Chapter 3

Harmonics Temporal Profile in High-Voltage Networks: Case Study

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Abstract

This chapter presents a case study about harmonics measurements in high-voltage networks. Measurements were conducted at two locations in the main interconnected system (MIS) of Oman. Voltage and current THDs were recorded for a period of 1 week. The power quality analyzer was set to record required data for a period of 1 week, and the observation period for each recorded value is 10 minutes. At the first location, the grid station (132/33) is feeding industrial as well as other customers. The second grid station (220/132/33 kV) is dedicated to large industrial customers including arc furnaces and rolling mills. The power quality analyzer was installed at the 132 kV side of power transformers at both locations. Recorded data are analyzed, and temporal harmonics profiles are studied. A clear temporal variation of harmonics similar to that of aggregate load and local voltage profiles was observed at the grid station feeding mixed residential and industrial loads. However, this correlation between system load and harmonics profile diminishes at the grid station dedicated for heavy industrial loads.

Keywords: harmonics, measurements, load profile, temporal profile, standards

1. Introduction

Harmonics are caused by non-linear loads, which draw a non-sinusoidal current from a sinusoidal voltage source. Examples of such harmonic-producing loads, which are used extensively in the industry, include inverters, DC converters, electric arc furnaces, static VAR compensators, switch-mode power supplies (SMPS), and AC or DC motor drives. Other loads such as photocopiers, personal computers, laser printers, fax machines, battery chargers, fluorescent lamps, and UPSs are also a source of harmonics that can be found in the commercial sector [1, 2].

Large industrial loads are often connected to transmission networks due to large power requirements. Such loads are often non-linear and may include rolling mills driven by variable speed drives or could be an arc furnace. These non-linear loads are sources of harmonics. Harmonics that propagates from the industrial loads degrades the power quality at the electrical system. Harmonics can cause problems to different electrical equipment such as generators, motors, transformers, capacitors, and cables. In addition, it can lead to reduced capacity and efficiency of power systems.

The harmonic content in any network varies with time depending on the share of non-linear loads as well as system status. Examining temporal harmonic profile can help understanding system performance at different loading conditions. To examine the temporal profile, harmonics measurements were conducted at two industrial load grid stations of Oman Electricity Transmission Company (OETC) network in the Main Interconnected System (MIS) of Oman.

2. Harmonic limits according to the international standards and Oman's national regulations

In this section, the indices conventionally used for measurement of voltage and current harmonic distortion and the harmonic distortion limits placed in IEEE standard 519, IEC standard 61000-3-6 and Oman's national regulations are presented.

2.1. Voltage and current harmonic distortion indices

The total harmonic distortion (THD) is used to define the effect of harmonics on the power system voltage. IEEE 519-2014 defines the THD as "the ratio of the root mean square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmonics, expressed as a percent of the fundamental". In other words, the THD is the contribution of all harmonics to the fundamental. The THD is calculated as described by the following formula:

$$THD = \frac{\sqrt{\sum_{h=2}^{h_{max}} M_h^2}}{M_1} \tag{1}$$

where M_1 is the rms value fundamental component of the voltage or current signal.

To evaluate the current harmonic distortion, the total demand distortion (TDD) is commonly used. IEEE 519-2014 defines the TDD as "the ratio of the root mean square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmonics, expressed as a percent of the maximum demand current"

$$TDD = \frac{\sqrt{\sum_{h=2}^{h_{max}} I_h^2}}{I_m} = \frac{\sqrt{I^2 - I_1^2}}{I_m} \tag{2}$$

where I_m is the maximum demand load current and I_1 is the rms value of the fundamental component.

2.2. IEEE standard 519 harmonic distortion limits

IEEE standard 519 gives harmonic distortion limits for both the current and the voltage signals in power systems [3]. **Tables 1** and **2** show relevant voltage and current distortion limits. The allowable voltage THD is based on the voltage level, while the current TDD limit is given based on the voltage level and the ratio of the short circuit current to the rated load current.

According to IEEE STD 519-2014, statistical analysis of 1-week short-time harmonic measurements is required to calculate the 95th and 99th percentile values for comparison with the recommended limits. While current harmonics are evaluated based on 95th and 99th percentiles, voltage harmonics are evaluated based on 95th percentile only.

2.3. IEC standard 61000-3-6 harmonic distortion limits

IEC Standard 61000-3-6 specifies the allowable harmonic distortion limits as shown in **Table 3** [4].

PCC voltage	Individual harmonic magnitude (%)	THD (%)
V ≤ 1 kV	5	8
1 < V ≤ 69 kV	3	5
69 < V ≤ 161 kV	1.5	2.5
V > 161 kV	1	1.5

Table 1. Voltage THD limits according to IEEE 519-2014 [3].

Voltage	Isc/I(load)	TDD (%)	<11	11 ≤ h < 17	17 ≤ h < 35	35 ≤ h ≤ 50
<69 kV	<20	5	4	2	1.5	0.6
	20–50	8	7	3.5	2.5	1
	50–100	12	10	4.5	4	1.5
	100–1000	15	12	5.5	5	2
	>1000	20	15	7	6	2.5
69–161 kV	<20	2.5	2	1	0.75	0.3
	20–50	4	3.5	1.75	1.25	0.5
	50–100	6	5	2.25	2	0.75
	100–1000	7.5	6	2.75	2.5	1
	>1000	10	7.5	3.5	3	1.25
>161 kV	<25	1.5	1	0.5	0.38	0.1
	25–50	2.5	2	1	0.75	0.3
	≥50	3.75	3	1.5	1.15	0.45

Table 2. Current distortion limits according to IEEE 519-2014 [3].

Odd harmonics non-multiple of three (%)			Odd harmonics multiple of three (%)			Even harmonics (%)		
h	MV	HV-EHV	H	MV	HV-EHV	h	MV	HV-EHV
5	5	2	3	4	2	2	1.8	1.4
7	4	2	9	1.2	1	4	1	0.8
11	3	1.5	15	0.3	0.3	6	0.5	0.4
13	2.5	1.5	21	0.2	0.2	8	0.5	0.4
$17 \le h \le 49$	$1.9\frac{17}{h} - 0.2$	$1.2\frac{17}{h}$	$21 < h \le 45$	0.2	0.2	$10 \le h \le 50$	$0.25\frac{10}{h} + 0.22$	$0.19\frac{10}{h} + 0.16$

Table 3. IEC 61000-3-6 voltage harmonic limits [4].

