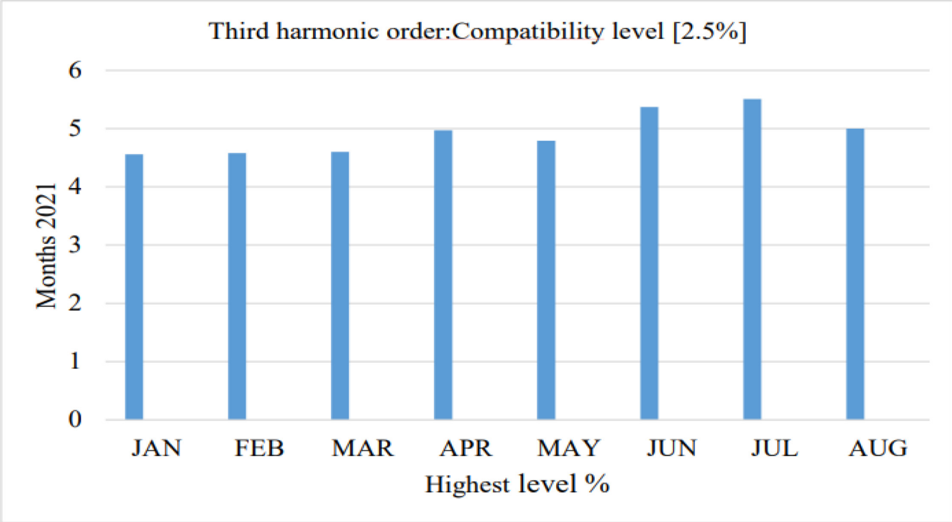

Figure 11. Peak levels of the third harmonic order observed

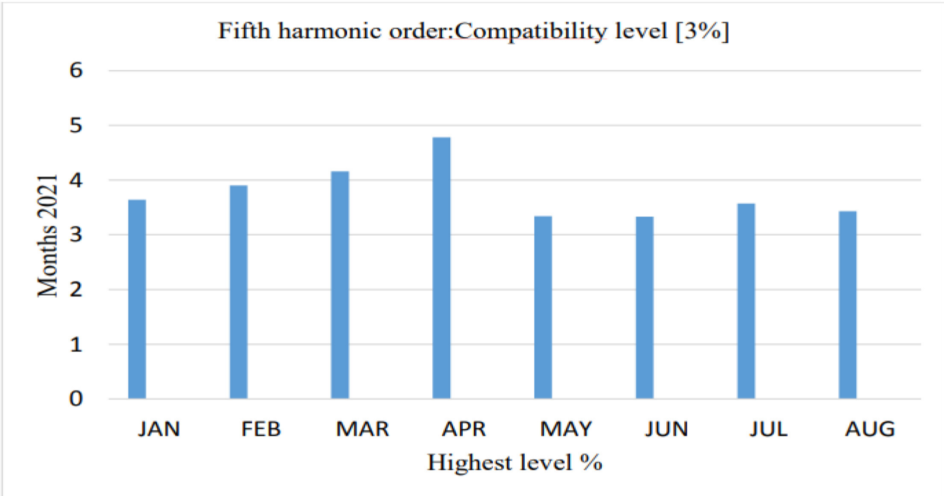

Figure 12. Peak levels of the fifth harmonic order observed

Figure 13 clearly indicates that 3rd and 5th harmonic are the highest contributors to THD. **Figure 14** shows output voltage for two phases for October 2021, clearly highlighting two power quality issues: phase imbalance and harmonic. This imbalance in harmonic content can result to overload of neutral conductor. Spectral analysis showing harmonics content is as shown in **Figure 15**. It can be seen that VTHD compatibility level was violated throughout the month.

