Püvi, Verner; Tukia, Toni; Lehtonen, Matti; Kütt, Lauri

Survey of a power quality measurement campaign in low-voltage grids

Published in:
Electric Power Quality and Supply Reliability Conference and Symposium on Electrical Engineering and Mechatronics, PQ and SEEM 2019

DOI:
10.1109/PQ.2019.8818232

Published: 01/06/2019

Document Version
Peer reviewed version

Please cite the original version:
Püvi, V., Tukia, T., Lehtonen, M., & Kütt, L. (2019). Survey of a power quality measurement campaign in low-voltage grids. In *Electric Power Quality and Supply Reliability Conference and Symposium on Electrical Engineering and Mechatronics, PQ and SEEM 2019* [8818232] IEEE. https://doi.org/10.1109/PQ.2019.8818232

Survey of a Power Quality Measurement Campaign in Low-Voltage Grids

Verner Püvi
Department of Electrical Engineering and Automation
Aalto University
Espoo, Finland
verner.puvi@aalto.fi

Toni Tukia
Department of Electrical Engineering and Automation
Aalto University
Espoo, Finland
toni.tukia@aalto.fi

Matti Lehtonen
Department of Electrical Engineering and Automation
Aalto University
Espoo, Finland
matti.lehtonen@aalto.fi

Lauri Kütt
Department of Electrical Power Engineering and Mechatronics
Tallinn University of Technology
Tallinn, Estonia
lauri.kutt@taltech.ee

***Abstract*— With an increasing share of renewable energy generation becoming connected to distribution grids, power quality has attracted the attention of grid operators and academia. However, to obtain a realistic picture, power quality distortions caused by renewables should be superimposed on already existing emissions in grids. Measured household load data is tedious to acquire and is not publicly available. This paper presents the data from a low-voltage feeder measurement campaign and it is divided into voltage and feeder current analyses. The voltage parameters are validated as per EN 50160. The measured data includes measurements from feeders supplying single-family homes as well as one apartment building. A total of 24 weeks of 10-second mean values were recorded in the Helsinki region of Finland. Results indicate that the voltage quality is within the acceptable limits. The feeder currents show load unbalance in single-family homes and high utilisation rate of feeders supplying multiple customers.**

Keywords—load modeling, power measurement, power quality, signal resolution

I. INTRODUCTION

Power quality has gained much attention in recent years due to the widespread utilization of electronics and other non-symmetrical loads. Consequently, the number of publications on this topic have significantly increased in the last decade, due to issues such as overvoltage and voltage unbalance (Fig. 1). Research based on measured data can provide promising solutions for most issues and could offer a firm basis for further studies on supply voltage quality and load characteristics.

The measurement data can reach an extensive size. To manage such big data, some generally accepted practices have evolved over time. For example, guidelines have been proposed for reporting power quality surveys as well as summarizing and visualizing data structure [1]. More recently, a power quality index was introduced for quantifying power quality parameters in grids [2]. With advances in measurement technology, power quality measurements have become readily accessible. For example, measurements from hundreds of sites were obtained in a survey conducted in the 1990s in the USA and Canada [3]. However, this work mostly focused on the voltage data and analysed the compliance to the power quality requirements.

In the last decade, several research groups from around the world have collected measurement data for power quality assessment. Different load types were measured for more than a year in Germany [4]. Data were aggregated on 10-minute scale, and power quality was analysed according to EN 50160. Challenges affecting power quality in the distribution grids of various countries were surveyed by the international council of large electric systems (CIGRE) [5]. However, the survey mostly consisted of qualitative data. To meet the requirements set in the standard, power quality has been validated for residential and public grids in Poland [6] and for an educational building in India [7]. Power quality parameter deviation caused by industrial customers in Estonia were studied in [8].

In addition to analysing power quality, voltage and current measurement data have been used for research in a wide range of other areas. Energy consumption characteristics were modelled based on apartment consumption data from Hong Kong [9]. In [10], measurement profiles from 200 detached houses were analysed in Sweden. Over 100 low-voltage grids were measured in Germany to provide data for harmonic studies [11]. The prevailing negative sequence voltage and imbalanced current emissions in low-voltage grids were analysed in [12] for comparison of 1- and 10-minute aggregated data. In [13], a statistical model of household load was developed based on 1-minute resolution measurements in the United Kingdom, and the effect of the time resolution was analysed. However, this study disregarded a resolution time of 10 seconds and 1 hour.

This paper presents a survey of low-voltage measurements and compares the results at different time resolutions. Presented data can be utilised for modelling power quality indices and feeder loads at low-voltage substations. Grid hosting capacity studies require that load characteristics be superimposed on the disturbances caused by the distributed renewable generation. The available headroom for the renewable generation would then be revealed.

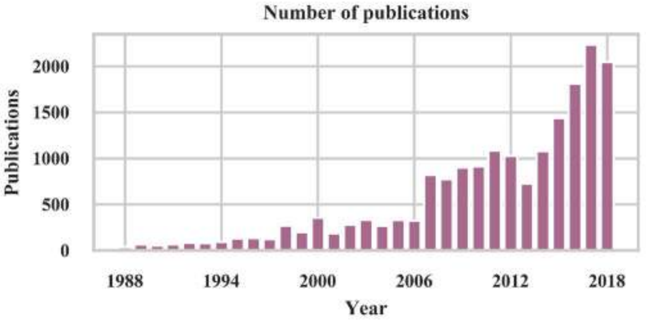

Figure 1: Number of publications on "power quality" in Scopus database under "energy" and "engineering" sections

