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Mapping and assessment of harmonic voltage levels for railway traction supply stations in Sweden

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ABSTRACT

Assessing harmonic distortion measurements in the electric railway power systems (ERPS) requires evaluating the time-varying behavior, interactions, and performance in different time scales. This paper aims to map and assess harmonic voltage levels in 13 traction converter stations for the Swedish railway power supply system, with findings that have direct practical implications. For that, measurements from the public and railway grid sides for 69 weeks are analyzed. Statistical values are explored for the harmonic voltage spectra and total harmonic distortion (THD) variation. The public grid side measurements are investigated using 95th percentile weekly values, and performance is evaluated by comparing the recommended planning levels of IEC 61,000–3–6. The intraweek variation complements the information about the time-varying behavior of the THD. The 95th percentile, minimum daily values, and intraday variation are explored to understand the time-based behavior since there are no reference limits from standards for comparison, looking to the railway grid side. Extended analysis is placed on the railway grid side to highlight some aspects of measurement time-aggregation based on 10-min values, and time-series trend analysis is used to confirm traffic planning impact. Discussion and findings regarding railway operation, the technology deployed at the traction converter station, time-varying behavior, traffic planning impact, measurement time-aggregation, and spectra patterns were presented.

1. Introduction

In electric railway power system (ERPS), voltage and current distortion (waveform distortion) is caused mainly by power electronic converters application in traction converter stations, auxiliary circuits, and onboard of the rolling stocks, with disturbance levels dependent on operating conditions, arrangements, and converter topology [1]. As a trend in power systems over the last decades, the spread of static power electronics conversion has increased, moving towards more efficiency and higher power requirements [2]. It impacts several challenges regarding interoperability among equipment, systems, and subsystems, which are addressed as power quality (PQ) issues. In addition, interaction between ERPS and the public is a concern regarding issues for both sides of the operation.

The ERPS has always been a particular case regarding waveform distortion, where performance limits are not well defined for all environment involved in those systems, with the exemption of compatibility with train detection systems and voltage quality [3–7]. Because of that, more tolerance to high distortion levels is placed compared with public distribution and transmission power systems [8]. Correctly managing those disturbances improves reliable operation and minimizes adverse effects on equipment, grid components, and other crucial subsystems like signaling, communication, and protection. Assessing harmonic distortion measurements in the traction power supply is a way to understand and evaluate the time-varying behavior, interactions, and performance in different time scales in ERPS [9]. Such assessment should be performed at several points of interest in ERPS, such as the connection between the traction supply stations and the public grid or the distribution feeders on the railway side.

Two investigation methodologies can be addressed for harmonic distortion assessment: measurement-based analysis and modeling. The first consists of modeling the traction power supply infrastructure and harmonics source (moving loads) to analyze how the current emission impacts the voltage distortion levels in the connection points considering the operating points, types of locomotives, system resonances, etc. Examples have been evaluating harmonic power flow in 16 $^{2}/_{3}$ Hz

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system [15], the impact of using special transformers (e.g., V-V) on harmonic cancellation in the 50 Hz railway power supply [10], development of combined equivalent circuits for the harmonic sources for evaluating the impact of aggregation of multiple traction loads on PQ [11], evaluation of harmonic resonance in a 2 × 25 kV 50 Hz system to investigate the interaction of special loads with rolling stock within the system [12], statistical studies for resonance in a 1 × 25 kV 50 Hz supply with Steinmetz circuit [13], modeling and evaluation of traction vehicle including on-board power electronics [14], and other comprehensive studies investigating the impact of harmonic modeling for high-speed railways [16–19].

Measurement-based methodologies are also helpful and can support analysis that aims to evaluate the impact of operating conditions on the current and voltage distortion parameters performance in different timescales. Pantograph quantities measurement has been shown efficient to address this kind of evaluation by providing suitable time resolution on the scale of sub-1-min, and mainly allows inferences on the time-varying dependency and interaction of waveform distortion from rolling stocks [20–22], and that can be explored for analyzing the impact of distortion power terms on energy measurement [3,23], overvoltage and resonance identification [24], etc. This type of measurement is ideal for assessing specific interactions or contributions of the time-varying behavior of each rolling stock in the grid. However, those measurements are usually available on testing conditions or short periods of operation. It happens due to higher time and frequency resolution, which implies a higher need for data storage or management and heavy coordination depending on the measurement location. Fixed installations (traction supply stations or lineside points) in ERPS with PQ monitoring devices have standardized measurements based on traditional requirements and recommendations, usually in terms of 10-minute values or, in better scenarios, 1-minute values. Those measurements are usually available for studies within the stakeholders in ERPS. They can also bring supportive information on the aggregated effect of the operation and represent long-term variations of harmonic distortion for evaluation within weeks to months. It can also evaluate standard performance with the public transmission grid at the connection point.

An analysis is performed on measurements made near the traction substation for a 27 kV 60 Hz system in New Haven, USA, interacting with the public grid [25]. The monitoring was placed on both sides of the traction substation, single-phase 27 kV, and at the 115 kV transmission grid for 24 h. The results show that the third harmonic current and the total demand distortion exceed the limits IEEE 519–1992 (an older version of currently IEEE 519–2022 [26]) recommended. In [27], the contribution of harmonic emission from traction loads on connection points with renewable power plants is investigated for a week. The work used IEC 61,000–3–6 guidelines to define the emission limits and approach the multi-point measurement due to background distortion harmonics and multiple sources, including traction loads. The measurement points were at the point of connection of a wind farm and the point of connection of a traction substation, both located at a 132 kV system in South Africa. The investigation findings show that the railway system's emission contribution should be addressed in the investigation, looking into factual moments of operation of the traction load.

In [28], measurements from a 220 kV/25.7 kV traction substation serving the Wuhan-Guangzhou high-speed electrified railway in China, was examined. They manage to show the correlation between harmonic levels and railway traffic operations, and despite this correlation, the harmonic levels remain in compliance with regional requirements. Also, the work in [29] discusses the daily distribution characteristics of harmonics under various operating conditions in a Chinese high-speed railway. It presents characteristic harmonic spectra for voltage and current, revealing a power function relationship between harmonic voltage distortion and system operating currents. Long-term measurements are assessed in [30] for the Croatian transmission grid to evaluate the impact of the railway power grid in their system, and harmonic distortion shows compliance with the national code. Lastly, one can find several works looking at the effects of DC railway systems in public grids [20,31,32].

As described above, in the literature, it is possible to find several works that propose study cases on the assessment of harmonic distortion measurements on different time scales for different types of ERPS. Although there is a lack of work on the characterization of waveform distortion studies of 16.7 or 16 $^2/_3$ Hz single-phase railway, most studies focus on 50/60 Hz systems or DC systems [9]. This kind of system is approached in detail further in this paper. It has unique characteristics that require different approaches, such as the deployment of traction converter stations, no direct connection between the single-phase railway system and the public grid, different technologies of frequency converters, the operating frequency being different from the public grid systems, and more extensive system extension.

This paper aims to extensively map and assess harmonic voltage distortion in traction converter stations for the Swedish railway power supply system. Measurements from both sides of 13 traction converter stations are analyzed within 69 weeks, using 10-min values. Statistical values are explored for the harmonic voltage spectra and total harmonic distortion (THD) variation. The public grid side measurements are investigated using 95th percentile weekly values, and the performance is evaluated by comparing the measurements to the recommended planning levels of IEC 61,000–3–6 [33]. The intraweek variation complements the information about the time-varying behavior of the THD. The 95th percentile and minimum daily values are explored to assess the variations in time since there are no reference limits from standards for comparison at the railway grid side. The intraday variation is also evaluated for the railway grid side. Extended analysis is conducted on the railway grid side to highlight some limitations of 10-min values and a time-series trend analysis to confirm aspects of traffic planning impact. The contributions of this work are highlighted below. Some works in the literature provide similar approaches for assessing long-term harmonic measurements in other kind of power systems: trend analysis on long-term time-varying harmonic distortion data [34–36], identification of patterns and correlations in long-term measurements of power quality for different site locations [37,38], and other examples of applications, as for HVDC link site [39] or renewable power plants [40].

1. Mapping patterns and evaluation of harmonic voltage levels in the Swedish traction power supply for several stations, providing assessment on time-varying aspects, technology signature, traffic impact, infrastructure, comparisons, and recommendations.
2. Proposing an extensive screening using traditional methods for long-term harmonic distortion measurements as statistical values for different time scales and representations, comparison with standards when it is suitable, and trend analysis.
3. Findings linking railway operation knowledge with the results from the proposed analysis, which can be used for future assessment or for support towards electromagnetic compatibility standardization and planning.
4. Proposing an assessment and inference framework that can be reproduced for other electrified transportation systems with similar characteristics regarding operation impact on waveform distortion as electrical road systems, electric vehicle charging infrastructure, etc.

After this introduction, Section 2 presents aspects of Swedish railway electrification and traction converter stations. Section 3 details the methods and study case approached in this work. Section 4 shows the assessment results for the public grid side., while Section 5 presents the results for the railway grid side. Lastly, Section 6 concludes the paper.

