Energy Community Regulatory Board

Guidelines of Good Practice on the Implementation and Use of Voltage Quality Monitoring Systems for Regulatory Purposes

Ref: C12-EQS-51-03
3 December 2012

Council of European Energy Regulators ASBL
28 rue le Titien, 1000 Bruxelles
Arrondissement judiciaire de Bruxelles
RPM 0861.035.445

Energy Community Regulatory Board
Am Hof 4, 1010 Vienna
Energy Community Secretariat

INFORMATION PAGE

Abstract

This document (C12-EQS-51-03) is a document on Guidelines of Good Practice on the Implementation and Use of Voltage Quality Monitoring Systems for Regulatory Purposes, which has been jointly developed by CEER and the ECRB.

This document seeks to assess the voltage quality monitoring programmes currently in place in European countries (both CEER member countries and regulators of the Energy Community). Drawing on the results of this assessment, CEER and the ECRB developed a set of guidelines to recommend best practices for facilitating regulators and transmission operators in their monitoring tasks.

Target Audience

Energy suppliers, consumer representative groups, network operators, Member States, academics, Energy Community Contracting Parties and Observers and other interested parties.

If you have any queries relating to this paper please contact:
Ms Natalie McCoy
Tel. +32 (0)2 788 73 35
Email: natalie.mccoy@ceer.eu

Mrs Nina Grall-Edler
Tel: +43 1 5352222 27
Email: nina.grall@energy-community.org

Related Documents

CEER and ECRB documents:

- "5th CEER Benchmarking Report on Quality of Electricity Supply", [CEER/ECRB], [December, 2011], Ref. [C11-EQS-47-03], http://www.energy-regulators.eu/portal/page/portal/EER_HOME/EER_PUBLICATIONS/CEER_PAPERS/Electricity/Tab/CEER_Benchmarking_Report.pdf

Table of Contents

Table of Figures/Tables

EXECUTIVE SUMMARY

In the 5th CEER Benchmarking Report on Quality of Electricity Supply in 2011, 18 countries reported having an operational voltage quality monitoring system already in place. In addition, the majority of network operators in most countries perform voltage quality monitoring on a continuous basis at one or more locations. The number of voltage quality monitors in operation in the public distribution and transmission networks has seen significant growth in recent years, largely due to a number of technical developments. The cost of monitoring equipment has dropped significantly, making it less of a barrier for installing a larger number of them. At the same time, their performance has increased. Furthermore, the costs of ancillary technologies, like communication, data storage, data processing and visualisation of results have significantly decreased; whereas their performance has improved in parallel. The appearance of smart meters with a voltage-quality monitoring functionality is the most visible proof of such development.

Recent and on-going developments within the power grid, and the equipment connected to it, have further resulted in an increased interest in voltage quality; for examples photo-voltaic installations, energy-efficient lighting and wind power. This results in further interest in voltage quality monitoring. These guidelines of good practice concern mainly the monitoring of voltage quality, however, the additional costs of including monitoring of the current quality is limited. The report does not cover short-duration measurements, for example for verification of customer complaints or for trouble shooting. The result is a set of guidelines supported by CEER as well as by ECRB.

These guidelines of good practice discuss, among others:

- Possible applications of the results from voltage quality monitoring programmes and the drivers behind them;
- The number of monitors and at which locations in the network they should be placed, as well as the length of the measurement period;
- Standardisation of methods, in particular for disturbances - a common set of indices for benchmarking;
- Reporting and publishing results of voltage quality monitoring programmes - a common format of data display; and
- Financing frameworks.

More detailed findings and recommendations can be found in the individual chapters, but the main overall conclusions that can be drawn from this assessment and subsequent set of guidelines include:

<u>1. Voltage quality monitoring programmes are important tools for voltage quality regulation</u>
Voltage quality is an important aspect of the service that network operators provide to their connected customers. As such, network operators should be transparent about the level of quality they deliver. Voltage quality monitoring programmes can facilitate the delivery of such transparency.

There are sufficient applications regarding regulation introduction, regulation enforcement, research and transparency to justify countries implementing a voltage-quality monitoring programme. The costs of such a programme are a small part of the total costs of operating the electricity networks.

Such a monitoring programme can be fully run by network operators or installed by the NRA and operated by the network operator with NRA access to data.

2. All possible applications should be kept in mind
Even if the purpose of a programme is initially limited, small changes in the set-up of a programme or of parameters recorded or calculated, can allow future applications at no or very small extra cost. The setting up of such a programme should be done in close cooperation between NRAs and stakeholders, especially network operators.

3. Voltage quality monitoring programmes should be funded through network tariffs
It is deemed that the benefits, with regards to the wide range of possible applications, outweigh the costs of voltage quality monitoring programmes. The most appropriate way of funding such a programme is through network tariffs. This can however vary between countries based on the local tariff structure and regulation.

4. Results should be made available regularly
Publication of the results and making data available in other ways are important parts of a voltage-quality monitoring programme. These guidelines recommend that the NRA publishes the main results from the programme and that data should be made available to other stakeholders, including the general public. Where no objections from individual network users or other important objections exist, all data should be made available for free or at a reasonable cost, for research and education purposes.

5. Diversification of indices and methods is to be avoided
A number of voltage quality monitoring programmes have already been launched in some countries. There are large differences between these programmes making it difficult to compare the results and to exchange knowledge and experiences. The guidelines strongly recommend that voltage quality monitoring programmes are harmonised according to the proposal in this report. The need for harmonisation applies to, among others, the choice of monitor locations, types of disturbances monitored, characteristics recorded and indices calculated. Beyond the list of indices for benchmarking, which is recommended as a harmonised set of indices to be obtained from every programme where possible, we recommend that each country obtain additional indices that specifically reflect the local circumstances.

Terminology use to be resolved:

- ✓ “customer” or “network user”
- ✓ “supply terminals”, “point of connection” or “connection point”

List of References

Reports and documents by the European Energy Regulators:
[1] “Quality of Electricity Supply: Initial Benchmarking on Actual Levels, Standards and Regulatory Strategies”, April 2001
http://www.energy-regulators.eu/portal/page/portal/EER_HOME/EER_PUBLICATIONS/CEER_PAPERS/Electricity/2001/1ST_CEER_BENCHMARKING_REPORT_QUALITY_OF_SUZPPLY.PDF

[2] “3rd CEER Benchmarking Report on Quality of Electricity Supply 2005”, December 2005, Ref. C05-QOS-01-03
http://www.energy-regulators.eu/portal/page/portal/EER_HOME/EER_PUBLICATIONS/CEER_PAPERS/Electricity/2005/CEER_3RDBR-QOES_2005-12-06.PDF

[3] “5th CEER Benchmarking Report on the Quality of Electricity Supply 2011”, April 2012. Ref C10-EQS-47-03 (joint deliverable with the ECRB)
http://www.energy-regulators.eu/portal/page/portal/EER_HOME/EER_PUBLICATIONS/CEER_PAPERS/Electricity/Tab/CEER_Benchmarking_Report.pdf

[4] Public Consultation Paper: “Towards Voltage Quality Regulation in Europe”, December 2006, Ref E06-EQS-09-03

[5] Conclusions Paper: “Towards Voltage Quality Regulation in Europe” (and evaluation of comments paper), July 2007, Ref E07-EQS-15-03
http://www.energy-regulators.eu/portal/page/portal/EER_HOME/EER_PUBLICATIONS/CEER_PAPERS/Electricity/2007/E07-EQS-15-03.pdf

[6] “Guidelines of Good Practice on Estimation of Costs due to Electricity Interruptions and Voltage Disturbances and accompanying “Study on Estimation of Costs due to Electricity Interruptions and Voltage Disturbances”; December 2010, Ref C10-EQS-41-03, TR F6978
http://www.energy-regulators.eu/portal/page/portal/EER_HOME/EER_PUBLICATIONS/CEER_PAPERS/Electricity/2010/C10-EQS-41-03_GGP%20interuptions%20and%20voltage_7-Dec-2010.pdf

Other activities and papers by CEER members:
[7] E. Fumagalli, L. Lo Schiavo, F. Delestre “Service Quality Regulation in Electricity Distribution and Retail”, Springer, 2007.

Other references:
[8] “EN 50160”, CENELEC standard, 2007 and 2010

http://www.cenelec.eu/dyn/www/f?p=104:110:4283075340032155::::FSP_PROJECT,FSP_LANG_ID:21352,25

[9] "EN 61000-4-30", CENELEC/IEC standard, 2003 and 2009
http://www.cenelec.eu/dyn/www/f?p=104:110:2115832933635801::::FSP_PROJECT,FSP_LANG_ID:14653,25

[10] CIGRE TB 261
http://www.cigre.org/

[11] CIGRE TB 412
http://www.cigre.org/

[12] "Draft Guide for Voltage Sag Indices- internal document" (P1564/D18) IEEE Standards Activities Department, August 2012.

[13] CIGRE Working Group C4112, draft chapters as available April 2012.

[14] M.H.J. Bollen, I.Y.H. Gu "Signal processing of power quality disturbances", IEEE Press, 2006.

[15] J.Kilter, et al. "Current practice and future challenges for power quality monitoring – CIGRE C4.112 perspective", International Conference on Harmonics and Quality of Power (ICHQP), Hong Kong, June 2012.

[16] P. Caramia, G. Carpinelli, P. Verde "Power quality indices in liberalized markets", Wiley, 2009.

[17] "IEC 6100-4-7", CENELEC standard, 2002
http://www.cenelec.eu/dyn/www/f?p=104:110:6877339331294368::::FSP_PROJECT,FSP_LANG_ID:13905,25

1 Introduction

1.1 Background

Since the 1st Council of European Energy Regulators (CEER) Benchmarking Report on Quality of Electricity Supply (QoS) in 2001 [1], the role of NRAs has been continuously recognised in facilitating the development and setting of standards for voltage quality (VQ), as well as regulating VQ through economic incentives.

Voltage quality monitoring (VQM) systems were addressed for the first time in the 3rd CEER Benchmarking Report on QoS in 2005 [2], where 6 European countries reported to have operational (or under commissioning) VQM systems already in place. By the 5th CEER Benchmarking Report on QoS in 2011 [3] (a joint deliverable of CEER and the ECRB-hereinafter "5th BMR on QoS"), there were 18 European countries reported to have an operational VQM system. In addition, the majority of network operators in most countries perform voltage quality monitoring on a continuous basis at one or more locations.

For the purposes of this report, considering the joint work by CEER and the ECRB, the term "*European countries*" refers to CEER Members and Observers and the Contracting Parties of the Energy Community (EnC). In the same sense, the use of "*regulators*" or "*NRA(s)*" refers to all the national regulatory authorities for energy of the countries mentioned here above.

Regulators consider VQ regulation, including VQM, as an important part of the general regulation of the wider electricity networks. Three reports should be specifically mentioned here: the 2006 public consultation paper on VQ regulation [4]; the corresponding 2007conclusions paper [5] and the 2010 Guidelines of Good Practice on cost estimation for QoS [6].

The number of VQ monitors in operation in the public distribution and transmission networks has seen a significant growth in recent years, largely due to a number of technical developments. The cost of monitoring equipment has dropped significantly, making it less of a barrier for installing a larger number of them. At the same time, their performance has increased. Furthermore, the costs of ancillary technologies, like communication, data storage, data processing and visualisation of results have significantly decreased; whereas their performance has improved in parallel. The appearance of smart meters with voltage-quality monitoring functionality is the most visible proof of such development.

A final important contributing factor is the appearance of international standards related to VQM, in particular EN 50160[1] and EN 61000-4-30. This has allowed comparable results to be obtained by different monitoring devices, which in turn has made it easier to exchange knowledge and experiences, for instance between different countries.

[1] The Energy Community Treaty obliges the Contracting Parties to implement certain European technical standards (Article 21-23 of the Treaty). According to Procedural Act PHLG 2007/04, this includes EN 50160. The other standards referred to in the present report are not part of the so-called Generally Applicable

Recent and on-going developments within the power grid, and the equipment connected to it, have further resulted in an increased interest in VQ; for examples photo-voltaic installations, energy-efficient lighting and wind power. This results in further interest in VQM.

Voltage quality is considered, in a range of reports by regulators (CEER/ERGEG and the ECRB), as factor in the quality of supply as well as the continuity of supply and quality of service. Voltage quality is also, in the technical literature, seen as part of power quality, next to current quality. This report concerns mainly the monitoring of voltage quality, however, the additional costs of including monitoring of the current quality is limited. Therefore, most VQM programmes are in fact power-quality monitoring programmes and at several locations in this report the current-quality aspects will be considered as well.