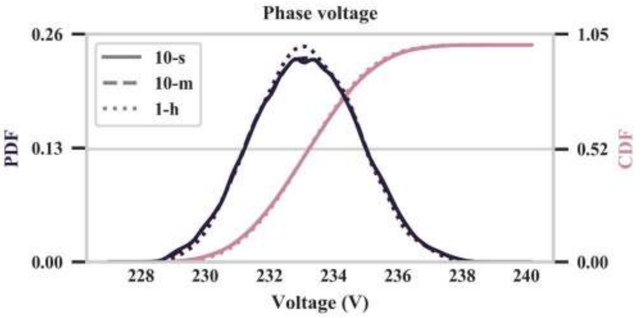

Figure 2: Aggregated probability of phase voltages and cumulative distribution functions at measured substations in three different averaging intervals

II. THE MEASUREMENT CAMPAIGN

The measurement campaign was carried out in the Helsinki region of Finland during the autumn of 2018. Three power quality loggers were utilized to record the voltages and currents at outgoing feeders of three sites (low-voltage substations A, B and C). Loggers were measuring for eight weeks, which sums approximately 24 weeks of measured data, with some interruptions due to measurement probe recombination. Data comprises measurements from three single-family homes, six feeders supplying 5–10 households and one feeder supplying an apartment building with 18 dwellings. Single-family home measurements were included due to the worst case load imbalance and the ease to be relatable with rural regions, which have more significant power quality concerns. Chosen households were located in residential districts and had no local generation nor electric vehicles. The 10-second time resolution has proven to provide the wide range of smaller measurement resolutions and to be slow enough utilizing memory resource efficiently. The voltage probe error was 0.1 %, and the current probe error stayed below 2 % with the lowest measurable current of 2 A.

III. RESULTS FOR VOLTAGE

In this section, the voltage parameters are discussed and voltage parameter differences are demonstrated at 10-second, 10-minute and 1-hour time resolutions.

A. Voltage magnitude

The probability density and the cumulative distribution functions of the phase voltages for three time resolutions are shown in Fig. 2. The voltage levels are within acceptable limits as per [14]. However, most of the time, customers experience slight overvoltage. In addition, lower resolution yields lower of peak values and decreases variance of the measured voltage.

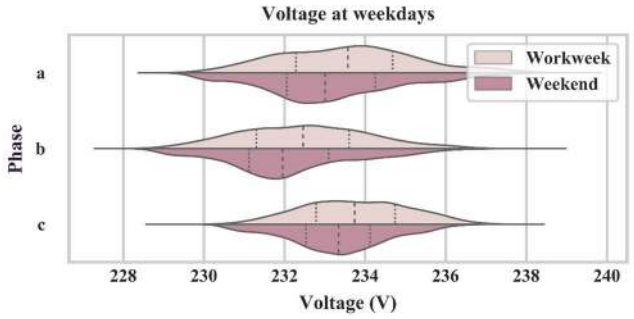

Figure 3: Probability distributions of voltages per day type for each phase

The voltage dependency of the day type is displayed in Fig. 3. All the phases experience slightly lower voltage during weekends. The phase voltage variations during the day are shown in Fig. 4. The voltage drop during the morning and evening peak hours can be distinguished at all sites. The correlation between the phase voltage levels is apparent and depends on the time of day. The voltage level variations between different sites also have similarities, especially within the same distribution company (sites A and B).

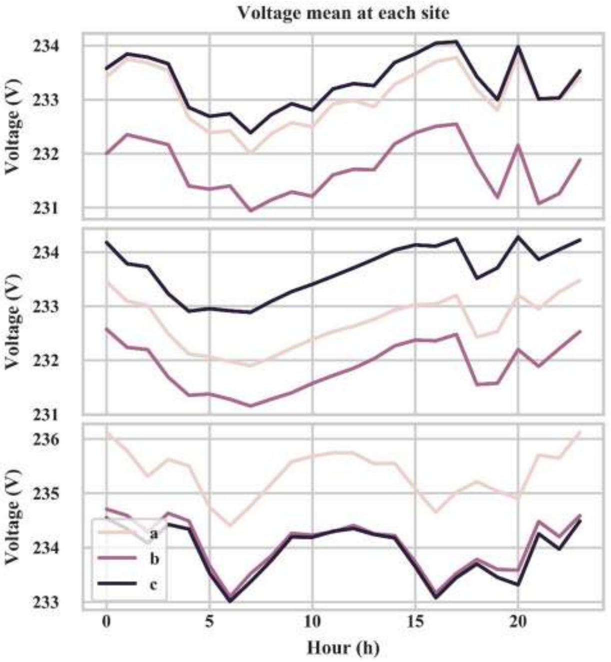

Figure 4: Phase voltages (a, b, c) during a day at each site (top to bottom: A, B, C)

B. Voltage unbalance

Voltage unbalance is defined as the ratio of negative sequence and positive sequence voltages and is limited to 2 % of 10-minute mean value over one week time period [14]. The voltage unbalance levels at the measured sites are presented in Fig. 5. The measured voltage unbalance is significantly below the 2 % limit. However, the employed time resolution has a remarkable impact on the values. Even though the voltage unbalance is standardised as 10-minute mean values, the actual values have higher volatility and can reach higher numbers.