2. Swedish railway traction power supply

The configuration and solution for the railway traction power supply depend on technical factors and historical decisions regarding the electrification process's starting time [41]. For instance, the historical process of railway electrification in Sweden is documented in [42]. Many solutions are developed in different systems, but one can summarize them in four categories: single-phase AC systems at railway frequency, single-phase AC systems at public grid frequency, DC systems, and three-phase AC systems. Those infrastructures are extensively discussed in the literature regarding the description of the power delivery system, advantages and disadvantages, application of different types, and electromagnetic compatibility [8,43,44]. In Sweden, the single-phase AC system at railway frequency is deployed for heavy-traction transportation. Some details about this system are described in this section. See below some information about the Swedish electrified railway (information summarized from [45–49]), also illustrated in Fig. 1.

- Power supply: Power is delivered from the public power supply, 60 to 132 kV 50 Hz grid. The railway supply for the moving loads is delivered at 15 kV 16 $^2/_3$ Hz in single-phase system. The power needs to be converted through frequency converter stations, that are located along the whole railway tracks for determined distances. Those converter stations deploy rotary or static converter for executing the frequency conversion. The traction stations supply the catenary system locally and directly (called decentralized solution).
- Frequency Converters:
  - Rotary Frequency Converter (RFC): A rotary converter comprises a three-phase synchronous motor operating at 50 Hz and a single-phase synchronous generator on the same shaft, running at 16 $^2/_3$ Hz. The motor has 12 poles, while the generator has 4, allowing for a convenient conversion of the frequency to one-third.
  - Static Frequency Converters (SFC): Static converters are constructed using power electronic components, with thyristors being the primary elements. These static inverters are available in three different configurations: direct converters (or cycloconverters), DC-link converter (PWM-thyristor-based two-level or three level), and modular multilevel converters.
- Catenary system and return current: The usage of boost transformer and autotransformer in the catenary system is intended to reduce the stray currents and interferences caused by the high ground resistivity in Sweden.
  - Boost-transformer (BT) system: Located 5 km apart from each other in the catenary system, a transform with ratio 1:1 forces the current path from the rail to the converter via return conductor with ground connection.
  - Autotransformer (AT) system: A transformer is located every 10 km in the catenary system, and it is placed between a negative feeder and the contact line, while the rail is connected to the mid-point of the transformer. The output power is higher in those systems (ideal for heavier applications and trains) and the distance is higher because of doubled voltage. The AT system consists of a two-phase system where the AT conductors have the potential of 15 kV but with the phase reversal 180° The AT system operates with a 15 kV potential and a 180° phase reversal, resulting in an effective supply voltage of 30 kV.
- Auxiliary grid: The auxiliary power line operating at 11 to 22 kV 50 Hz, located on top of the catenary poles, delivering power to signals, heating, technology buildings, and station buildings. Both two-phase and three-phase systems can be found in the extensive infrastructure. Transformers are employed where electricity is required to lower the voltage to 230/400 V. In case of no such infrastructure, the public grid is utilized, but isolation strategies are required.
- 132 kV 16 $^2/_3$ Hz feeding system: The system is a two-phase system with 180° between the phases fed by transformers which are connected to the 15 kV railway grid. It is present in part of the railway infrastructure in Sweden, allowing a reduction in the number of traction converter stations as it allows higher distances between stations.

3. System information, measurements, and assessment

The study in [48] provided initial steps towards investigating harmonic distortion levels in the 16 $^2/_3$ Hz side for the Swedish system. This work extends the analysis to establish a comprehensive mapping and assessment of harmonic voltage levels in traction converter stations in Sweden. The methodology aims to characterize the harmonic voltage spectra and the voltage distortion variation along the period of the measurements, providing both statistical values and time-varying behaviors in the daily to week scales.

The performance evaluation using recommended planning levels is explored for the 50 Hz side since, for that electromagnetic environment, there is a framework for evaluating weekly values. Due to a lack of standardization establishing limits or recommended values for the railway grid side, this work will highlight the range of distortion to provide specific comparison considering daily values. Also, the intraweek and intraday variation is explored for the public and railway grid sides, respectively.

The measurements consist of the recorded 10-min aggregated values for voltage harmonics performed by the PQ instruments from Swedish

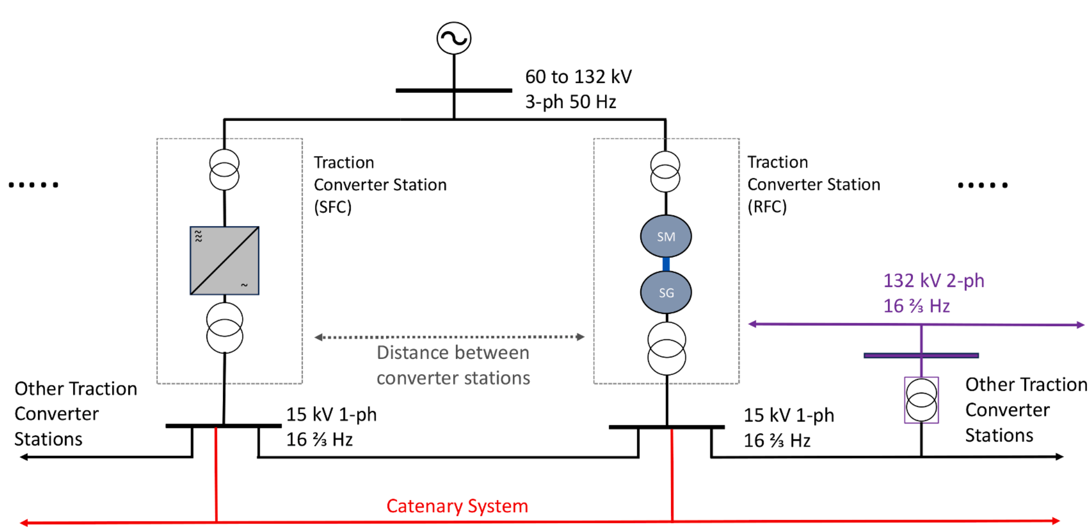

Fig. 1. Schematics overview of the traction power supply in Sweden.

company Metrum AB for monitoring power quality in the Swedish railway infrastructure for 69 weeks (starting from 1st August 2021). The stations are named as in Table 1, and they differ by the type of frequency converter used in the station, power quality monitor measuring in the station, between BT and AT system, and if it is connected to 132 kV 16 $^{2}/_{3}$ Hz two-phase grid. All information and data available/authorized are described and assessed in the paper. Additionally, data from a station with 6-second values (a few days in April of 2023) was used to perform a comparison and assess the impact of measurement aggregation. The following analysis is investigated.

- For the 50 Hz side:
  - Assessment of the weekly 95th percentile of the harmonic orders up to 50th. Results will explore the maximum, 95th percentile, mean and minimum value for the 69 weeks.
  - Checking the violation of weekly values of individual harmonics in comparison with the planning levels recommended by IEC 61,000–3–6.
  - Assessment of the total harmonic distortion (THD) time-variation considering the 95th percentile weekly value.
  - Checking the violation of weekly values of THD in comparison with the planning level recommended by IEC 61,000–3–6.
  - Statistical values of the months' 95th percentile of THD intraweek variation: range, 95th percentile, and mean values.
- For the 16 $^{2}/_{3}$ Hz side:
  - Assessment of the daily 95th percentile of the harmonic order up to 100th or 50th, depending on the range available of the instrument. Results will explore the maximum, 95th percentile, mean and minimum value for the 69 weeks.
  - Assessment of THD time-variation considering the 95th percentile and minimum daily value.
  - Statistical values of the weeks' 95th percentile of THD intraday variation: range, 95th percentile, and mean values.
  - Application of Seasonal-Trend Decomposition using Loess (STL) [50] for assessing similar long-term trend of THD daily 95th percentile from station in the same path with sharing traffic, and correlation of weekly seasonal components for THD between stations. The correlation is calculated using Pearson correlation coefficients [51].

Table 1
Traction converter stations details.

Station	PQ Monitor	Frequency Converter*	System	Connected to the 132 kV 16 $^{2}/_{3}$ Hz 2-phase feeding
A	PQX3-FR	2 x MVA TGTO (DC-link converter)	BT	No
B	PQ122	1 × 14 MVA TGTO 2 × 15 MVA SF C2 (DC-link converter)	AT	Yes
C	PQ122	3 × 17 MVA MMC (Modular Multilevel Converter)	AT	No
D	PQ122	2 × 15 MVA MEGAMACS (DC-link converter)	BT	Yes
E	PQ122	4 × 15 MVA MEGAMACS (DC-link converter)	AT	Yes
F	PQ122	2 × 15 MVA MEGAMACS (DC-link converter)	BT	Yes
G	PQX3-FR	2 × 15 MVA MEGAMACS (DC-link converter)	BT	No
H	PQX3-FR	3 x Q38 1 x Q38 HOG (Rotary converter)	AT	No
I	PQX3-FR	3 x Q50 (Rotary converter) 4 × 24 MVA MMC (Modular Multilevel Converter)	BT	Yes
K	PQX3-FR	1 x Q38 1 x Q38 HOG 2x Q48 (Rotary converter)	AT	No
L	PQ112	3 × 14 MVA TGTO (DC-link converter)	BT	Yes
M	PQ112	2 × 15 MVA YOQC (Direct converter) 1 × 14 MVA TGTO (DC-link converter)	AT/BT	No
N	PQ112	3 × 13 MVA YOQC (Direct converter)	AT/BT	Yes

A description of each type of converter was presented in Section 2, and more details can be accessed in ref. [46], for instance.