1.2 Scope and structure of the report

This report covers VQM programmes of a longer duration (i.e. one year or more). Measuring of the current is included in this report, where relevant, but the main emphasis is on voltage quality itself. The report does not cover short duration measurements, for example for verification of customer complaints or for trouble shooting.

In Chapter 2, an overview of possible applications of the results from VQM programmes is given; regulatory applications as well as other drivers for voltage quality monitoring. These applications form the basis for setting up VQM programmes. The properties of such a programme are discussed in Chapter 3, including recommendations on the number of monitors, monitor locations and duration of the monitoring period. Chapter 4 discusses the kind of disturbances that should be monitored and the indices that can be calculated from the recorded voltage waveforms. A set of indices for benchmarking purposes is proposed in Chapter 4 as well. Chapter 5 addresses the publication of the results from a VQM programme and the availability of the monitoring data. Finally, Chapter 6 discusses the financing of VQM programmes.

1.3 Customer perspective

When voltage quality is poor, problems can arise in the use of electrical appliances and equipment; lasting damage, reduced efficiency, flickering lights and even explosion or fire. These issues are often not known or expected by smaller/residential customers and it is thus of greater importance that sufficient technical regulation behind the scenes is in place.

Voltage quality is affected by all the parties connected to the power system and therefore has wider implications for all consumers of energy; not only large industrial users.

Regulators use GGP like these to help organise and coordinate their procedure for monitoring voltage quality to ensure that consumers receive a guaranteed, satisfactory and safe level of electricity supply.

1.4 Project organisation

These Guidelines of Good Practice (GGP) were written by a technical drafting team consisting of colleagues from both CEER and ECRB members. Input was obtained from the 5th BMR on QoS (to which most European countries provided information), from the answers to additional questions sent to voltage quality experts and other contacts at national regulatory agencies in selected countries, from draft versions of the report by CIGRE working group C4.112, from other technical literature and from the experience of the drafting team members. Feedback was further obtained from a reviewing team consisting of a subset of the above-mentioned experts. The report was also submitted to the Electricity Quality of Supply and Smart Grid Task Force of CEER, to the Customer Working Group of the ECRB and passed through both approval processes in parallel. The result is a set of guidelines supported by CEER and the ECRB.

2 Regulatory applications and other drivers for voltage-quality monitoring

A number of possible applications for VQM programmes were identified during the work leading up to the GGP, based on the European and EnC[2] legal frameworks and current practices in different countries. The emphasis in this report is mainly on those applications where the results from the monitoring programme are used for regulation of the network operator, so-called regulatory applications. Recognised applications and drivers for a VQM programme are discussed in Section 2.1. Each subsection briefly describes the application and what is considered as good practice when using results from VQM programmes for this application. Recommendations from this chapter are presented in Section 2.2.

2.1 Applications and drivers

2.1.1 Compliance monitoring

Compliance monitoring as a regulatory application concerns comparing the voltage-quality indices for individual sites with existing legal, regulatory and licencing obligations.

Checking compliance of the emission from individual network users with emission standards or local rules is not seen as a regulatory application, but as a part of network activity. It is discussed in Section 2.1.10.

Requirements on VQ exist in all European countries; this can either be through the EN 50160 or other national regulations. However, countries differ in how the compliance with requirements is verified. Since it is the responsibility of the network operator to maintain an acceptable level of voltage quality and to ensure that the quality at connection points complies with the requirements, direct obligation for the actual monitoring needed for compliance verification should be thus given to the network operators. In addition to self-monitoring, NRAs should have the legal right to perform an independent verification; a wide-spread VQM programme is a useful tool for this either by using VQM operated by the network operator or a VQM programme completely under the control of the NRA. It should be noted however that for complete compliance verification, continuous monitoring is needed for all points of connection. With the existing level of technology and costs, this is not a practical solution and is expected to remain the case for the time being[3]. In any case, these GGP do not consider it necessary to verify complete compliance.

An NRA should have the authority to instruct a network operator to take measures in case the trends in VQ levels warrant such action. The responsibility for maintaining sufficient VQ shall remain, however, fully with the network operator and the NRA shall in no way take over any of this responsibility.

[2] http://www.energy-community.org/portal/page/portal/ENC_HOME/ENERGY_COMMUNITY/Legal

[3] The availability of a future generation of smart meters could make compliance monitoring at each connection point.

2.1.2 System performance monitoring

System performance monitoring consists of monitoring of the performance of the system as a whole, with predefined objectives. It can also involve acquiring knowledge of average performances of the network and an understanding of significant trends in the overall network, specific regions, voltage levels, types of network and a specific set of sites, such as monitoring the impact of distributed generation and new types of customers (e.g. electric cars) on VQ. Based on the data obtained from such monitoring procedures, decisions are normally made by the network operator with respect to network development planning. This is considered as a ‘normal’ part of the network operator’s duties for guaranteeing the existing and future performance of the network. When the monitoring is done by the network operator, any planning levels used, e.g. for the connection of new customers, are appropriate indices for system performance.

When a VQM programme is in place, it should be used by the NRA to obtain an independent view on the performance of the system and on any trends in performance. System performance monitoring should be designed and implemented through the involvement of all interested and responsible parties for VQ monitoring and regulation, taking into account the scope of monitoring and the amount of data that has to be collected.

2.1.3 Specific site monitoring

Specific site monitoring is monitoring aimed at providing information on VQ at a specific site in the network. This kind of monitoring is an issue of major importance in the case of complaints by network users, new customers wanting to know the VQ before being connected to the grid, or in the case of voltage quality contracts.

The data collection, storing and access possibilities for a VQM programme should be of such quality that the data can be used for describing the VQ level at individual sites in sufficient detail, without the need for extensive additional measurements. This holds especially for voltage dips and swells, where long measurement periods are typically needed before the number of events can be estimated.

Complaints
The normal reaction following complaints by network users about VQ is to perform measurements at this location. When a VQM programme is in place, data from that programme can be used without the need for additional measurements. This allows for a faster reaction, a better correlation between the complaint and disturbance levels, and a comparison over a much longer period than would have been practical with temporary monitoring. It will also allow the study of the VQ at the exact moment of, for example, incorrect operation of equipment.

The handling of such complaints is normally addressed by the network operator, but in the case of disagreement, the NRA can try to resolve the matter or order an independent investigation. When a VQM programme, as defined in Chapter 3, is in place, the GGP recommend accessing data from the programme for verification of complaints. To better resolve complaints, it is important that access to raw data or data after low-level processing is made possible. The data should be stored in such a way that such access is possible without significant additional effort. To enable the NRA to perform an independent verification of complaints, the NRA should have access to the VQM data in sufficient detail. This holds especially for events like voltage dips and swells, for which long monitoring periods are needed. This means that the VQM programme should be such that the number of dips for most points of connection can be estimated with reasonable accuracy from the data obtained.

Pre-connections
VQM programmes can give useful information on expected VQ levels to individual customers and to the overall customer base. New customers should have the right to know VQ levels before choosing the most suitable site (and voltage level) to connect their facilities to the grid, to be able to quantify in advance potential damages, plan counteractions to prevent them, use right equipment and design processes with adequate levels of immunity.

When this application is envisaged, it is important to define the VQM programme, including data storage and accessibility, in such a way that this application is not unnecessarily hindered.

Contracts
A tool for the market is the possibility for network users and network operators to sign quality contracts or agreements concerning VQ. In some countries, optional guarantees (for instance a maximum number of voltage dips per year) in association with permanent VQM can be purchased by sensitive customers as insurances. A VQ contract can also include emissions limits. In this case, monitoring is likely to be included as well. VQM monitoring can also be done prior to the signing of the contract.

Usually VQ contracts are not a regulatory issue, but they can become on in the case of disputes. In this event, the NRA should have access to ex-post data from relevant sites in order to verify that the network operator is fulfilling contractual obligations.

2.1.4 Benchmarking

The importance of using monitoring programmes for benchmarking purposes has been recognised at both the EU and EnC level and covered throughout CEER (and joint ECRB) benchmarking reports, especially on the continuity of supply. The same importance holds for voltage quality. However, VQM programmes are still not fully applied for the benchmarking of VQ on the national and international levels.

To allow for benchmarking, it is important that different networks use the same indices and that they are obtained in an identical way. In order to have reliable, robust and relevant benchmarking results, certain preconditions should be established; including harmonised measurements, data collection and publication processes among all network operators, as well as uniform reporting to the NRA in terms of scope and format. Without such harmonisation, any comparison would result in a discussion about the way in which the indices were calculated. Within one country, the NRA, or other competent body, can define appropriate indices. Where VQ indices are reported for individual network operators within a country, benchmarking becomes possible. Benchmarking between countries, e.g. at European or EnC level, requires an international agreement on standards. Currently no such standards on VQ indices exist. A set of indices for benchmarking is proposed in Chapter 4.

2.1.5 Network development and investment approval

Network development is one of the core tasks of the network operator and, under the principles of output regulation, the NRA should be involved to a limited extent in this process. However, investments associated with network development have, in many countries, a direct impact on the tariffs to be paid by the network users. In this case, the network operator will need approval from the NRA, either on a case-by-case basis, as an annual investment plan, or over a pre-defined regulatory period. Network planning is at first driven by the requirement to transmit electrical energy, i.e. by the loading (consumption and production). In certain cases, VQ also has to be considered in network planning. Supply voltage variations in rural distribution networks are the main example, but also harmonics and other disturbances are considered sometimes. In existing networks, insufficient VQ or a trend towards insufficient VQ at a certain location should also be a driving force for additional development of the network.

A sufficient VQM programme, intentionally or as a spin-off, provides the network operator with information on what is needed for network development. NRAs should encourage network operators to use the results from VQM in network development planning. Additionally, VQM data, when available, should be used by the NRAs as criteria in the approval process for network development plans and related investments within the price approval process. This can be done through requirements on network operators for presenting such plans or by giving the NRA, or an independent body, access to the data.

2.1.6 Reporting and publishing of VQM results

Reporting and publishing of VQM results is an important VQM application. See Chapter 5 for further details.

2.1.7 Further development of VQ regulation

The setting or approving of standards and requirements for quality of service and supply, or contributing thereto together with other competent authorities, is a direct regulatory role according to Directive 2009/72/EC (Article 37 (h))[4].

In some European countries, the need for VQ regulation is recognised by NRAs and there is strong intention to include VQ regulation in their future regulatory plans. However, in other European countries, there are no immediate plans for VQ regulation, at least as long as there are no major complaints received.

[4] Directive 2009/27/EC is not yet applicable in the Energy Community. The 3rd Energy Package has been adopted by the Energy Community Ministerial Council for implementation into legislation of the Contracting Parties by 2015 at the latest.

There are different approaches to setting requirements as part of VQ regulation. One can use customer requirements and put requirements such that the impact on end-user equipment is limited. This is to some extent the approach behind the EN 50160, where the voltage characteristics are strongly related to the compatibility levels, which in turn are used as a basis for setting equipment immunity standards.

For events like voltage dips and swells, such an approach is not feasible. A certain number of dips, even severe dips, must be accepted to prevent excessive costs. VQM can obtain existing levels, which can be used to prevent setting limits too high or too low. It should be noted that this will not result in the optimal grid, with minimum total costs, but it will allow a balancing of the changes in costs and benefits for the different stakeholders.

In those European countries which have already installed a robust VQM system that provides reliable and complete sets of VQ data needed by the NRA in order to introduce VQ regulation, NRAs should use VQM data to define clear, understandable and functional performance standards.

The results from VQM programmes also give information on the kind of disturbances for which the levels are too high. This in turn, together with feedback from network users (e.g. in the form of complaints) can be used to decide which regulatory instruments should be developed.

2.1.8 Remedial and mitigation measures

Remedial measures are measures taken to improve or restore the voltage quality to its earlier level. Mitigation measures are measures for lessening the impact of voltage disturbances on customers and the network. One of the most frequent applications of VQM is to select such measures for recognised VQ problems. This application plays also a role in the aforementioned network development. Recognised VQ problems can be a result of compliance monitoring, system performance monitoring, specific site monitoring, verification of compliance by network users, or monitoring for research purposes.

The role of the regulator is limited, as selecting and implementing the most appropriate remedial and mitigation measures is seen as the full responsibility of network operators. This should not, however, hinder the use of a VQM programme for regulatory purposes as a basis for selecting remedial and mitigation measures as well.

2.1.9 Network operators and end-users awareness

This application is typically under the control of the network operator, but justifies the start of VQM programme in any case.

Both network operators and consumers have duties. VQM programmes help to make both parties aware of their responsibilities.

