IEC TR 61000-3-18

Edition 1.0 2024-02

TECHNICAL REPORT

Electromagnetic compatibility (EMC) –
Part 3-18: Limits – Assessment of network characteristics for the application of harmonic emission limits – Equipment connected to LV distribution systems not covered by IEC 61000-3-2 and IEC 61000-3-12

IEC TR 61000-3-18:2024-02(en)

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colour inside

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CONTENTS

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ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 3-18: Limits – Assessment of network characteristics for the application of harmonic emission limits – Equipment connected to LV distribution systems not covered by IEC 61000-3-2 and IEC 61000-3-12

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IEC TR 61000-3-18 has been prepared by subcommittee 77A: EMC – Low frequency phenomena, of IEC technical committee 77: Electromagnetic compatibility. It is a Technical Report.

The text of this Technical Report is based on the following documents:

Draft	Report on voting
77A/1197/DTR	77A/1202/RVDTR

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

A list of all parts in the IEC 61000 series, published under the general title *Electromagnetic compatibility (EMC)*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

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INTRODUCTION

IEC 61000 is published in separate parts, according to the following structure:

Part 1: General

General considerations (introduction, fundamental principles)

Definitions, terminology

Part 2: Environment

Description levels

Classification of the environment

Compatibility levels

Part 3: Limits

Emission limits

Immunity limits (in so far as they do not fall under the responsibility of the product committees)

Part 4: Testing and measurement techniques

Measurement techniques

Testing techniques

Part 5: Installation and mitigation guidelines

Installation guidelines

Mitigation methods and devices

Part 6: Generic standards

Part 9: Miscellaneous

Each part is further subdivided into several parts, published either as international standards or as technical specifications or technical reports, some of which have already been published as sections. Others will be published with the part number followed by a dash and a second number identifying the subdivision (example: IEC 61000-6-1).

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 3-18: Limits – Assessment of network characteristics for the application of harmonic emission limits – Equipment connected to LV distribution systems not covered by IEC 61000-3-2 and IEC 61000-3-12

1 Scope

This part of IEC 61000, which is a technical report, reports on the development of a methodology for adapting IEC equipment emission limits from IEC 61000-3-2 and IEC 61000-3-12 for use in regions not covered by these documents. It identifies gaps in the existing equipment emission limit standards concerning their international applicability and identifies public power system characteristics important for the evaluation of harmonic voltage performance.

The purpose of adapting the above-mentioned IEC equipment harmonic emission standards in a particular region is to maintain similar electromagnetic compatibility (EMC) of equipment up to 75 A per phase in the public power systems in those regions.

NOTE The boundaries between the various voltage levels differ amongst different countries (see IEC 60050-601:1985, 601-01-28). This document uses the following terms when referring to 50 Hz and 60 Hz system voltages:

– low voltage (LV) refers to $U_n \leq 1$ kV;

– medium voltage (MV) refers to 1 kV < $U_n \leq 35$ kV;

– high voltage (HV) refers to 35 kV < $U_n \leq 230$ kV.

EMC requirements can have economic and societal impacts; these have not been considered in the development of this document. The consideration of these factors generally occurs in the technical committees working on development and maintenance of emission limit standards.

2 Normative references

There are no normative references in this document.

3 Terms, definitions and abbreviated terms

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1 Terms and definitions

3.1.1
distribution system operator
DSO
party operating an electric power distribution system

[SOURCE: IEC 60050-617:2009, 617-02-10, modified – electric power has been added to the definition.]

3.1.2
distributed energy resource
DER
generator (with its auxiliaries, protection and connection equipment), including loads having a generating mode (such as electrical energy storage systems), connected to a low-voltage or a medium-voltage network

[SOURCE: IEC 60050-617:2017, 617-04-20, modified – changed to singular]

3.1.3
electromagnetic compatibility
EMC
ability of equipment or a system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment

[SOURCE: IEC 60050-161:2018, 161-01-07]

3.1.4
(electromagnetic) compatibility level
the specified electromagnetic disturbance level used as a reference level for co-ordination in the setting of emission and immunity limits

Note 1 to entry: By convention, the compatibility level is chosen so that there is only a small probability that it will be exceeded by the actual disturbance level. However electromagnetic compatibility is achieved only if emission and immunity levels are controlled such that, at each location, the disturbance level resulting from the cumulative emissions is lower than the immunity level for each device, equipment and system situated at this same location.

Note 2 to entry: The compatibility level can be phenomenon, time or location dependent.

[SOURCE: IEC 60050-161:1990, 161-03-10]

3.1.5
emission limit (of a disturbing source)
specified maximum permitted emission of a source of electromagnetic disturbance

3.1.6
electric power network
network
particular installations, substations, lines or cables for the transmission and distribution of electricity

Note 1 to entry: Electric power network can also be referred to as electric power system (system).

[SOURCE: IEC 60050-601:1985, 601-01-02]

3.1.7
harmonic (component)
component of order greater than 1 of the Fourier series of a periodic quantity

[SOURCE: IEC 60050-161:1990, 161-02-18]

3.1.8
point of connection
point of interconnection
POC
POI
reference point on the electric power system where the user's electrical facility is connected

[SOURCE: IEC 60050-617:2009, 617-04-01, modified – in the term "point of connection" and "POI" have been added.]

3.1.9
point of common coupling
PCC
point of a power supply network, electrically nearest to a particular load, at which other loads are, or can be, connected

Note 1 to entry: These loads can be either devices, equipment or systems, or distinct customer installations.

Note 2 to entry: In some applications, the term "point of common coupling" is restricted to public networks.

[SOURCE: IEC 60050-161:1990, 161-07-15]

3.1.10
reference network model
RNM
95^{th} percentile representation of a power system by means of one circuit designed with lines, cables, equipment, and loads having specified configurations for an intended study

Note 1 to entry: A reference network model for obtaining the 95^{th} percentile of steady-state voltage performance might be different from a reference network model for obtaining the 95^{th} percentile of voltage harmonic distortion.

3.1.11
network sensitivity
ratio of change produced in a network variable by injection of a known disturbance

Note 1 to entry: The change in harmonic distortion level in a network by injection of harmonic current is one example of sensitivity that can be used for comparative purposes.

3.1.12
system impedance
impedance of the supply system as viewed from the point of common coupling

[SOURCE: IEC 60060-161:1990, 161-07-16, modified – "supply" has been removed from the term.]

3.1.13
topology
<network or power system> relative position of the ideal elements representing an electric network.

[SOURCE: IEC 60050-603:1986, 603-02-04]

3.2 Abbreviated terms

C_{fh}	Conversion factor
CP95	95th percentile
DER	Distributed energy resource
DSO	Distribution system operator
EMC	Electromagnetic compatibility
h	Harmonic of order
LV	Low voltage
MV	Medium voltage
HV	High voltage
NA	North America
PCC	Point of common coupling
POC	Point of connection
POI	Point of interconnection
RNM	Reference network model
$S_{h_{RNM}}$	95th percentile of the harmonic voltage at the POIs of the RNM
$S_{h_{Target}}$	95th percentile of the harmonic voltage at the POIs of the targeted network
S_R	Sensitivity ratio
SSE	Sum-squared error
SWER	Single-wire earth-return
THD	Total harmonic distortion
U_{NEW}	Supply voltage for the new limits
U_R	Voltage ratio
U_{RNM}	Phase-to-neutral European voltage, which is 230,94 V computed from the phase-phase nominal voltage, which is 400 V
xPyW	x-phase y-wire where x and y are numeric

4 General

IEC documents defining equipment harmonic current emission limits are largely based on European power systems having three-phase three-wire (3P3W) MV feeder topologies supplying three-phase four-wire (3P4W) LV distribution networks through delta-wye transformation. Typically, such LV systems serve hundreds of customers via many kilometres of cables, usually in a grounded configuration. This feeder topology results in a significant portion of the voltage total harmonic distortion (THD) at any given LV point of interconnection (POI) being caused by aggregation of harmonic currents flowing through the LV network impedance.

