Visualization of Power Quality Data

Christoph Kattmann
Stefan Tenbohlen
Institute of Power Transmission and High Voltage Technology
University of Stuttgart
Stuttgart, Germany
christoph.kattmann@ieh.uni-stuttgart.de

***Abstract*—The visualization of massive amounts of data is a challenge for the evaluation of power quality, where hundreds of data points per second and location can be generated. Based on the theoretic foundations of data visualization, common visualizations for the current state of power quality as well as aggregated values are reviewed and analyzed. For several examples, the mapping from data point properties to visual dimensions is shown and discussed, highlighting the importance of the definition of exact goals for a visualization and illustrating possible pitfalls. In particular, the challenge of visualizing norm compliance is discussed and a proposal for a suitable plot type is made.**

***Index Terms*—Power quality, Data visualization, Power grids**

I. Introduction

A. Motivation and Contribution

The collection of overwhelming amounts of data is a trend in all of technology. In power and energy technology, one example for this is power quality measuring and analysis. These measurements are conducted at various sites in the electric grid in order to assess the supplied voltage in great detail. They are often employed when there are problems with electric equipment or to determine the compliance to the norms and regulations in the jurisdiction. During a typical power quality measurement, at least the values in Table I are recorded for all three phases.

TABLE I
Minimal Amount of Values of Power Quality Measurements

Value	Unit	no of values
RMS Voltage	V	3×1
Total Harmonic Distortion (THD)	%	3×1
Harmonics (2. - 25.)	%	3×24
Flicker	-	3×1
Frequency	Hz	1
Asymmetry	%	1

These are 27 individual values for each phase. Together with the voltage frequency and asymmetry, there are at least 53 numerical values for one power quality measurement device at one point in time. All of these values have limits in the European norm EN 50160 [1], which additionally contains regulations for and informations about voltage dips and total supply interruptions. A power quality survey therefore produces great amounts of data and it is a considerable challenge to present the results in a correct and understandable fashion. Showing all recorded time series (at least 53) and events is not helpful for an overview of the important data points and the determination of norm compliance. Fortunately, there are ways to sensibly aggregate power quality data and effectively visualize norm compliance. This paper aims to outline the theoretic foundations of data visualization and its application to power quality data and contribute to the awareness about the visualization of norm compliance.

Of course, norm compliance is only one possible goal of power quality surveys. The CIGRE working group C4.112 has published numerous documents about power quality measurements, highlighting different goals, methods and visualizations [2] [3].

For these goals, it is usually necessary to record many more values like RMS of current, total demand distortion (TDD), harmonics of current, apparent power, power factor and more during power quality measurements. These do not have threshold values in EN 50160, but they are of interest for more detailed analysis. For the sake of focus, only the visualization of values that are relevant for compliance is discussed in this paper. However, the theoretical foundations are naturally applicable to these advanced tasks as well.

The goal of the chosen visualization has to align with the goal of the measurement itself: A professional engineer looking to thoroughly assess the situation can understand different levels of complexity and abstraction than someone just looking at compliance with no further ambitions. The presence of different levels of previous knowledge is a general problem in data visualization, but it is generally recommended to transport the information as clearly and simple as possible.

B. Related Work

Many publications discuss the results of power quality measurements, but visualization is rarely explicitly discussed. Gasch et al. [4] assessed visualizations with a focus on risk assessment in multiple locations and several types of graphs are shown in the publications of the aforementioned CIGRE working group C4.112, but the theory of data visualization not commonly presented.

II. Theory of Data Visualization

A. Foundations of Visualization

The purpose of data visualizations is to convey data in a more accessible way than is possible with just plain text and numbers. Using basic visualizations, it is much easier to overlook large datasets, grasp the characteristic properties of data and detect outliers and abnormal values. Depending on the type of visualization, some properties of the underlying data are conveyed more effectively than others. It is therefore vital for a successful visualization that the purpose of the visualization is clearly identified and potential shortcomings are kept in mind. The human visual system is a pattern violation detection machine. It was a matter of life and death for our ancestors to quickly detect dangers in their surroundings, and so evolution clearly favored a visual system that can detect even tiny disturbance in an otherwise static, ordered, or known environment. As a result, humans are exceptionally powerful at detecting trends and outliers. These capabilities can be used by visualizing data so that visual disturbances in a pattern only occur for relevant outliers.