PCC voltage	Individual harmonic magnitude (%)	VTHD (%)
Low voltage (415 V)	—	2.5
Distribution level (11, 33, 66 kV)	1.5	2
Transmission level (132, 220 kV)	1.5	2

Table 4. Voltage THD limits according to national Omani codes.

2.4. Harmonic distortion limits according to Oman’s national regulations

Allowable harmonic distortion levels in Oman are dictated by the grid code [5] and the distribution code [6] for high-voltage and medium-voltage networks, respectively. The grid code specifies that the maximum THD should not exceed 2% with no individual harmonic greater than 1.5% for transmission networks (220 and 132 kV). The distribution code dictates that the maximum THD in distribution networks (66, 33 and 11 kV) systems should not exceed 2.0% with no individual harmonic greater than 1.5%. For low voltage line (415 V), the total harmonic distortion limit is 2.5%. Individual harmonic distortion level should be below 1.5% for both transmission and distribution networks (**Table 4**).

3. Harmonics temporal profile at grid station A

3.1. Harmonics measurements at grid station A

Figure 1 shows MIS system and the locations of grid stations under study. The grid station A consists of four 132/33 kV parallel transformers (TX1 to TX4). Each transformer is 75 MVA capacity. As the grid station is located adjacent to a 600 MW power generation facility, the maximum short circuit level on 132 kV side is 27.54 kA. The grid station is supplying electricity to a cement factory, an industrial area, industrial area housing, a university campus, and a hospital.

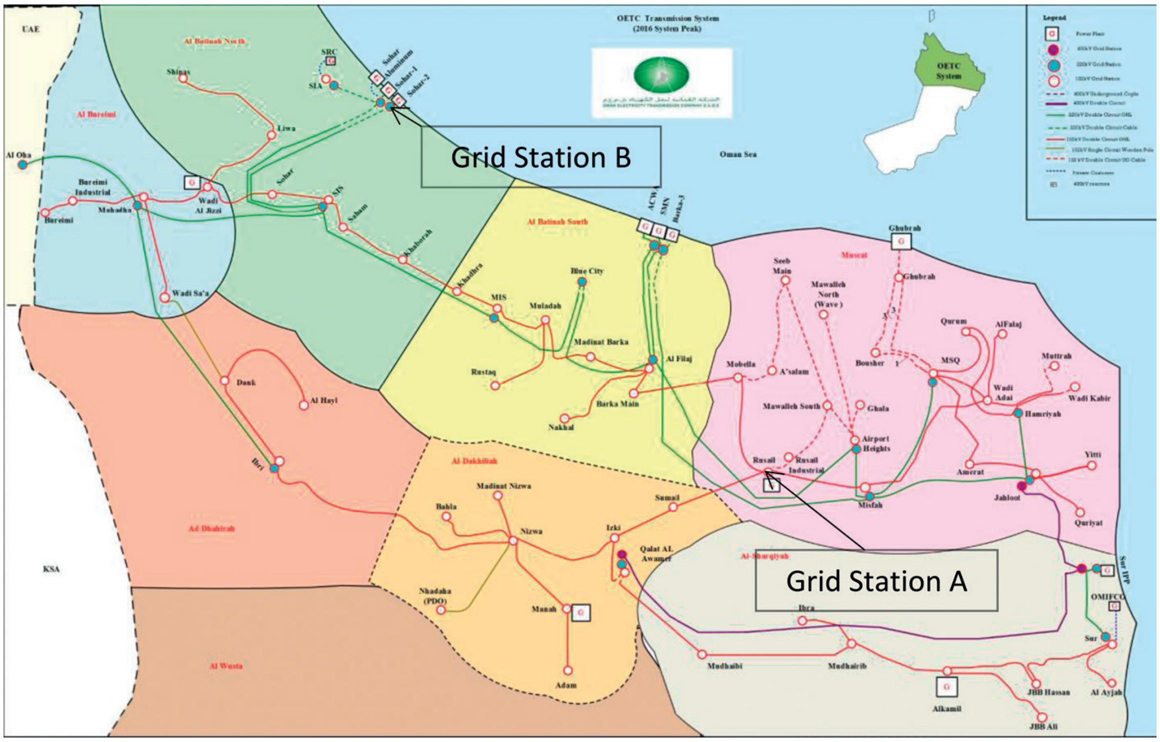


Figure 1. Main interconnected system [7].

Measurements were conducted using Hioki 3196 Power Quality Analyzer Meter [8]. The current clamps were installed on transformer one (TX1). Ten-minute average values were recoded over a period of 1 week starting from 17th of January 2012. This study was part of power quality study in MIS [9–12]. A summary of measurements is presented in **Figure 2**.