According to available historical information, existing emission limit studies were based on this European feeder topology with the knowledge that approximately 25 % of the contribution to voltage distortion comes from the LV system. Even though the use of delta-wye transformation effectively blocks zero-sequence harmonics from returning to the MV network, there was no special consideration given for modelling different sequence harmonics, only h5 (negative sequence) and h7 (positive sequence) orders were simulated. Historical documents explaining the method used to establish the emission limits that led to the IEC documents are no longer available, thus the exact method used at that time is difficult to recover. However, recent field measurements carried out in European countries have shown that the actual limits are effective in keeping the harmonic voltage below compatibility levels at most locations. This document does not redefine the approach used to establish emission limits. The objective is to report an appropriate methodology to adapt the existing limits in order to reproduce, for other countries, the same performance as observed in European countries.

Numerous power system topologies exist around the world that have characteristics differing from the 3P3W MV distribution systems used in Europe, which supply a small number of large MV/LV transformer stations. The following are examples of regions having power systems sufficiently different from those of Europe; adaptation of IEC emission limits can be beneficial for them in pursuit of EMC:

- North America: While there are regional differences within North America, generally the MV networks are 3P4W systems with multi-grounded neutrals. They supply hundreds of small MV/LV transformers (mixed single-phase and three-phase), and each serves only a few customers compared to those of Europe which serve hundreds of customers. MV feeders tend to be significantly longer than in Europe, so shunt capacitors and regulating transformers installed at various locations along the feeders are used to control the voltage. Of special note are the 1P3W LV networks supplying 120/240 V service to residential and other small single-phase customers. The three-phase LV networks used for larger multi-unit residential buildings, larger commercial, or industrial customers are 3P4W grounded systems having very short service cables, often less than 100 m in length.
- Japan: The population density in Japan is comparable to that of Europe. The MV system is significantly shorter than that in North America; its 3P3W MV distribution system operates at 6,6 kV to supply residential, commercial, and small industrial sectors. Since this MV system distributes the phase voltage without a neutral conductor, the single-phase LV systems are powered by transformers connected phase-to-phase. An open-delta transformer is used when three-phase voltage is required. Unlike in Europe, the connection of MV/LV transformers allows for triplen harmonics to circulate on the MV network (though not as zero-sequence components). Since the MV network voltage is about three times lower than that found in Europe, the number of customers supplied from it is also lower. On the other hand, an extension of the MV network at 22 kV, like that of Europe, is used to supply the 6,6 kV power system as well as larger MV customers. As in North America, the MV/LV transformers supply residential and small commercial customers with two voltages, however the supply is 100/200 V instead of 120/240 V.
- Australia: The Australian power system might be described as a hybrid topology having characteristics similar to both European and North American networks. They are similar in urban environments to Europe where short MV systems supply a few larger MV/LV transformers which in turn supply many customers in densely populated areas at 230/400 V. However, Australian systems also cover vast open territories using 1P1W MV networks using earth for return currents, called a single-wire earth-return (SWER) system. These are like North America in the sense that they serve rural areas using long single-phase networks, specifically like Canada where some distribution feeders exceed 200 km in length. However, the SWER system serves very few customers and has a lot of capacitance to ground due to its long length, thus the Ferranti effect – normally seen on lightly loaded transmission systems – is a concern here. For this reason, voltage regulation is implemented using shunt reactors instead of shunt capacitors.

Given the physical differences in systems such as impedance, customer density, service voltage, wiring, and grounding configurations it is reasonable to conclude that such topologies are impacted differently by harmonic emissions. As such, emission limits might be adjusted according to the power system capability to maintain the harmonic voltages below the applicable targets. Consider the following important characteristics that impact harmonic distortion performance differently:

– North American lower-impedance LV systems served by higher-impedance MV systems perform differently than European distribution systems in the sense that most of the harmonic aggregation occurs at the MV level. The harmonic voltage drops at the LV level due to having shorter cables and fewer customers, and therefore contribution to voltage THD in each LV network is very small (<< 5 % of voltage THD); when aggregated at the MV level it becomes apparent that most of the voltage distortion occurs by aggregation of load currents flowing through the impedance of the MV system (>> 95 % of voltage THD).
– The very long single-wire earth-return (SWER) distribution systems in Australia are characterized by light loading and high capacitance to ground; thus, shunt inductors are used to lower the voltage level along the MV lines. The high capacitance of the system in parallel with these inductors leaves it vulnerable to resonances.

The two examples noted above are causes for uncertainty as regions having different power system characteristics than Europe adopt the IEC harmonic emission limits without any local adaptations.

This document reports on the development of design characteristics for a benchmark European distribution power system that can be used for the purpose of modelling harmonic performance. The harmonic distortion level of the reference network model (RNM), when used with the recommended harmonic load, aligns well with present-day IEC compatibility levels. Subclause 7.2 describes in detail the origins of the data used to develop the RNM. A methodology is described for comparing other distribution systems to the European benchmark system for the purpose of adapting IEC harmonic current emission limits (IEC 61000-3-2 and IEC 61000-3-12) for effective use with those networks. The methodology was developed and tested using power system models from both Canada and Japan. Annex B and Annex C include power system details and the resulting limits from applying the methodology for both Canada and Japan respectively.

5 State of existing IEC standards

5.1 Overview of existing standards

IEC 61000-3-2 and IEC 61000-3-12 establish harmonic emission limits for equipment with input currents ≤16 A per phase and ≤ 75 A per phase, respectively. The limits are intended for equipment that is connected to the public LV distribution system in attempt to control the voltage THD in the electromagnetic environment. These standards form one part of the harmonic EMC framework intended to control harmonic distortion in the environment. When these standards are adopted in a region, then a baseline distortion level can be expected if these standards function as intended. DSOs can then enforce further harmonic controls on large customers through application of IEC TR 61000-3-6, which accounts for the baseline distortion level controlled by IEC 61000-3-2 and IEC 61000-3-12. The proper application of these standards is therefore of utmost importance to maintain EMC in the network.

The existing standards were created for European public distribution systems, and as such are based on characteristics of those systems. This leaves potential gaps with respect to their applicability in other regions of the world where the characteristics of the public supply systems differ. The obvious gaps which exist in the standards relate to applicable voltage levels and frequencies. The less obvious gaps with respect to differing system and sequence impedances exist because only one network model was used to determine the limits.

5.2 Voltage gaps

IEC 61000-3-2:2018 states the following in 6.1:

"The requirements and limits specified in this document are applicable to the power input terminals of equipment intended to be connected to 220/380 V, 230/400 V and 240/415 V systems operating at 50 Hz or 60 Hz. Requirements and limits for other cases are not yet specified."