The measurements have been carried out using the instruments PQX3-FR and PQ122 at the converter stations. The instruments comply with IEC 61,000–4–30 (Class A) [52]. For harmonics and THD, these instruments measure data every ten minutes. The PQX3-FR measurements are available up to 100th harmonic for the 16 $^{2}/_{3}$ Hz side and up to 85th for the 50 Hz grid. At the same time, PQ122 goes up to the 50th harmonic for both sides of interest. The 50th harmonic for the 16 $^{2}/_{3}$ Hz system corresponds to 833.3333 Hz, and the 100th order will be approximately 1666.66667 Hz. So, there are limitations to assessing distortion on the 16 $^{2}/_{3}$ Hz side from the switching frequency of rolling stocks or signatures from the onboard converters and limited calculation of the THD (up to 2 kHz by definition), especially for the PQ112 measurements. The quality of the data for the proposed study was verified. Permanent measurements located in the stations can produce inaccurate data, "not a number" data (NaN), or data that is out of the scope of the investigation. The causes for those undesired data can be related to communication issues, missing data due to interruption of instrument power supply, damage or maintenance in the measurement equipment, and time desynchronization. Quasi-state measurement was used, so values that contain other power quality events regarding the significant drop in voltage at the main frequency are excluded (handled as NaN instead) to cope with the proposed scope.

4. Harmonic levels on public grid side

For the public grid side, some examples will be illustrated and explicated in more detail to highlight the points in the discussion (stations A, B, C, H, M, N). The findings will include all other stations in a summary at the end of this section.

4.1. Station A

The results from Station A show the presence of the 12-pulse components (11th,13th, 23rd, 25th, 35th, 37th, 47th, and 49th) from the DC-link converter. Those components vary between 0.2 % and 0.6 % of the fundamental voltage. The only individual harmonic violating the planning level is the 5th, with amplitude values ranging up to 8 % and a mean value higher than 6 %. Although other low-order harmonics, such as the 5th and 7th harmonic, are typical in transmission systems, and the significant contribution may come from the upstream grid, the high fluctuating amplitude can have some impact on the traction converter station. The THD for this station was in violation for 67 weeks for the weekly 95th percentile, the same number as the 5th harmonic violation. The intraweek variations show different magnitudes between weekends and working days. During working days, the THD can reach up to 9 %, and during weekends, up to around 6 %. The intraweek curves also show that the working day variations present lower values during nights than the rest of the day. Fig. 2 illustrates the results of the 50 Hz side assessment for Station A.

4.2. Station B

Station B, with two types of DC-link converter, also shows the 12-pulse components are present, with maximum values varying between 0.1 % and 0.6 %. Other harmonics, such as 3rd, 5th, and 7th, have a mean value above 1 %. Individual harmonics were violated for the 5th harmonic <10 times; for the 6th, around 36 times; and 7th, with >40 violations. The THD was in violation for 22 weeks. The intraweek variations show no significant difference between magnitudes over the weekdays but highlight that the THD can have values between 4 % and 5 % with few occurrences above that. Fig. 3 illustrates the results of the 50 Hz side assessment for Station B.

4.3. Station C

Station C has a low value of THD magnitude, lower than 1 % for the weekly 95th percentile, and contains violations for harmonic 39 and 33. Looking to the spectra, there is a characteristic broad band of distortion in the range from 1000 Hz to 2500 Hz, with similar amplitudes for odd and even harmonics, which can also indicate the presence of inter-harmonics. MMC in traction supply applications has been characterized by this type of broadband emission, including issues with a higher frequency range in the PCC, as illustrated in [53,54]. The amplitude of those components is in the ranging between 0.1 % and 0.2 %, showing a sustained pattern. The violations can be indicative that come from components caused by the traction power supply since those harmonics are not typically present in the background voltage. The intraweek statistics show higher magnitudes during working days and some occasions of reductions of THD for a few days below 0.6 %. During working days, the nights present lower values than the rest of the day. Fig. 4 illustrates the 50 Hz side assessment results for Station C. Fig. 4(b) shows a case of missing data due to the unavailability of the measurement device or exclusion due to voltage variation, abnormal events, and unreliable data. Station C was a station with a higher number of missing data.

4.4. Station H

No violation is assessed for station H, presenting THD with levels below 1 %. Station H only has rotary converters so that slot harmonics can be expected. The 3rd harmonic present values are as high as the 5th and 7th harmonics. The 12-pulse components can be seen, but there is no static converter at this station, showing that these components might come from other loads connected at transmission level. The intraweek variations show a constant pattern variation over the week below 1 %, with no long duration (one 10-min value) peaks of THD between 1 % and 2.5 %. Fig. 5 illustrates the results of the 50 Hz side assessment for Station H.

4.5. Station M

There is a combination of the direct converter and DC-link-converter at Station M, the results present a violation only for the 5th harmonic, around 40 weeks in violation. The violation of the THD happens 5 weeks in the investigated period, with values <3.5 %. The 5th harmonic ranges up to 3.3 %, and the 12-pulse converter signature has values up to around 0.5 %. The intraweek shows higher variations for workdays compared to weekends, with a difference higher than 1.5 % for maximum values. Fig. 6 illustrates the results of the 50 Hz side assessment for Station M.

4.6. Station N

Station N does not violate the THD during the campaign. Still, the individual limits violate the 3rd, 21st, 27th, and 33rd. There is an increase in amplitude for components higher than 2 kHz. If one considers the calculation of THD up to 50th order, it will violate for 58 days due to the high amplitude of harmonics above 2 kHz. The intraweek curves show a lower distortion for the weekends. Although, the highest values during working days are from night hours rather than the rest of the day. Considering all data points, THD ranges up to 3.3 %. Fig. 7 illustrates the results of the 50 Hz side assessment for Station N.

4.7. Discussion

Table 2 summarizes the findings discussed below for all stations, violation of THD and individual harmonic orders, patterns of different magnitude levels between working days and weekends, and which harmonics were violated. Fig. 8 shows the violin plots for each station on the public grid side, which contain the distribution of values of THD for all measurements. The violin plot helps to summarize the comparison regarding the different locations. Some discussion points about the results are highlighted below for the public grid.

- Violation of THD occurs for stations with DC-link converters. Also, individual violations appear for some DC-link type converter stations 5th, 6th, and 7th harmonics, where the number of violations is significantly higher. Even if the impact of the total distortion comes from those low-order harmonics in violation, which are typical harmonics in the background and not emissions from the converters, further investigation (e.g., harmonics responsibility) should take place to confirm the impact of those stations' connection in the PCC. The impact of the static frequency converters or installed filter impedances can play a role when looking at voltage levels.

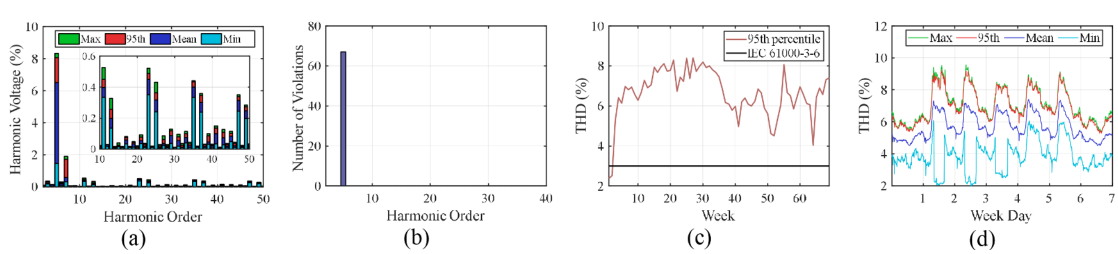

Fig. 2. Results of 50 Hz side assessment for Station A: harmonic voltage statistical weekly variation (a), number of violations per harmonic order according to IEC 61,000–3–6 (b), weekly variation of THD (c), and THD intraweek monthly variation statistics (d).

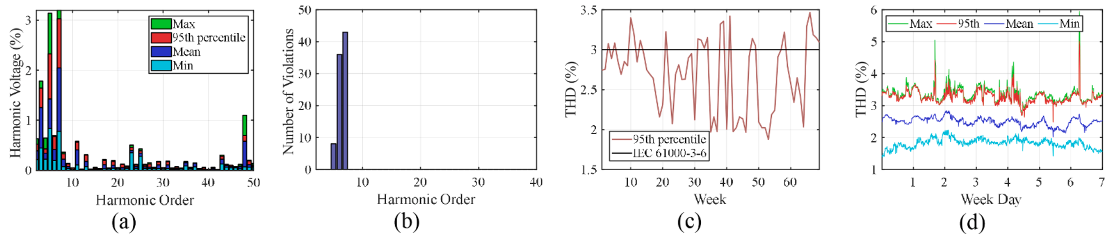

Fig. 3. Results of 50 Hz side assessment for Station B: harmonic voltage statistical weekly variation (a), number of violations per harmonic order according to IEC 61,000–3–6 (b), weekly variation of THD (c), and THD intraweek monthly variation statistics (d).