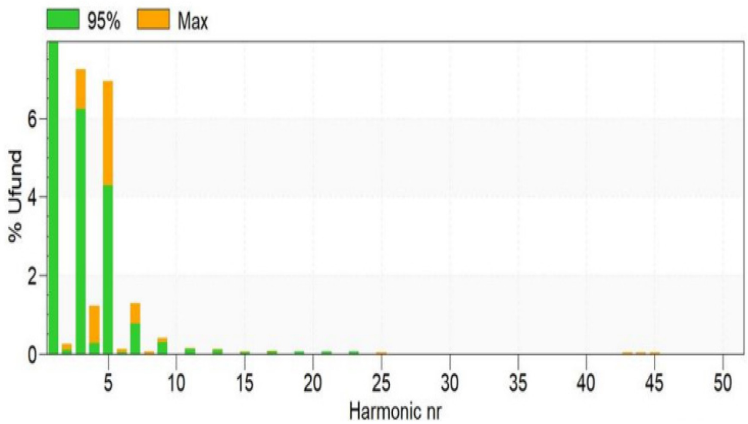

Figure 13. The peak levels of the 1st to 50th harmonic orders observed in October

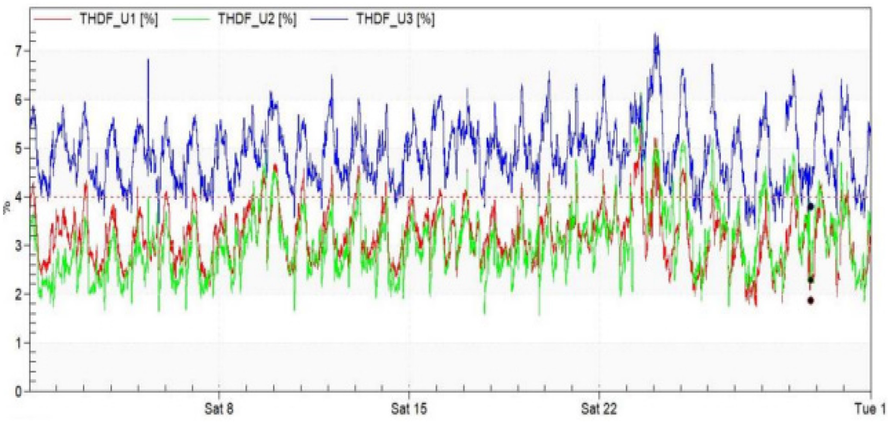

Figure 14. Output voltages for two phases

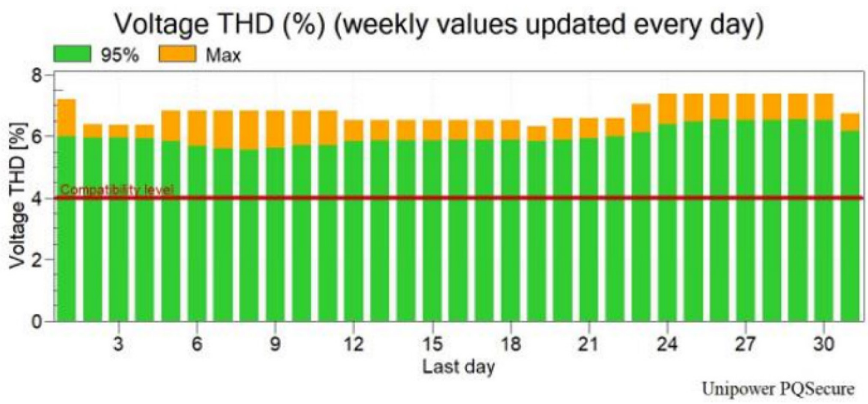

Figure 15. Daily VTHD levels for October 2021

Figure 16 shows daily records of 3rd harmonics. It can be seen that for the whole month, 3rd harmonics violated the power quality standard of 2.5% confirming Figure 10 which captures average values of 3rd harmonics for 8 months. Similarly, in Figure 17, 5th harmonic order levels recorded are above the compatibility level at 3%, confirming Figure 11 which captures average values of 5th harmonics for 8 months.