TABLE II
Visual Dimensions and their characteristics

Visual Dimension	Quantitative	Categorical
position (x & y)	++	++
length	++	
size, area	++	
angle	+	+
color saturation	+	
color hue		++
shape, icon		++

TABLE III
Properties of power quality measurements

Property	Type
measurement value	quantitative
measurement type	categorical
time	quantitative
norm conformity	categorical
location	can be both

B. Visual Dimensions

Scientific data is usually visualized in two-dimensional space for display and print. This gives the x- and y-axis as natural visual dimensions, i.e. properties in which data points can visibly differ. Other visual dimensions can be size, color (or more precisely, saturation or hue), shape, stroke pattern or angle [5]. Every information that is to be visually transported using a graph has to be mapped to at least one of those visual dimensions. However, their capabilities in visualizing different data values can differ significantly. As an example, numerical, continuous data can be quantified and compared much better using position or size as visual dimension than using color or shape. An overview of possible visual dimensions is given in table II. Additionally, the given visual dimensions are rated for their capabilities in visualizing quantitative and categorical data properties.

Often, visualizations implicitly map properties to more than one visual dimension. A bar graph for instance maps a value to the y-position, length and size. This places a great emphasis on that property and it is therefore easy to compare values with great precision and detect outliers.

C. Data Properties

Associated with one data point of a power quality measurement are the properties in Table III. The location of a measurement could be reasonably given as a categorical (substation name) or quantitative (coordinates) property.

The measurement value in this case is the actual reading, e.g. 231 V, while the associated measurement type is e.g. 'Voltage in phase 1'.

D. Visualization as a Mapping between Data Properties and Visual Dimensions

The task of visualization of power quality data now becomes a matter of mapping the properties of a measured data point to a suitable visual dimension.
Depending on the purpose of the visualization, some data properties can be mapped to more prominent visual dimensions, with the most prominent visual dimensions usually being position and size. A time series of the voltage in all three phases at one measurement site for instance is represented by the mapping outlined in Table IV. Measurement values and time are mapped to the most prominent visual dimensions, x- and y-position. The resulting figure is shown in Figure 1.

TABLE IV
Mapping of data point properties: Miseries

Property	→	Visual Dimension
measurement value	→	y-axis (position)
measurement type	→	color hue
time	→	x-axis (position)
norm conformity	→	-
location	→	-

In order to visualize a norm violation, it is possible to display a threshold line in a time series plot. For many thresholds in

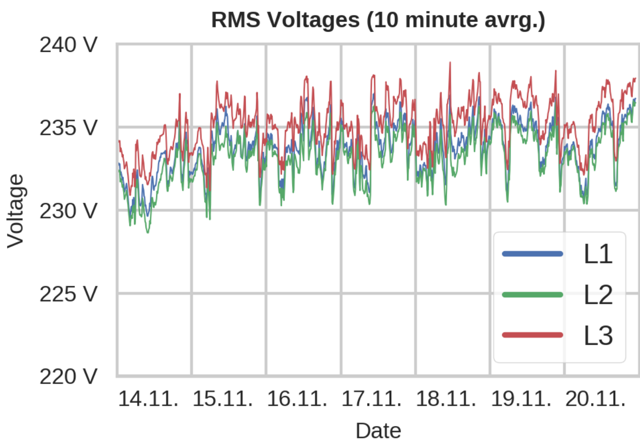

Fig. 1. Time series of Voltages using the mapping in Table IV

power quality norms however, this can be very misleading as the EN 50160 only requires a certain percentage of values to be in a certain range, e.g. 95% of THD values at a maximum of 8%. This is further discussed in section IV.

III. Visualization of the Momentary State of Power Quality

A. Motivation and Basics

For online measurements with continuous surveillance, it is important for a visualization to transport the momentary state of power quality at one or more locations. The values shown, however, still actually represent an aggregated amount of data. RMS values, harmonics, flicker and THD all are only defined for at least one half-cycle of the actual voltage waveform. Ten cycle aggregations are used as an intermediate aggregation in IEC 61000-4-30, so this is a reasonable aggregation for 'momentary' values. It also yields a convenient 5 Hz refresh rate.