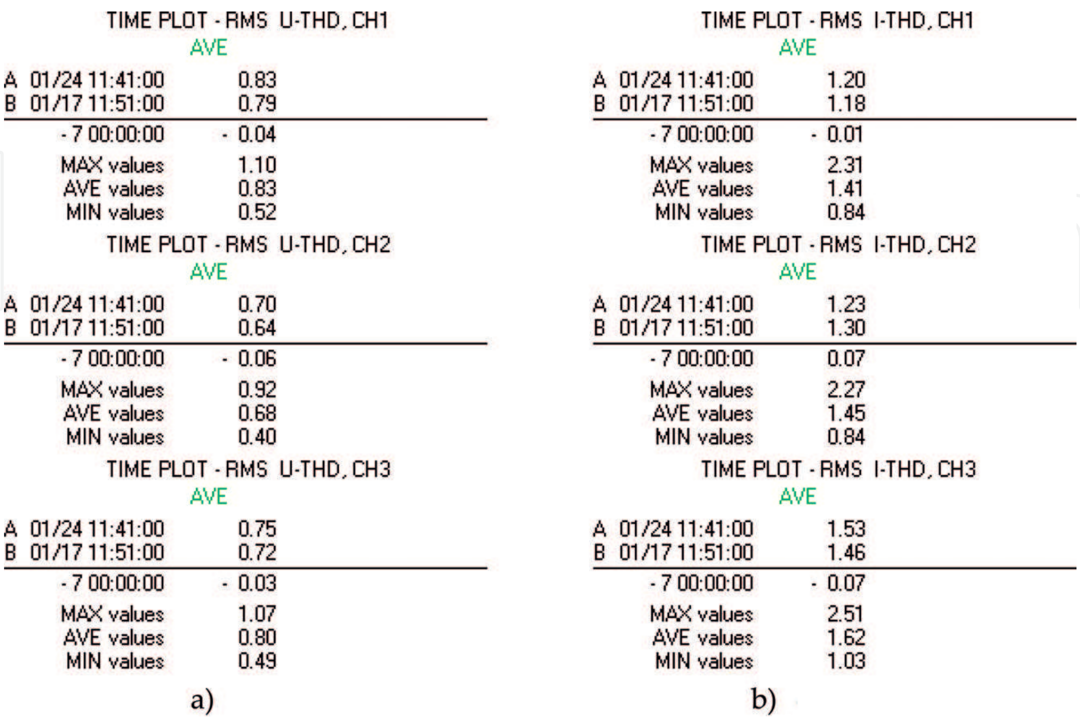


Figure 2. Summary of THD measurements at grid station a. (a) Voltage THD (b) current THD.

For the voltage signals, **Figure 1** shows that the average THD at the high-voltage side is between 0.84 and 0.68%, the maximum THD is between 1.07 and 0.92%, and the minimum THD level is between 0.40 and 0.52%. For the current signals, the THD at the high-voltage side (132 kV) ranges between 0.84 and 2.52%.

Histograms of voltage THD and current TDD at grid station A are presented in **Figure 3**. Since the measurements were conducted at 132 kV voltage level, the corresponding voltage THD limit is 2.5%. Using the voltage THD histograms presented in **Figure 3**, the 95th percentiles are calculated for different phases. A comparison between the 95th percentile of voltage THD and IEEE Std 519 limit is presented in **Table 5**.

To calculate the current TDD, Eq. (2) is used. The TDD is a function of individual harmonics and maximum demand load current. Using measurements, the maximum demand load

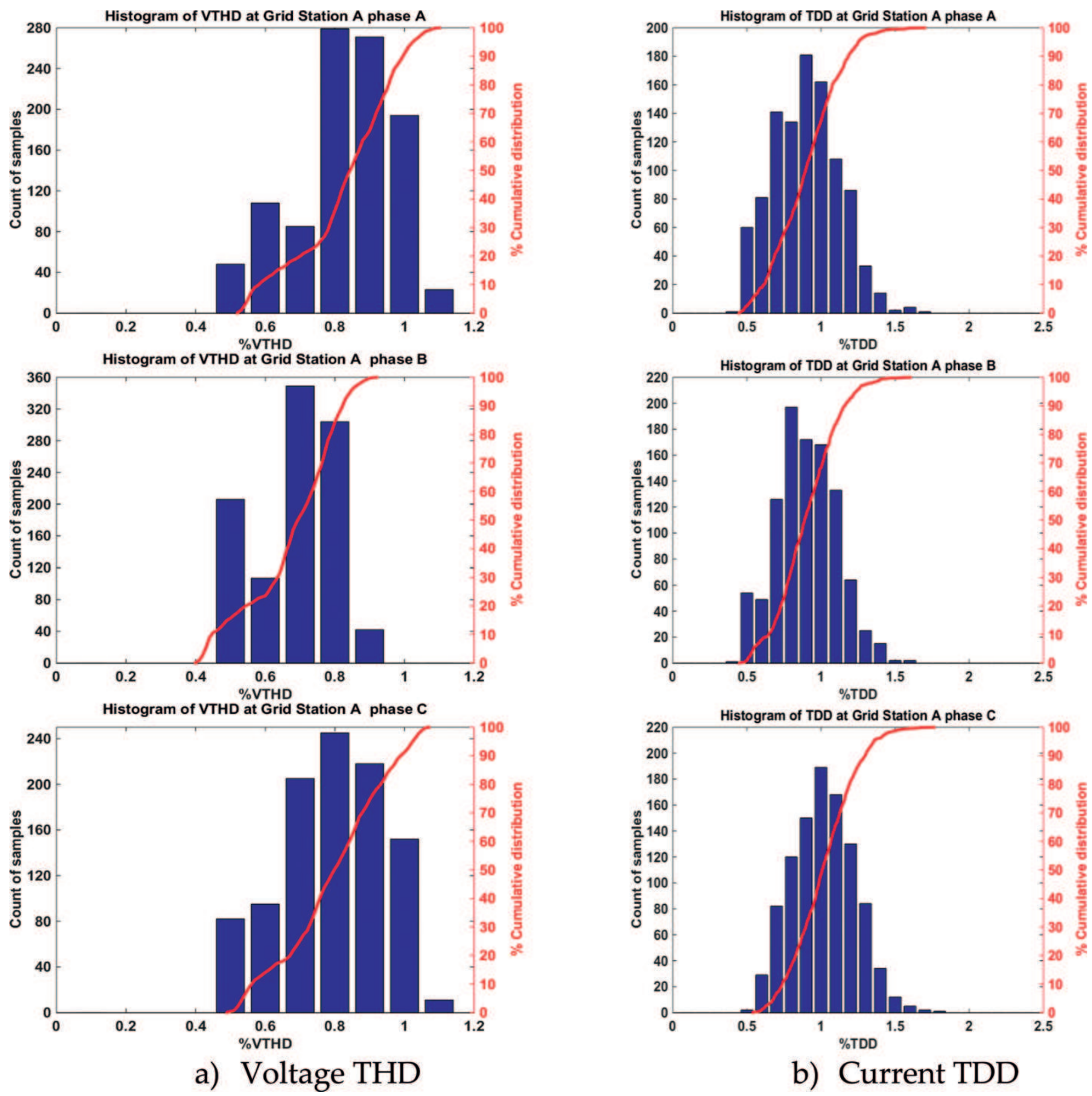


Figure 3. Histograms of THD measurements at grid station A. (a) Voltage THD (b) current TDD.