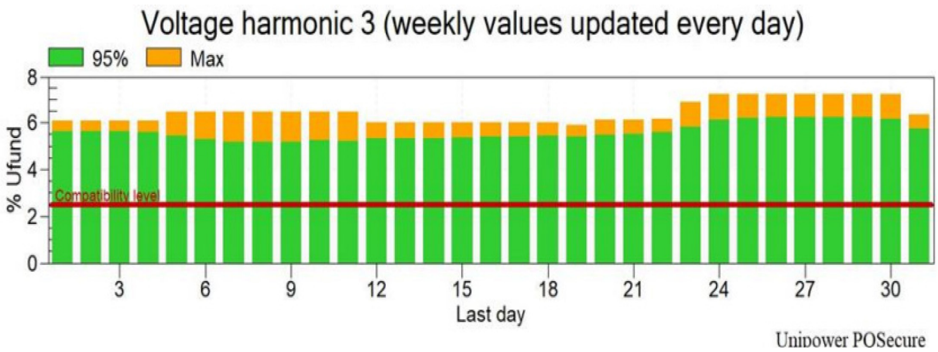

Figure 16. Daily records of 3rd harmonics for October 2021

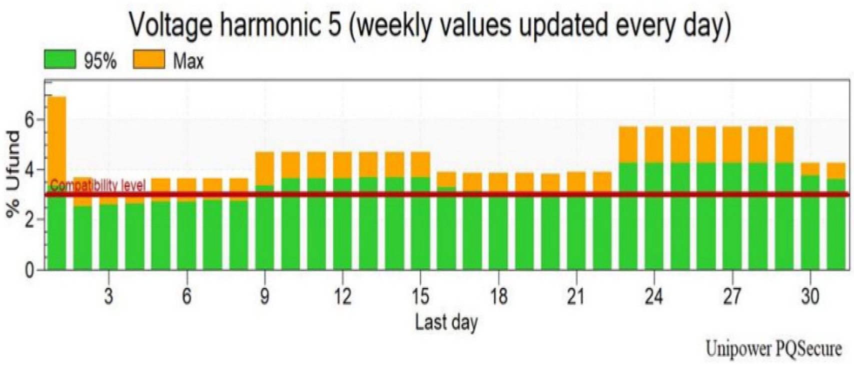

Figure 17. Daily records of 5th harmonics for October

Table 18 shows the summary for Ehenye power quality parameters and their status, clearly indicating power quality issues with individual harmonics, THD and unbalance test. In addition, there are 35 voltage sags recorded.

Table 18. Eheke power quality parameter status

Power quality parameter	Status
Power frequency	Passed
Unbalance	Failed
Supply voltage limit	Passed
Supply voltage compatibility	Passed
THD	Failed
Individual harmonics	Failed
Number of sags	35
Number of swells	0
Number of interruptions	0

Proposed quality mitigation measures for Network 3: No mitigation measures have been adopted for Eheke network covered by hammer mills owned by peasant farmers. This is due to lack of technical and financial capability. Unfortunately, NORED, a distribution company has not adopted any mitigation measure as well. Based on the investigations done, this paper recommends the following:

- NORED should consider using optimized harmonic filters to reduce or eliminate harmonics in the Eheke distribution network;
- Priority and significance must be given to the Electricity supply agreement (ESA) between the power utility and the customers, which should specify harmonic limits for smooth harmonic monitoring;
- Tariff restructuring should be considered where penalty factor is imposed on consumers operating above the stipulated limit, while giving royalties to those operating at higher power factors. This is missing in current tariff.

CONCLUSION

This paper has undertaken a detailed investigation into the critical issue of harmonics in distribution networks, addressing the challenges posed by diverse load scenarios including low power factor, residential areas, and a university campus. The initial phase involved thorough data collection and analysis, revealing distinct power quality challenges associated with each scenario. Notably, very low power factor loads were identified as sources of voltage distortion, residential areas exhibited heightened harmonic content due to hammer mills with star/delta starts and variable speed drives (VSDs), and the university campus presented a complex mix of loads, including computers, a Solar PV plant, and air-conditioning units, resulting in time-varying harmonic profiles.

The comprehensive assessment of harmonic levels and voltage distortions provides a nuanced understanding of the unique challenges posed by each scenario, establishing a valuable baseline for future studies. Moreover, the paper delves into a range of mitigation approaches tailored to counteract the identified harmonic issues, offering practical solutions for improving power quality and enhancing network reliability. These findings contribute significantly to the field of power system engineering and distribution network management, providing a rich resource for power system engineers, utility companies, and researchers engaged in power quality studies. By addressing the specific challenges posed by different load scenarios and proposing effective mitigation strategies, this research advances our knowledge and practical capabilities in ensuring the robustness and reliability of distribution networks amidst the escalating demand for electricity in modern power systems.