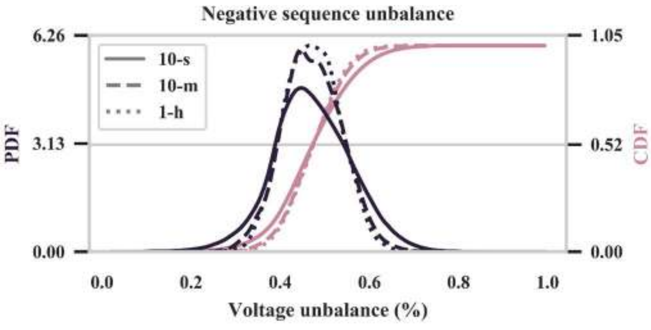

Figure 5: Probability and cumulative distribution functions of the negative sequence voltage unbalance

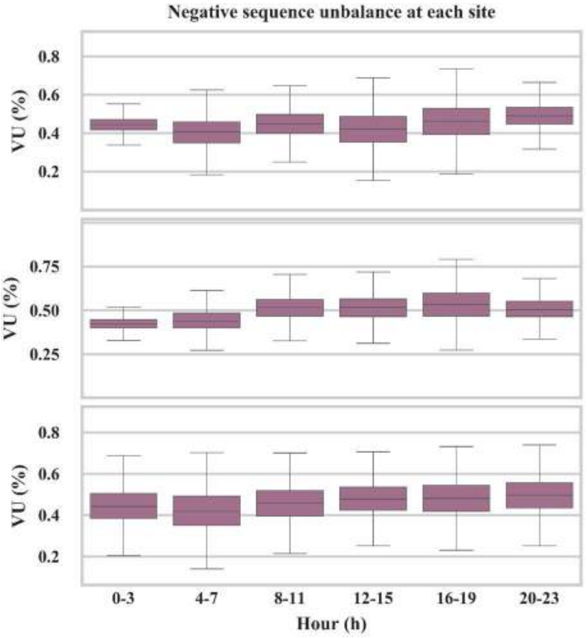

Figure 6: 10-sec voltage unbalance during the day at each site (top to bottom: A, B, C). Box plot horizontal lines indicate max, third quartile, median, first quartile and min values. Outliers (0.7% of data) are not shown.

The voltage unbalance dynamics over a day is demonstrated in Fig. 6. The figure reveals that the voltage unbalance varies marginally at each site and seems to increase in the daytime. However, the changes are insignificant and the median remains at the value shown in Fig. 5.

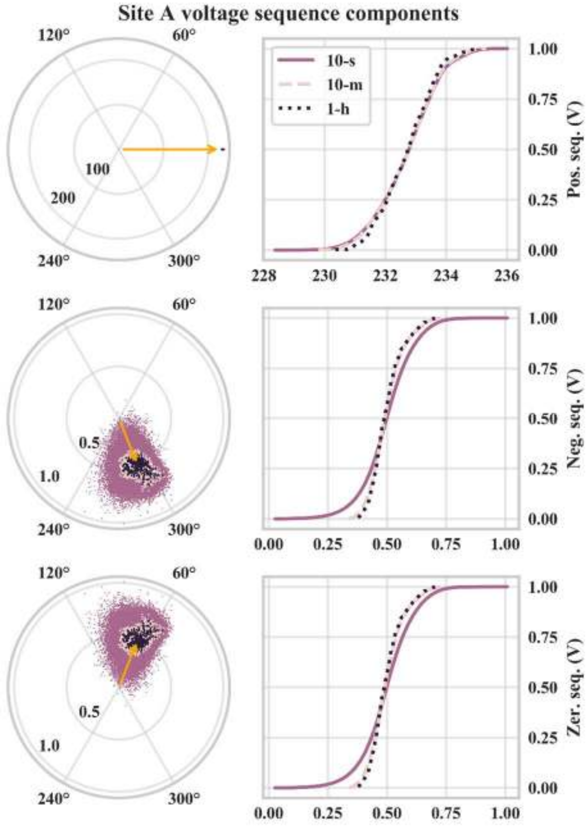

Figure 7: Angles and magnitudes of voltage sequence components at site A

C. *Sequence components*

Due to the three-phase configuration of the power system, it is naturally exposed to the asymmetric values between the phases. Three phases with unequal voltage magnitude, rotated 120° with respect to each other, oppose the voltage values of one another, causing the resultant sum vector to be off the zero-point. The unbalanced sum vector has non-zero magnitude and distinctive direction.

The angles and magnitudes of the positive, negative and zero sequence voltages at site A can be seen in Fig. 7. The arrow in the figure indicates the prevailing angle and magnitude of a sequence component. The change of the time resolution has an effect on the magnitude, shaving the peak values with longer averaging periods and decreasing variance, while the angle of a prevailing component remains the same.

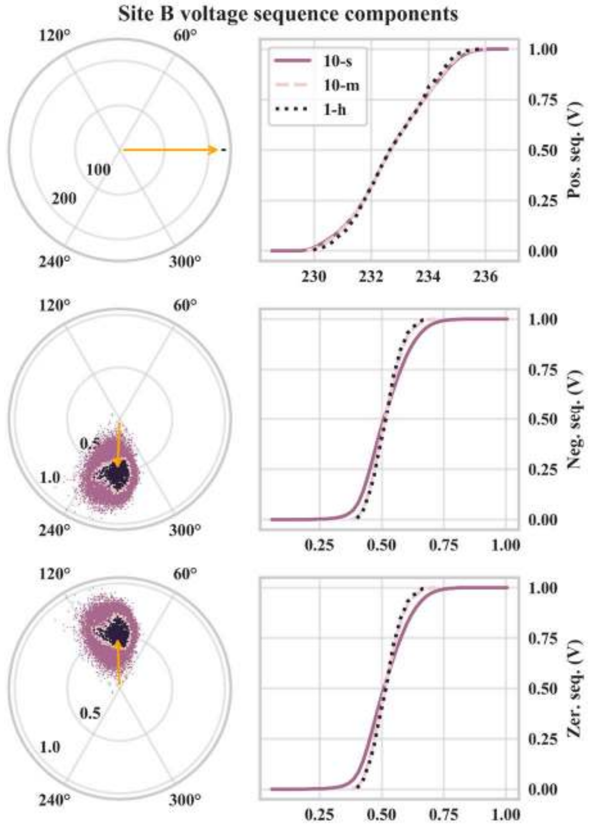

Figure 8: Angles and magnitudes of voltage sequence components at site B

Figure 8 depicts the sequence components of site B. The positive sequence component demonstrates great stiffness and fluctuations around the nominal voltage value are negligible. The magnitudes of negative and zero sequence components are comparable to site A. The prevailing angles are almost the same, which can be explained by the similar phase voltage levels: c > a > b (Fig. 4). The sequence components of site C can be seen in Fig. 9. The dominating phase a voltage in site C yields a different prevailing angle of the negative and zero sequence components while the positive sequence component remains the same as in the case of the other measurement sites. The angle of the highest variance is in the direction of the phase a.