	Duration [ms]				
Residual voltage u [%]	10 – 200	200 – 500	500 – 1000	1000 – 5000	5000 – 60000
90 > u ≥ 80	CELL A1	CELL A2	CELL A3	CELL A4	CELL A5
80 > u ≥ 70	CELL B1	CELL B2	CELL B3	CELL B4	CELL B5
70 > u ≥ 40	CELL C1	CELL C2	CELL C3	CELL C4	CELL C5
40 > u ≥ 5	CELL D1	CELL D2	CELL D3	CELL D4	CELL D5
5 > u	CELL X1	CELL X2	CELL X3	CELL X4	CELL X5

Figure 1 – Classification of voltage dips

according to the standard EN 50160, with the distinction between major and minor dips

An important example is given by the recent classification of dips envisaged by EN 50160 "*Voltage characteristics of electricity supplied by public electricity networks*" that, combined with EN 61000-4-11 "*Electromagnetic compatibility (EMC) - Part 4-11: Testing and measurement techniques - Voltage dips, short interruptions and voltage variations immunity tests*", provides a useful tool for sharing responsibilities between network operators and end-users. Considering Figure 1, where the immunity curve of class 3 is put into evidence, network users should equip their installations with devices immune to dips above the curve. On the other side, network operators should hinder dips below the immunity curve.

In this respect, VQM programmes play an important role as recording dips allows both network operators and network users to become aware of the problem and of the size of it.

Monitoring the status of the grid itself is essential for network operators in order to prevent problems having an effect on the customers outside their responsibilities, to maintain the stability of the grid and to detect trends for adopting the needed actions to solve VQ problems in adequate time.

Such an environment allows NRAs to promote initiatives aimed at making sensitive users (vulnerable to severe voltage events) aware that they are part of a unique process which requires them to be properly equipped with suitable devices, yet at the same time inducing grid operators to reduce the level of disturbances to which end-users cannot be made immune, only through their devices.

Availability of VQ data constitutes a good starting point for discussions on which indicators are most suitable to represent the network performance for a single point and for an aggregation of points.

2.1.10 Verification of compliance by network users

In order to ensure an acceptable voltage quality for all users, network operators often place limits on the emissions of users' installations. These limits are based on recommendations and guidelines from international organisations or are based on local rules.

Standardisation and certification, possibly combined with tests and simulations prior to connection to the network, are often sufficient to ensure that emissions are kept low. VQM is still useful to detect those few cases where installations do have excessive emissions, which allows the concerned network operator to require the improvement of the installation in case the excessive emission results in problems in the grid or for other network users that cannot be resolved in a more cost-effective way.

2.1.11 Transition to smart grids

VQM programmes may play an important role in the transition towards smart grids. Due to the important changes expected on low-voltage (LV) and medium-voltage (MV) networks and the increasing amount of distributed generation and new types of loads, it is very likely that VQ will be significantly impacted. Both improvements and deteriorations are to be expected, but these impacts are difficult to anticipate and VQM remains the most accurate and reliable way of keeping track of them.

2.1.12 Research and education

Research and education is an important driver and an important application of VQM. Several topics which require extensive data sets on VQ need to be further studied, including:

- correlation between measured data and the structure and characteristic of the network, load characteristics, distributed generation;
- assessment of the impact on VQ of future possible grid evolutions (increasingly meshed distribution networks, islanded distribution networks supplied with distributed generation only …);
- costs of poor VQ and impacts on the lifetime of electrical equipment/installations (customer installations, generating units, components of electrical networks). In addition to VQM, this also requires further in-depth, long-term studies, customer inquiries, field tests, etc.

Such studies can rely either on targeted VQM programmes in limited test areas, or extensive, long-term monitoring programmes. In either case, the dissemination and sharing of information and knowledge should be promoted whenever possible.

2.2 Recommendations

According to the possible applications considered in this chapter, these GGP advise starting VQ monitoring programmes as a tool for:

- continuous monitoring aimed at verification of compliance and VQ regulation introduction or further enforcement;
- further understanding of relations between network properties, disturbances and equipment behaviour with the aim of improving compatibility/immunity that can be obtained, to the advantage of society as a whole;
- benchmarking analysis of VQ both at the national and international levels;
- collecting data in order to set or improve technical standardisation;
- research and education aimed at gaining knowledge from the data collected, leading further to continuous VQM programme implementation.

When a VQM programme is in place, it is possible to implement other applications in parallel, such as obtaining information on local VQ to existing users, following complaints, future users prior to their connection to the network (especially industrial users who are generally the most sensitive to VQ), or in the case of VQ contracts.

The GGP especially recommend that the results from VQM programmes are used for identifying and dealing with new challenges in the system, such as the impact of distributed generation and new types of customers or in facilitating the transition to smarter grids.

When starting the process of setting up a VQM programme, all potentially needed applications should be considered; bearing in mind that an initially well-designed VQM programme could allow manifold applications immediately or following minor inexpensive adjustments. In order to have a wider insight into required applications of VQM programmes, close cooperation between interested parties, especially NRAs, network operators and network users, but also equipment manufacturers and researchers, is recommended in the early phases of establishing the VQM programme.

3 Properties of the monitoring programme

This chapter gives guidelines on the properties of national VQM programmes. The GGP are based on the assumption that the programme has one or more of the applications discussed in Chapter 2. This Chapter concerns the number of monitors, at which locations in the network they should be placed and the length of the measurement period. Each of these aspects is discussed separately for different voltage levels. Also, the use of smart meters for household customers is specifically addressed for VQM in LV networks. Furthermore, guidelines are given regarding the use of fixed and portable monitoring instruments and for which applications each type is suitable.

3.1 Monitoring in EHV and HV networks

For extra high-voltage (EHV) and high-voltage (HV)[5] networks, we consider it good practice to measure the VQ at all EHV/HV, EHV/MV and HV/MV substations[6] and at the connection points of all EHV and HV customers, producers (power stations) and consumers (industrial customers). The number of substations and the number of customers in the EHV and HV networks is relatively small, thus the costs of VQ monitoring at these locations will be limited (see Chapter 6 for further discussion on the costs of VQM programmes). For non-regulatory purposes, it may be advantageous to monitor at other EHV and HV substations as well. In some European countries, it may also be advantageous to monitor at the interface points between network operators at these voltage levels. Firstly, monitoring at the connection points of EHV and HV customers gives information on the VQ to which these customers are exposed, whereby voltage dips are generally most important. Secondly, monitoring with EHV and HV customers gives information on any adverse contribution from these customers to the VQ experienced by other customers (referred to as “emissions” which could result in the following VQ disturbances: harmonics, flicker, rapid voltage changes and unbalance).

Regarding the location of monitoring instruments in the HV/MV substations, the GGP recommend that they are placed on the MV side of the transformers. This location ensures that the measured VQ resembles the VQ as experienced by the network users from this transformer as closely as possible. This is true for voltage dips and for disturbances where the main source is in the EHV or HV network (like flicker due to large industrial installations). However, for harmonics and voltage unbalance, the VQ in most cases differs significantly between the measuring location at the substation and at the point of connection of the network users. Correlation between the measurements at the HV/MV substation and at the MV/LV substations can provide more information on this. To make this possible, there should at least be a few monitors downstream of every HV/MV substation.

---

[5] According to the standard EN 50160 high-voltage (HV) networks are defined as follows: 36 kV < Un ≤ 150 kV.

[6] In chapter 3 only HV/MV substations are explicitly mentioned hereafter. However, in the entire chapter the recommendations given for HV/MV substations could also be applied to EHV/MV substations, should any such substations exist in a country.

Monitoring in the EHV and HV networks should be permanent at all measuring locations. Permanent measurement means that the monitoring instrument remains at the same location for the entire year. Permanent measurement will provide a representative image of all VQ aspects[7] at each measuring location.

3.2 Monitoring in MV networks

As mentioned in Section 3.1, voltage quality should be permanently monitored on the MV side of the transformer in all HV/MV substations. Given the current costs and state of technology, monitoring permanently (for 52 weeks per year) at all locations in the MV network is not recommended.

In MV networks, it is good practice to measure the VQ at a selection of MV customers and MV/LV substations. Guidelines for selecting the customers and the number of substations for monitoring are given separately below. For MV customers, the measurement location should be at the point of connection or at a convenient location close to the point of connection. For MV/LV substations, the measurement location should be on LV side of a transformer in order to obtain the best estimation of the VQ as experienced by the LV customers.

The exact number of monitoring locations in MV networks is expected to vary between different countries due to the specific network structure and other local circumstances. Different approaches are possible:

1. a random selection of locations at national level or per network operator, or within another defined area that is of special interest for benchmarking (see Section 3.5);
2. a small number of monitors (less than 10) in each MV network at representative locations (i.e. behind each HV/MV transformer);
3. a large number of monitors (more than 10) in a selected number of MV networks typical for that country or service territory[8].

Each of the above-mentioned approaches has its advantages and disadvantages. The choice strongly depends on local circumstances and on the applications of the results from the VQM programme.

VQ monitoring may not be necessary for MV customers if the VQ at a nearby MV busbar in HV/MV substations is being monitored already. This is especially true for the monitoring of the number of voltage dips in MV networks. If VQM at the connection points of MV customers is deemed necessary or preferred, then the selection of MV customers should primarily be based on their susceptibility to VQ disturbances. In practice, this will mainly be the customer’s susceptibility to voltage dips and transients. If the current is also monitored at the MV customer’s connection point, then MV customers who emit or are expected to emit high levels of VQ disturbances should be selected for monitoring as well. VQM at MV customers

[7] Voltage events are large rare deviations from the normal voltage that require a trigger mechanism to be captured by a VQ monitor. See Chapter 4 for further discussion on the difference between "continuous phenomena” and "voltage events”.

[8] Typical with respect to for example customer density, climate, percentage of underground cables, type of network users. Also, a number of “typical urban networks” or “typical rural networks” may be chosen.

with high emissions levels is mostly of interest to the network operator for planning purposes. Regulators are interested in the VQ at a customer's connection point as supplied by the network operator as well as the changes of the VQ performance in grids. Especially in the latter case, VQ could be used as an indicator to identify changes in network performance.

Similarly to monitoring in the EHV and HV networks, these GGP recommend that permanent VQM over an entire year (52 weeks at each location) should be performed in the MV networks. The reasons why permanent monitoring is recommended are the same: it is required for obtaining a clear picture of the number of voltage events, such as voltage dips and transients, and it enables the observation of seasonal influences on the VQ in MV networks.

3.3 Monitoring in LV networks

In LV networks, VQM should be performed at the connection points of a selection of LV customers. For a national monitoring programme that aims to obtain a statistically relevant picture of the VQ for all LV customers, a random sample of LV customers throughout the country should be selected. This random sample of LV customers will tend to be a small fraction of the total number of LV customers in any particular country. The VQ at these connection points may be monitored permanently or for the period of at least one entire week. This will be further discussed in Section 3.4.

In the future, smart meters may be integrated into national VQM programmes as many household customers will have smart meters installed. It is important to consider VQM in the selection of functionality of smart meters. Currently available smart meters, even if equipped with VQ functionalities, are able to detect only a limited set of voltage disturbances[9]. At present, affordable and readily available smart meters are able to monitor the main disturbances that most domestic customers are sensitive to: supply voltage variations. Supply voltage variations are considered to be the most important VQ parameter to be monitored in the LV networks because problems with the supply voltage tend to be very local and especially impact on LV customers. It is possible for voltage dips and swells to be measured using smart meters as well. Voltage swells require a measurement in the LV network, but voltage dips can also be obtained from the monitoring performed at HV/MV substations[10]. In the foreseeable future, smart meters are not expected to be adopted for use in the monitoring of harmonics and flicker in the LV networks. This implies the VQM by smart

[9] This varies between manufacturers and will certainly be subject to future changes. However, most currently available smart meters at LV are not able to monitor the following disturbances: flicker, voltage unbalance (for single-phased meters), harmonic and interharmonic voltage, mains signalling voltage, transient overvoltages and voltage transients, dips and swells.

[10] Voltage swells do not pass through a distribution transformer connecting the MV network to a LV network. Thus, any voltage swell that originates in the MV network will not be experienced by the customers connected in the LV network. In addition, swells are mainly caused by two occurrences: (1) earth faults that cause a drop in the voltage of one phase will often result in a rise in the voltage in the other two phases, and (2) a sudden reduction or disconnection of load followed by a tap-changer operation, which will be most severe for LV customers in remote locations.

meters will always have to be accompanied by VQM by more sophisticated monitoring devices in the LV or MV networks, in order to obtain a complete picture of the VQ experienced by the connected customers.