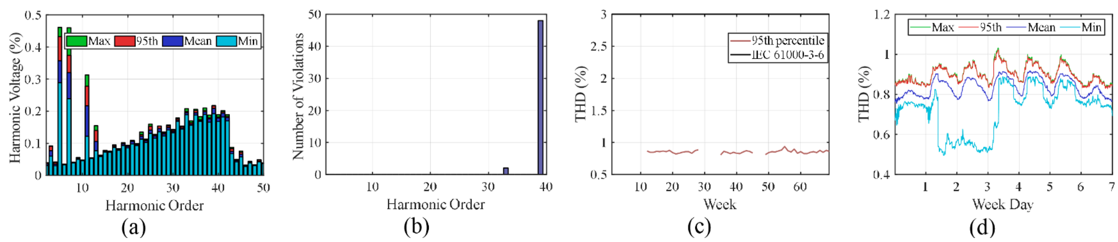

Fig. 4. Results of 50 Hz side assessment for Station C: harmonic voltage statistical weekly variation (a), number of violations per harmonic order according to IEC 61,000–3–6 (b), weekly variation of THD (c), and THD intraweek monthly variation statistics (d).

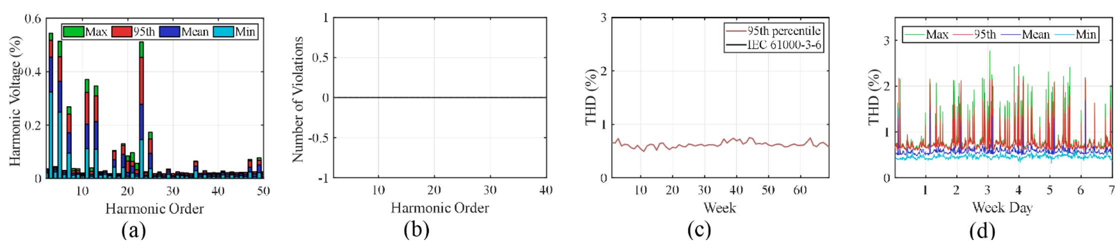

Fig. 5. Results of 50 Hz side assessment for Station H: harmonic voltage statistical weekly variation (a), number of violations per harmonic order according to IEC 61,000–3–6 (b), weekly variation of THD (c), and THD intraweek monthly variation statistics (d).

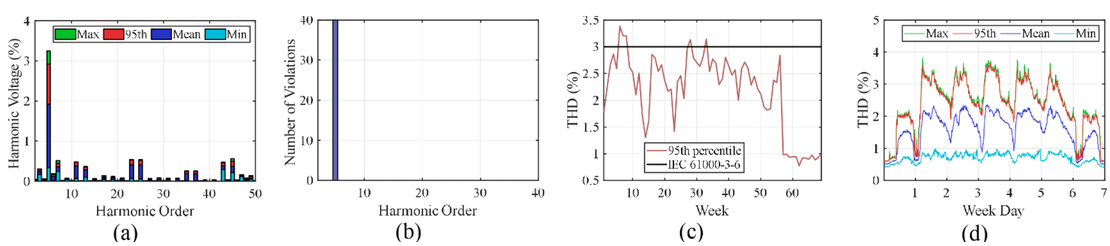

Fig. 6. Results of 50 Hz side assessment for Station M: harmonic voltage statistical weekly variation (a), number of violations per harmonic order according to IEC 61,000–3–6 (b), weekly variation of THD (c), and THD intraweek monthly variation statistics (d).

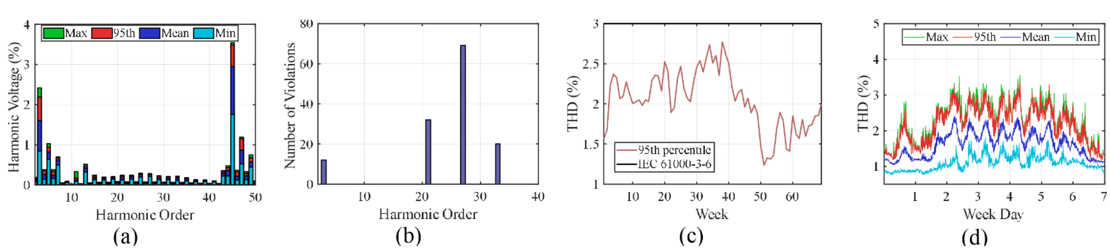

Fig. 7. Results of 50 Hz side assessment for Station N: harmonic voltage statistical weekly variation (a), number of violations per harmonic order according to IEC 61,000–3–6 (b), weekly variation of THD (c), and THD intraweek monthly variation statistics (d).

- The rotary converter stations present an expressively low value for individual harmonics and THD. No violations are seen for those stations.
- The MMC converter stations do not present violations of THD, with low values of overall distortion.

Table 2
Measurement findings for each station.

Station	THD Violation (number of weeks)	Individual Harmonic Violation (number of weeks)	Higher levels during working days than weekends	Individual harmonics in violation
A	Yes (67)	Yes (67)	Yes	5th
B	Yes (22)	Yes (10, 36, 40)	No	5th, 6th, 7th
C	No	Yes (2, 48)	Yes	33rd, 39th
D	Yes (9)	Yes (46)	No	7th
E	No	Yes (5, 1)	Yes	6th, 7th
F	No	No	Yes	–
G	Yes (5)	Yes (61)	Yes	7th
H	No	No	No	–
I	No	No	Yes	–
K	No	No	No	–
L	Yes (11)	Yes (37, 49)	No	5th, 6th
M	Yes (5)	Yes (40)	Yes	5th
N	No	Yes (12, 32, 69, 20)	Yes	3rd, 21st, 27th, 33rd

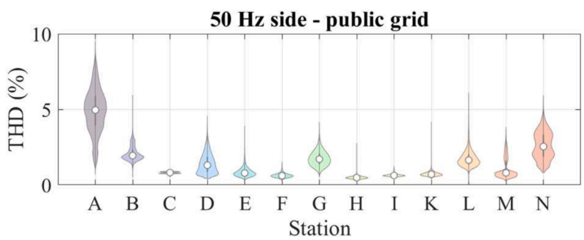

Fig. 8. THD violin plots for each traction converter station at the public grid side.

- Some distinguishing violations of high-order harmonics are observed in stations deploying only MMC (Station C) or direct frequency converter (Station N).
- The intraweek patterns show that some station measurements don't show significant differences between working days and weekends, and those with higher values for working days present higher values between working hours.

5. Harmonic levels on railway track side

5.1. Station A

From station A, the results show that individual harmonics have a factor higher than two between the 95th percentile daily values and the minimum values. A descendent pattern from the low-order odd harmonics is visualized, with 3rd harmonic presenting the highest value. The switching frequency signature is present between 60 and 90 orders, varying around 0.1 % to 1 % depending on the frequency. The 95th percentile daily value for THD varies around 4 %, with sporadic increases up to 10 % in some cases. The time-varying behavior corresponds to higher values during the working days and reduction on the weekends due to the traffic characteristic of the station. The daily range between the minimum and 95th percentile also gives good information on how the impact of the train operation affects the total distortion. From the intraday patterns, it is expected that there will be higher distortion during the night and possible increased distortions between 9:00 and 15:00. It is expected that some stations will have higher distortions during the night due to the starting traffic for freight trains that will run higher distances and delivery good along the day. The statistical values of daily variations show that the harmonic distortion can reach 12 %. Fig. 9 illustrates the 16 $^2/_3$ Hz side assessment results for Station A.

5.2. Station B

For station B, the 19th and 17th order components deviate from the descending pattern, besides presenting small value compared to the low-order harmonics. The THD varies around 9 % to 14 % during the whole period for the daily 95th percentile, with values varying according to the traffic pattern of the week, as can be seen in one-week interval example. The daily minimum values of THD for this station are between 4 % and 8 %. The intraday patterns also show an increase in the total distortion during the nights, between 19:00 and 5:00, but the decrease around the rest of the day is smoother. Fig. 10 illustrates the results the 16 $^2/_3$ Hz side assessment results for Station B.

5.3. Station C

Looking at an MMC converter station, the distorted voltage levels do not differ much from the DC-link stations if one observes the daily 95th percentile and mean values. There are significantly higher values for the even harmonics looking to maximum values. Those values reflect the short period of higher THD and the daily patterns above 3 %. To date, it is not known why those values occur. Some higher values of harmonics were observed after 45 this. The THD's time-varying irregular behavior is observed during the workdays but is still higher when compared with the weekends. The daily values show the THD ranging from 0.5 % to 3 %, but it is possible to see that it can reach a value above 5 % by looking at the intraday variations. The intraday variation also shows a slightly higher distortion between 0:00 and 5:00. A descendent pattern deviation can also be seen for the 17th and 19th orders. Fig. 11 illustrates the 16 $^2/_3$ Hz side assessment results for Station C.