IEC 61000-3-12:2011 states the following in Clause 1, second paragraph:

"The limits given in this edition apply to equipment when connected to 230/400 V, 50 Hz systems."

It then goes on to state the following in NOTE 1:

"The limits for the other systems will be added in a future edition of this standard."

The following voltages, known to be used elsewhere in the world, are presently not mentioned in the equipment harmonic emission limit standards. This might not represent the whole list of voltages not previously considered:

Single-phase voltages:

100 V, 110 V, 115 V, 120 V, 127 V, 200 V

Three-phase voltages:

3P4W systems: 100/200 V, 120/208 V, 127/220 V, 277/480 V, 347/600 V

3P3W systems: 190 V, 200 V, 240 V, 440 V, 480 V

5.3 Frequency gaps

The IEC standards are sometimes restricted to 50 Hz supply systems; the 60 Hz power system frequency is used in many parts of the world:

- 60 Hz supply limits are presently specified in IEC 61000-3-2
- 60 Hz supply limits are not presently specified in IEC 61000-3-12

5.4 System impedance considerations

IEC TR 61000-1-4 provides the historic rationale for the harmonic limits defined in IEC 61000-3-2 and IEC 61000-3-12. IEC TR 61000-1-4:2022states the following with respect to network characteristics and rationale for equipment harmonic limits in Clause 1:

"Some concepts in this document apply to all low voltage AC systems, but the numerical values apply specifically to the European 230 V/400 V 50 Hz system."

IEC TR 61000-1-4:2022, Annex A, Clause A.1 goes on to state the following:

"The typical percentage impedances in European networks are given in Figure A.1. The partition of the total compatibility level into the parts assigned to each voltage level reflects roughly the relation of these percentage impedances. In order to account for the geometric summation of the voltage drops, the value of 25 % for the LV-network is increased with respect to the value which can be derived from the ratio of the impedance values. 25 % of the total compatibility level is therefore used in IEC 61000-3-2 and IEC 61000-3-12 for the assessment of the maximum harmonic currents from non-linear loads in the LV-network for 230 V 50 Hz systems."

It follows, therefore, that public distribution supply systems in other regions of the world which are known to have different network characteristics require special consideration when introducing IEC equipment harmonic current emission limits.

6 General approach

The general approach of this study is to compare the harmonic sensitivity of different power systems and use the resulting voltage distortion differences to adapt the existing harmonic current emission limits for application to the target network. Numerous different ways to characterize networks and model harmonic sensitivity were studied in attempt to find a simplified approach, one that would provide accurate results and account for all the local variations that can exist in a power system. Regrettably, studies using voltage droop and clustering of feeder characteristics did not reveal any promising simplifications that are accurate enough to be useful; thus detailed harmonic modelling of the target power system in comparison with the benchmark European system is identified as the most accurate and reliable means of determining the network's sensitivity to harmonic current injection.

The methodology presented in this document is based on studies using real power system models obtained from various DSOs in Europe, North America, and Asia. Modern scripting techniques included with some modelling software allow for harmonic simulation at every customer connection point of the whole power system, thereby providing the detailed results that will be used for finding the 95th percentile levels to use for comparative analysis. It is noted that the methodology aims to evaluate the sensitivity of each electrical network to harmonic currents rather than to evaluate the real harmonic level that is expected. The harmonic sensitivity level is the 95th percentile of the harmonic voltage distortion at all customer POIs in the target region, given a specific harmonic load injection at each POI.

The tasks undertaken to implement the developed methodology are described in this document; they are as follows:

a) the European RNM is developed for easy implementation in any power system modelling software;
b) the harmonic load profile is defined;
c) a scripting interface with power system modelling software is used to assess the harmonic power flow at every POI in the power system. A detailed Python™ [1] script for use with CYMDIST[2] models is provided in Annex D for users of that software;
d) the statistical methods for analysing the results are defined;
e) the resulting procedure is the technical basis for translating the IEC equipment harmonic current emission limits for use in the target network, based on the resulting power system harmonic sensitivity.

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1 Python is the trade name of a product supplied by PythonTM. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the product named. Equivalent products may be used if they can be shown to lead to the same results.

2 CYMDIST is the trade name of a product supplied by Eaton. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the product named. Equivalent products may be used if they can be shown to lead to the same results.

The methodology in this document provides only a technical basis for applying limits in regions not covered by IEC 61000-3-2 and IEC 61000-3-12, with the primary goal of maintaining EMC equivalent to that which has been achieved in Europe. To complete the process of setting limits by consensus, in a second step, the impact of suppression measures on physical, operational, manufacturing and the overall economic aspects will also be considered, and the limits will be negotiated with all essential parties.

7 Detailed implementation of the methodology

7.1 Overview

According to IEC TR 61000-2-1:1990, Clause 4, the compatibility level covers at least 95 % of cases of an entire population. Since compatibility levels and harmonic emission limits have been designed for European countries, this entire population refers to the POIs of all customers in Europe. In other words, the 95th percentile of all harmonic levels at POIs in Europe should not exceed the level of compatibility established in IEC 61000-2-2. If the same harmonic current flows in a network whose design is different from that of the European reference network, the 95th percentile of the harmonic level could be either lower or higher than the compatibility level, depending on whether the network is less or more sensitive to harmonic loads. To maintain the level of the harmonic voltage in accordance with electromagnetic compatibility requirements, this methodology works on the principle that emission limits are adjusted according to the sensitivity of the electrical network to harmonic currents flowing in its components.

Clause 7 reports on a methodology to use for finding the conversion factor C_{fh} for each harmonic order h to adjust the harmonic emission limits that allow a non-European network to keep the 95th percentile of the harmonic voltage below the compatibility level. Finding the appropriate conversion factors will allow other regions outside of Europe to adopt IEC 61000-3-2 and IEC 61000-3-12 equipment harmonic current emission standards with deviations to account for local network designs.

NOTE This document only provides the methodology, it does not provide the conversion factors for different regions around the world. It is the responsibility of EMC representatives in each region outside of Europe to assess whether or not their power system might give just cause for adaptation of the IEC limits, and if so to conduct their own studies to determine the appropriate conversion factors.

7.2 European reference network model (RNM)

7.2.1 History

The DSO Observatory project launched at the end of 2014 created a database of the largest energy distribution systems operated in European countries. As a result of this project, the European Commission published a report in 2016, Distribution System Operators Observatory [2][3]. The data available in this report represents a comprehensive collection of the European power distribution system architecture and characteristics and the data is updated approximately every two years.

In total, 79 of the 190 European DSOs contributed to the collection of data from the Joint Research Centre of the European Commission (JRC). The collaborators manage more than 70 % of the electricity supplied by all European DSOs representing more than 2 000 TWh of electricity supplied to over 200 million customers per year, covering a total area of more than 3 million km^2. The collected information and data have been used by other researchers and groups to develop detailed RNMs to analyse the impacts of various LV network interactions such as distributed energy resources (DERs).