Once smart meters with VQM capabilities become widely used, then the VQ at the connection point of a much larger percentage of LV customers may be monitored. However, these GGP do not recommend measuring all VQ disturbances at all customers and all of the time. This would result in vast quantities of data and could result in large problems with data management.

Problems due to very large quantities of data can be avoided in at least two ways:

1. The VQ at the connection points of some LV customers should be monitored permanently for statistical purposes. The selection of monitored LV customers could be changed annually on the basis of a rotating system.
2. All LV customers could be monitored on the basis of warning and alarm levels, for example, warning if the levels exceed 90% of the requirements and alarm if the levels exceed the requirements in total.

For the future, we recommend that NRAs include VQ measurements in the functionality of at least a fraction of all installed smart meters. With regard to smart meters, it is important to know whether the measurements are performed in accordance with international standards and/or good engineering practice.

It is important to exploit the possibilities of available and installed smart meters to the extent and benefits possible. However, it should be ensured that VQM through smart meters does not result in an excessive increase in the price of the meters or of the tariffs for network users. CEER and the ECRB do not deem it necessary to monitor all VQ phenomena through smart meters for all LV users.

3.4 Fixed versus portable measuring instruments

Long-term VQM programmes in the LV networks can be set up in two different ways:

1. A limited number of portable monitors can be used to monitor at each location, for example one week before being moved to another location; or
2. A higher number of monitors is used and permanently installed to monitor over a period of years.

VQM programmes based on portable monitors are cheaper in capital costs but likely to be more expensive in operational costs. They will also allow more locations with high levels of VQ disturbances to be found. In at least 14 full days (midnight to midnight) of monitoring, per location and one working day without monitoring between two locations, about 20 locations can be monitored in one year for each monitor. Over a five-year period the number of locations monitored is 100 times the number than if fixed monitoring locations are used.

VQM programmes based on fixed monitors have the following advantages:

- they will give a better overall view of the VQ at each location;
- they will be able to provide information on seasonal variations; and

- they will give information on voltage dips, swells and other relatively rare voltage events.

Due to the huge number of possible measuring points in the LV grid, a compromise of costs and completeness of information is necessary. Therefore, for monitoring harmonics, supply voltage variations, unbalance, flicker and individual rapid voltage changes, using portable monitors is considered acceptable as long as they are combined with a number of locations with fixed monitors to provide information on seasonal variations. To obtain information on voltage dips and swells, fixed monitors are considered necessary.

3.5 Statistical approaches for selection of monitoring locations

If the results from a VQM programme are to be used for statistical purposes (e.g. average or 95% values of disturbance levels), it is important that the selection is statistically relevant and that the sample (i.e. the number of monitoring locations) is sufficiently large.

The following approach is recommended for the selection of monitoring locations[11]:

1. Choose a group of equivalent locations for monitoring, for example the LV customers in the rural parts of a specific network operator[12].
2. Randomly select a number of locations that will be monitored from the set of all possible locations (e.g. all rural LV customers). The minimum number of locations depends on the application and on the level of accuracy that is to be achieved. The following minimum numbers are suggested for each set of locations:
   - 20 if only averages over all locations will be reported;
   - 200 if 95% values[13] over all locations will be reported;
   - 1000 if 99% values over all locations will be reported.

Note that if all locations are selected (e.g. all EHV and HV customers), this is always a statistically relevant selection. Furthermore, it is noteworthy that the number of locations to be selected is independent of the total number of locations. For example, 20 out of 100 EHV and HV substations is an equally valid selection as 20 out of 5 million LV customers.

Monitoring the VQ at a limited number of locations, say *N*, in a system with many locations, can be used to estimate the statistical parameters of VQ indices. Examples of such statistical parameters are the average and the 95% value of a site index (see Chapter 4) over all customers connected to a network.

The larger the number of monitors, the more accurate the estimation of those statistical parameters is. Uncertainty in the estimation of an average value depends on the number of monitors ("number of samples" in mathematical terms) and the spread of the index among

[11] This approach is valid at any voltage level and for any type of network.

[12] For each different group of equivalent locations for monitoring, a new selection of monitoring locations must be made in order to obtain a statistically relevant sample.

[13] The 95% value is the value that is exceeded by only 5% of a population (in the case of VQ monitoring, at 5% of the monitoring locations).

the different locations (in mathematical terms, the so-called “standard deviation” is what matters most)[14]. The error in the estimation is $1/\sqrt{N}$ times the spread among the different locations.

Assuming that most of the values of the index for the different locations, say 90% of them, are within 50% of the average value, they are between 0.5 and 1.5 times the average value. For a VQM programme with 20 monitors, the error (uncertainty) in the estimation of the average would be $50\% / \sqrt{20} = 11\%$. With 10 monitors, the error would be 16%, but with 100 monitors, the error would be 5%.

One of the difficulties is that the spread among the different locations is not known before the VQM programme has started. The decision about how many monitors are needed to obtain a given accuracy thus depends on information that can only be obtained once those monitors are in place. The recommended value, a minimum of 20 monitoring locations, has been based on a compromise between achieving an acceptable accuracy and limiting the number of monitors.

There are well-defined methods for calculating the accuracy of an estimation of the average value. There are no equivalent methods for the 95% value. The actual value is the one where all possible locations (e.g. all customers in the country) are considered. In reality, VQM takes place at a limited number of locations and the 95% value is estimated as the value that is exceeded by 5% of the monitored location[15]. The accuracy of this estimation strongly depends on the distribution of the values, especially the distribution of the highest values. It is therefore important that there are sufficient samples available above the 95% value. The basis of the recommendations in these guidelines is that there should at least be 10 samples available above the 95% value. This requires a total sample size (number of monitors) of 200, as 5% of the population is above the 95% value. Following the same reasoning, there are 1000 monitor locations needed to obtain an acceptable estimate for the 99% value.

3.6 Recommendations

This chapter gives guidelines of good practice for the design of a VQM programme: the guidelines concern the number of monitors, at which locations in the network they should be placed and the length of the measurement period.

In EHV and HV networks, it is good practice to monitor the VQ at all EHV/HV, EHV/MV and HV/MV substations and at the connection points of all EHV and HV customers, producers (power stations) as well as consumers (industrial customers). Given that the number of monitoring points will be relatively small, the costs of continuous VQM at these points in the network are expected to be limited.

---

[14] In particular, the total number of locations has almost no impact on the error, provided this number is “sufficiently high”. See relevant documents about statistics for a more elaborate explanation.

[15] There are alternative estimation methods that result in a higher accuracy. Those methods are not further discussed here, apart from mentioning that most of those methods require some pre-knowledge about the distribution of the values through the population.

In MV networks, these GGP recommend to monitor the VQ at all MV busses of all EHV/MV and HV/MV transformers and at a selection of MV/LV substations and connection points of MV customers. The exact number of measurement locations is expected to vary between countries due to differences in network structure.

In LV networks, it is good practice to monitor the VQ at a random selection of connection points of LV customers throughout the country for a statistically relevant sample. For VQM in the LV networks, it is possible to use both fixed and portable instruments. Portable monitors are considered acceptable as long as they are combined with a number of locations with fixed monitors. Fixed instruments will give a better overall view of the VQ at each monitoring location, but monitoring with portable instruments tends to be cheaper in capital costs and allows the monitoring of more locations. Furthermore, smart meters might become part of VQM in the future. However, smart meters are currently only able to measure a limited set of VQ disturbances.

4 Voltage quality disturbances and indices

This chapter gives guidelines on which phenomena to measure and which characteristics and indices to record. Two international standards prescribe and recommend several options: EN 50160 [8] and EN 61000-4-30 [9]. Recommendations are also found in CIGRE TB261 [10] and CIGRE TB412 [11].

4.1 Disturbances

The VQ disturbances[16] that are treated in the European voltage characteristics standard EN 50160 are reproduced in Table 1 – disturbances treated by EN 50160

:

"continuous phenomena"	"voltage events"
✓ Supply voltage variations ✓ Flicker ✓ Voltage unbalance ✓ Harmonic voltage ✓ Interharmonic voltage ✓ Mains signalling voltage	✓ Interruptions ✓ Voltage dips ✓ Voltage swells ✓ Single rapid voltage changes ✓ Transient overvoltages[17]

Table 1 – disturbances treated by EN 50160

In Table 1, a distinction is made between "continuous phenomena" and "voltage events". Continuous phenomena require continuous measurements, with representative values recorded typically every 10 minutes using the time-aggregation methods prescribed in EN 61000-4-30. Voltage events require a triggering mechanism as well as characteristics to be calculated upon triggering. This is described in detail for voltage dips in the 5th BMR on QoS.

Power frequency is mentioned in EN 50160 but is generally not seen as a VQ phenomenon. The responsibility of maintaining the frequency within narrow ranges - around 50 Hz - lies with the system operator. There are, however, two exceptions for which frequency variations could become a VQ issue. The first exception concerns small islands that are not interconnected to the main electricity network. In this case, it is recommended to monitor

[16] The text of EN 50160 does not give a clear general term for this. In the definitions, the term "conducted disturbance" is given, which is described as an "electromagnetic phenomena". Furthermore, a distinction is made between "continuous phenomena" and "voltage events". In this GGP we will use the general term "disturbance" in line with the 5th BMR on QoS.

[17] The term "transient overvoltage" is used in EN 50160, whereas other documents and also some NRAs use the term "voltage transient". These two terms should not be used synonymously; similarly, measurement methods and methods for characterisation are different. Further technical discussion on this is beyond the scope of this document as such methods are still in an early stage of development.

frequency as well. The second exception is the unlikely event of island operation, where it could be important to have suitable data made available. Most power quality monitors do have the possibility to monitor power frequency. Such data is not of interest for obtaining information on voltage quality, but could be important for the post-mortal analysis of a large black-out or for real or suspected cases of uncontrolled island operation. Suitable indices and characteristics need to be developed for this by the network and system operators.

EN 50160 further treats “interruptions of the supply voltage”; in this report these are not seen as part of voltage quality but as part of continuity of supply. Most power quality monitors do however have the possibility to record short and long interruptions. Such recordings, at or close to supply terminals, can form an important verification for continuity of supply statistics obtained from breaker operations in the grid. This especially holds for short interruptions.

Based on the survey conducted as part of the 5th BMR on QoS and an informal survey during the drafting stage of this GGP, it was concluded that almost no European countries monitor all the disturbances listed in Table 1. However, most European countries do monitor some of the disturbances: supply voltage variations, flicker, harmonic voltage, voltage dips and voltage swells. Different reasons were given in response to the mentioned surveys for selecting the phenomena to be monitored.

As a reason for choosing specific phenomena, reference is typically made to EN 50160 or to the equivalent GOST 13109-97[18].

Whenever a VQM programme is in place, it is good practice to record as many disturbances as the equipment is able to monitor. As already mentioned before, power frequency should, when practically feasible be recorded for other purposes. The same holds for short and long interruptions. Data on power frequency and interruptions will not be used by the regulator for VQ purposes, but it might be useful input for the network or system operator.

4.2 Characteristics

For each phenomenon specific characteristics are calculated from the sampled voltage waveforms. This is typically done in the monitoring instrument so that the user of the instrument often has no control over this and may not always have all the information available about how these calculations are done. The majority of monitoring instruments on the market calculates the characteristics according to EN 61000-4-30, Class A.

4.2.1 Voltages to be used for evaluation

For a measurement in a three-phase system or at the supply terminals of a customer having a three-phase supply, the phase-to-phase, phase-to-neutral and phase-to-ground voltages can be measured. There is more information about the grid operation to be obtained from

[18] GOST 13109-97 “Electric energy. Electromagnetic compatibility of technical equipment. Power quality limits in public electrical systems”.

phase-to-neutral or phase-to-ground voltages. However, for the evaluation of voltage quality, these GGP recommend that the following voltages are used:

- For measurements in solidly-grounded LV networks (which covers the majority of LV networks in Europe) the phase-to-neutral voltage should be used for the evaluation of voltage quality;
- In all other cases, the phase-to-phase voltages should be used.

4.2.2 Continuous phenomena

For flicker, voltage unbalance, harmonic voltage, interharmonic voltage and supply voltage variations, the characteristic is, according to EN 61000-4-30, calculated over a 10-minute interval using specific time-aggregation rules. For flicker, an additional characteristic is obtained over each 2-hour interval. The standard also allows for shorter periods, for example 1 minute. Most European countries use 10-minute values, which is also the default value for most monitoring equipment.

When a window other than 10-minutes is used in VQ regulation, this other window should also be used for voltage quality monitoring. In case of uncertainty of future developments in VQ regulation, a 1-minute monitoring period offers more flexibility. The 10 minutes can easily be obtained from the 1-minute values by using time aggregation rules.