Phase	VTHD P95	VTHD IEEE limits
A	1.03	2.5
B	0.85	2.5
C	1.03	2.5

Table 5. Measured voltage THD 95th percentile versus IEEE Std 519-2014.

current is 369 A. The short circuit level at grid station A is obtained from OETC capability statement. The TDD limit based on $I_{SC}/I_L = 39$ is 4%. A comparison between the 95th and 99th percentiles of current TDD and IEEE Std 519 limits is presented in **Table 6**.

3.2. Harmonics temporal voltage profile at grid station A

When system loading increases, more voltage drop occurs. Therefore, the temporal voltage profile reflects the daily load profile. The voltage profile measured at grid station A is presented in **Figure 4**.

The voltage THD exhibits a daily profile similar to that of the load as demonstrated in **Figure 5**. Considering individual harmonics, the figure shows that the dominant harmonic components are the 5th and the 7th followed by the 3rd and 11th. There is a small trace of the 13th and 9th harmonics.

3.3. Current harmonics temporal profile at grid station A

Unlike voltage THD, current THD does not exhibit a clear daily profile. **Figure 6** demonstrates that the dominant harmonic components are the 5th and the 3rd. There is a small trace of the 7th harmonics. It is worth mentioning that a cement factory is connected to this feeder.

3.4. Reasons for temporal variations

The temporal variations of the voltage and current THD are associated with the variations of the harmonic-producing loads. Normally, the individual harmonic distortion is linked to specific harmonic-producing loads. Station A is a grid station that is connected to a cement factory and an industrial area where many non-linear loads are fed from this station. Such loads are variable frequency drive (VFD) and switch-mode power supplies (SMPS), in which both are considered main sources of the 5th harmonics (H5). This explains the dominance of the 5th and the 3rd harmonic currents contamination.

Phase	TDD P95	TDD P99	TDD IEE limits
A	1.25	1.42	4
B	1.24	1.30	4
C	1.36	1.52	4

Table 6. Measured current TDD 95th and 99th percentiles vs. IEEE Std 519-2014.

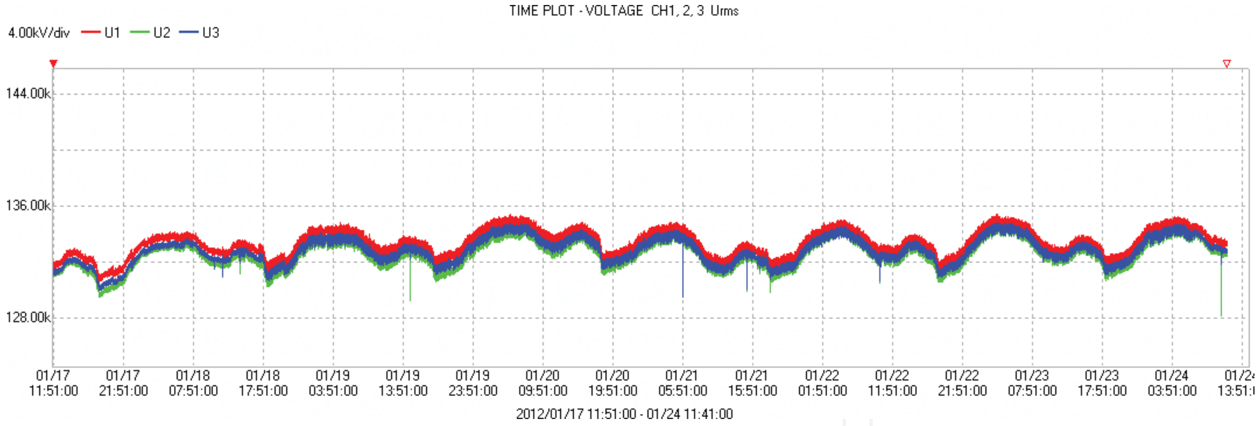


Figure 4. Voltage temporal profile at grid station A.

Figure 5. Voltage harmonics temporal profile at grid station A. (a) Voltage THD and (b) individual harmonics.

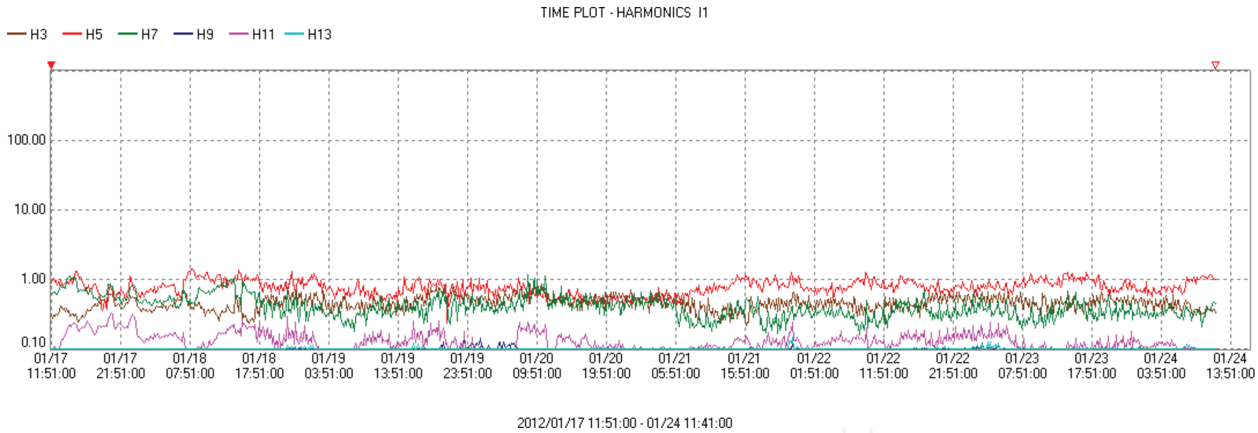


Figure 6. Current harmonics temporal profile at grid station A.

4. Harmonics temporal profile at grid station B

4.1. Harmonic measurements at grid station B

Grid station B consists of two 220/132 kV parallel transformers (TX1 and TX2). Each transformer is 500 MVA capacity. The grid station B is located close to two power generation facilities. The maximum short circuit level on 132 kV side at the time of measurements is 17.96 kA. The grid station is supplying electricity to large industrial customers via 132 kV feeders as well as smaller industrial customers via two 132/33 kV transformers. Ten-minute average values were recoded using Hioki 3196 Power Quality Analyzer Meter [8]. The current clamps of the analyzer were connected to a 132 kV feeder supplying a steel smelter. Measurements were recoded over a period of 1 week starting from 28 January 2012. A summary of measurements is presented in **Figure 7**.