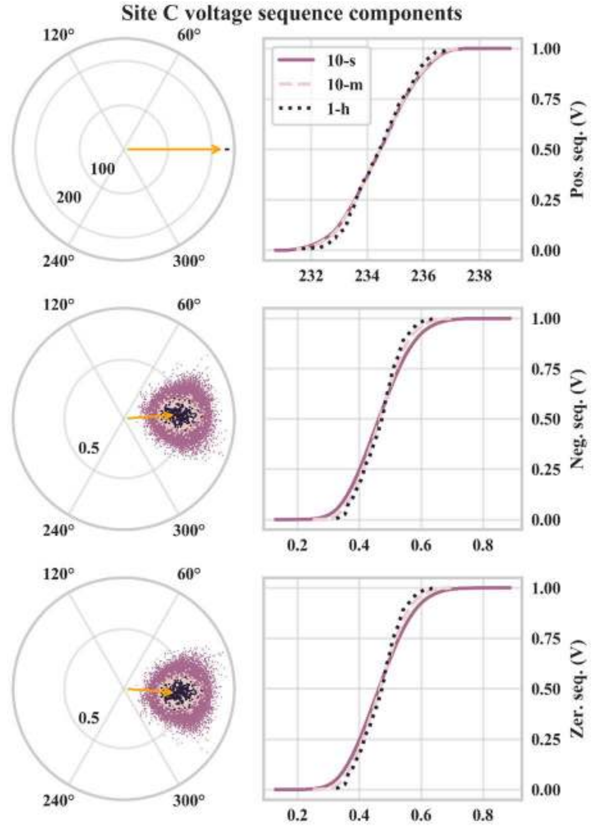

Figure 9: Angles and magnitudes of voltage sequence components at site C

D. Frequency

The nominal frequency of the supply voltage in Finland is 50 Hz and is defined over 10-second period mean value. The power system is in constant power balance by adjusting generation levels according to demand. However, due to the inertial properties of the greater part of generators, the power balance gets out of the equilibrium at sudden load changes. The measured frequency is displayed in Fig. 10. The power system maintains stable frequency at the nominal level.

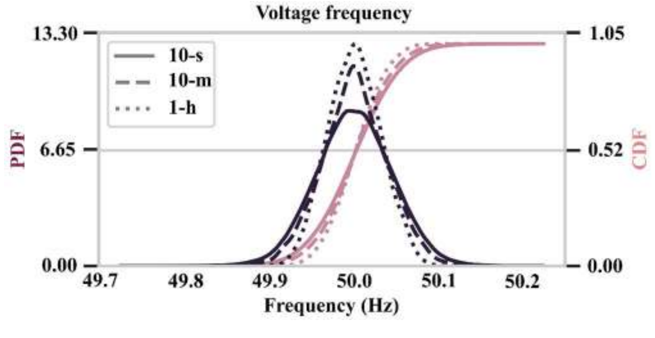

Figure 10: Frequency probability and cumulative distribution functions

Finland is a part of the Nordic System Operation Agreement that sets the obligation to maintain the nominal frequency. Fingrid, the transmission grid operator in Finland, has a set of procurement channels to balance the power level. The frequency containment reserve for normal operation balances frequency in range of 50 ± 0.1 Hz and reserve for disturbance in range of 49.50 – 49.90 Hz [15].

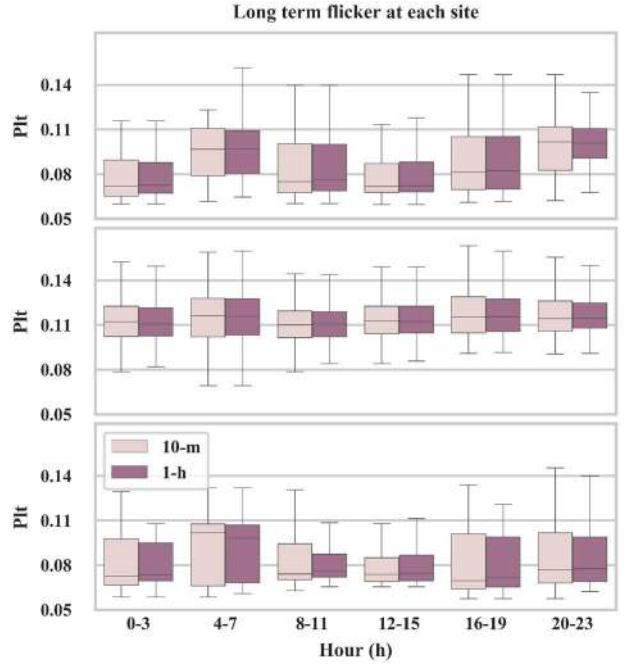

Figure 11: Long-term flicker over a day at each site (top to bottom: A, B, C)

E. Flicker

Flicker is a change in experienced luminance caused by the sudden change of voltage level. It is divided into two separate parameters: short-term and long-term flicker. The long-term flicker levels over the day are shown in Fig. 11. The flicker must remain below 1 in a correctly operated grid [14]. The long-term flicker remains well below the limit at all the sites. However, flicker rise can be noticed during the morning and evening peak hours. The change in time resolution cause no significant difference in the flicker level.