It is also recommended to calculate characteristics over shorter intervals. Some monitors give highest and lowest (1 cycle or 10 cycle) rms voltage for each 1 or 10-minute interval. Especially for supply voltage variations, such information is important for understanding the causes of limits being exceeded, for explaining certain equipment problems and for the setting of future limits.

4.2.3 Flagging

The standard EN 61000-4-30 defines a flagging concept for 10-minute periods during which a voltage dip, a voltage swell or an interruption occurs. This standard only defines the method to be used for flagging, but not the further process for the flagged data.

Not only dips, swells and interruptions result in unrealistic values of some harmonics and interharmonics; flicker severity and unbalance, transients and single rapid voltage changes can have this effect too. At this moment, no standardised algorithm exists to address this, but users are warned to be aware of unexpectedly high single values of harmonic or interharmonic groups, flicker or unbalance.

The following is considered good practice:

- Flagged 10-minute values (or 1-minute values in case these are used) should be removed from the statistics for flicker, voltage unbalance, harmonic voltage and interharmonic voltage.
- The same holds for 10-minute or 1-minute values during which a transient or a single rapid voltage change occurs.
- For supply voltage variations, only flagged values due to interruptions should be removed. All other values, included flagged values due to voltage dips, etc. should be included in the calculation of the indices.

It is also recommended to keep track of the time stamps of values that have been removed from the data. When a large number of values is removed the resulting indices (e.g. over one week) will have limited value and it may be decided to not report those.

4.2.4 Voltage events

Voltage events are characterised by one or more “event characteristics”. For voltage dips, the event characteristics residual voltage and dip duration are defined in EN 61000-4-30. The discussion surrounding additional voltage-dip characteristics has been on-going for many years and despite the reported need for such, especially to quantify unbalance, no standard methods are available. A definition considering the three-phase unbalance is part of a draft version of an Institute of Electrical and Electronics Engineers (IEEE) standard [12] that is currently in the approval process.

Both residual voltage and duration for a voltage dip are, according to EN 61000-4-30, calculated from the one-cycle rms voltage calculated every half-cycle[19]. In a three-phase system this value is obtained for three voltage channels, which could be either phase-to-phase, phase-to-neutral or phase-to-phase voltage (see Section 4.2.1).

The residual voltage is the lowest of one-cycle rms voltages in any of the three channels. The duration is the time during which any of the three one-cycle rms voltages is below a voltage-dip threshold. The standard does not define the value of this threshold, but it is recommended to select it at 90% of the nominal voltage in LV and MV networks and at 90% of the sliding reference voltage (see IEC 61000-4-30 for definition) in HV and EHV networks. The definition of the event characteristics is also illustrated in Figure 2. Voltage-dip characteristics are discussed in more detail in the 5th BMR on QoS.

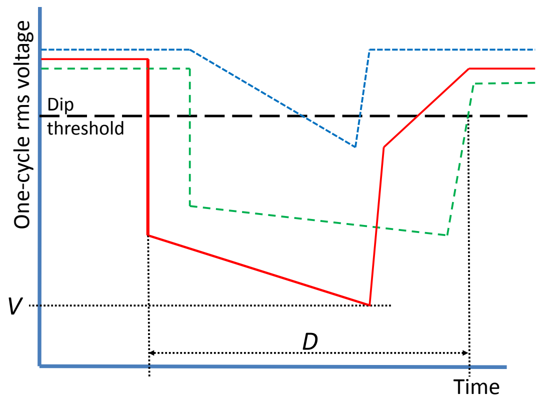

Figure 2 – Voltage-dip characteristics in a three-phase system according to EN 61000-4-30: D is the dip duration; V is the residual voltage. The red solid, green dashed and blue dotted lines indicate the one-cycle rms voltage for the three voltage channels.

[19] For equipment class A. Somewhat lesser requirements exist for Class S.

For voltage swells, the event characteristics defined in EN 61000-4-30 are "maximum swell voltage" and "swell duration". Like for voltage dips, they are calculated from the one-cycle rms voltage. The highest value of this voltage is the maximum swell voltage; the duration is the time during which the one-cycle rms voltage is above a voltage-swell threshold in at least one of the voltage channels. It is recommended to choose the voltage swell threshold equal to 110% of the nominal voltage in LV and MV networks and at 110% of the sliding reference voltage in HV and EHV networks.

No standardised methods exist at the moment for calculation of characteristics for transient overvoltages, mains signalling voltages or for single rapid voltage changes. Characteristics for single rapid voltage changes are defined in Norwegian and Swedish VQ regulations. Characteristics for single rapid voltage changes and for mains signalling voltage are included in the latest draft of EN 61000-4-30 (February 2012).

There are no known developments towards standardised methods for calculating characteristics of transient overvoltages. When such events are recorded, it is important to clearly indicate how the characteristics have been calculated.

4.3 Indices

A number of VQ indices are drawn from characteristics obtained over a longer period, as mentioned in Section 4.2. This period can range from one day to several years, but one week and one year are the most common periods used. These "site indices" and "system indices" are a measure of the VQ at one location over a longer period of time. Also, for the calculation of indices, a different approach is used for continuous phenomena and for voltage events.

4.3.1 Continuous phenomena

From the 1-minute or 10-minute values recorded over a longer period (e.g. one week or one year), one or more statistical indices can be obtained. The average value would be an obvious choice, but the average is rarely a good indicator for VQ. Using high-percentile values like 95% or 99% would be more appropriate. The reason for this is that the impact on end users is determined mainly by the higher values; however a widely-held opinion is that extreme values are not indicative either. Another reason for not considering the highest values is that they can be due to measurement artefacts that passed the flagging process or in case no removal of flagged data has taken place.

Next to high percentile and extreme values, the number of percentage of values exceeding a threshold can be used as an index. In some cases, it is also worth considering the number of consecutive values exceeding a threshold. The threshold may be the limit according to the local VQ regulations or a lower value.

For harmonic and interharmonic voltages, an informative annex with EN 61000-4-30 (Annex B) suggests to use a daily assessment of the 3-second values, next to the assessment of 10-minute values over of period of one week or longer.

Annual indices may be obtained through a two-stage process. As a first stage, daily or weekly values are obtained, for example the weekly 99% values. During the second stage, an annual index is obtained from the daily or weekly values, for example the highest daily or weekly 99% value.

The compliance testing according to EN 50160 uses 99% or 95% values over one week and compares these with the objective. As a result, 99% or 95% values and one-week measurement periods are common in many European countries.

Several European countries report specifically when a site does not comply with the requirements. These requirements can be either the EN 50160 requirements or stricter requirements that are set in national regulation. For a specific location, the number of weeks per year during which the requirements are not complied with can be used as an indicator. Alternatively, for each week of the year, the number of percentage of sites for which the requirements are not complied with can be used as an indicator. The latter can be used to study seasonal variations in VQ.

To study trends in VQ it is good practice to introduce additional indicators that quantify when the levels exceed, for example, 75% or 95% of the limit values.

For each voltage level, VQ indices can be calculated based on the number of sites and weeks not complying with the requirements. The index gives the percentage of sites and weeks for which the requirements are complied with; it can be calculated as follows:

$$I_{KEE} = \frac{\sum_{i=1}^{N}(N_i - W_i)}{\sum_{i=1}^{N} N_i}$$

where W_i is the number of weeks of non-compliance at location i, N_i the number of weeks of monitoring at location i and N the number of monitor locations.

Separate VQ indices can be calculated for supply voltage variations, harmonic voltage and flicker. The equation which can be used is the same as the previous one; the difference being that W_i is than the number of weeks of non-compliance for supply voltage variations, harmonic voltage and flicker, respectively.

4.3.2 Voltage events

4.3.2.1 Voltage dips

For voltage dips, characteristics (typically residual voltage and duration) are calculated for each triggered event. Over a longer period, (typically one year) site indices are calculated. Site indices give the number of events per year with certain characteristics. According to EN 50160 the number of voltage dips per year shall be calculated for each of the cells.

The calculation of site indices and system indices for voltage dips is discussed in the 5th BMR on QoS. A common method is to give the number of dips per year for each of the cells in the voltage-dip table recommended in EN 50160. Such tables can be reported for each of the sites at which monitoring takes place, as an average across all sites and for a number of percentiles (e.g. the 75 and 95 percentile). Also, other national experiences show that the highest number of dips at one particular location can be reported for each of the cells in the voltage-dip table or that annual statistics on voltage dips can be reported for geographical regions. Further classification can be made based on the type of network user (consumer, producer, distribution network and railway) and based on the origin of the voltage dip (network user, network, lightning, other weather phenomenon, other).

4.3.2.2 Voltage Swells

According to EN 50160 the number of voltage swells per year shall be calculated for each of the cells.

A distinction can be made between "major swells" and "minor swells" in the same way as was proposed for voltage dips in the 5th BMR on QoS. A possible distinction is shown in Figure 3. This curve can be used to distinguish between "minor swells" and "major swells". Separate statistics on each of these should be used for comparing performance between network operators and to track trends in VQ performance.

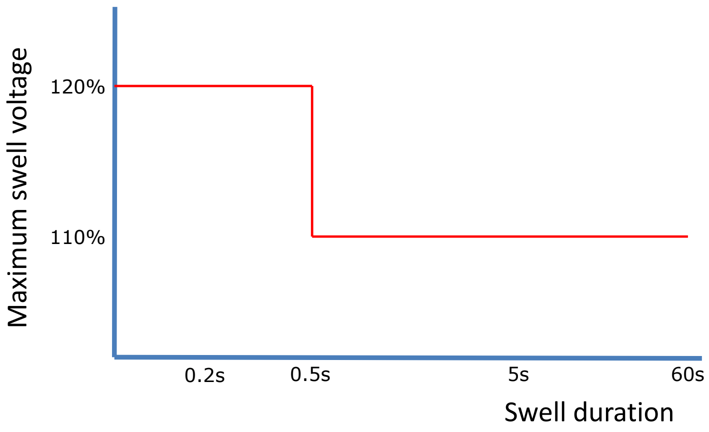

Figure 3 – Example curve to distinguish between minor and major voltage swells

4.3.2.3 Rapid voltage changes

For rapid voltage changes, possible indices for one location are the number of events exceeding a certain magnitude for each day. Over a one-year period, the average value, a high percentile value and the number of days during which a certain number of events is exceeded, can be used.

4.3.3 Number of Complaints

The number of customer complaints with respect to voltage quality can be recorded, as well as the number of justified complaints. The number of justified complaints, as a share of the total number of customers, could be used as an indicator.

Indices on customer complaints are a useful source of feedback for DSOs and NRAs but should not be used for benchmarking purposes because of the difficult nature of quantifying and comparing complaints.

4.3.4 Indices for Benchmarking

In Annex 3, a set of indices is proposed that can be used for benchmarking the performance of different network operators and of different countries. It is recommended to calculate and publish these indices as a minimum, whenever the number and selection of monitoring locations makes this possible. In addition, it is recommended to calculate and publish additional indices based on local and national circumstances, for example based on compliance with national regulation.

Most of the indices proposed are calculated for LV and MV networks. It is recommended to calculate similar indices for HV and EHV networks whenever data from sufficient monitoring locations is available.

In Annex 3, a large number of indices are defined; site indices as well as system indices. The site indices are only calculated as an intermediate step. The indices for benchmarking, that would need to be reported during benchmarking, are the system indices. The site indices might be used internally by a network operator or within a country for benchmarking of individual sites.

Only the system indices results in a significant number of indices and reporting them may appear a rather tedious process. However, the amount of data to be recorded and stored is, at most, only slightly impacted by the large number of indices. Also, the amount of computing power to calculate the indices is very limited.

The relatively large number of indices is needed to be able to benchmark the multiple dimensions of voltage quality.

Similarly, the proposed indices are not intended to serve for tariff regulation; so again the number of indices is not really a key concern.

4.4 Recommendations

The following is considered good practice by CEER and the ECRB:

- ✓ When setting up a VQM programme all disturbances as listed in EN 50160, see Section 4.1, should be monitored. The lack of standardized measurement methods for some disturbances (most notably voltage transients and transient overvoltages) makes benchmarking impossible, but does not prevent feedback to network operators and NRAs on the performance of the network.
- ✓ Follow the standards whenever possible
- ✓ Use a broad set on characteristics and indices, beyond what is used for reporting or benchmarking. Even here there is no need to be limited to standard methods, but standard methods should be included.
- ✓ Use commonly-agreed indices for benchmarking.