For the voltage signals, **Figure 7** shows that the average THD at the high-voltage side is between 0.97 and 0.90%, the maximum THD is between 0.97 and 0.90%, and the minimum THD level is between 0.28 and 0.32%. For the current signals, the THD at the high-voltage side (132 kV) ranges between 33.09 and 2.28%. Despite the high-current distortion, the voltage THD is small due to the high short circuit capacity.

The current waveform at grid station B is highly distorted as shown in **Figures 7–9**.

It is worth noting that the dominant harmonic components are the 5th, the 7th, the 11th, the 13th and the 17th orders. In addition, there is a clear content of the 2nd, the 3rd, and other harmonic orders.

Histograms of voltage THD and current TDD at station B are presented in **Figure 10**. Using the voltage THD histograms, the 95th percentiles are calculated for different phases. A comparison between the 95th percentile of voltage THD and IEEE Std 519 limit is presented in **Table 7**.

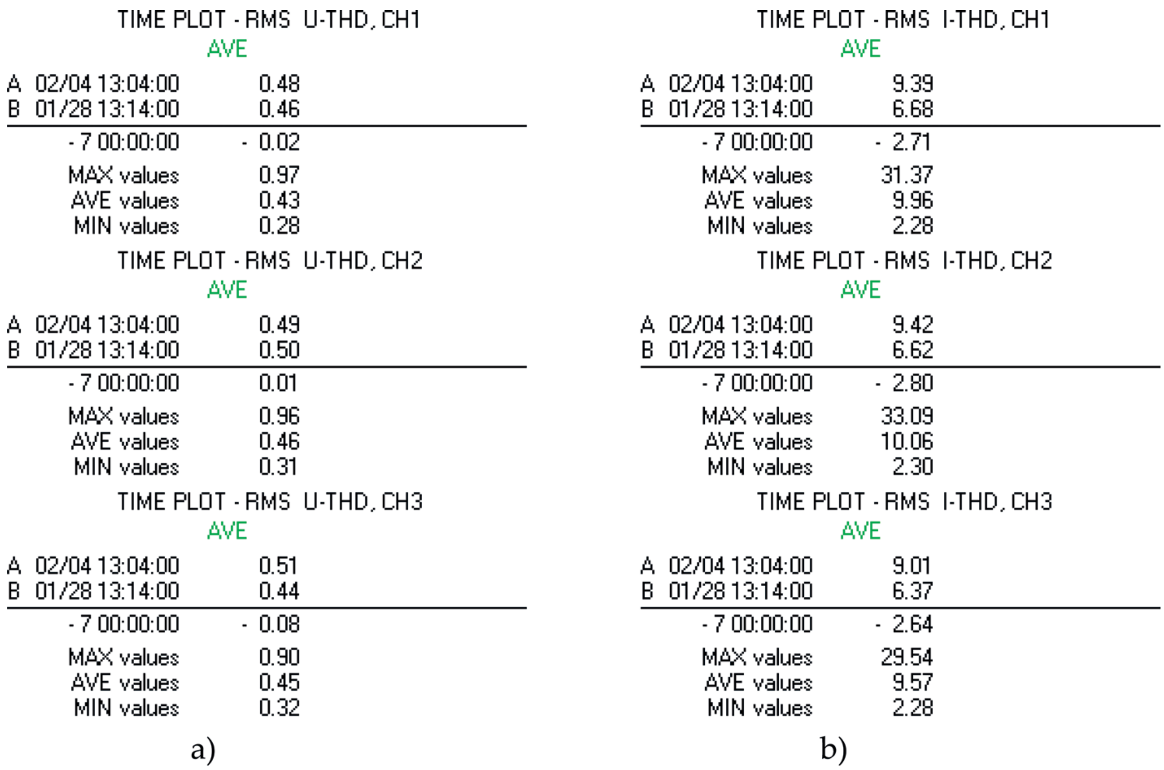


Figure 7. Summary of THD measurements at grid station B. (a) Voltage THD and (b) current THD.

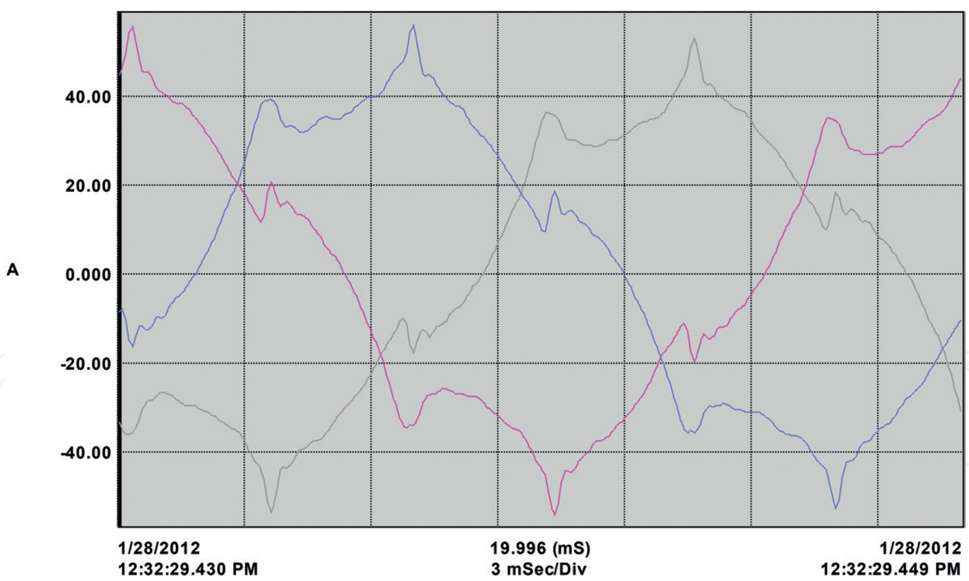


Figure 8. Current waveform of the 132 kV feeder at grid station B.