5.4. Station D

At station D, the THD has higher values during working days compared to the weekends. The THD varies between around 8 % to 14 % for the whole period. The 3rd harmonic is ranging up to 12 %. There is little dependency on time allocation looking at the intraday patterns; the distortion presents high levels all day. It also shows that distortions above 15 % occur. Fig. 12 illustrates the 16 $^2/_3$ Hz side assessment results for Station D.

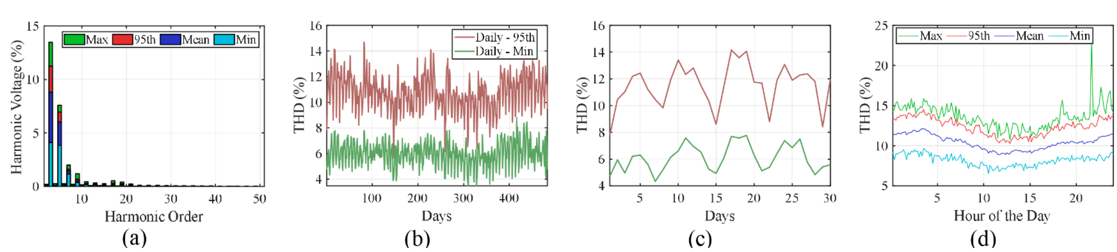

Fig. 9. Results of 16 $^2/_3$ Hz side assessment for Station A: harmonic voltage statistical daily 95th percentile variation (a), daily variation of THD (b), one week sample for daily variation of THD (c), and THD intraday weekly variation statistics (d).

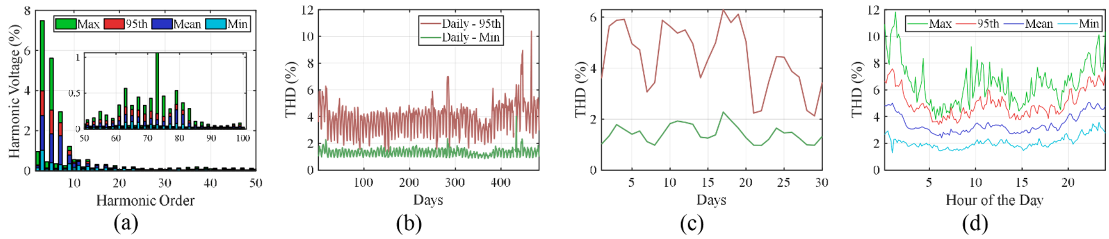

Fig. 10. Results of $16\,^{2}/_{3}$ Hz side assessment for Station B: harmonic voltage statistical daily 95th percentile variation (a), daily variation of THD (b), one week sample for daily variation of THD (c), and THD intraday weekly variation statistics (d).

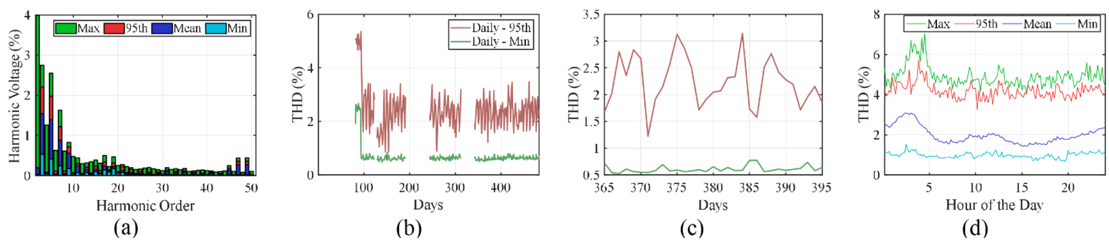

Fig. 11. Results of $16\,^{2}/_{3}$ Hz side assessment for Station C: harmonic voltage statistical daily 95th percentile variation (a), daily variation of THD (b), one week sample for daily variation of THD (c), and THD intraday weekly variation statistics (d).

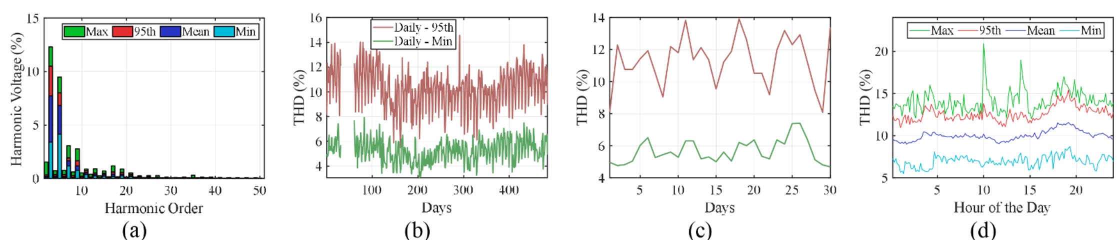

Fig. 12. Results of $16\,^{2}/_{3}$ Hz side assessment for Station D: harmonic voltage statistical daily 95th percentile variation (a), daily variation of THD (b), one week sample for daily variation of THD (c), and THD intraday weekly variation statistics (d).

5.5. Station E

The THD variation does not present discrepancies between working days and weekends, which can indicate that the traffic and operation are the same for the whole week. The 5th harmonic shows higher statistic values than the third harmonic for this station. Considering the analyzed period, the THD varies around 4 % to 6 %, and the low-order even harmonics are more unusual for DC-link converter stations. Components at 19th and 17th harmonics are also observed with higher values than regular DC-link converters, with mean values of daily 95th percentile above 2 %. The intraday variation is slight except for the maximum value, which shows a high level of variation at irregular intervals. Fig. 13 illustrates the $16\,^{2}/_{3}$ Hz side assessment results for Station E.

5.6. Station F

At station F, there is a more regular pattern between weekdays and weekends for the THD variation, with expected 95th percentile values from 8 % to 12 % and a minimum from 4 % to 6 %. The same pattern of harmonic voltage distortion for a typical railway grid side is expected with the pattern deviation for the 17th and 19th harmonics. The intraday variation shows higher distortion during the nights, and a decrease between 5:00 and 15:00. Fig. 14 illustrates the $16\,^{2}/_{3}$ Hz side assessment results for Station F.

5.7. Station G

Station G shows higher values of the 5th harmonic. With not as high magnitude compared with the other stations, the THD ranges from around 3 % to 6 %. The switching frequency signatures appear between

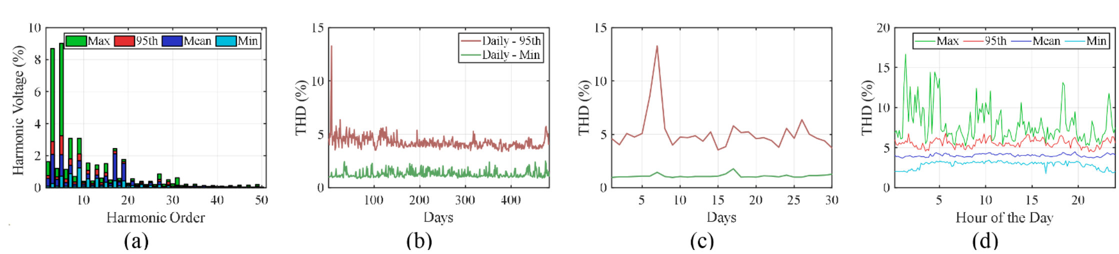

Fig. 13. Results of $16\,^{2}/_{3}$ Hz side assessment for Station E: harmonic voltage statistical daily 95th percentile variation (a), daily variation of THD (b), one week sample for daily variation of THD (c), and THD intraday weekly variation statistics (d).

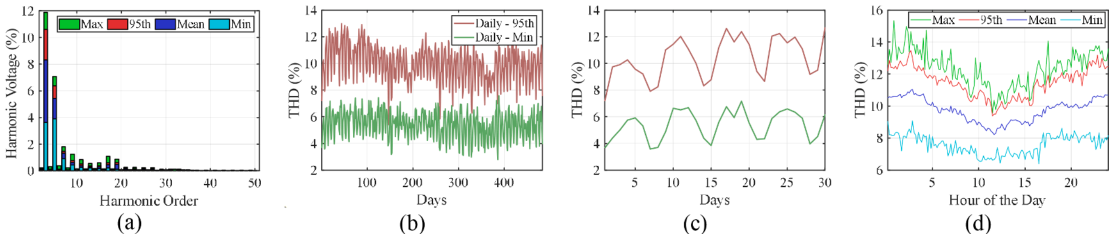

Fig. 14. Results of 16 $^{2}/_{3}$ Hz side assessment for Station F: harmonic voltage statistical daily 95th percentile variation (a), daily variation of THD (b), one week sample for daily variation of THD (c), and THD intraday weekly variation statistics (d).

harmonic 50 and 100 with amplitudes up to 0.4 %, looking at the daily 95th percentile values. The traffic variation corresponds with the working days or not but is irregular during the mid-week value. The intraday patterns show a higher total distortion between 20:00 and 5:00, with distortions ranging up to 10 %. Fig. 15 illustrates the 16 $^{2}/_{3}$ Hz side assessment results for Station G.