The RNM proposed by the European Commission for the MV semi-rural system [2] was tested for assessing the harmonic sensitivity. This RNM supplies 34 LV networks which each supply 108 customers [2]. The simulation of this RNM, carried out with each customer injecting the

3 Numbers in square brackets refer to the Bibliography.

harmonic current of Table 4, gives a result for the 95th percentile of the voltage harmonic at the POIs equal to a level of 46 % to 584 % of the compatibility levels depending on the harmonic order considered. The results demonstrate why that RNM, which is mainly intended for economic studies of DER implementation on the electrical system, cannot be used to assess the harmonic sensitivity without being adjusted.

7.2.2 Adjusted RNM for assessing harmonic sensitivity

The RNM for assessing harmonic sensitivity is a simplified equivalent model of a European distribution system. It is expected to meet the following requirements:

a) the architecture of MV and LV electrical systems are similar to that documented by the European Commission (see [2]);
b) the implementation in simulation software is simple, allowing for repeated cut and paste of various network components;
c) the nominal voltage is 230 V and the load flow voltages at each customer POI should be 230 V ± 10 % per phase;
d) the currents in cables and transformers do not exceed their specifications;
e) each customer is supplied by three-phase service;
f) the load of each three-phase customer is 1,5 kVA (0,5 kVA/phase) [4] with a lagging power factor of 0,98; and
g) the harmonic current per phase generated by each three-phase customer is that from the 230 V column of Table 4 divided by 3.

NOTE 1 The RNM is a fictional EU feeder meant to supply the 95th percentile distortion levels for simulation purposes. It is not a real network, albeit it has similarities to EU networks.

NOTE 2 Some European DSOs supply residential customers with three-phase service, while some supply one-phase service. The service type that one uses for the RNM is an arbitrary selection and does not impact the final results (i.e. a 1,5 kW one-phase service can also be modelled as three-phase service with 0,5 kW per phase).

NOTE 3 Each feeder connected to the substation contributes to the harmonic level of the main bus. To obtain the same level of voltage harmonic distortion at the main bus, the short-circuit power is increased according to the number of feeders it supplies. In reality many feeders are often supplied from the same bus, in which case the short circuit power would increase accordingly; it is often 200 MVA or more. The 90 MVA fault level was selected for the RNM to give a simple equivalent source impedance for modelling one feeder.

For a simplified implementation, the type and length of the MV lines between each node are the same. In addition, all LV networks are identical. The network model is thereby quickly realized in software by cutting and pasting very few elements that simply repeat over and over again and are equidistant apart.

The adopted MV power system connects 29 identical LV networks, each separated by 2,11 km of overhead line (see Figure 1). The repeating LV network uses two sizes of cables, larger trunk cables near the transformer station and smaller service cable as the load decreases farther away from the station (see Figure 2). Each block in Figure 1 represents one LV network supplying 153 customers. This LV network is detailed in Figure 2 where the number of long cable sections between each customer (11 m apart) is indicated in red and the number of customers in blue.