Using measurements, the maximum demand load current is 208 A. The short circuit level at grid station B is obtained from OETC capability statement. The TDD limit based on $I_{SC}/I_L = 91$ is 6%. A comparison between the 95th and 99th percentiles of current TDD and IEEE Std 519 limits is presented in **Table 8**.

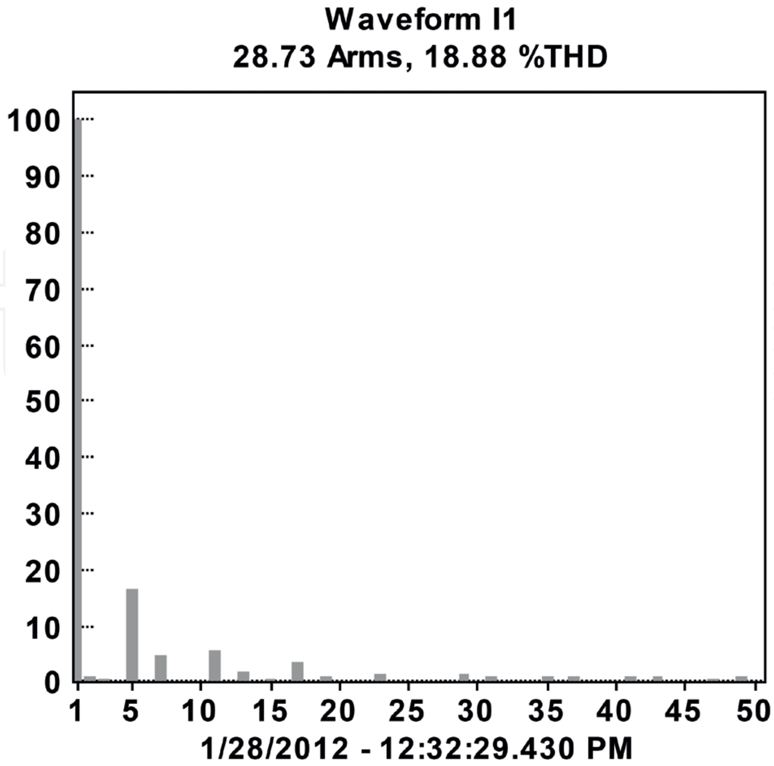


Figure 9. Grid station B current spectrum.

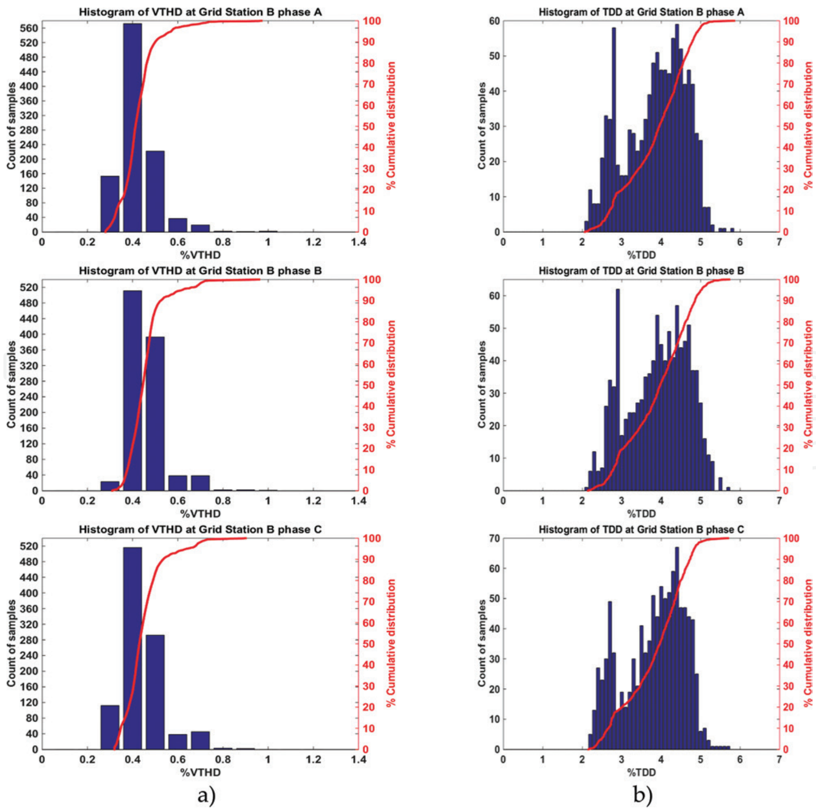


Figure 10. Histograms of THD measurements at grid station B. (a) Voltage THD and (b) current TDD.

Phase	THD P95	THD IEEE limits
A	0.58	2.5
B	0.621	2.5
C	0.641	2.5

Table 7. Voltage THD 95th percentile vs. IEEE Std 519-2014 at station B.

Phase	TDD P95	TDD P99	TDD IEEE limits
A	4.92	5.16	6
B	5.02	5.31	6
C	4.84	5.13	6

Table 8. Current TDD 95th and 99th percentiles vs. IEEE Std 519-2014 at station B.

4.2. Voltage harmonics temporal profile at grid station B

The voltage profile measured at grid station B is presented in **Figure 11** below. The daily diurnal profile is not clear due to high variability caused by load operations. These voltage fluctuations are attributed to fluctuation load current as seen in **Figure 12**.

Figure 13 presents the voltage THD as well as evident individual harmonics temporal profiles. It is worth nothing that no clear diurnal profile exists. Moreover, the dominant harmonic components are the 11th, the 13th, the 7th and the 5th. There is a small trace of the 3th and 9th harmonics. There is a very small trace of the 2nd harmonic as seen in **Figure 14**.

A similar observation can be seen in the 2nd location, where individual harmonic distortion is related to specific harmonic-producing loads. Station B is a grid station that supplies with proximity close to the largest industrial area in Oman. There are many non-linear loads fed from this station such as steel factories and aluminum smelters. The arc-furnaces loads, either induction furnaces or DC arc furnaces, along with static var compensators (SVCs) contribute significantly to the harmonic components of 11th, 13th, 7th, and 5th order.

4.3. Current harmonics temporal profile at grid station B

Figure 15 presents the current THD and individual harmonics profile at grid station B. It is worth noting that these profiles are highly fluctuating similar to measured current profile shown in **Figure 12**. It is worth mentioning that the dominant harmonic components are the 5th, the 11th, the 7th, and the 13th. In addition, there is a clear content of the 2nd, the 3rd, and other harmonic orders.