5.8. Station H

At Station H, the measurements show a descending pattern until the 11th harmonic and an increasing deviation from the 13th to the 19th. As observed in other rotary converter stations, the even harmonics have a higher magnitude than in DC-link converter stations. Switching frequency signatures are seen around order 1000 Hz and 1333 Hz, which can originate from the signatures of rolling stocks or other nearby stations. The 95th percentile THD ranges around 3 % to 6 % most of the time. The differences between this station's working days and weekends are not clearly observed. The intraday variation shows that the distortion usually varies around a certain level throughout the day. Fig. 16 illustrates the 16 $^{2}/_{3}$ Hz side assessment results for Station H.

5.9. Station I

There is a mix between the rotary and MMC converters in Station I, and they have effects and distortion, like Station C, up to the 50th harmonic converter. The harmonic voltage distortion is low compared to other stations, and the effect of the traffic on the THD is observable on weekends and working days. The daily 95th percentile THD varies from 2 % to around 3.5 %. From the intraday patterns, it can be highlighted that the constant variation in the same level apart from the maximum curve shows an increased distortion, with THD reaching levels above 8 %. From the variation of the daily value, it happens between day 100 and day 200. Lastly, some switching frequency signatures appear between order 80 and 90, with amplitude reaching 0.3 %. Fig. 17 illustrates the 16 $^{2}/_{3}$ Hz side assessment results for Station I.

5.10. Station K

Station K shows similar harmonic voltages as station H; both apply rotary converters for frequency conversion, and high-order signature harmonics also appear around 1000 Hz. THD also shares an irregular impact from traffic from the daily statistic values, with no remarkable difference between working days and weekends, ranging from around 1.5 % to 6 %. The intraday variation shows no significant dependency daytime for higher or lower levels of THD. Fig. 18 illustrates the 16 $^{2}/_{3}$ Hz side assessment results for Station K.

5.11. Station L

The typical observed DC-link converter station spectra are seen for station L, except for the 17th and 19th harmonics. Even harmonics are relatively low in magnitude, and the THD varies between 7 % and 16 % for the 95th percentile values. The traffic affects the THD but increases during the weekends and final days of the working days week. This pattern might be related to the low number of passenger trains. Individual harmonics, such as 3rd harmonics, can reach values higher than 14 % and 5th harmonics higher than 10 %. The intraday variation shows a pattern of flat variation around the same level. Fig. 19 illustrates the 16 $^{2}/_{3}$ Hz side assessment results for Station L.

5.12. Station M

Station M is applying direct converter technology (YOQC). The daily values of THD vary between 3 % and 15 %, with descending levels for the low-order odd harmonics. Individual harmonics as the 3rd can reach up to 15 %. There is a clear difference between the daily values for weekends and working days. The intraday variation shows that the THD can reach a level around 20 % and there is higher distortion between 20:00 and 05:00. Fig. 20 illustrates the results of the 16 $^{2}/_{3}$ Hz side assessment for Station M.

5.13. Station N

Station N applies YOQC mixed with a DC-link converter. The THD daily values range between 5 % and 13 %, and lower values are expected for the weekends. There is nothing remarkable about the spectra, as it seems typical to the railway side. The intraday variation shows that higher distortion is expected at night. Fig. 21 illustrates the 16 $^{2}/_{3}$ Hz side assessment results for Station N.

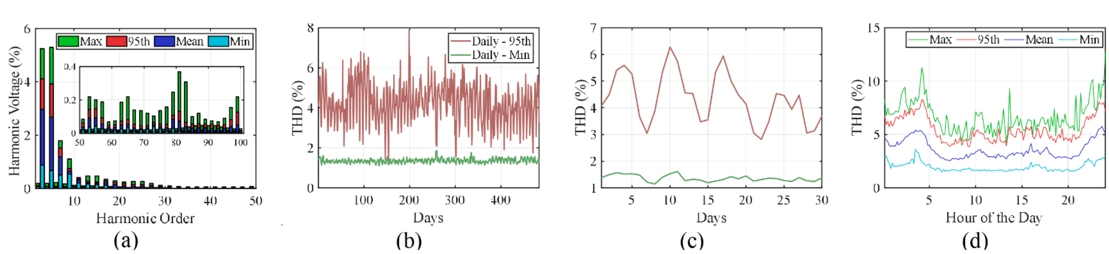

Fig. 15. Results of 16 $^{2}/_{3}$ Hz side assessment for Station G: harmonic voltage statistical daily 95th percentile variation (a), daily variation of THD (b), one week sample for daily variation of THD (c), and THD intraday weekly variation statistics (d).

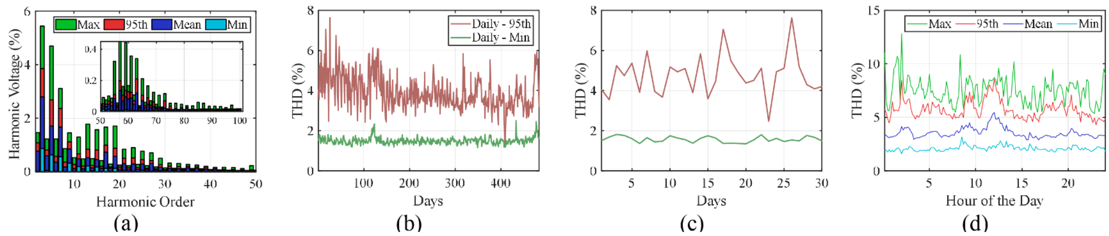

Fig. 16. Results of 16 $^{2}/_{3}$ Hz side assessment for Station H: harmonic voltage statistical daily 95th percentile variation (a), daily variation of THD (b), one week sample for daily variation of THD (c), and THD intraday weekly variation statistics (d).

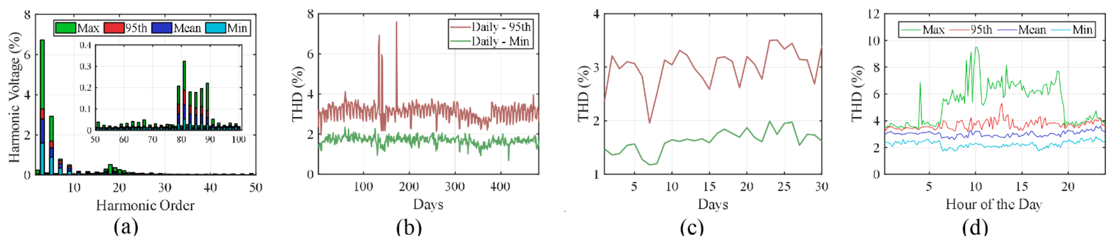

Fig. 17. Results of 16 $^{2}/_{3}$ Hz side assessment for Station I: harmonic voltage statistical daily 95th percentile variation (a), daily variation of THD (b), one week sample for daily variation of THD (c), and THD intraday weekly variation statistics (d).

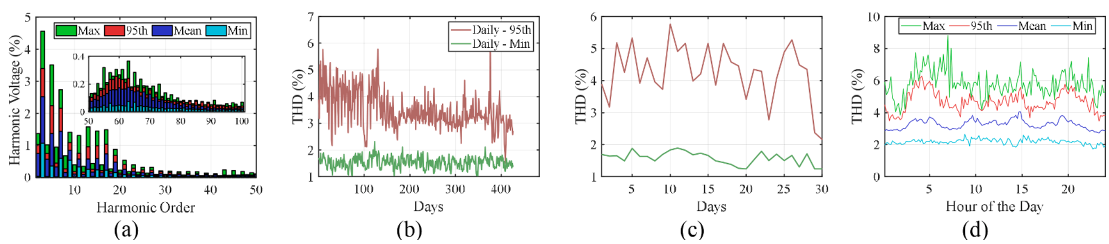

Fig. 18. Results of 16 $^{2}/_{3}$ Hz side assessment for Station K: harmonic voltage statistical daily 95th percentile variation (a), daily variation of THD (b), one week sample for daily variation of THD (c), and THD intraday weekly variation statistics (d).

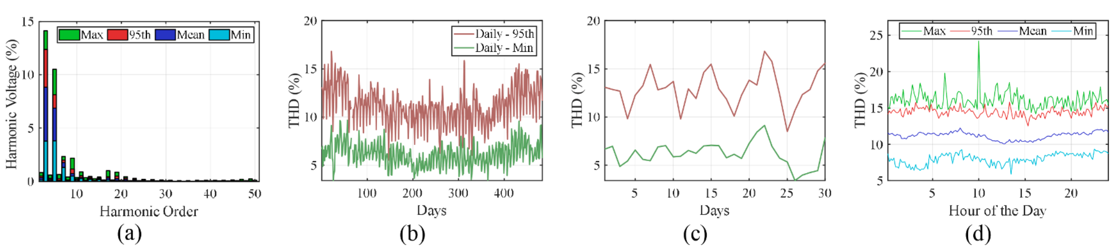

Fig. 19. Results of 16 $^{2}/_{3}$ Hz side assessment for Station L: harmonic voltage statistical daily 95th percentile variation (a), daily variation of THD (b), one week sample for daily variation of THD (c), and THD intraday weekly variation statistics (d).