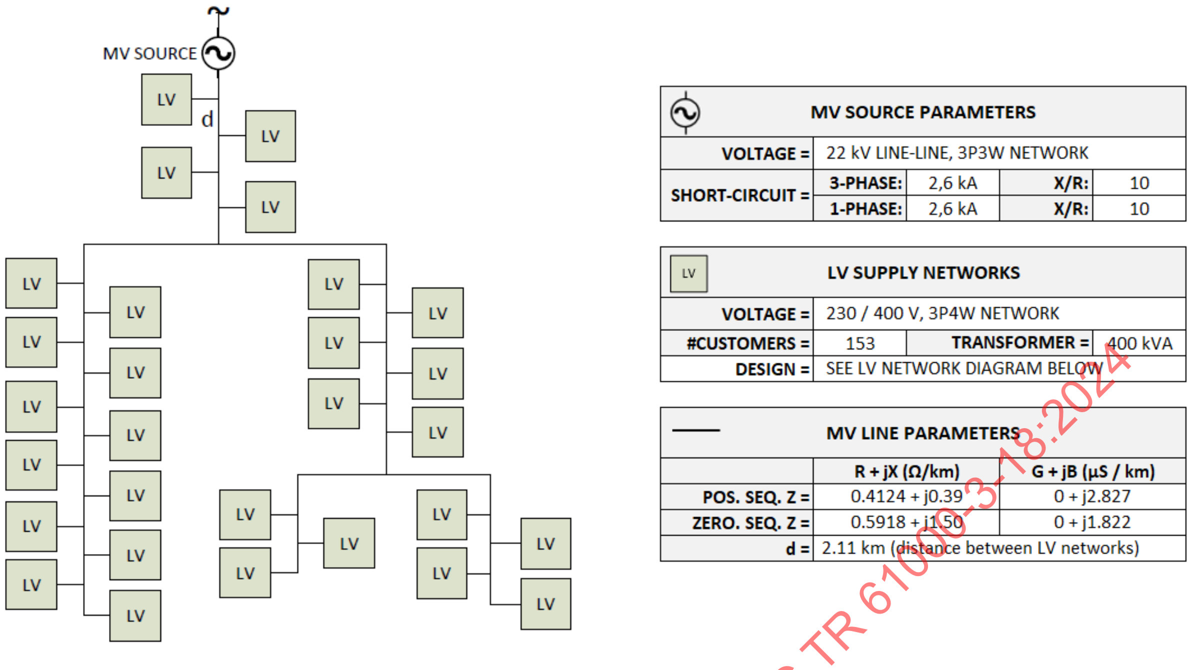

Figure 1 – Reference network medium-voltage power system

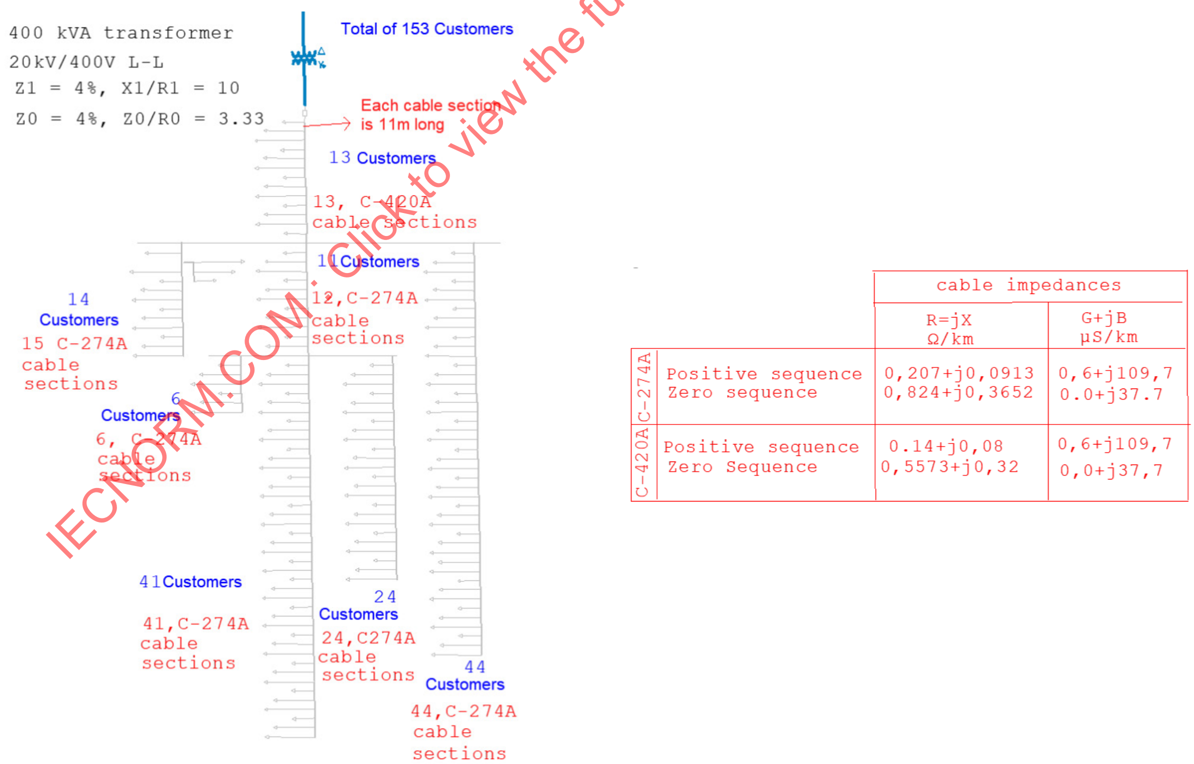

Figure 2 – LV network of 153 customers supplied by a 400 kVA transformer

The LV network of Figure 2 has the following important characteristics:

1) it supplies 153 three-phase customers at 230/400 V;

2) each customer has a load of 1,5 kVA (0,5 kVA/phase) with lagging power factor of 0,98;
3) the load model is a parallel R-L type (if a series R-L type is used then the power factor is equal to 1);
4) each customer injects the harmonic current defined in the 230 V column of Table 4 divided by 3;
5) the short-circuit power at the HV/MV substation is set at 90 MVA and it supplies only one MV feeder (if copying and pasting this MV feeder, multiply the short-circuit power by the number of feeders in order to maintain the same 95th percentile of the harmonic voltage at the POCs of the LV customers);
6) the overhead line and cable impedances are published in Table 4-4 and 4-6 of the European Commission report [2], and shown in Figure 1 and Figure 2;
7) the π-type configuration is used for the line and cable models; and
8) the MV/LV transformer is rated at 400 kVA, which is most commonly used in Europe [2].

The RNM was developed such that the 95th percentile of the harmonic voltages at LV customer POIs are approximately equal to the compatibility levels within ±2,5 % (see Table 1) when modelled using the CYMDIST software. When the DSO network models are being studied using CYMDIST then the RNM is not modelled, rather the IEC compatibility levels can be used to represent the European benchmark harmonic levels. However, if the study is conducted with another simulation software, the harmonic results might vary, due to the detail of the network component models and the algorithm used. In this case, simulation of the RNM can be necessary to find the correction factor to apply to the results.

Table 1 – Modelled RNM voltage distortion compared with compatibility levels

Harmonic number	CP95 (%)	CL (%)	Difference	Harmonic number	CP95 (%)	CL (%)	Difference
3	5,028	5,000	0,56 %	23	1,391	1,408	-1,22 %
5	5,969	6,000	-0,51 %	25	1,256	1,274	-1,39 %
7	4,915	5,000	-1,70 %	27	0,199	0,200	-0,42 %
9	1,522	1,500	1,46 %	29	1,044	1,061	-1,57 %
11	3,457	3,500	-1,24 %	31	0,960	0,975	-1,56 %
13	2,958	3,000	-1,40 %	33	0,198	0,200	-0,96 %
15	0,404	0,400	1,04 %	35	0,836	0,833	0,41 %
17	1,969	2,000	-1,55 %	37	0,767	0,773	-0,79 %
19	1,737	1,761	-1,37 %	39	0,197	0,200	-1,26 %
21	0,301	0,300	0,48 %				

7.3 Harmonic current model

To study the impact of harmonic emissions in the power system, an electrical power research establishment proposed the harmonic current emission model to be used in computer simulation in the early 1980s [4]. This current was the aggregation of that produced by five consumer devices. Researchers considered the number of devices per customer (k_{sat}) and the number of devices from the same category used simultaneously (k_{sim}) to select the five devices. A summation rule, as defined in IEC TR 61000-3-6, used a coefficient of 1,2 to compensate for other attenuating factors including phase angle. Assumptions or simplifications were also used due to limited resources to perform complex simulations at the time. With the evolution of simulation tools, it is now possible to model the entire MV and LV network. As a result, a summation coefficient of 1,5 is used today instead of 1,2, which is the outcome determined by more elaborate simulations. Table 2 and Table 3 show the currents and factors considered in the 1980s but using a summation factor of 1,5 which is more suitable for today's models.

Table 2 – 5th harmonic current (h5) per household proposed by [4]

h	Apparatus	Current	k factors		$(I \times k_{sat} \times k_{sim})^{1,5}$ (A)
		I (A)	k_{sat}	k_{sim}	
5	TV receiver	0,5	0,8	0,7	0,1482
	Phase-controlled heater	0,12	0,2	0,4	0,0009
	Light dimmers	0,55	0,5	0,6	0,067
	Fluorescent lamp	0,12	0,9	0,6	0,0165
	Phase-controlled motor	1,14	0,8	0,3	0,1431
				Sum:	0,3757
			Total	$\sqrt[1,5]{\Sigma(I \times k_{sat} \times k_{sim})^{1,5}}$	0,5207

Table 3 – 7th harmonic current (h7) per household proposed by [4]

h	Apparatus	Current	k factors		$(I \times k_{sat} \times k_{sim})^{1,5}$ (A)
		I (A)	k_{sat}	k_{sim}	
7	TV receiver	0,4	0,8	0,7	0,106
	Phase-controlled heater	0,09	0,2	0,4	0,0006
	Light dimmers	0,38	0,5	0,6	0,0385
	Fluorescent lamp	0,07	0,9	0,6	0,0073
	Phase-controlled motor	0,77	0,8	0,3	0,0794
				Sum:	0,2319
			Total	$\sqrt[1,5]{\Sigma(I \times k_{sat} \times k_{sim})^{1,5}}$	0,3775

It is true that today's TV receivers are completely different from those of the 1980s; however, the distortion produced by the 1980s TV receivers has been replaced by the distortion produced by numerous other devices that stay connected all the time such as personal computers, modems and routers, small portable device chargers, and various smart devices used in modern homes.

It is important to note the goal of this document is not to establish the realistic load model for modern-day residential locations, it is to compare harmonic sensitivities of different networks with the intent of adjusting existing emission limits to be appropriate for the target network. It is therefore appropriate to use similar data and assumptions that were originally used to develop the electromagnetic compatibility standards.

A DSO in Europe provided the network model of 20 feeders selected to represent the best variety of the entire electricity system. This network was simulated using the harmonic current of the devices proposed by a research establishment (Table 2 and Table 3). The simulation showed that the 95th percentile of the fifth and seventh harmonic voltages were almost equal to the IEC compatibility level. The difference of the 95th percentile of the harmonic level of the simulated network with the compatibility level was only 2,5 % for h_5 and 0,5 % for h_7. This simulation was carried out with a real network and the harmonic current from Table 2 and Table 3 validates the proposal made by a research establishment 40 years ago.

Simulation of these European feeders allowed for each odd harmonic current up to the 39th order to be adjusted so as to obtain the 95th percentile of the harmonic voltage equal to the compatibility level. Table 4 shows the resulting harmonic currents per LV customer to be used for the simulation of the entire electrical system.