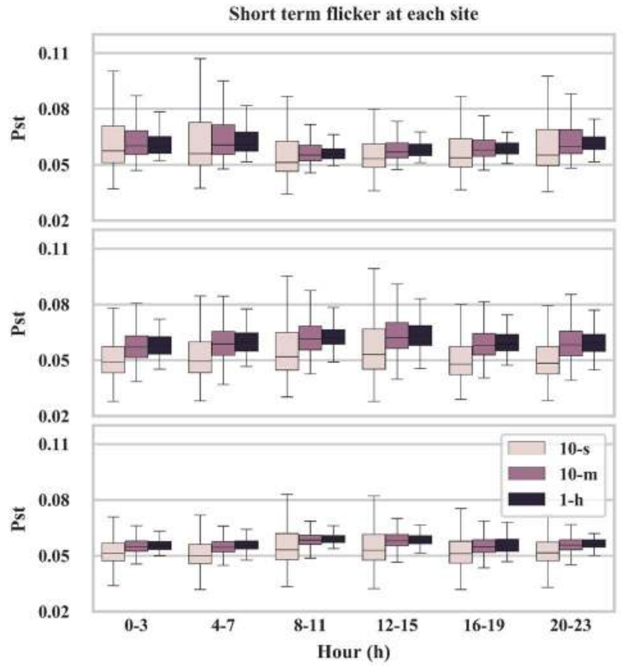

Figure 12: Short-term flicker over a day at each site (top to bottom: A, B, C)

The short-term flicker over a day is plotted in Fig. 12. The recommended planning level for short-term flicker should not exceed 1 [16]. The time resolution has considerable effect on the flicker values. The smaller resolution decreases variance and, in majority of cases, increases the median value.

F. *Harmonics*

The non-linear loads account for the majority of the loads in modern households. Due to the non-linearity, the power is chopped from the supplying grid in the pulse resembling waveforms. This leads to a crippled voltage sinusoid and operational issues in transformers, electric machines and converters. Nevertheless, the fundamental component and harmonics can be broken down by the Fourier transform: decomposition of a waveform into sinusoidal sub-frequencies. This would disclose the most contributing harmonics.

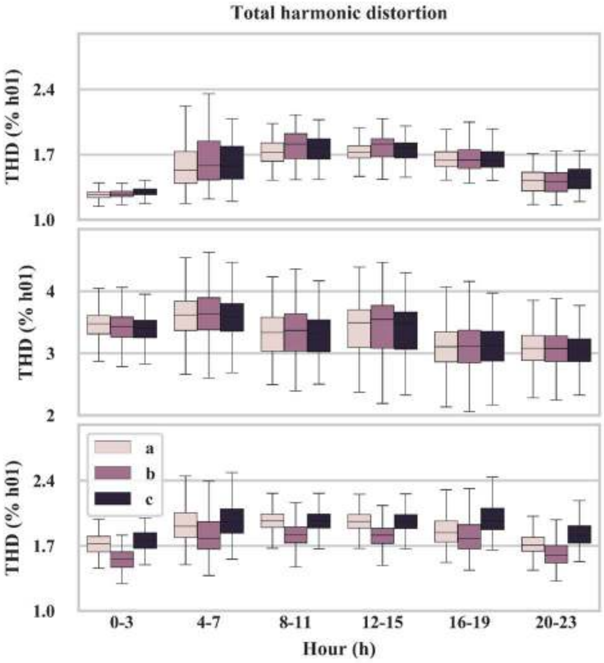

Figure 13: The boxplot of the voltage total harmonic distortion in each phase at each site (top to bottom: A, B, C)

The total harmonic distortion (THD) is the ratio of the sum of squares of the all harmonic components and the fundamental component. The THD limit is set in the standard [14] and should be less than or equal to 8% for voltages. The measured THD values are presented in Fig. 13. It can be seen that THD retain similar variations and levels amongst the phases. However, the change over time during the day can be clearly noticed. Generally, THD is higher during the daytime at all the measured sites. Unfortunately, the THD represents the cumulative weight of the harmonic emission in the grid. The detailed voltage level of each harmonic remains unknown.

The harmonic voltage breakdown is shown in Fig. 14, which displays averaged 10-minute RMS values of each harmonic component. The even harmonics have values close to zero. The lower odd harmonics demonstrate higher values, especially site B with the 5th harmonic reaching 3 %. All the harmonic levels remain below the limits set in [14].

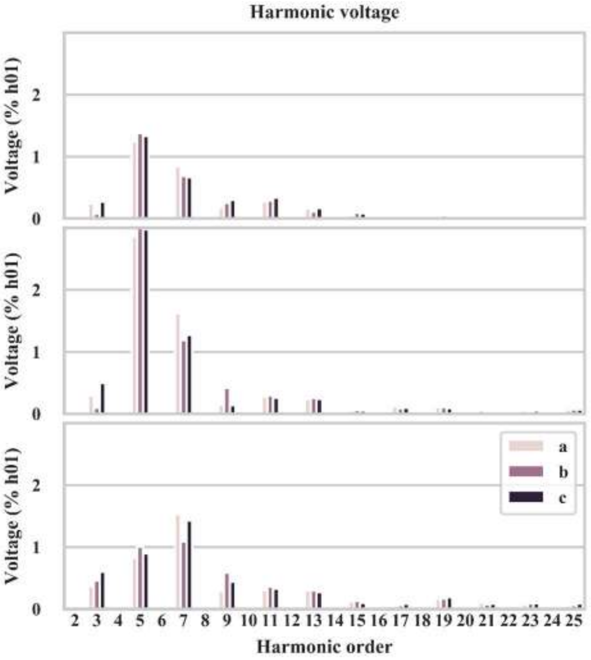

Figure 14: Harmonic voltages with respect to the fundamental component of each phase at each site (top to bottom: A, B, C)

IV. RESULTS FOR CURRENT

In this section, the load currents of each feeder are analysed. The difference between three feeders types – a single-family house, 5–10 houses and an apartment building – is presented. The time resolution impact of the indices is demonstrated and discussed in brief.