As only the current moment is shown, the time doesn't need to be mapped, so the y-position mapped to time in the time series example can be used differently.

A common visualization uses the y-axis for the categorical measurement type, yielding a bar graph as described in Table V and shown in Figure 2. In order to map the values of the different types to a common y-axis, the values are scaled to the compliance thresholds, usually given by EN 50160. The harmonics are not shown individually, only the worst harmonic is displayed. It is important to note that a momentary value higher than the compliance threshold does not necessarily mean that a norm violation is taking place. This can be due to the data not being aggregated to ten minute averages according to IEC 61000-4-30, or the actual norm threshold not being an absolute limit.

It is possible to visualize the norm conformity of every measurement type using color, usually signaling a norm violation using a red color.

This basic type of graph, often additionally differentiating between phases, can be found in many power quality evaluation programs. It is very simple and allows an assessment of the level of conformity at a glance. However, the mapping does not use the strengths of the visual dimensions to their full potential. The measurement values of the different measurement types on the y-axis have no relation to each other, they cannot be compared, so this important capability of the visual dimension 'y-position' is not used.

Another way to map the properties of the momentary state of power quality is shown in Table VI and Figure 3.

TABLE V
Mapping of data point properties: Bar Graph

Property	→	Visual Dimension
measurement value	→	y-axis (position), length
measurement type	→	x-axis (position)
time	→	-
norm conformity	→	(color hue)
location	→	-

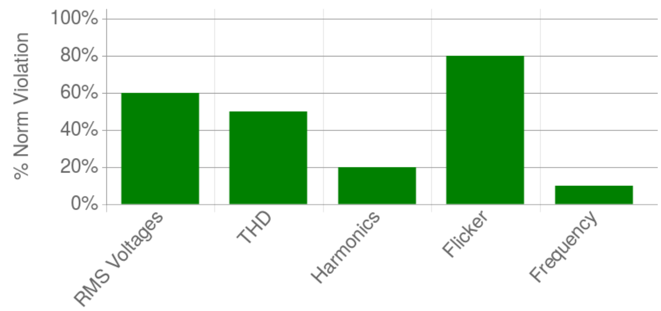

Fig. 2. Bar chart outlining the momentary state of power quality at one location as specified by the mapping described in Table V

TABLE VI
Mapping of data point properties: Radar Chart

Property	→	Visual Dimension
measurement value	→	length
measurement type	→	angle
time	→	-
norm conformity	→	(color)
location	→	(position)

This visualization of the current state of power quality in a radar chart contains less exact information than the bar chart, as the length of one spike in the chart cannot be evaluated as precisely as the length of one bar. This is not as big of a disadvantage as it seems, as the bar chart presents a comparability between the measurement types that is not really useful. In return, the radar chart is much more compact and presents the entire information in one shape. These

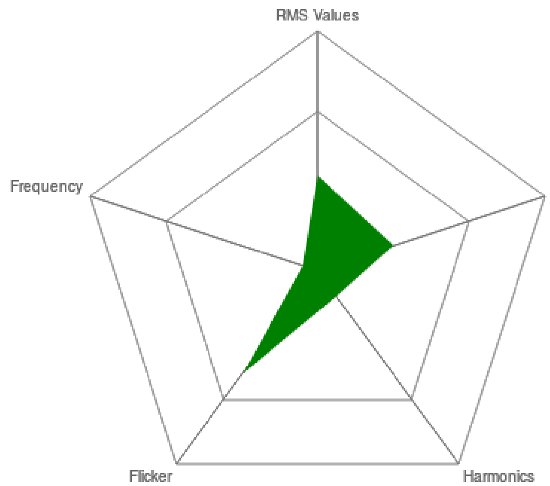

Fig. 3. Radar Chart outlining the current state of power quality at one location

properties allow a comparability between different locations more naturally than using a bar chart. The radar chart is therefore useful when multiple states of power quality have to be presented, e.g. at different locations on a map. It can be quickly evaluated even when scaled to a much smaller size and presents no 'fake' detail like the bar chart.