5 Reporting of the results

In general, there are several different parties interested in the performance of networks concerning VQ:

- In particular NRAs should have detailed information about VQM results for the different applications discussed in Chapter 2. For example, for system performance monitoring or in cases of disagreements between users and network operators concerning VQ, it could be helpful for NRAs to have VQ data available to perform independent investigations. Therefore, it is important that NRAs have access to the raw data from any network operator whenever needed. In addition, the NRA is interested in information about VQ at system-level, in order to obtain detailed knowledge about the general grid performance. Therefore, it could be useful for NRAs to collect VQ data from network operators.
- Network operators also have a need for VQ data. Nowadays, the requirements that have to be fulfilled by networks are rapidly changing; for example due to increasing amounts of decentralised power generation. Therefore, the network operators knowledge about the current level of VQ and its development is becoming more important, allowing them to take further steps in case of VQ decline. The need for VQ data by the network operator means that any network operator should have access to all data concerning its own network and the customers connected to that network.
- Individual network users have an interest in data concerning voltage quality at their point of connection, current or future connection. The interest from individual network users is limited, as long as there are no adverse consequences of high levels of VQ disturbances. Furthermore, it will be difficult for many domestic and small commercial customers to make use of VQ data. The main interest will come from medium sized and large industrial customers, whose industrial processes can be disrupted by certain disturbances. In these cases, VQ data allow users to properly design their plants. These disturbances are mostly voltage dips and transients due to faults and switching actions in the grid. However, LV customers connected, for instance, to rural lines of the network may suffer from supply voltage variations, voltage swells and transient overvoltages.
- Identified trends or regional VQ may be of interest to the general public and other stakeholders. Therefore, it might be useful if the reports and studies are published to inform the public of the status of VQ in their country.
- Research and education institutions are interested in extensive raw data sets on VQ for their studies as described in Section 2.11.6.

5.1 Reporting and publishing data

Reporting and publishing VQM results, as a simple regulatory instrument of VQ regulation, is recommended in CEER (and joint ECRB) Benchmarking Reports on QoS as a first step towards VQ regulation based on economic incentives.

In European countries, there exist different rulings concerning the reporting and publication of VQ data by the DSOs/TSOs. In some countries, DSOs/TSOs must report their individual VQ results on their websites, in reports, to the NRA and/or to industrial customers if contractually bound. In other countries, DSOs/TSOs only monitor the VQ in their networks on a voluntary basis for internal use and they may or may not publish the results. In other

European countries, no VQM exists at all. In most of the European countries that do have VQM systems installed, VQM results are still not regularly published.

It is a complex technical challenge to implement national VQM involving all DSOs/TSOs. As a result, it must be ensured that data is collected and published in a uniform manner. Therefore, it is necessary to establish uniform rules for VQ data which will be:

- reported by the DSOs/TSOs to the NRA or research institutions; and
- published by NRAs or by DSOs/TSOs on websites or in reports.

Chapter 2 recommends that a national VQM programme should be designed and implemented through a centralised approach with the involvement of all interested and responsible parties for VQ monitoring and regulation, taking into account scope of monitoring and the amount of data that have to be collected. For regulation purposes, it is recommended that VQ data is reported to the NRA. The NRA could act as a “collection point” for the results of VQM from the different DSOs/TSOs. The NRA should be given the right to audit the reported (raw) data. The centralisation of the VQ data of all DSOs/TSOs in one database would make it simpler to compare and analyse.

Before the results are reported to the NRA or published, the completeness and plausibility of the collected data must be ensured by the party responsible for the VQM.

VQ data can be published by:

- NRAs;
- DSOs/TSOs;
- other organisations.

The publication of VQM results can be useful before other regulatory instruments, like standards or incentive mechanisms, are established. Comparative publications of VQM results may incite network improvements (see Section 5.6).

It is recommended that the NRA regularly publishes the results of individual network operators, at least at a national level (see Section 5.4). This should improve the public perception of VQ and increase network operators’ and customers’ awareness. As a minimum, NRAs should implement a consistent VQM ruling for the publication of data. A uniform publication methodology is as important as a uniform reporting methodology, in order to compare and analyse the collected data. If different reporting and publication methodologies are used it is necessary to publish these inconsistencies as well [7].

Generally, it is recommended that additional useful information and findings concerning VQ are published with VQ data. This additional information may contain current national standards and explanations (e.g. concerning VQM period, VQM equipment, aggregation level of published data).

Reporting and publishing obligations should be clearly legally defined and overlapping of responsibilities should be avoided.

5.2 Details of data to be reported

The recommended level of detail of VQ data to be reported depends on their use and should take into account the following scopes:

1. Publication of VQ data on a national or regional level by the NRA.
2. Publication of VQ data for research purposes.
3. Reporting to single customers regarding the VQ on their connection point.

For the publication of VQ data on a national or regional level (for example per TSO or DSO), the VQ data recorded from several monitoring sites should be aggregated and analysed, for example using the set of indices for benchmarking proposed in Chapter 4. In the case where the NRA or TSO/DSO makes the VQ data publicly available, it is recommended that aggregation of the VQ data should prevent information on the electrical processes of individual (industrial) customers behind the connection point to become widely known. In addition, any publication of VQ data on a national or regional level should contain all of the VQ parameters that are monitored in the national/regional monitoring programme. An analysis of the published data should also not be missing in this publication.

On one hand, transparency should be a driver pushing VQM; on the other hand privacy issues can limit the publication of data. Particular attention must be paid to what data should be kept anonymous, especially when data of individual customers behind the connection point is concerned.

Also, publication of data for research purposes should be aggregated to such a level as to not reveal too much information of individual (industrial) customers as well. This means that for some monitoring sites in HV or MV networks, raw VQ data should not be published and access should only be made possible through protected mechanisms.

For the reporting to a single customer of VQ data on its connection point, it is recommended that the report contains the raw data. Furthermore, VQ data on the single connection point might be compared to VQ levels of similar connection points in neighbouring networks or to the national VQ levels of similar connection points. When no data is available for the connection point of a specific customer, and this customer requests data, results from one or more nearby monitoring points should be provided, yet ensuring the privacy of other customers. In these cases, it should be indicated to the customer that VQ at its connection point might differ from VQ at the monitor locations. Alternatively, sufficient network data should be made available to the customer that requests it, to make such an assessment.

Regarding the detail of reporting of data on supply voltage variations, it is recommended to consider publication of the following information:

- The number of monitoring sites with a voltage outside a given range for more than a given percentage of time for each week of a given period;
- The number of monitoring sites with voltage outside a given range for more than a given percentage of time for one, two, three or more weeks.

The aggregation criteria used for supply voltage variations could be extended to other VQ disturbances like flicker, harmonics, voltage unbalance, etc.

5.3 Criteria of aggregation

Aggregation of VQ data may be based on different characteristics of monitoring sites in the VQM programme. Therefore, a characterisation of each monitoring site, in terms of specific network parameters, is suggested. The measured VQ disturbances may then be correlated with these specific network parameters:

- Type of network (cable / overhead / mixed);
- Length of network cables;
- Type of system earthing (isolated neutral/ compensated);
- Voltage level (EHV / HV / MV / LV);
- Type of customer (household / small business / industrial);
- Distributed generation (present / high / low / absent);
- Degree of customers with self-generation (yes / no);
- Type of region (urban / suburban / rural);
- DSO (small, medium, large).

By selecting one or more criteria of aggregation, it is possible to correlate one VQ disturbance to one or more basic parameters. For example, for voltage dips, it is of interest to compare the behaviour of cable and overhead lines, the difference between HV networks and MV networks and performances of different DSOs or different regions. For supply voltage variations, it is of interest to report the effects of the presence of distributed generation in the networks, as well as the difference between short and long lines.

In order to obtain studies and reports of high quality and detail, it is worth thoroughly analysing the characterisation of monitoring sites when setting up new VQ monitoring programmes.

5.4 Frequency of reporting

The recommended frequency for reporting of VQ data should take into account the following scopes:

- Research and demonstration;
- Regulation and implementation;
- Individual measurements.

For the publication of aggregated VQ data, that should be publicly available, these GGP recommend publishing a report at least once a year. The report should also contain an analysis of the observed trends.

For the publication of aggregated VQ data for the use by universities and other research institutions, it is good practice to make this data available online frequently. This will allow research institutions to have access to the most recent VQ data available.

For the publication of individual data upon request by the customer, it is recommended that the frequency of reporting be agreed *ex-ante* between the customer and the network operator. In many European countries, customers may request VQ monitoring by the network operator at their connection point, often at additional cost. It is further recommended that the network operator provides the customer with VQ data at least monthly, but preferably daily or after every major disturbance. Alternatively, the customer could be given access to the data for its own connection point.

5.5 Methods of reporting

The chosen method of reporting strongly depends on the objectives of the VQM programme (for example: research/demonstration, implementation/regulation, individual measurement) and the duration of the VQM programme.

The internet seems to be a common and powerful platform for the publication of data. For research or demonstration purposes, it is recommended that the website of the NRA or the research centre which performs the monitoring programme should be used for the reporting of results. In this case, it is advisable to make only aggregated data available to the general public. As already mentioned, for reasons of privacy the publication of individual (or single monitoring site) data should be protected through online security mechanisms (e.g. a user-specific password). In general, mechanisms should be in place to protect the interests of the network operator and of individual customers. This could be achieved, for example, by not revealing the exact measurement location.

For implementation or regulation programmes, in addition to the website of the NRA or research centre, data could be published on the respective websites of network operators as well. This published data should also comply with the recommendations regarding aggregated and single measurement location data as described above. It is recommended that the publication of VQ data by network operators be made mandatory by the NRA according to *ex-ante* rules.

Other ways to be considered for the reporting of VQM results are periodic reports on paper or press releases by the NRA or TSO/DSO. In the case of VQM programmes for implementation or regulation, attachments to bills or customer dedicated pages on the websites of network operators are advisable. From these web-pages, but through security mechanisms, customers may also be informed about VQ data at their connection points.

The duration of the monitoring programme has an impact on the frequency of publication.

5.6 Comparative publications

Comparative publications are possible for aggregated data (see Section 5.3) in order to compare performances.

Comparative publications are advisable only for implementation or regulation programmes, where publication rules have to be known ex-ante, or for programmes where the monitoring activity has reached a minimum level of “maturity”[20]. Such comparative publications are assessable only by the regulator, for all network operators.

[20] In principle, the guarantee that the same VQ disturbance is recorded in the same way by all network operators, starting from the hardware installation of VQ monitoring devices and current/voltage transducers until its final storage in the control centre in the required data format.

In principle there are two main objectives behind comparative publications:
- Pushing improvements in networks, especially those with worse performances in respect to those with better performances (reputation lever);
- Giving preliminary information to end-users, thus facilitating the choice of the installation of their productive facilities according to the measured voltage quality available in different sites.

Further objectives can be identified in:
- Analysis of behaviours of different aggregations;
- Study of remedies.

5.7 Usability of data

To make the analysis of VQ data possible, even in an aggregated way, their usability is of paramount importance, especially if they come from monitoring systems of different manufacturers or if network operators provide multiple data. In other words, reporting should also allow for the easy merging of data coming from different systems.

Achieving the use of a common data format by all parties is essential. Statistical time-efficient data analysis is facilitated by a common data format. The use of a common data format is facilitated by avoiding the use of proprietary software or data base or communication protocols between VQ monitoring devices and the control centre. In this context, attention should be paid also to interoperability and scalability of systems when the number of monitoring devices exceeds several dozen. Therefore, reporting should be harmonised and standardised. NRAs should promote harmonisation and a common format to:

(i) collect data;
(ii) publish data (data interpretation/collection);
(iii) report data to NRAs;
(iv) use data for benchmarking.

One aspect that deserves to be mentioned is the possibility of making available on-line queries with parameterisable and flexible data aggregation criteria. This system capability is powerful as it allows targeted data drawings, immediately ready for statistical analysis.

5.8 Recommendations on reporting and publishing

The following is considered good practice by CEER and the ECRB:

- NRAs should publish the main results from VQM programmes, including compliance with VQ regulation and observed trends, in a report at least once a year.
- A centralised approach should be used in designing data collection and reporting systems.
- Data should be made available to all interested parties, when necessary, according to security mechanisms aiming at protecting the interests of network operators and of individual customers.
- Initiatives should be taken in order to inform users about their responsibilities.
- The use of the internet is strongly encouraged for the publication of VQ data.

- Comparative publications are recommended for pushing improvements in networks and giving suitable and preliminary information to end-users.
- Avoid the use of proprietary software of VQM systems, facilitate interoperability and promote standardised common data formats.