Table 4 – Harmonic load injection at each customer POI in the modelled network

h	I (mA) 230 V 1-φ	I (mA) 120V 1-φ	Angle	*h*	I (mA) 230 V 1-φ	I (mA) 120V 1-φ	Angle	*h*	I (mA) 230 V 1-φ	I (mA) 120V 1-φ	Angle
2	314,4	602,6	0	15	26,4	50,7	79	28	20,6	39,4	0
3	765,2	1466,7	164	16	25,2	48,4	0	29	63,4	121,4	257
4	96,8	185,6	0	17	121,6	233,1	121	30	20,1	38,5	0
5	510,6	978,6	-27	18	24,6	47,1	0	31	58,4	112,0	43
6	48,2	92,3	0	19	106,4	203,8	267	32	20,0	38,4	0
7	363,3	696,4	142	20	22,9	43,9	0	33	11,9	22,7	197
8	35,4	67,8	0	21	18,6	35,7	68	34	19,8	38,0	0
9	117,8	225,7	-49	22	22,1	42,4	0	35	51,4	98,5	348
10	33,4	64,0	0	23	84,3	161,7	228	36	19,1	36,7	0
11	226,3	433,7	119	24	21,6	41,5	0	37	47,5	91,1	123
12	31,8	61,0	0	25	76,1	145,8	19	38	19,6	37,6	0
13	188,3	361,0	-76	26	21,0	40,2	0	39	11,8	22,5	241
14	27,0	51,8	0	27	12,0	23,1	140	40	19,6	37,5	0

NOTE 1 The harmonic current in Table 4 applies for a single-phase customer where all the devices are connected to the same phase. When the customer is supplied by a three-phase service, the values in Table 4 are divided by 3 and applied to each phase.

NOTE 2 If the customer is supplied at another voltage, U_{TARGET}, the current at 230 V from Table 4 is multiplied by the ratio 230/U_{TARGET}. Table 4 shows the current multiplied by this ratio when the apparatus is supplied at 120 V.

NOTE 3 The amplitudes and the phase angles in the table are derived from a single-phase four-diode rectifier bridge.

7.4 Methodology for adapting IEC equipment harmonic emission limits

7.4.1 General

The harmonic limits have been established, in principle, to allow harmonic current to flow in the European power system without producing harmonic voltages exceeding the compatibility levels. For the networks of other countries, the adapted emission limits resulting from this methodology are based on the same objective of keeping the harmonic voltages below the compatibility levels. In short, the harmonic current allowed in various countries will produce the same 95th percentile of the harmonic voltage at customers' POIs – this is the founding principle from which the methodology was developed for translating IEC emission limits to be used in power systems having different characteristics than those of Europe.

The European RNM produces the benchmark for harmonic voltage when each customer injects the harmonic current of Table 4. The target countries can also simulate the European RNM, as defined in this document, using their preferred software to establish the benchmark voltage distortion levels. The benchmark is the 95th percentile of the harmonic voltage of each order. For example, the simulation made with CYMDIST software supplied the benchmark distortion levels found in Table 1; it is known that other commercial softwares produce different results, possibly due to the way they model loads, cables and lines, transformers, and other power system characteristics. The target network will therefore also be simulated using the same software so that the comparison with the benchmark distortion levels is accurate. The benchmark distortion levels, and the results of the target network simulation make it possible to evaluate the conversion factor C_{fh} of the emission limits for each harmonic order.

7.4.2 Conversion factor (C_{fh})

To adapt the IEC equipment harmonic current emission standards to a different type of network, the simulation provides the sensitivity ratio S_R necessary to develop the conversion factor for the emission limit of each harmonic order. For each harmonic order h, the conversion factor C_{fh} is multiplied by the limit of the IEC standards in order to adapt them according to the sensitivity performance of the target power system (Equation (1)). Each of these conversion factors makes it possible to convert the limit of the harmonic order associated with it. This C_{fh} (Equation (2)) is the S_R of the power system multiplied by the voltage ratio U_R and the compatibility level ratio CL_R (Equation (3)).

The approach consists in comparing the harmonic sensitivities of the European reference network ($S_{h_{RNM}}$) and that of the target network ($S_{h_{Target}}$) where the new harmonic emission limits are to be determined. The sensitivity levels are expressed in terms of the 95th percentile of the level of harmonic voltages when all customers connect the same load and inject the same harmonic current into the power system. The ratio (S_R) of the European network distortion to that of the target network becomes one of the factors necessary to compute the conversion factor C_{fh} (Equation (2)). The other factor is the ratio of the LV voltage of the RNM (U_{RNM} = 230,94 V) over the nominal voltage of the target network U_{target}.

$$limit_h = c_{fh} \times limit_{IECh} \tag{1}$$

where

$$C_{fh} = S_R \times U_R \times CL_R = \frac{S_{h_{RNM}}}{S_{h_{TARGET}}} \times \frac{U_{RNM}}{U_{TARGET}} \times \frac{CL_{NEWh}}{CL_{IECh}} \tag{2}$$

When converting percentage-based limits, such as in IEC 61000-3-2, Class C, the factor U_R is omitted from Equation (2).

h=harmonic order

$$U_{RNM} = \frac{400V}{\sqrt{3}} = 230{,}94\,V \tag{3}$$

U_{NEW} = supply voltage for the new limits;

$S_{h_{RNM}}$ = 95th percentile of the harmonic voltage at the POIs of the RNM;

$S_{h_{Target}}$ = 95th percentile of the harmonic voltage at the POIs of the targeted network;

CL_{NEWh} = level of network compatibility for which the new limits will be set;

CL_{IECh} = IEC 61000-2-2 compatibility level for harmonic h.

7.5 Sensitivity ratio S_R

The calculation of the harmonic sensitivity ratio for each harmonic order uses the 95th percentile of the voltage distortion level of the POIs of the entire target network and that of the European RNM. The load conditions of the two networks are as follows:

- total load is fixed at 1,5 kVA with a power factor of 0,98 per customer;
- the parallel RL load model is used in the simulation;
- π cable and line models are used in the simulation;
- each customer injects the defined harmonic current from Table 4 .

NOTE 1 To maintain the correct relationship between systems that supply three-phase service to LV customers, the total power, and the current emission of harmonics per phase, are divided by 3.

NOTE 2 Only the voltage distortion at the POI of connected customers is simulated.

The RNM includes all customers connected with three-phase services, since this is often the case in European's LV networks.

The harmonic current to be used in the simulation for other countries is first assumed to be the same per customer as that used for the simulation of the RNM (Table 4). Then, the ratio of the 95th percentile of harmonic voltages obtained by the simulation of the RNM and that of the target network gives the S_R factor to be applied to the harmonic current limits. In addition to this factor, the ratio between the nominal voltage of the RNM (230 V) and that of the target network is also to be considered, per Equation (2).

8 Simulation considerations

8.1 Overview

Due to the network architecture, the operating conditions of the targeted network can differ from those of networks in European countries. To obtain comparable results, the operating conditions for European RNM and the target network need to be the same in the simulation.