NOMENCLATURE

C	Capacitance of the capacitor	[F]
f	Frequency of power supply	[Hz]
I_r	Receiving end current	[A]
j	Imaginary unit of complex part of impedance	[Ω]
L	Longitudinal inductance of the line	[H]
l	Length of the transmission line	[m]
Y	Admittance	[S]
n	Order of the tuned filter	[-]
Q_c	Quality factor of a capacitor	[-]
R	Resistance	[Ω]
r	Real part of impedance	[Ω]
S	Complex variable representing frequency	[Hz]
V_r	Receiving voltage (transmission line)	[V]
V_s	Sending voltage (transmission line)	[V]
w	Square of frequency	[Hz]
Z	Impedance	[Ω]
X	Reactance	[Ω]
X_c	Capacitive reactance	[Ω]

Greek letters

ω	Angular frequency	[rad]

REFERENCES

1. C. Ferrolho, F. Barata, and P. Gambôa, "Power quality and modeling analysis of a university campus electrical distribution system," in 2022 International Conference on Electrical, Computer and Energy Technologies (ICECET), 2022, pp. 1–6, https://doi.org/10.1109/icecet55527.2022.9872840.
2. N. Manichal Meitei, D. Tamang, and S. Gao, "Power Quality Improvement Using Smart Harmonic Analysis Indicator Technique for IEEE 15-Bus Radial Distribution System," in 2021 International Conference on Advances in Electrical, Computing, Communication and Sustainable Technologies (ICAECT), 2021, pp. 1–5, https://doi.org/10.1109/icaect49130.2021.9392410.
3. J. Windarta, C. Radityatama, and E. Handoyo, "Analysis of Energy Consumption Intensity and Electric Power Quality in UNDIP Campus," in 2021 4th International Conference on Energy Conservation and Efficiency (ICECE), 2021, pp. 1–5, https://doi.org/10.1109/icece51984.2021.9406298.

4. T. Li, H. Wu, H. Chen, T. Liu, and J. Wang, "Theoretical Analysis and Optimization of Line Losses in Medium-Low Voltage Distribution Networks for Rural Power Grid Planning," in 2023 8th Asia Conference on Power and Electrical Engineering (ACPEE), 2023, pp. 403–410, https://doi.org/10.1109/acpee56931.2023.10135985.
5. H. A. Al Issa, A. Khasawneh, O. Sotnik, O. Miroshnyk, O. Sotnik, and S. Tymchuk, "Influence of the Value of the Power Factor of Electricity Consumers in the Residential Sector of the Village on the Technical and Economic Indicators of Low-Voltage Electrical Networks," in 2021 IEEE International Conference on Modern Electrical and Energy Systems (MEES), 2021, pp. 1–4, https://doi.org/10.1109/mees52427.2021.9598687.
6. D. Chopade, R. Holmukhe, and H. Mehta, "Passive Shunt Harmonic Filters for Power Quality Improvement in Bharati Vidyapeeth University's Dhankawadi Campus, Pune," in 2021 International Conference on Technology and Policy in Energy and Electric Power (ICT-PEP), 2021, pp. 276–280, https://doi.org/10.1109/ict-pep53949.2021.9600936.
7. S. Aldebawy, A. Draz, and A. El-Fergany, "Harmonics Mitigation Using Passive Filters in Distribution Networks Penetrated with Photovoltaic power," in 2022 23rd International Middle East Power Systems Conference (MEPCON), 2022, pp. 1–5, https://doi.org/10.1109/mepcon55441.2022.10021757.
8. P. Ayar and Evans. E. Ojo, "Investigation and mitigation of harmonics for variable speed drives: A case study for a soap manufacturing industry," in 2022 30th Southern African Universities Power Engineering Conference (SAUPEC), 2022, pp. 1–6, https://doi.org/10.1109/saupec55179.2022.9730673.
9. A. Sahib and H. Al-Baidhani, "Power Factor Improvement by Shunt Capacitor Bank at 33 Kv Busbar in a Distribution Substation," in 2022 3rd Information Technology To Enhance e-learning and Other Application (IT-ELA), 2022, pp. 206–209, https://doi.org/10.1109/it-ela57378.2022.10107963.
10. X. Tan, X. Li, Z. Cui, and Y. Tao, "Research on Optimization Model of Voltage Quality Improvement Project in Medium and Low Voltage Distribution Network," in 2022 7th International Conference on Power and Renewable Energy (ICPRE), 2022, pp. 264–269, https://doi.org/10.1109/icpre55555.2022.9960627.
11. A. Wen, L. Jin, M. Ma, E. Lei, W. Du, and K. Ma, "Low Voltage Control Configuration Method for Remote Rural Distribution Network Coordinated by Voltage Regulator and Capacitor," in 2023 6th International Conference on Energy, Electrical and Power Engineering (CEEPE), 2023, pp. 543–547, https://doi.org/10.1109/ceepe58418.2023.10167301.
12. Sunbul, A. Alduraibi, and F. Zare, "Harmonics Mitigation Filter for High-Power Applications," IEEE Access, vol. 10, pp. 111406–111418, 2022, https://doi.org/10.1109/access.2022.3215142.
13. S. Pan et al., "Switching Frequency Minimized Harmonic Mitigation: A Multiobjective Optimized Modulation Strategy for High- Power Converters," IEEE Trans Power Electron, vol. 38, no. 9, pp. 11080–11090, 2023, https://doi.org/10.1109/tpel.2023.3287482.
14. Q. Xu et al., "A Harmonic Source Localization Method Based on Critical Admittance Screening With Adjusted Coefficient of Determination," in 2022 Asian Conference on Frontiers of Power and Energy (ACFPE), 2022, pp. 530–534, https://doi.org/10.1109/acfpe56003.2022.9952248.
15. Y. Wang, M. Yu, X. Ma, X. Xiao, C. Wang, and C. Liu, "A General Harmonic Probability Model Based on Load Operating States Identification," IEEE Transactions on Power Delivery, vol. 38, no. 4, pp. 2247–2260, 2023, https://doi.org/10.1109/tpwrd.2022.3213646.
16. P. Kalkal and A. V Ravi Teja, "An Approach in Selective Harmonic Mitigation Technique for Reduction of Multiple Harmonics with Only Two Switchings Per Quarter," in IECON