6 Financing of voltage-quality monitoring

The implementation of a national VQM programme and the reporting of results improves the transparency of distribution system operators activity and performance, whilst providing additional information to customers that can use it, for instance, to choose the best location to get connected to the network or to decide, during the purchase process of equipment, the respective degree of immunity to voltage disturbances. However, in spite of all electricity consumers benefiting from national VQM programmes, it is in the industrial consumers' perspective that those benefits are more evident and easily assessed.

It becomes clear from the applications presented in Chapter 2, that there are benefits to be gained from implementing a national VQM programme; however, there are also costs associated and, therefore, financing frameworks must be considered in order to ensure effective implementation. The definition of a VQM financing framework should include two main steps: the costs assessment and the respective financing plan.

6.1. VQM Costs Assessment

In analysing the financing framework of a national VQM programme, costs of VQM are assessed through carrying out an inventory of the whole costs associated to the VQM programme implementation (capital expenses) and maintenance (operational expenses). Considered capital costs comprise of VQM device and installation costs, while operational expenses consist of calibration, data collection, transmission, analysis and storage, as well as the results dissemination costs.

a) Survey for European countries

In order to assess the costs of the national VQM programmes implemented in the different European countries, a questionnaire was sent to NRAs inquiring about the respective capital and operational costs. Some countries have submitted answers with the available VQM programme costs. However, most NRAs with VQM programmes informed that the respective costs are not, or not yet, available.

The answers submitted by different European countries comprise of the capital and the operational expenses of their VQM programmes. Since the expenses presented by the different NRAs are not harmonised, direct conclusions cannot be drawn. However, the data collected is useful for estimating the costs of implementing a national VQM programme.

According to the data collected, the capital cost of a VQM programme, per monitoring device (including installation), is between 3 000 and 15 000 Euros. The reason for such a wide range of capital costs is not fully clear, however, it is observed that the costs are influenced by the class of measurement and the ability to measure the voltage and current characteristics. Class A devices for measuring voltage and current characteristics present costs exceeding 10 000 Euros. However, capital costs decrease when only voltage is monitored and when class A is not required. In that case, capital costs per monitoring device can be limited to 3 000 Euros.

The survey has established that besides the capital costs of devices, the installation cost corresponds to approximately 25% of the capital costs

The life-time of a VQM device is, according to the experience of some NRAs, about 10 years, mainly due to disruptions in the software used by the device.

Regarding operational expenses, figures submitted by the different NRAs lead to an annual expenses range between 375 and 1 500 Euros per device. This wide range is due to the fact that different NRAs include different types of costs in their figures.

In one of the surveyed programmes, the inventoried operational expenses, 375 Euros/device per year are associated with data transmission (35%), storage and analysis (35%) and with the hardware and software maintenance (30%).

In another country, in which the overall annual operational expenses are estimated at 1 000 Euros/device, besides the data transmission and the hardware and software maintenance expenses, the cost of the class A device calibration was also reported. According to the reported data, this calibration should be performed every two years and its cost corresponds to 750 Euros, representing an operational expense of 375 Euros/device per year. This expense with calibration has the same magnitude as the overall operational expenses reported in the programme described above.

Information on portable measuring programmes costs was only available from a small number of European countries. In one case, 500 Euros operational expenses were declared. Those expenses refer to a single week measuring campaign per device. In another case, 3 500 Euros annual operational expenses per device were declared. This value comprises of the expenses with the device install/uninstall, calibration, maintenance and data transmission for 3 months measuring campaigns (4 different locations per year).

b) Estimation for a hypothetical medium-size European country

Based on some of the data reported by the different countries, it is possible to estimate the costs associated to a national VQM programme implementation in a hypothetical medium-size European country. For such estimation, it is assumed that in the country, the grid comprises of 150 EHV/HV substations, 650 HV/MV substations, 5 000 MV feeders, 120 000 MV/LV transformers and 10 million customers. Assume also that the reference annual expenses for that grid are 83 Euros per customer for the capital expenses and 70 Euros/customer for the operational expenses.

If the national VQM programme, as recommended in Chapter 3, covers all the EHV/HV and HV/MV substations and also covers 0,5% of the MV/LV transformers, the number of measurement devices to install is about 1 400 units.

Considering a capital cost between 5 000 and 10 000 Euros/device with a 10 year life-time and a 10 year plan to roll out the national VQM programme, capital expenses between 0,7 and 1,4 million Euros per year are obtained. This investment represents between 0,08% and 0,17% of the 830 million Euros to which correspond the overall capital expenses with the grid in one year.

Regarding the national VQM programme operational expenses, they represent 525 000 Euros per year, the equivalent to 0,08% of the annual operational expenses of the grid, 700 million Euros. These costs are computed considering the 1 400 installed units, each one with operational expenses of 375 Euros/year. However, if the device calibration cost (375 Euros/year) is added to the expenses above, the total national VQM programme operational expenses double, representing 0,15% of the annual operational expenses of the grid.

This example of estimating expenses for a national VQM programme implementation in a hypothetical medium-size European country is performed considering a completely new VQM programme. However, this is not the case in most European countries because they have already some kind of VQM programmes running. In such countries, only an expansion of their programmes is required and, consequently, lower expenses are expected.

6.2. Financing Framework

The implementation of a national VQM programme, due to a large number of grid sites intended to be measured, implies some investment in the device, as well as some maintenance costs.

With the objective of determining which mechanisms are used to finance the national VQM programmes underway in the different European countries and identifying which entities are responsible for defining and approving those financing mechanisms, a questionnaire was sent to NRAs.

Regarding the identification of the entities responsible for defining the financing framework and its approval, the questionnaire answers show that in most European countries the TSOs and DSOs are responsible for designing such mechanisms, while the NRA is responsible for approving it within the TSOs and DSOs annual budget or over a regulatory period.

It also should be mentioned that, in the NRAs answers, it is highlighted that when the TSOs and DSOs submit their annual budget for approval, the investment associated to the VQM programme is not clearly indicated.

According to the information submitted by NRAs, most national VQM programmes are financed by grid tariffs, mostly with the contribution of all connected customers (socialised costs). Another practice can be that a VQM programme relies on the support of national and/or European research funds.

The fact that a national VQM programme is being financed by the use of grid tariffs, as is the practice in most European countries, may lead to a sense of unfairness for some of the connected customers, namely residential customers, as they do not expect to receive direct benefits from national VQM programme implementation. However, well designed grid tariffs can avoid this issue and evenly distribute the expenses of a national VQM programme across the different types of customers.

Assuming that in most European countries the industrial customers, which are the main direct beneficiaries of a national VQM programme implementation, represent less than 5% of all the customers and more than 50% of the annual consumed energy, spreading national VQM programme expenses by the consumed energy is an example of a fair incorporation of the costs into the tariffs. This approach enables an almost negligible cost increase per consumed kWh and, simultaneously, enables customers to contribute to the national VQM programme expenses in proportion to their energy consumption. Also, spreading costs by ratio of subscribed power or maximum hourly consumption per month gives a fair incorporation of the costs into the tariffs.

6.3. Recommendations

According to the questionnaire results, for most NRAs with national VQM programmes underway, the expenses for their programmes are not available. In this regard, it is recommended to for NRAs to follow their national VQM programmes and to keep an inventory of the respective expenses.

According to the current practice in most European countries with national VQM programmes underway, it is a reasonable approach to allocate the costs of a national VQM programme to all connected customers throughout the use of grid tariffs, provided that those costs do not exceed 0,2% of the capital and operational expenses of the grid and most customers benefit from the implementation of such programmes.

However, in order to better balance the costs and benefits of the different type of customers and avoid some sense of unfairness of the connected customers that do not expect direct advantages from a national VQM programme implementation, special attention should be given to grid tariffs design.

The experiences reported in this GGP demonstrate that in most European countries, NRAs are responsible for approving the annual budget for national VQM programmes. However, the figures of such investments should be more detailed and transparent.

It is further recommended that network operators, where needed in cooperation with research institutes and universities, develop methods to apply VQM data towards a more cost-effective planning and operation of the electricity network. The results from this development should be disseminated, at least, at a European level.

7 Conclusions

This chapter summarises the main findings and conclusions from these guidelines. More detailed findings and recommendations are also found in the individual chapters.

1. Voltage quality monitoring programmes are important tools for voltage quality regulation

Voltage quality is an important aspect of the service network operators provide to their connected customers. As such, network operators should be transparent about the level of quality they deliver. Voltage quality monitoring programmes can facilitate the delivery of such transparency.

There are sufficient applications regarding regulation introduction, regulation enforcement, research and transparency to justify countries implementing a voltage-quality monitoring programme. The costs of such a programme, along the lines proposed in Chapter 3 and as shown in Chapter 6, are a small part of the total costs of operating the electricity networks.

Such a monitoring program can be fully run by network operators, or installed by the NRA and operated by the network operator with NRA access to the data. Which option is most appropriate depends on national circumstances.

2. All possible applications should be kept in mind

When setting up a VQM programme it is important to consider all possible applications, for example according to the list in Chapter 2. Even if the purpose of a programme is initially limited, small changes in the set-up of a programme or of parameters recorded or calculated, can allow future applications at no or very small extra cost. The setting up of such a programme should be done in close cooperation between NRAs and stakeholders, especially network operators.

3. Voltage quality monitoring programmes should be funded through network tariffs

It is deemed that the benefits, with regards to the wide range of possible applications, outweigh the costs of VQM programmes, as shown in Chapter 6. The most appropriate way of funding such a programme is through network tariffs. This can however vary between countries based on the local tariff structure and regulation.

4. Results should be made available regularly

Publication of the results and making data available in other ways, as discussed in Chapter 5, are important parts of a VQM program. These GGP recommend that the main results from the program, including compliance with VQ regulation and important trends, are published in a report at least once a year. Such a report can be published by an NRA, network operators or transmission system operators and combined with similar reports on continuity of supply and/or commercial quality.

In addition, data should be made available to other stakeholders, including the general public. Where no objections from individual network users or other important objections exist, all data should be made available for free or at a reasonable cost, for research and education purposes.

5. Diversification of indices and methods is to be avoided

A number of VQM programmes have already been launched in some European countries. There are large differences between these programmes making it difficult to compare the results. Such a diversification also makes it more difficult to exchange knowledge and experiences.

The GGP strongly recommend that VQM programmes are harmonised according to the proposal in Chapters 3 and 4. The need for harmonisation applies to, among others, the choice of monitor locations, types of disturbances monitored, characteristics recorded and indices calculated.

Beyond the list of indices for benchmarking, which is recommended as a harmonised set of indices to be obtained from every programme where possible, each European country is recommended to obtain additional indices that specifically reflect the local circumstances.

Annex 1 – CEER and the ECRB

The Council of European Energy Regulators (CEER) is the voice of Europe's national regulators of electricity and gas at EU and international level. Through CEER, a not-for-profit association, the national regulators cooperate and exchange best practice. A key objective of CEER is to facilitate the creation of a single, competitive, efficient and sustainable EU internal energy market that works in the public interest.

CEER works closely with (and supports) the Agency for the Cooperation of Energy Regulators (ACER). The forerunner to ACER was the European Regulators' Group for Electricity and Gas (ERGEG). ERGEG was established by the European Commission in November 2003 (Decision 2003/796/EC), as its formal advisory group of energy regulators on Internal Energy Market issues. With ACER fully operational since March 2011, ERGEG was dissolved by the Commission, with effect from 1 July 2011 (Decision of 16 May 2011, repealing Decision 2003/796/EC). Some of ERGEG's works passes to ACER (e.g. the Regional Initiatives) and some (such as the work formally carried out by the ERGEG Electricity Quality of Supply and Smart Grids Task Force) to CEER.

ACER, which has its seat in Ljubljana, is an EU Agency with its own staff and resources. CEER, based in Brussels, deals with many complementary (and not overlapping) issues to ACER's work such as international issues, smart grids, sustainability and customer issues.

The work of CEER is structured according to a number of working groups and task forces, composed of staff members of the national energy regulatory authorities, and supported by the CEER Secretariat.

Commission Decision establishing ERGEG
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:296:0034:0034:EN:PDF

Commission Decision dissolving ERGEG
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:129:FULL:EN:PDF

The **E**nergy **C**ommunity **R**egulatory **B**oard (ECRB) is an Institution of the Energy Community established by Article 58 of the Energy Community Treaty. The ECRB takes the role of a coordination body of the national regulators of the Energy Community for exchanging knowledge and developing common best practice solutions for implementing the Energy Community Treaty in a harmonised way.
The Energy Community extends the EU internal energy market to South East Europe and beyond. The general **objective** of the Energy Community is to create a stable regulatory and market framework in order to attract investments for a stable and continuous energy supply; create an integrated energy market allowing for cross-border energy trade and integration with the EU market; enhance security of supply and competition; and improve the environmental situation. The Contracting Parties have committed themselves to implement the relevant *acquis communautaire* on electricity, gas, renewables, environment and security of supply. In addition energy efficiency and new aspects of renewable energy are discussed.