4.4. Reasons for temporal variations at grid station B

Comparing voltage temporal profile at grid station A with grid station B, it can be concluded that this variation depends on the type of loads available. While in grid station A, the variation

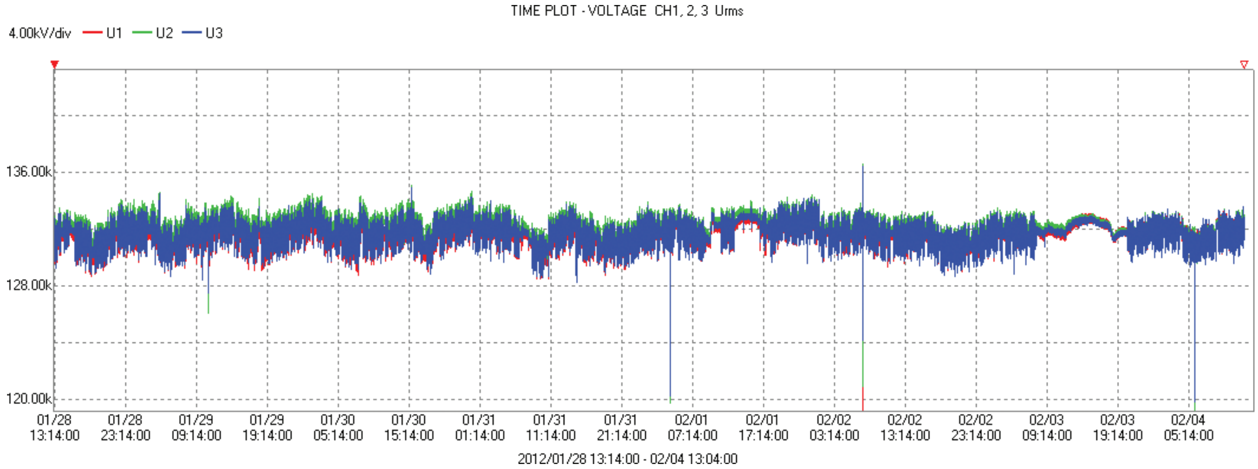


Figure 11. Voltage temporal profile at grid station B.

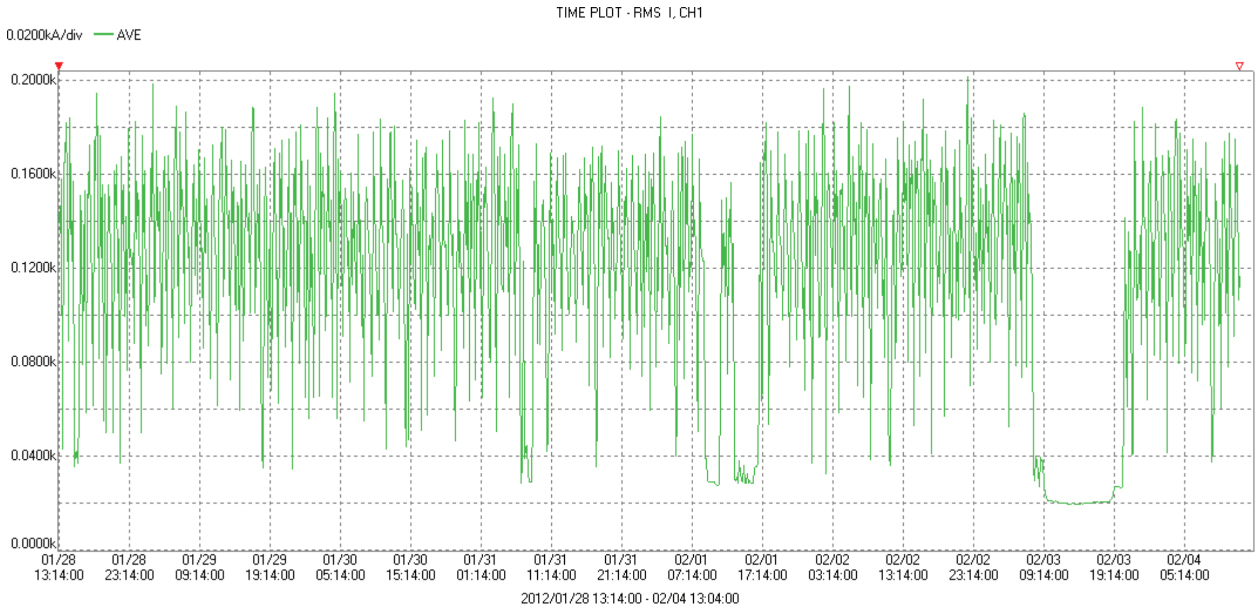


Figure 12. Fluctuating load current at grid station B.

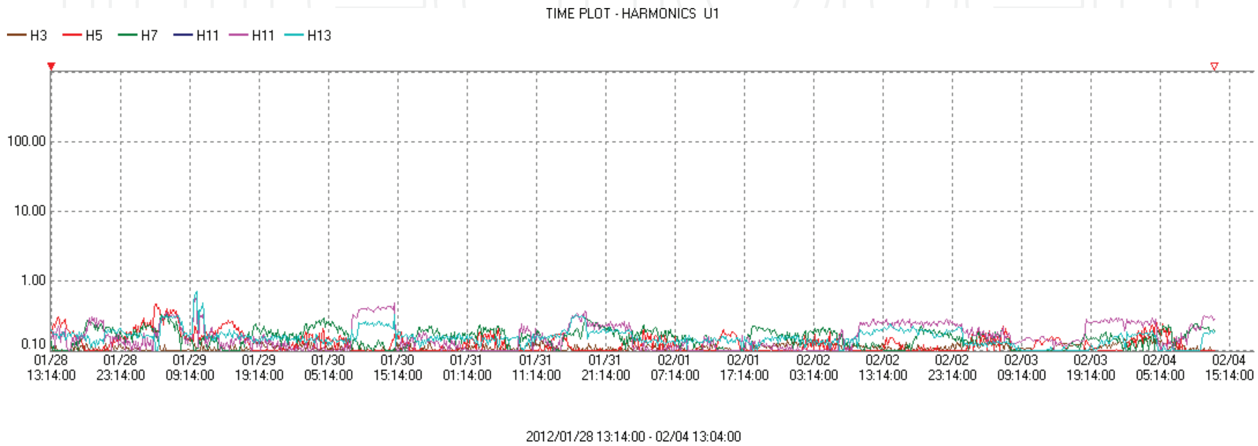


Figure 13. Voltage harmonics temporal profile at grid station B.