Performing the harmonic analysis of a network requires specialized knowledge and understanding of the software capabilities, settings, and limitations. Due to the size of the entire network in most countries, the analysis should be automated through a scripting interface with the model software. Due to the complexity and volume of POIs to assess, it is unreasonable to perform the task manually. The programming is generally done through a common computer language interfaced with the modelling software. For example, some simulation software, like CYMDIST and PowerFactory[4], support the use of Python to program the settings, inputs, feeders, etc., using specific functions developed for each application to engage with its simulation capabilities.

Simulation software that supports such code-based automation is generally very sophisticated with many options for selecting different models for sources, lines, cables, equipment, and loads. Without the proper knowledge, the options selected can lead to very different results. Many DSOs do not have either the expertise or the harmonic simulation capabilities to perform the evaluation of the harmonic voltages of their entire network, whereby the sensitivity to harmonics can be estimated using only the maximum values of the harmonic distortion levels of each feeder of the targeted network. This can still require extensive work for the user if scripting options are not available, however computing the maximum distortion levels found in each feeder is far simpler than finding the distortion levels at every POI. Sampling theory can further

4 PowerFactory is the trade name of a product supplied by DIgSILENT Gmbh. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the product named. Equivalent products may be used if they can be shown to lead to the same results.

help avoid the complexity of automation by reducing the number of feeders to analyse. This method is detailed further in 8.3.

8.2 Simulation model adjustment

The adjustment of the harmonic limits for the target network is justified by its differences from that of European countries. Regarding the load, the main difference is the number of phases that supply the customer. Other differences can require special attention depending on the specific network to be considered.

In some European countries, the loads of all customers are supplied by the three-phase electrical distribution system. In contrast, several countries supply all residential customers and some commercial and industrial customers with single-phase service. Nevertheless, customers in Europe as well as those in other parts of the world use comparable devices and entertainment equipment, which produce similar harmonic currents. Unlike the single-phase customer, the three-phase customer distributes total harmonic currents on each phase. Moreover, the average load level of commercial and industrial customers is higher than that of residential customers. Therefore, to ensure a comparable harmonic current and load level, the following considerations apply to the power distribution model:

a) For three-phase customers, the simulation is set to use 1/3 of the harmonic current emission per phase and 1/3 of the total load per phase, for example 1,5 kVA load becomes 0,5 kVA/phase with a power factor of 0,98.

b) For single-phase customers, the simulation is set to consider the source of the harmonic current and the load of the customer connected to the same phase, for example 1,5 kVA/phase with a power factor of 0,98.

In Europe, voltage regulation equipment such as shunt capacitor banks or auto-transformers with tap changers are rarely needed due to the very short length of the MV feeders. In comparison, the networks in North America are very long and often use such equipment for maintaining suitable voltage for all customers. For an evaluation of the sensitivity factor comparable to that of Europe, all voltage control equipment on the MV feeders is either disconnected or bypassed in the models, depending on the type of installation (shunt or series). One example is capacitor banks, which cause resonances in the power system; shunt banks are disconnected, and series banks are bypassed to eliminate simulation complications caused by any potential resonances. The goal is to find the natural performance of the power system due to inherent design characteristics that cannot reasonably be changed. When resonances are identified in the real world, from capacitor banks for example, then mitigation is easily applied by the DSO to deal with it, hence that consideration is not factored into these simulations.

8.3 Studies with only the maximum harmonic distortion of each feeder

For statistical analysis of the entire electrical system, each node supplying the POI of at least one customer is configured in the simulation software. Since each feeder connects many nodes, selecting the one that produces the maximum distortion levels cannot be done efficiently without the support of a programming function such as Python. However, it can be done manually by selecting only the nodes at the end of each branch of the feeder. One of these nodes will typically yield the maximum harmonic distortion level on the feeder since the potential for resonances is mitigated by removing the capacitor banks.

The 95th percentile of all feeder maximum voltage distortion levels as well as the maximum distortion level of the RNM are used for the sensitivity calculation. This approach has been tested in Canada with 5 000 MV feeders supplying 7,1 million customers with more than 1 million MV/LV transformers. The harmonic voltage at each customer's POI was obtained by simulation according to the method described in this document. The error of the sensitivity factor S_R, evaluated only from the feeder maximums, reached 18 % compared to the sensitivity factor obtained from using the harmonic levels from all the POIs on the whole power system. The modified approach is thus not perfect, however it could be the only means to conduct the assessment if the use of advanced scripting tools is not possible.

8.4 Sampling the feeders of the entire power system

Simulation work can be reduced by using sampling theory to simulate fewer feeders. The sample size is set to obtain a valid number of samples in the population. This size can be computed as shown in Equation (4):

$$S_{\text{size}} = \frac{N \times Z^2 \times p(1-p)}{N \times e^2 + Z^2 \times p(1-p)} \quad (4)$$

where:

N = total number of feeders in the whole population;

p = proportion of customers or spot loads producing harmonics at the same time. There is no statistic available for this information. The literature suggests using p = 0,5 when the information is not available. The parameter will be discussed later in this document;

e = desired maximum error by sampling the population for the statistical analysis. In practice the maximum tolerable error is often selected as 5 %;

Z = variable computed from the confidence level (C_{L}) according to Equation (5):

$$Z = \sqrt{\frac{0{,}82 + 0{,}812\ C_L^2 - 0{,}9778 C_L^4}{1 - 1{,}7654 C_L^2 + 0{,}664 C_L^4}} \quad (5)$$

For example: C_{L} = 0,95 => Z = 1,958 476

Applying this to a targeted network using a population of 1 472 feeders, the Z value is 1,96 for 95 % confidence:

$$S_{\text{size}} = \frac{1472 \times 1{,}958476^2 \times 0{,}5(1-0{,}5)}{1472 \times 0{,}05^2 + 1{,}958476^2 \times 0{,}5(1-0{,}5)} = 304{,}28 \cong 305$$

The expected sampling error can be estimated with Equation (6):

$$e = Z\sqrt{p(1-p)\left(\frac{1}{S_{\text{size}}} - \frac{1}{N}\right)} = 0{,}05 \quad (6)$$

According to Equation (6), the sampling error of 305 feeders from the population of 1 472 feeders would be approximately 5 %. This approach has been tested in Canada. A difference up to 30 % on the evaluation of the sensitivity factor was observed by comparing the results of the study with the whole network to that of only 305 randomly selected departures.

9 Statistical analysis

Statistical analysis involves finding the 95$^{\text{th}}$ percentile of N values, where N is the number of spot loads or POIs. It is assumed that each of these values has the same probability of occurring.

After evaluating the harmonic level at each spot load, the values of each harmonic rank are sorted in ascending order. There are numerous options for constructing the initial cumulative frequency curve from the data set; a popular one is the Median Approximation, which is the median rank of the i^{th} sorted number of n data points. While the median rank is a detailed calculation, it is easily approximated as follows:

$$F\left(x_i\right) = \frac{i - 0{,}3}{n + 0{,}4} \tag{7}$$

An example of creating the cumulative function $F(x)$ with n = 40 data points (see Table 5) is shown below using the Median Approximation method. Other methods such as Exact Median, Mean, and White's Formula are not discussed here, but may be used if desired:

Table 5 – Creating the cumulative data function

i	*F(xi)*	
1	0,017 327	= (1 - 0,3)/(40 + 0,4)
2	0,042 079	= (2 - 0,3)/(40 + 0,4)
3	0,066 832	= (3 - 0,3)/(40 + 0,4)
	↓	↓
38	0,933 168	= (38 - 0,3)/(40 + 0,4)
39	0,957 921	= (39 - 0,3)/(40 + 0,4)
40	0,982 673	= (40 - 0,3)/(40 + 0,4)

10 Conclusions

Historically, equipment harmonic current emission limits were defined by considering the impedance of the European LV network, the MV/LV harmonic ratio, and other impact factors associated with equipment harmonic currents. Field measurements taken since the implementation of the harmonic emission standards have demonstrated that power system harmonic voltages remain below their respective compatibility levels at 95 % of service locations, thereby validating the effectiveness of the standards.