A. *Ratio of mean and maximum currents*

The ratio of mean and maximum current magnitudes highly resembles the load factor, used to evaluate the utilization rate of the electric systems from the perspective of power demand. In addition, the ratio resembles the variance of the current. The lower ratio hints to nearly no power being drawn from the grid on average, making an occasional load of a household appliance to seem as a significant spike in load profile. The mean and max values are taken over a two-week period with three different time resolutions: 10 seconds, 10 minutes and 1 hour.

The ratios are demonstrated in Fig. 15, where the values of the single households (hh) and the apartment building (ap) are compiled into the left column, top to bottom, and feeders with 5–10 are households are displayed on the right column. The left-most cluster incorporates measurements at the 10-second, middle cluster the 10-minute and right-most cluster the 1-hour time resolution.

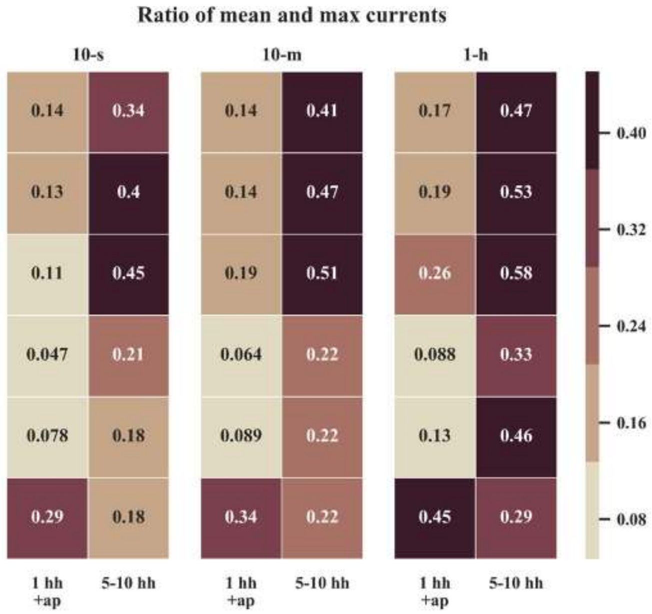

Figure 15: Ratio of mean and maximum current of each feeder at three time resolutions

At the 10-second time resolution, single-family house ratios are around 10%, while the feeders with several customers experience 20–40% of mean current with respect to the maximum. This indicates a more volatile load and lower feeder utilization rate of a single home. By shifting the time resolution, the ratios tend to rise. As visualized above, the use of low time resolution shaves the maximum peak value and concentrates data around the mean value.

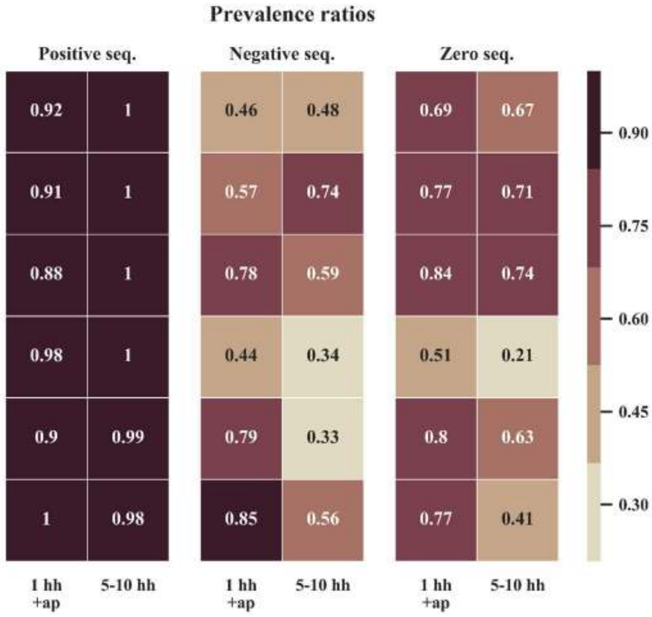

Figure 16: Prevailing ratios of positive, negative and zero sequence currents of each feeder at three time resolutions

B. *Prevalence ratios*

The prevalence ratio (PR) quantifies the similarity of summarized phasors over time. High prevalence ratio indicates the dominance of a phasor over the majority of a measurement campaign, while the low prevalence ratio hints to a chaotic phasor affinity with phases. The prevalence ratio is defined as per [12] and is calculated for positive, negative and zero sequence components of each feeder load. The ratios calculated at the 10-second resolution can be seen in Fig. 16.

The prevalence ratios of the positive sequence component mostly exceed 90 % and, as per [12], can be classified as high prevalence. The negative sequence prevalence ratio can be classified as no prevalence, except for the apartment building (bottom-left value), that has the highest ratio among the measured feeders. The zero sequence prevalence ratios tend to have slightly higher values at the feeders with single-family homes.

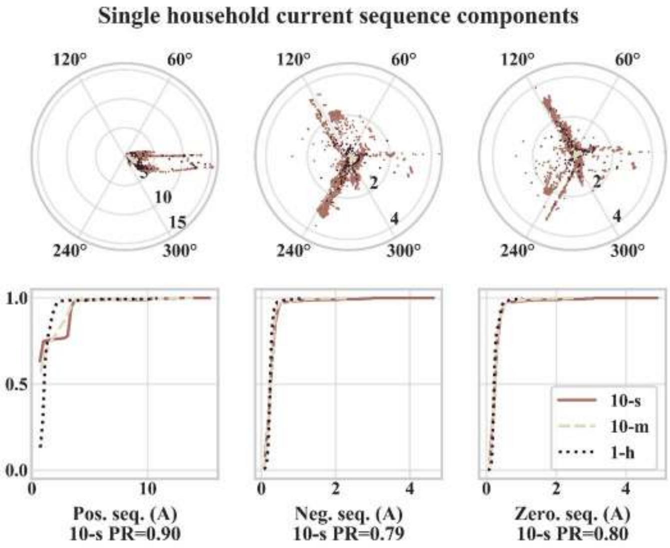

Figure 17: Angles and magnitudes of the positive, negative and zero sequence components of the single-family home feeder current

C. *Sequence components*

Electric current can be partitioned to the sequence components, similarly to the voltage. In this section, load currents of three feeders are depicted in sequence component angles and magnitudes. In addition, currents are presented in three time resolutions.