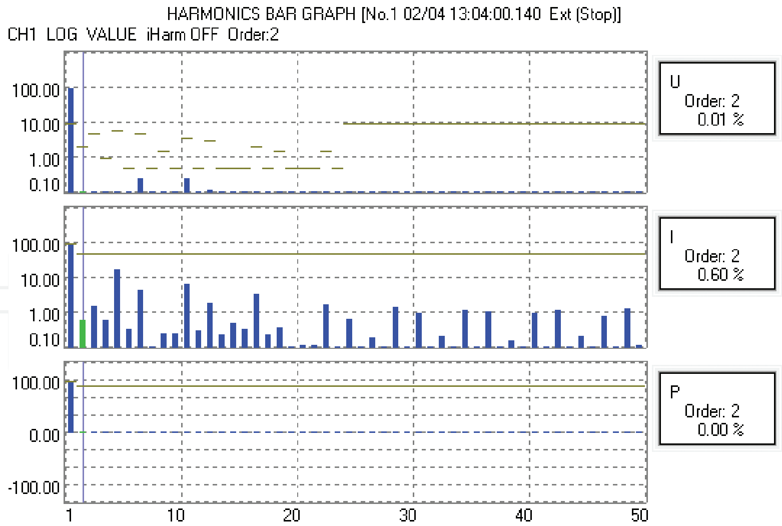
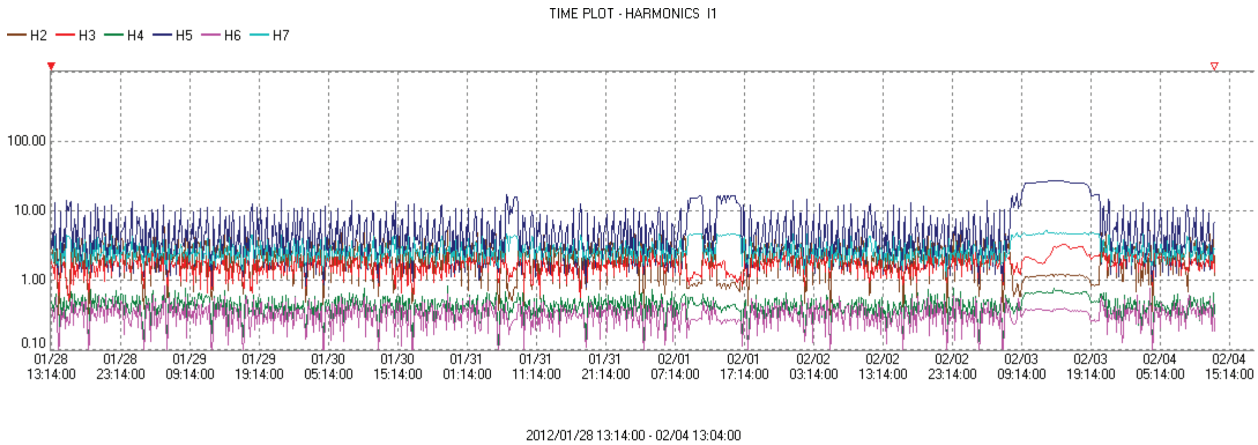
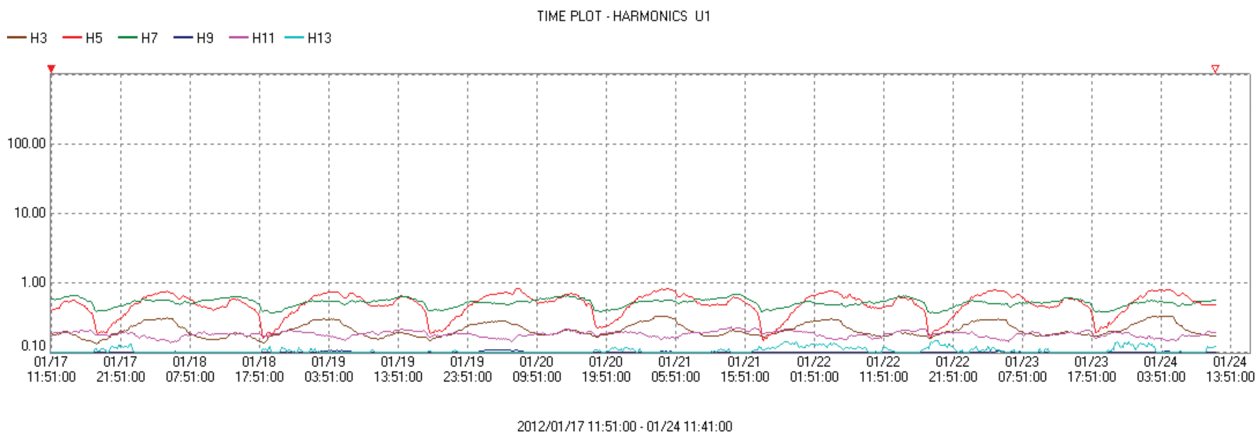


Figure 14. Harmonics bar graph at grid station B.



(a)



(b)

Figure 15. Current harmonics temporal profile at grid station B. (a) 7th and lower orders (b) 8th and higher orders.

reflects almost the daily load profile but in grid station B the variation is completely different owing to the existing of steel industries. Furthermore, although there is high current distortion in grid station B, the voltage THD is small due to the high short circuit capacity.

5. Conclusions

Harmonics were measured and analyzed for two grid stations in the main interconnected system of Oman. The first grid station is feeding both industrial and residential customers, while the second grid station is dedicated to large industrial customers including arc furnaces and rolling mills. A clear temporal variation of harmonics similar to that of aggregate load and local voltage profiles was observed at the grid station feeding both residential and industrial customers. However, this correlation between the system load and harmonics profiles diminishes at the grid station dedicated for heavy industrial loads.

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