The key objective of the cooperation of energy regulators within the ECRB is to support the harmonized development of regulatory rules in the Energy Community.
Within the necessary range of national specificities, **streamlining of regulatory measures and providing a stable regulatory market framework** remains a key promoter for market integration, facilitation of investments, competition and security of supply.
The activities of the ECRB are characterised by the following **objectives and priorities**:

- Development of competitive national gas and electricity markets
- Integration of national markets and development of competitive regional markets in electricity and gas
- Identification and abolishment of barriers for cross border trade and competition
- Protection of customers and social issues
- Regulatory aspects of security of supply
- Network security and quality of service
- Regulatory aspects of renewable energy and energy efficiency

For further information please refer to www.ecrb.eu and www.energy-community.org.

This report was prepared by the Electricity Quality of Supply and Smart Grids Task Force of CEER's Electricity Working Group in cooperation with the ECRB's Customer Working Group.

Annex 2 – List of abbreviations

Term	Definition
CEER	Council of European Energy Regulators
GGP	Guidelines of Good Practice
NRA	National regulatory authority
VQ	Voltage quality
VQM	Voltage quality monitoring
LV	Low voltage
MV	Medium voltage
HV	High voltage
EHV	Extra high voltage
ECRB	Energy Community Regulatory Board
EnC	Energy Community
TSO	Transmission system operator
DSO	Distribution system operation
kWh	Kilo watt hour
rms	Root mean square
5th BMR on QoS	5th CEER Benchmarking Report on Quality of Electricity Supply (a joint deliverable with the ECRB)

Annex 3 – Indices for Benchmarking

1. **Supply voltage variations**

For benchmarking purposes, locations in the LV and MV network should be considered, with a preference for locations at or close to the supply terminals of domestic customers whereby separate indices for LV and MV networks should be calculated. Locations should be selected using the methods described in Section 3.5.

The rms voltage should be calculated over a 10-minute period as defined in EN 61000-4-30. Flagged values due to interruptions should be removed from the statistics (see also Section 4.2.3).

For every monitor location, the 0.5% and 99.5% values over one calendar year should be used as site indices.

For every monitor location, the following site indices should be calculated over each calendar year:

- ✓ The 0.5% value of the min and max 10-minute rms voltages over the year;
- ✓ The 99.5% value of the min and max 10-minute rms voltages of the year;
- ✓ The number of 10-minute rms voltages that are at least 110% of the nominal voltage;
- ✓ The number of 10-minute rms voltages that are at most 90% of the nominal voltage.

In a three-phase system, these four indices should be calculated for each of the three voltage channels (phase-to-phase or phase-to-neutral, depending on the voltage level). The lowest of the three values of the first index and the highest of the three values for the other three indices should be used as a basis for calculating the system indices below.

For a system with at least 20 monitor locations, the following system indices should be calculated for each calendar year:

- ✓ The 5% value of the 0.5% site values;
- ✓ The 95% value of the 99.5% site values;
- ✓ The 95% value of the number of 10-minute rms voltages per site at least 110% of nominal;
- ✓ The 95% value of the number of 10-minute rms voltages per site at most 90% of nominal;
- ✓ The percentage of sites with at least one of the 10-minute rms voltages at least 110% of nominal;
- ✓ The percentage of sites with at least one of the 10-minute rms voltages at most 90% of nominal.

2. **Flicker**

For benchmarking purposes, locations separate indices for LV and MV should be calculated. Locations should be selected based on the statistics methods described in Section 3.5.

The 10-minute short-term flicker severity Pst should be calculated as defined in EN 61000-4-15. Flagged values due to interruptions, voltage dips, voltage swells, rapid voltage changes, voltage transients and transient overvoltages should be removed from the statistics.

For every monitor location, the following site indices should be calculated over each calendar year:

- ✓ The 95% value of the Pst over one year;
- ✓ The number of Pst values that exceed 1.0 during the year;
- ✓ The number of Pst values that exceed 1.5 during the year.

In a three-phase system, these three indices should be calculated for each of the three voltage channels (phase-to-phase or phase-to-neutral, depending on the voltage level). The highest of the three values should be used as a basis for calculating the system indices below.

For a system with at least 20 monitor locations, the following system indices should be calculated for every calendar year:

- ✓ The 95% value of the 95% values for each site;
- ✓ The 95% value of the number of Pst values that exceed 1.0;
- ✓ The 95% value of the number of Pst values that exceed 1.5;
- ✓ The percentage of sites for which at least one of the Pst values exceeds 1.0;
- ✓ The percentage of sites for which at least one of the Pst values exceeds 1.5.

3. Voltage unbalance

For benchmarking purposes, locations at MV and at LV should be used. Separate indices should be presented for the MV side of HV/MV or EHV/MV substations, for MV side of MV/LV substations, for LV side of MV/LV substations, for locations in the LV network, and for the supply terminals of LV customers.

The 10-minute ratio of negative and positive voltage (“unbalance”) should be calculated as defined in EN 61000-4-30. Flagged values due to interruptions, voltage dips, voltage swells, rapid voltage changes, voltage transients and transient overvoltages should be removed from the statistics.

For every monitor location, the following site indices should be calculated over each calendar year:

- ✓ The 99% value of the unbalance over one year;
- ✓ The number of unbalance values that exceed 2% during the year;
- ✓ The number of unbalance values that exceed 1.5% during the year.

For a system with at least 20 monitor locations, the following system indices should be calculated for every calendar year:

- ✓ The 95% value of the 95% values for each site;
- ✓ The 95% value of the number of unbalance values that exceed 2%;
- ✓ The 95% value of the number of unbalance values that exceed 1.5%;
- ✓ The percentage of sites for which at least one of the unbalance values exceeds 2%;
- ✓ The percentage of sites for which at least one of the unbalance values exceeds 1.5%.

4. **Harmonic voltage**

For benchmarking purposes, locations at MV and at LV should be used. Separate indices should be presented (assuming there are sufficient monitor locations available) for the main MV substations, for MV side of MV/LV substations, for LV side of MV/LV substations, for locations in the LV network and for the supply terminals of LV customers.

The 10-minute harmonic subgroup should be calculated as defined in EN 61000-4-30 and EN 61000-4-7 [17]. Flagged values due to interruptions, voltage dips, voltage swells, rapid voltage changes, voltage transients and transient overvoltages should be removed from the statistics.

This would result in 40 different values, all of which are of interest to the network operator and the NRA, but for benchmarking purposes a reduction is needed. The following “harmonic characteristics”, obtained over each 10-minute interval, should be used for benchmarking purposes:

- ✓ Harmonic subgroup 3 (in LV networks only);
- ✓ Harmonic subgroup 5;
- ✓ Harmonic subgroup 7;
- ✓ The total harmonic distortion over all odd harmonic subgroups of order 9 through 39;
- ✓ The total harmonic distortion over all even harmonic subgroups of order 2 through 40.

For every monitor location, the following site indices should be calculated over each calendar year, for each of the above-mentioned harmonic characteristics:

- ✓ The 99% value of the harmonic characteristic over one year;
- ✓ (For harmonic subgroups 3, 5 and 7) The number of values that exceed the EN 50160 values during the year;
- ✓ (For harmonic subgroups 3, 5 and 7) The number of values that exceed 75% of the EN 50160 values during the year;
- ✓ The number of 10-minute intervals during which at least one of the EN 50160 limits is exceeded.

In a three-phase system these four indices should be calculated for each of the three voltage channels (phase-to-phase or phase-to-neutral, depending on the voltage level). The highest of the three values should be used as a basis for calculating the system indices below.

For a system with at least 20 monitor locations, the following system indices should be calculated for every calendar year:

- ✓ The 95% value of the 99% values for each site;
- ✓ (For harmonic subgroups 3, 5 and 7) The 95% value of the number of values that exceed the EN 50160 limits;
- ✓ (For harmonic subgroups 3, 5 and 7) The 95% value of the number of values that exceed 75% of the EN 50160 limits;
- ✓ (For harmonic subgroups 3, 5 and 7) The percentage of sites for which at least one of the values exceeds the EN 50160 limits;
- ✓ (For harmonic subgroups 3, 5 and 7) The percentage of sites for which at least one of the values exceeds 75% of the EN 50160 limits;

- ✓ The 95% value of the number of 10-minute intervals during which at least one of the EN 50160 limits is exceeded.

5. Interharmonic voltage

No limits exist for interharmonic voltage in EN 50160 and there are no clear indications as to which limit values would be appropriate. Benchmarking is therefore limited to reporting the actual values, without comparing them to any objective value.

For benchmarking purposes, locations at MV or at LV should be used. Separate indices should be presented (assuming there are sufficient monitor locations available) for the main MV substations, for MV side of MV/LV substations, for LV side of MV/LV substations, for locations in the LV network and for the supply terminals of LV customers.

The 10-minute interharmonic subgroup should be calculated as defined in EN 61000-4-30 and EN 61000-4-7. Flagged values due to interruptions, voltage dips, voltage swells, rapid voltage changes, voltage transients and transient overvoltages should be removed from the statistics.

The total harmonic distortion over all interharmonic subgroups of order 2.5 through 39.5 should be used as an interharmonic characteristic. Interharmonic subgroups 0.5 and 1.5 are strongly related to flicker and therefore should not be included in the benchmarking index.

For every monitor location, the following site indices should be calculated over each calendar year:

- ✓ The 99% value of the interharmonic characteristic over one year.

In a three-phase system this index should be calculated for each of the three voltage channels (phase-to-phase or phase-to-neutral, depending on the voltage level). The highest of the three values should be used as a basis for calculating the system indices below.

For a system with at least 20 monitor locations, the following system indices should be calculated for every calendar year:

- ✓ The 95% value of the 99% values for each site.

6. Mains signalling voltages

As no standard definition exists for the measurement of mains signalling voltages, no indices for benchmarking are proposed here.

7. Voltage dips

Monitor locations can be in MV or LV networks. A further subdivision can be made between the main MV substations, for MV side of MV/LV substations, for LV side of MV/LV substations, for locations in the LV network, and for the supply terminals of LV customers.

Voltage dip residual voltage and duration should be calculated as defined in EN 61000-4-30. A dip threshold equal to 90% of the nominal voltage should be used; no hysteresis should be used. For each recorded dip, a record should be kept of the number of phase-to-phase (at MV) or phase-to-neutral (at LV) voltages for which the rms voltage falls below the voltage-dip threshold.

When multiple dips occur within a 10-minute interval, only one event should be counted for statistical purposes. The residual voltage of the aggregated event should be the lowest of the values from the individual events; the duration should be the longest of the values from the individual events.

For every monitoring location, the following site indices should be calculated for each calendar year:

- ✓ The total number of dips below the "indicative responsibility sharing curve" as proposed in the 5th BMR on QoS;
- ✓ The number of dips for which all three phase-to-phase or phase-to-neutral voltages get below the indicative responsibility sharing curve.

For a system with at least 20 monitor locations, the following system indices should be calculated for every calendar year:

- ✓ The average number of dips below the indicative responsibility curve;
- ✓ The average number of dips with all three phases below the indicative responsibility curve;
- ✓ The 95% value of the number of dips below the indicative responsibility curve;
- ✓ The 95% value of the number of dips with all three phases below the indicative responsibility curve.

8. **Voltage swells**

Monitor locations should be in solidly-grounded low-voltage networks and phase-to-neutral voltages should be measured.

Maximum swell voltage and duration should be calculated as defined in EN 61000-4-30. A swell threshold equal to 110% of the nominal voltage should be used; no hysteresis should be used.

When multiple swells occur within a 10-minute interval, only one event should be counted for statistical purposes. The maximum swell voltage of the aggregated event should be the highest of the values from the individual events; the duration should be the longest of the values from the individual events.

For every monitoring location, the following site indices should be calculated, for each calendar year:

- ✓ The total number of swells above the curve in Figure 1.

For a system with at least 20 monitor locations, the following system indices should be calculated for every calendar year:

- ✓ The average number of swells above the curve in Figure 1;

- ✓ The 95% value of the number of dips above the curve in Figure 1.

9. Single rapid voltage changes

As no standard definition exists for the measurement of mains signalling voltages, no indices for benchmarking are proposed here.

10. Voltage transients and transient overvoltages

As no standard definition exists for the measurement of voltage transients or transient overvoltages, no indices for benchmarking are proposed here.