In Fig. 17, sequence components of a single-family home are displayed. The positive sequence component conveys high prevalence as its phasors are predominantly facing the same direction. The negative and zero sequence components, however, are split between three phases and facing all the three directions. The magnitudes of the two components are in the same range. The operation points of single-phase loads can be clearly noticed, which hints to an uneven distribution of loads between the phases.

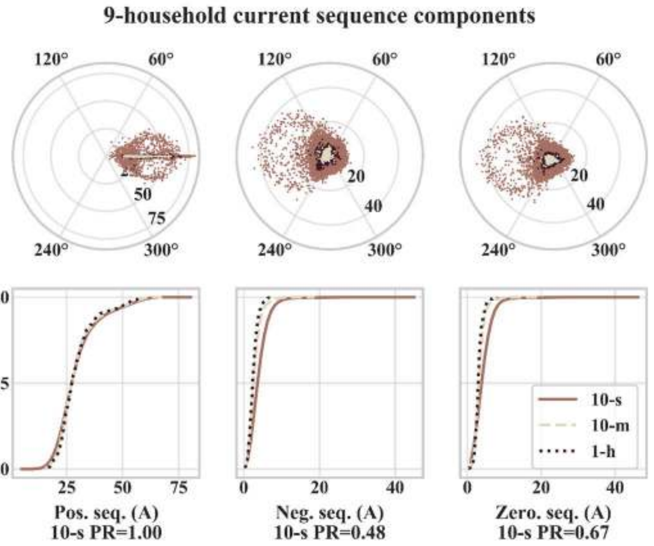

Figure 18: Angles and magnitudes of the positive, negative and zero sequence components of the 9-household feeder current

The sequence components of a feeder supplying 9 households are illustrated in Fig. 18. The positive sequence component has very high prevalence and magnitude. The negative and zero sequence components show noticeably higher consolidation, as the phasors form coherent clouds around zero points. That indicates a relatively even load distribution between the phases.

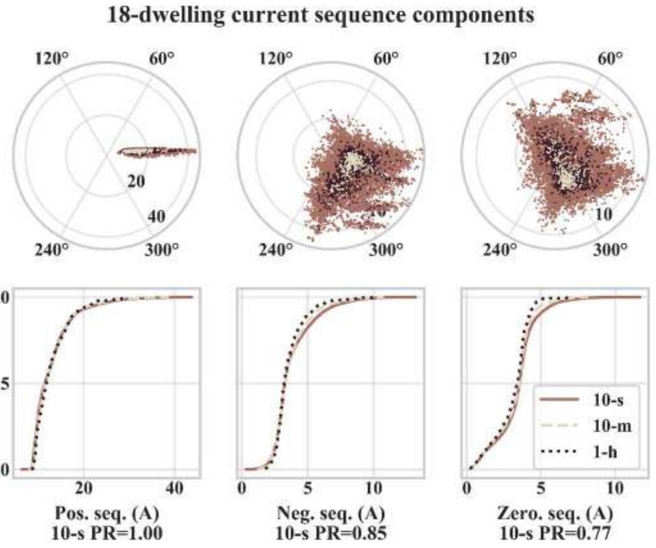

Figure 19: Angles and magnitudes of the positive, negative and zero sequence components of the 18-dwelling feeder current

The 18-dwelling apartment building sequence components are shown in Fig. 19. As expected, the positive sequence component has high prevalence. However, the negative and zero sequence components are dispersed over a wider area, meaning that the single-phase loads are decently distributed between the phases.

D. Power factor

Power factor is defined as a ratio of real and apparent power, and it represents the share of energy transferred in a feeder that actually does a useful work. Here, as the measured feeders only contained loads, the sign of the power factor shows the direction of the reactive power flow: leading power factor for load generating reactive power and lagging for reactive power consumption by a load. The power factor probability distribution at each unique feeder is visualized in Fig. 20.

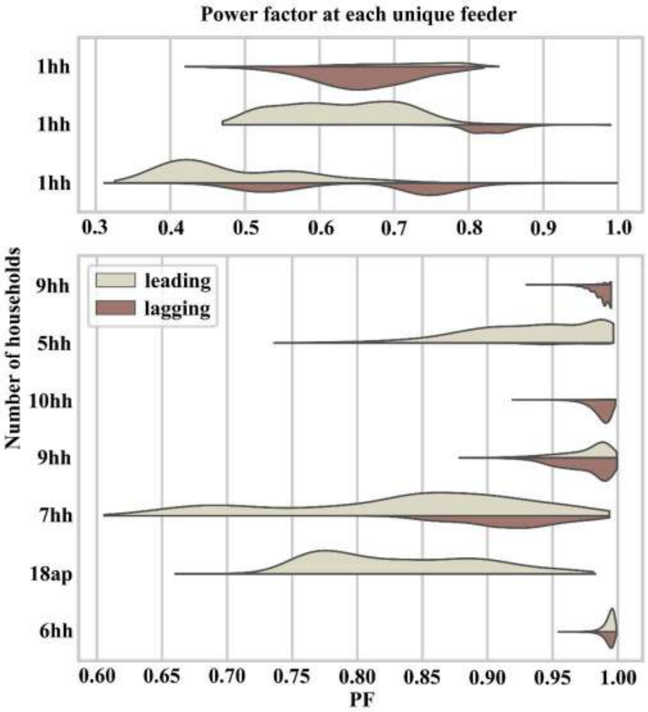

Figure 20: Probability distribution functions of the power factor at each unique feeder

The upper part of the plot depicts power factor of single-family homes while the bottom part depicts power factor of feeders supplying several households. The power factor heavily depends on the type of loads in the houses and predominantly either leading or lagging power factors were recorded. Nevertheless, the smaller number of customers tend to have lower power factor, which can be explained by low load currents. The feeders supplying multiple households experience high power factor.