2022 – 48th Annual Conference of the IEEE Industrial Electronics Society, 2022, pp. 1–6, https://doi.org/10.1109/iecon49645.2022.9968472.

17. A. Taghvaie, T. Warnakulasuriya, D. Kumar, F. Zare, R. Sharma, and D. M. Vilathgamuwa, "A Comprehensive Review of Harmonic Issues and Estimation Techniques in Power System Networks Based on Traditional and Artificial Intelligence/Machine Learning," IEEE Access, vol. 11, pp. 31417–31442, 2023, https://doi.org/10.1109/access.2023.3260768.
18. K. Kawamura, K. Fukushima, N. Okada, and K. Okawa, Evaluation of Countermeasures Against Harmonic Disturbances Caused by Agricultural Heat Pumps. 2023, https://doi.org/10.1109/isgteurope56780.2023.10407145.
19. A. M. Galadima, R. M. Idris, S. N. S. Nasir, and M. H. H. Buddin, "Harmonic Mitigation for Various Nonlinear Load Using Active Filter," in 2023 IEEE Conference on Energy Conversion (CENCON), 2023, pp. 98–102, https://doi.org/10.1109/cencon58932.2023.10369207.
20. E. Maghraoui, Y. Ledmaoui, O. Laayati, and A. Chebak, "Power Quality Analysis of an Open-Pit Mine Electrical Network: Case Study Benguerir MinEx," in IEEE EUROCON 2023 - 20th International Conference on Smart Technologies, 2023, pp. 233–238, https://doi.org/10.1109/eurocon56442.2023.10199053.
21. B. Derick, M. K. Kenneth and P. Lating, "Analysis And Mitigation of Ferranti Effect on Long Low Loaded Power Distribution Networks Case Study: Kalangala Infrastructure Service (Kis) Power Distribution Network," 2019.
22. H. M. Joshi, H. Nishant, and Kothari, "A review on Series Compensation of Transmission Lines and Its Impact on Performance of Transmission Lines," 2014. [Online]. Available: https://api.semanticscholar.org/CorpusID:212459889.
23. M. Lim, R. Tan, Ts. Dr. N. Permal, and J. Chin, "Single-Tuned Harmonic Passive Filter Design for AC Electric Railway Traction Power Substation," 2023, https://doi.org/10.1109/i-pact58649.2023.10434590.

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