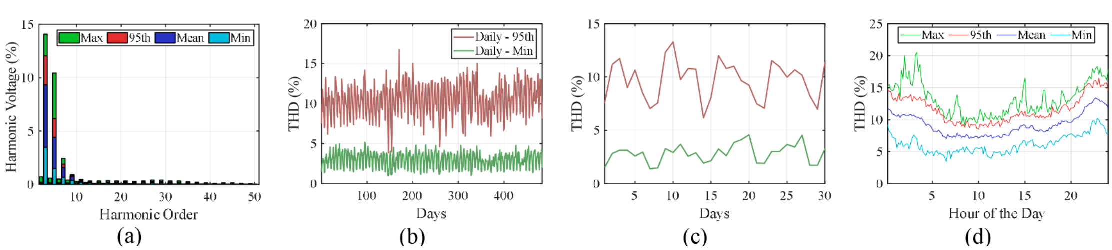

Fig. 20. Results of 16 $^{2}/_{3}$ Hz side assessment for Station M: harmonic voltage statistical daily 95th percentile variation (a), daily variation of THD (b), one week sample for daily variation of THD (c), and THD intraday weekly variation statistics (d).

5.14. Discussion

Some discussion points about the results are highlighted below for the railway grid side. Fig. 22 shows the violin plots for each station at the railway grid side, which contain the distribution of values of THD for the whole measurements. The violin plot helps to summarize the

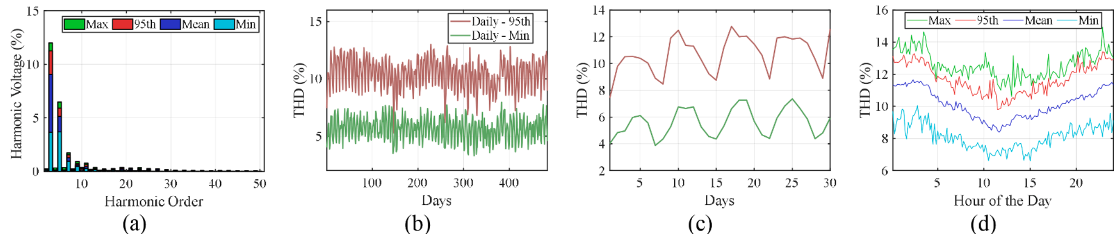

Fig. 21. Results of 16 $^2/_3$ Hz side assessment for Station N: harmonic voltage statistical daily 95th percentile variation (a), daily variation of THD (b), one week sample for daily variation of THD (c), and THD intraday weekly variation statistics (d).

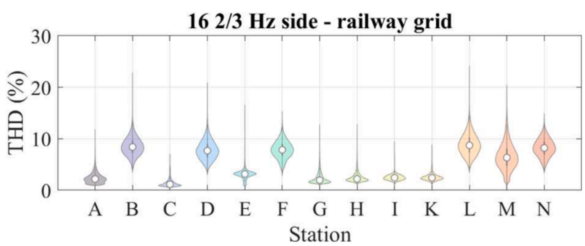

Fig. 22. THD violin plots for each traction converter station at the railway side.

comparison regarding the different locations.

- Five use DC link converters from the six stations (B, D, F, L, M, N) with higher THD values. Two have direct converter technology, but one is mixed with a DC-link converter. Excepting M, all are connected to the 132 kV feeding grid.
- Five stations (B, D, E, F, L) connected to the 132 kV feeding grid showed a deviation with the descending pattern for odd harmonics, with the presence of noticeably higher amplitude for the 19th and 17th. All converter stations are related to DC-link-based technology. Also, those converter stations typically have a high-pass filter installed in the railway grid side to minimize the effects of harmonics from the power electronics. The interaction of those filters with the grid impedances can explain a resonance around those frequencies. Those filters also explain a more dominant descending pattern with increasing frequency in the lower-order harmonics, which differs from rotary converter stations. Station C is the only one that also shows it but has other types of technology deployed and no connection with the 132 kV.
- A, B, C, D, F, G, I, M, and N show a pattern of higher total harmonic distortion during the workdays and lower on weekends. Station L shows the inverse pattern. The rest of the stations show no clear pattern.
- Even harmonics have higher amplitudes for stations K, H, and E. Station K and H are deploying rotary converters. However, from the analysis, it is possible to observe that station E is connected to those other two at a far end due to similar spectra patterns. Higher values of even harmonics are observed for station E as well.
- The THD levels are quite high compared to traditional power systems observing the railway grid side, such as public transmission and distribution grids. This can be related to the lack of standardization on managing voltage distortion in railway power systems. However, those values should be considered for future investigations of electromagnetic compatibility issues in those stations.
- The THD clearly reflects a dependency of traffic behavior on the railway system parameters, which can be confirmed with traffic planning and logging of the signaling system. This paper expresses this knowledge in engineering terms. Also, it is observable that some stations are expected to have higher distortion during nighttime (due to the freight trains operating from several stations starting in the middle of the night).
- The intraday and intraweek pattern depends on different parameters, looking at the 50 Hz side compared to the 16 $^2/_3$ Hz side. The distributions of the patterns are distinguished, and the time variation along the day does not follow the same trends and behavior. It indicates that the operation of the railway grid does not have a significant impact on the public grid. However, the background distortion from the 50 Hz transmission grid dominates at the PCC since the variation from the public grid depends on the types of loads and installation connected nearby.

5.15. Measurement time-aggregation

The instruments and assessments performed by the power system operators usually comply with IEC 61,000–4–30, which proposes time aggregation using 10-minute average values for power quality measurements [55,56]. Those values are enough for traditional power systems (distribution and transmission public grids) for routine power quality management with excessive data retention. Usually, the 10-min values are used for performance evaluation regarding limits and electromagnetic compatibility levels [57]. Although this choice should consider the source of disturbance and the effect to be evaluated, an aggregation interval that is too long can result in missing important information, and an interval that is too short can result in unnecessary data [58]. Systems and equipment exhibit significant production or consumption with dynamic variations for different scales of time, including sub-10-min values in modern power systems (e.g., renewable power plants, electric vehicle charging stations, etc.), has direct impact on power quality aspects, as expected for power supply of electrified railways systems and electrified roads [59,60]. For ERPS, it occurs due the dependence of waveform distortion with operating conditions and moving aspects of the load.

Fig. 23 shows the variation of harmonic voltage at a traction converter station (from a distinguished measurement campaign that verified analysis with higher time resolution) during 2 h on April 24, 2023, with the train starting to operate in the tracks supplied by the traction converter station from 14:45, for 6- *sec* values and 10-min values. It is noticeable that the averaging masks helpful information of the harmonic distortion variation that is correlated with the operating states of the locomotive in the line; there is a change in the variation behavior when the locomotive starts in the tracks. For example, one can see the distortion reaching values more than double the average value and dropping to values way below the average regarding 6- *sec* values for the harmonic orders shown. Additionally, it can be confirmed by the fact that the variance is increased with aggregated value when there is a rolling stock in operation, which means an increase on the distortion and uncertainty of the values. This variance increase is due to the operating transition between acceleration stages, braking, trajectory, driving style, and vehicle transported load, etc.

Since the railway systems lack standardization for waveform distortion performance quantification, those aspects should be considered when the mapping and assessment of harmonic voltage levels are performed using 10-min values. The 10-min values are still enough for assessing many effects of harmonic distortion, such as thermal effects,

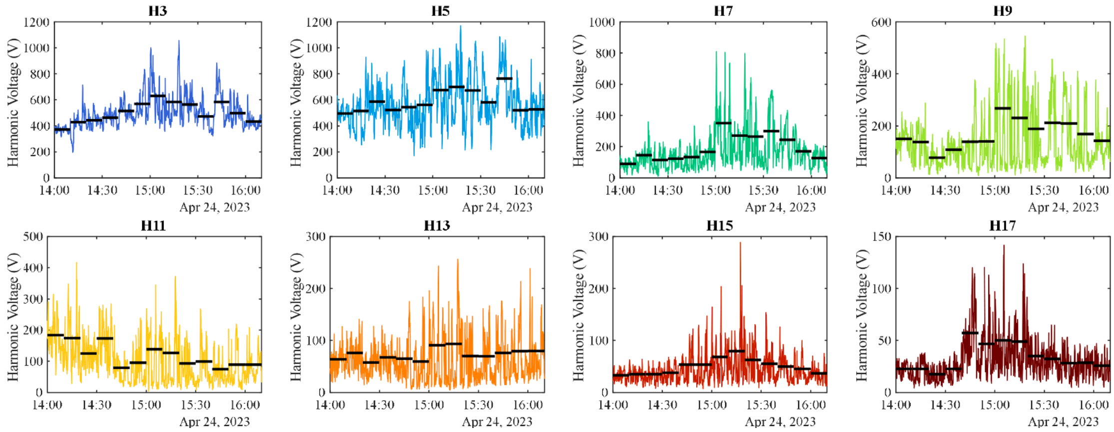

Fig. 23. Comparison of harmonic voltage (3rd to 17th odd harmonics) variation between 10-min average values (black lines) and 6-second values during a train passage for the railway grid side (16 $^2/_3$ Hz).

and have helpful information about the variations along the days and weeks that correspond to the global operation of the traction power supply. However, information on how individual locomotives impact the distortion levels at the railway grid side, effects on protection, signaling, communication, energy metering, or other fast interactions are out of scope. Those types of analysis require shorter aggregation intervals and, many times, are concerned with current variation, as in some standards on electromagnetic compatibility of track circuits for signaling [5,6]. Shorter time aggregation also means higher data storage and other factors to consider regarding processing and hardware. However, the available monitoring system has the capacity to increase the time resolution. An alternative is to use multiple time resolutions, as it is already done for PQ event detection, so the lower time-aggregation resolution is the primary option for storing the device. In comparison, the higher time-aggregation resolution serves as real-time monitoring that operates with the philosophy of a flagging system to capture variation beyond performance indexes to be developed or detect anomalies.