V. CONCLUSIONS

This paper summarized the data survey of a power quality measurement campaign conducted in Finland. The present findings provide better understanding of the power quality situation and the load characteristics of a low-voltage substation, and quantifies the voltage and load current parameters. The data presented can be used for assessing background disturbances and employed in studies related to, e.g. the hosting capacity of the distributed renewable generation in low-voltage distribution grids.

The voltage parameters were validated with respect to the power quality indices and proved the faultless functioning of monitored distribution grids. The results of the measured currents revealed significant difference in load unbalance depending on the customer number connected to a feeder. Compared to the several households connected to a feeder, a single household cause higher current variance and unbalance, as well as lower power factor, while several households connected to one feeder indicate more predictable load current, even load distribution between the phases, and higher power factor.

ACKNOWLEDGMENTS

The authors of the paper would like to extend their gratitude towards Jussi Vuorinen and Juha Mikkola from Helen Sähköverkko Oy, Juha Lehtinen from Caruna Networks Oy, and Pasi Salonen and Esko Kuhmonen from Relacom Finland Oy.

REFERENCES

[1] V. J. Gosbell, A. Baitch, and M. H. J. Bollen, “The reporting of distribution power quality surveys,” in CIGRE/IEEE PES International Symposium Quality and Security of Electric Power Delivery Systems, 2003. CIGRE/PES 2003., 2003, pp. 48–53.

[2] K. S. E. Gasch, J. Meyer, P. Schegner, “Efficient Power Quality Analysis of Big Data (Case Study for a Distribution Network Operator),” in 23rd International Conference on Electricity Distribution (CIRED), 2015.

[3] D. S. Dorr, T. M. Gruzs, M. B. Hughes, R. E. Jurewicz, Gurcharn Dang, and J. L. McClaine, “Interpreting recent power quality surveys to define the electrical environment,” in IAS ’96. Conference Record of the 1996 IEEE Industry Applications Conference Thirty-First IAS Annual Meeting, 1997, vol. 4, pp. 2251–2258.

[4] E. Gasch, M. Domagk, J. Meyer, S. Abdelrahman, H. Liao, and J. V. Milanovic, “Assessment of Power quality performance in distribution networks part I - Measurement campaign and initial analysis,” in 2016 17th International Conference on Harmonics and Quality of Power (ICHQP), 2016, pp. 164–169.

[5] J. Meyer, A.-M. Blanco, S. Rönnberg, M. Bollen, and J. Smith, “CIGRE C4/C6.29: survey of utilities experiences on power quality issues related to solar power,” in CIRED - Open Access Proceedings Journal, 2017, vol. 2017, no. 1, pp. 539–543.

[6] W. Grycan and G. Wisniewski, “Power Quality in Residential and Public Grids,” in 2018 Progress in Applied Electrical Engineering (PAEE), 2018, pp. 1–6.

[7] P. V. Kumar Reddy, M. Rajesh, K. Palanisamy, S. Umashankar, S. Meikandasivam, and S. Paramasivam, “Power quality survey and analysis at educational institution loads,” in 2016 International Conference on Circuit, Power and Computing Technologies (ICCPCT), 2016, pp. 1–7.

[8] T. Vinnal, K. Janson, H. Kalda, and T. Sakkos, “Supply voltage level optimization in industrial low voltage networks,” in 2012 Electric Power Quality and Supply Reliability, 2012, pp. 1–6.

[9] K. S. Y. Wan and F. H. W. Yik, “Representative building design and internal load patterns for modelling energy use in residential buildings in Hong Kong,” Appl. Energy, vol. 77, no. 1, pp. 69–85, Jan. 2004.

[10] J. Munkhammar, J. Rydén, and J. Widén, “Characterizing probability density distributions for household electricity load profiles from high-resolution electricity use data,” Appl. Energy, vol. 135, pp. 382–390, Dec. 2014.

[11] J. Meyer, A.-M. Blanco, M. Domagk, and P. Schegner, “Assessment of Prevailing Harmonic Current Emission in Public Low-Voltage Networks,” IEEE Trans. Power Deliv., vol. 32, no. 2, pp. 962–970, Apr. 2017.

[12] F. Möller and J. Meyer, “Survey on emission characteristic of the symmetrical components of voltage and current in LV grids,” in 2018 18th International Conference on Harmonics and Quality of Power (ICHQP), 2018, pp. 1–6.

[13] A. Wright and S. Firth, “The nature of domestic electricity-loads and effects of time averaging on statistics and on-site generation calculations,” Appl. Energy, vol. 84, no. 4, pp. 389–403, Apr. 2007.

[14] Standard, EN 50160 - Voltage characteristics of electricity supplied by public electricity networks. 2010.

[15] Fingrid, “Reserves and balancing power.” [Online]. Available: https://www.fingrid.fi/en/electricity-market/reserves_and_balancing/#reserve-obligations-and-procurement-sources. [Accessed: 28-Jan-2019].

[16] Standard, IEEE Recommended Practice for the Analysis of Fluctuating Installations on Power Systems. 2015.