B. Visualization of Momentary Norm Violations

Due the exact nature of the thresholds for the various power quality indices formulated by EN 50160, it is not trivial to indicate a norm violation of a momentary value. With the exception of the frequency, all indices mentioned in table I have only limits for their 10-minute aggregated values (the frequency is evaluated in 10-second aggregation intervals). A 10-period aggregated value can only serve as a suggestion that a norm violation might be occurring. Furthermore, the limits given often work on the 90^{th} or 95^{th} percentile. Table VII shows the limits for the values from Table I.

Therefore, a norm violation can only very rarely be associated to one specific value and more probably to the distribution of a measurement value over a longer period of time. This is a problem for all visualizations of the momentary state of power quality. It is therefore necessary to separately discuss the visualization of aggregated power quality data. Only for these visualizations which show data of one week or more it is possible to truly determine the compliance of a measurement to EN 50160.

IV. Aggregated Power Quality Data

For compliance measurements, data is usually collected for several weeks. The visualization of the resulting dataset therefore has to show a great amount of data. As mentioned,

TABLE VII
Power Quality Indices and their compliance requirements from EN 50160

Value	Aggregation interval	Limits (EN 50160)
RMS Voltage	10 Minutes	100% below $U_N + 10\%$ 95% above $U_n - 10\%$ 100% above $U_n - 15\%$
THD	10 Minutes	100% below 8%
Harmonics (2.-25.)	10 Minutes	95% below indiv. limits
Flicker	2 hours	95% below 1
Frequency	10 seconds	99.5% inside $f_N \pm 1\%$ 100% below $f_N + 4\%$ 100% above $f_N - 6\%$
Asymmetry	10 Minutes	95% below 2%

a norm violation occurs when the *statistical distribution* of a certain value violates specific thresholds.

Hence, it is appropriate to visualize the statistical distribution of the collected values. A boxplot is an established method for this. However, not all information transported by a boxplot is relevant for the norm compliance of a dataset. The median value, which is usually displayed using a line in the middle of the boxplot has no inherent meaning for a power quality index. Fig. 4 shows an example for a boxplot visualization of a power quality measurement. The statistical distributions of rms voltage, THD, long-term flicker and worst-case harmonics are displayed. With this setup it is possible to visualize a true norm violation according to EN 50160. However, the actual percentiles of the boxplot boundaries (normally 25% and 75% for the box) have to be modified and are not similar for different indices. Still, with knowledge about the nature of the individual thresholds it is possible to correctly indentify a violation. The visualization in Fig. 5 attemps to transport this knowledge more explicitly. Irrelevant whiskers are hidden, the norm thresholds are individually named and plot areas which can never be used (like negative THD, Flicker, and Harmonics) are left blank. Despite being more visually crowded, it is possible to distinguish norm violations quickly. Additionally, it is possible to signal a norm violation using red coloring on the boxes. Crucially, the visualization is not simpler than the information it has to convey. The various threshold definitions and limits require a visualization that is at least equally as complex.

The only informations missing in Fig. 5 are the lengths of the aggregation intervals (10 minutes for all values except flicker, which has a 2 hour aggregation interval) and he percentiles of the boxplots (95% for RMS voltage, flicker, harmonics, and asymmetry, but 99.5% for frequency). Both are obvious to an expert, but could be separatly mentioned in the plot title or caption. Most importantly, a norm violation produces an immediatly recognizable visual outlier.