5.16. Trend analysis

Trend analysis in time-series studies aims to identify patterns in long-term data. Often utilized in econometric subjects, it can also provide a decomposition of the variation behavior in measurements of harmonic distortion data. Those components can be divided into three categories: trends, seasonal and cyclic variations, and residual components [34,50,61]. As explained in the pointed references, the first corresponds to the average tendency of the data to move upwards or downwards within a given long-term period (slow variations), the second is variations characterized by periodic changes or short-term fluctuations, and the third one is the residual component of the time series that corresponds to an irregular or random behavior of the variable along the time.

Looking at those time-series components separately can be a valuable tool for capturing the behavior of long-term measurements and making correlations between time-series variations (different station measurements). STL decomposition [50] is applied to the daily 95th percentile THD for the railway traction converter stations in the same path of specific traffic demand. That means one can evaluate the effect of traffic planning throughout the year in correlation with the slow variation of the THD. Fig. 24 shows the normalized long-term trend components for traction converter stations in the same path. The values are normalized to highlight the variation level over time comparably. The slow variation of THD for stations E, H, and K, in Fig. 24 (top), shows a

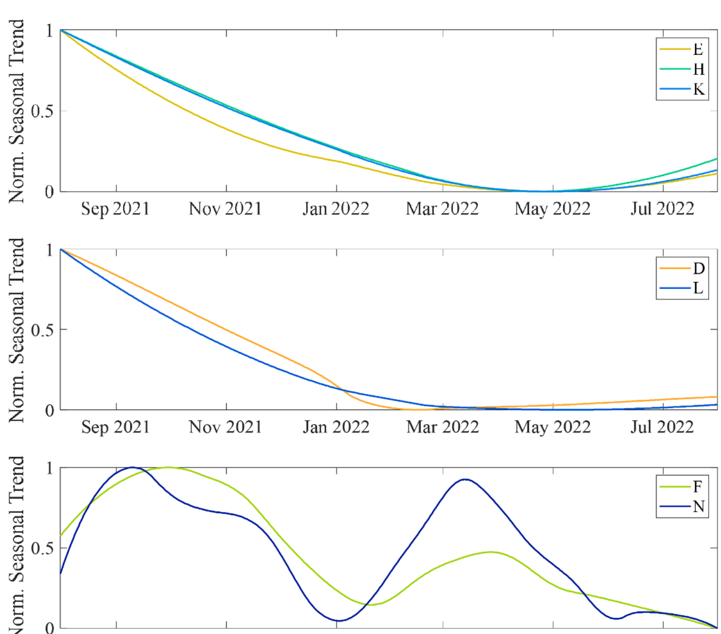

Fig. 24. Normalized long-term trend components for traction converter stations that are in the same path: E, H and K (top); D and L (middle); F and N (bottom).

reduction of the levels from September 2021 until the lowest average level in May 2022. That behavior is apparent for all three stations, indicating that the flux of trains in that path depends on the planning and types of trains in operation. This fact is also observed for stations D and L, as shown in Fig. 24 (middle). Although F and N have similar peak variations between September 2021 and November 2021 and around March 2022 and May 2022, those peaks happened without the same similarity as the other examples. The levels at those peaks change with different intensities, which can be explained because station N also has other significant traffic flow paths from nearby stations. Converter stations in dense traffic areas and connected with multiple other stations (>3) showed non-suitability with this analysis.

Besides the long-term trend, the random and seasonal components will describe other aspects of the operation's impact on the harmonic voltage distortion levels of the traction power supply. Looking at the seasonal effects, the STL analysis was set to observe periodic fluctuation in the weekly period along the whole measurement period. The aim is to visualize the correlation of fluctuation intensity along the week, corresponding to higher distortion among the stations during the workday compared to weekends. Fig. 25 shows these correlations between the stations in the format of a heat map of Pearson correlation coefficient, where from 0.8 to 1.0 indicates a positive, strong correlation, from 0.6 to 0.8 indicates a noticeable positive correlation, from −0.8 to −1.0 indicates a negative strong correlation, from −0.6 to −0.8 indicates a noticeable negative correlation, and between −0.6 and 0.6 indicates no correlation. The result confirms the one aspect discussed in SubSection 5.16 that the stations A, B, C, D, F, G, I, M, and N present the pattern variation of higher distortion levels during the workdays and reduction on the weekends, those present positive correlation on the seasonal components with each other. It does not occur for the stations with no sharing correlation of seasonal components, where this pattern wasn't observed.

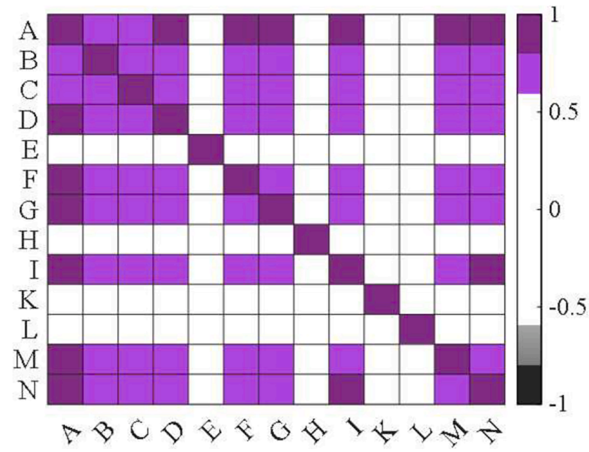

Fig. 25. Correlation between weekly seasonal components of the traction converter stations.

6. Conclusions

The work proposed the assessment of long-term measurements in traction converter stations in Sweden considering the railway grid side and the public grid side. Combining traditional methods and visualization proposal suitable with railway application, extensive analysis was conducted, and the results provide significant information regarding the interactions and patterns of harmonic voltage levels in the railway system. Discussion and findings regarding railway operation, technology deployed at the traction converter station, time-varying behavior, traffic planning impact, measurement time-aggregation, and spectra patterns were presented. The work successfully allowed the mapping of the harmonic voltage levels in the Swedish system for part of the stations, and the methodology can be reproduced for other stations or systems.

For the 50 Hz side, the results illustrated that stations deploying rotary converters or MMC have expressive lower distortion when compared with other types of converters. However, some characteristics of high-order harmonics signature are expected from MMC at the point of connection. Regarding the violation of IEC 61,000–4–6, stations deploying DC-link converters have had THD violations for a significant number of weeks, caused mainly by the individual harmonic violations of low-order harmonics present in the background distortion, 5th and 7th harmonics. Some high-order harmonics from MMC and cycloconverter stations also present violations; those are triplen harmonics that present lower limits bounds by recommendation. Lastly, the measurements that show differences between patterns throughout the week show an increase, mainly in working hours.

For the 16 $^{2}/_{3}$ Hz side, there were quantified high levels of harmonic distortion on the statistical values, and comprehensive evaluation showed the stations with high distortion. A dependency on traffic is highlighted by time-varying behavior, and trend analysis over long-term and seasonal trends confirms this. Like traditional power systems, such as distribution systems with a final-consumer dependency, the impact of traffic shows a higher distortion during working days than on weekends. However, it is clearly observed that the not always distortion is higher during working hours, showing that the freight trains significantly impact traveling at night. Also, the pattern distribution has different time dependencies between two sides of the same station, indicating a dominant impact of the background distortion at the PCC for the 50 Hz side.

This information gathered in the findings and results can support future planning that incorporates harmonics distortion consideration in the design and maintenance of the ERPS. The screening data and framework presented can also support future recommendations on harmonic levels performance limits and system compatibility. Also, the paper provides valuable information to understand the potential of analysis of the aggregated interaction within ERPS for incorporating those aspects in further developments that aim to evaluate the system at the same timescale with available measurements. Future work recommendations are: apply the methodology for more extended measurements, primarily to expand the time series-trend analysis; combine the information from the results and discussion with data from the operation as the number of trains per hour/day/month; combine the results and discussion with data from alarms and problems in the grid that can be caused by harmonic distortion, e.g., track circuits failure, protection miss-activation, overvoltage, communication interference, etc.; apply machine learning algorithms for pattern identification or forecasting.

CRediT authorship contribution statement

Rafael S. Salles: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rebecca Asplund:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Sarah K. Rönnberg:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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