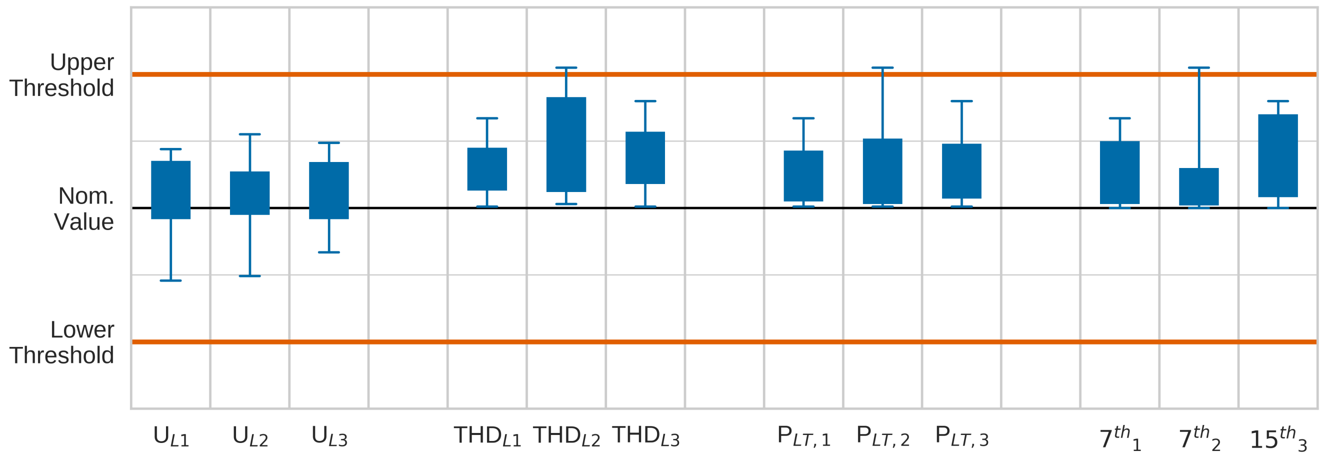

Fig. 4. Possible boxplot visualization of aggregated power quality data: all whiskers are shown, no indication of individual thresholds.

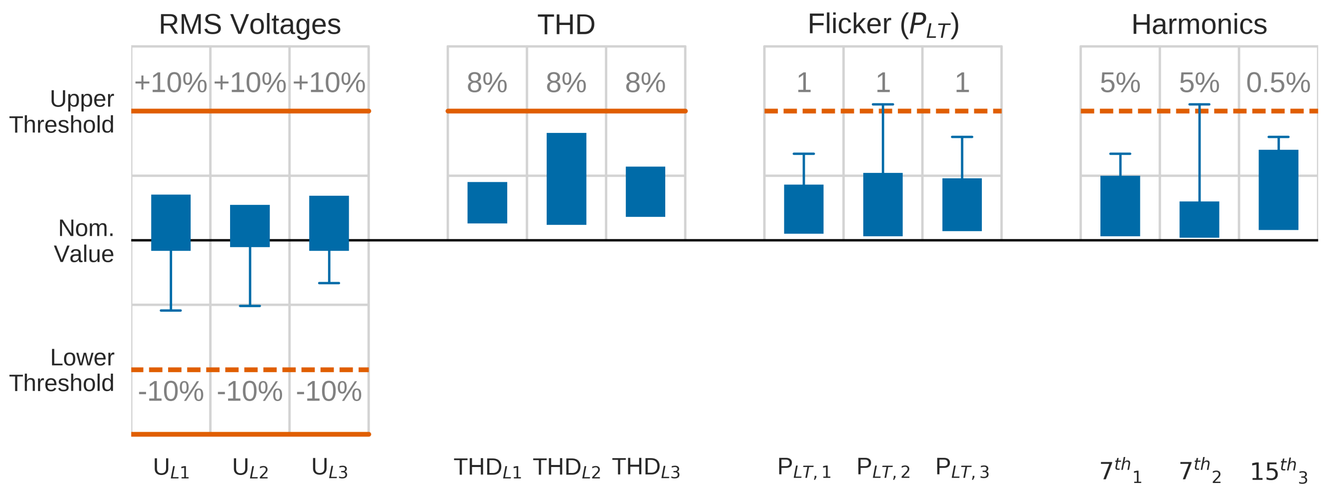

Fig. 5. Modified boxplot visualization of aggregated power quality data focussing on correct visualization of norm thresholds: irrelevant whiskers are hidden, individual thresholds are named - the information and the exact norm thresholds are therefore visualized at the same time.

V. Conclusion

The theoretic foundations of data visualization have been outlined and their application to the visualization of power quality data has been demonstrated with some examples. The concept of the mapping from a data point property to a visual dimension is a useful model and allows a standardized approach and classification of visualizations. The evaluation of power quality can, depending on the measurement scenario, have different goals and operate with different datasets. One of the most common goals of a power quality visualization is the verification of norm compliance. Because of the complex requirements for compliance in EN 50160, the visualization required to transport the intricacies has to trade simplicity for correctness. In any case, it is worth considering the details of power quality norm compliance for an effective visualization that conveys all necessary information, but does not oversimplify or misleads.

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