The European reference network model (RNM) was developed for this study such that harmonic simulation using the harmonic current model derived in 1980 for each customer results in the 95^{th} percentile voltage distortion levels being approximately equal to the compatibility levels. This reference network model is used to calibrate the simulation software to ensure that assessment of the harmonic sensitivity of the target network is accurate.

When connecting equipment in regions where IEC 61000-3-2 and IEC 61000-3-12 are not applicable, the impact factors associated with equipment usage characteristics are assumed to remain unchanged. What changes most is the harmonic sensitivity level of the network, which could result in different harmonic voltage distortion levels. The differences in distortion levels indicate whether the target network can accommodate more or less harmonic current injection than the IEC standards allow. This document presents a methodology that can be used to adapt the IEC equipment harmonic current limits in those regions where IEC 61000-3-2 and IEC 61000-3-12 are not applicable.

The power system harmonic sensitivity is influenced by numerous factors such as the MV/LV power system architecture, types of service cables, and size of transformers. Each feeder has its own characteristics, which influence the sensitivity level; thus, it is not possible to study only a few feeders to define this expected distortion levels for the whole power system. Instead, the whole power system is modelled to find the 95th percentile voltage distortion levels for each harmonic order; comparison of those distortion levels with the results of the RNM simulation determines the harmonic sensitivity of the target network.

Other potentially simpler methods of achieving the same results were researched during this study and the following conclusions are presented:

- Feeder clustering: Clustering of feeder characteristics has potential to achieve the desired outcome, however access to the type of feeder data required is challenging for DSO engineers, and machine learning programming skills are required to accomplish the clustering task; therefore, clustering was deemed too difficult to present as a methodology.
- Voltage droop: Modelling a power system's voltage droop performance is a simple task for DSO engineers, which has previously been suggested as a means to represent harmonic distortion, since both voltage droop and harmonic distortion are inherently linked to impedance. This study found that voltage droop is inherently too simplistic to represent harmonic performance; therefore, voltage droop was deemed not suitable to present as a methodology.

Annex A supplies more detail about the feeder clustering and voltage droop studies.

Using the methodology presented in this document requires scripting access to a large database of feeders in the target country, such that harmonic assessment can be conducted at every POI in the distribution system. While the task is not an easy one, it was determined to be the most effective for providing accurate results of system sensitivity to harmonic current injection and thereby determining appropriate translation coefficients.

This document also suggests two simplifications that can be used if the simulation software cannot support scripting to control its parameters and conduct batch processing to model the whole power system. The first simplification is to select harmonic model results from only the node at the end of each branch of each feeder. This simplification compromises accuracy, as it was observed to cause error up to 18 % in the sensitivity assessment of the target network. The second simplification consists of simulating a smaller portion of the entire network. This approach uses sampling theory, which allows for the reduction of the number of feeders to simulate. For example, instead of simulating 1 472 feeders, sampling theory indicates that modelling 305 feeders is enough to represent the entire population. Again, this approach compromises accuracy even further, as it was observed to cause error up to 30 % in the sensitivity assessment.

Annex A
(informative)

Other methods studied for comparing feeder harmonic sensitivity

A.1 General

Two other methods were considered for adapting equipment harmonic emission limits for use in regions outside of Europe. The main methods considered were as follows:

a) voltage droop;

b) clustering of feeders by various characteristics.

Extensive modelling with existing networks revealed that voltage droop comparisons do not provide accurate means of assessing the harmonic sensitivity of a network.

Clustering feeders by specific characteristics showed promise for assessing the harmonic sensitivity of a network; however, the feeder characteristics are difficult to derive. In order to find the characteristics for each feeder the user needs direct read access to their feeder model database and requires good programming skills to derive the required parameters.

A brief overview of the work conducted for each of these considerations is provided in Annex A.

A.2 Voltage droop

A.2.1 Explanation

Voltage droop was proposed as a potential simplified method to assess power system sensitivity to harmonics; it is the total voltage droop at any point in the system with all voltage regulation devices removed.

A.2.2 Voltage droop simulation

The network models used by DSOs are constructed for load flow simulation with all voltage regulators in service. Since each substation usually includes a voltage regulator, for the load flow simulation, the source impedance does not impact the results. Consequently, in such models each feeder was supplied by one source, which does not reflect the actual operating condition for the harmonic current flow. The voltage regulator at the substation was turned off and the source impedance was connected. The network model was also modified to connect all feeders to their appropriate bus at the substation, as is physically constructed. To obtain the real voltage droop and harmonic levels, all voltage regulators and transformers along the feeder were bypassed and capacitor banks were disconnected. The customer load model was defined as the CIGRE C-type load.

To establish the relation between voltage droop and harmonic distortion levels, the total active power of each customer was set to 1,5 kW at a PF of 0,979 and the harmonic source connected to each customer was set to the harmonic level generated by an equipment at 120 V (see Table 4).

When the LV cable length is short, as is the case in North America, the customers connected to each distribution transformer are regrouped and represented by a spot load connected at the MV level in the network model. The harmonic voltage considered for the analysis is that of the MV network, thus the harmonic injection was at the MV level. Consequently, the harmonic currents were adjusted according to the voltage ratio of 120 V service and the MV supply source.

A.2.3 Concept of the voltage droop approach

The concept consists of finding the relation between the voltage droop and the harmonic level using the simulation results at few POCs on the power system, each of them being located at various distances from the substation. When the relationship is established for each harmonic order, the 95th percentile of the voltage droop is used to calculate the 95th percentile of each harmonic order. Considering that the voltage harmonic and voltage droop both result from the current flowing in the same power system impedance, the relation between these two quantities was hypothesized to be highly correlated.

To validate the concept, the simulation of a real network model provided the harmonic voltage and voltage droop at the POC of each spot load of the entire power system. The scatter plot in Figure A.1 shows a cloud of values for h_3 and h_5, where it was expected to see a straight line.

These clouds of values are due to several phenomena, such as the unbalance voltage due to the unbalance of the load, which affects the droop on each phase separately. The power system is also composed of a mix of overhead lines and underground cables. The feeder models are made up of several small sections, each of which is composed of a series resistor and inductor along with two shunt capacitors (π model). As the frequency increases, the effect of the capacitor on the voltage drop also increases. Since this capacitor is different depending on whether the feeder is overhead or underground, the harmonic voltage is affected differently as the frequency increases. Therefore, the relation between the voltage droop and the voltage harmonic distortion is different according to the feeder section. It was then thought that an average might attenuate the effect of these phenomena and show a better relation between harmonic levels and voltage droop. A linear regression was used to find the mean in a two-dimensional plane. Figure A.1 supplies the linear equation as calculated by Excel[5] with the linear trend function.

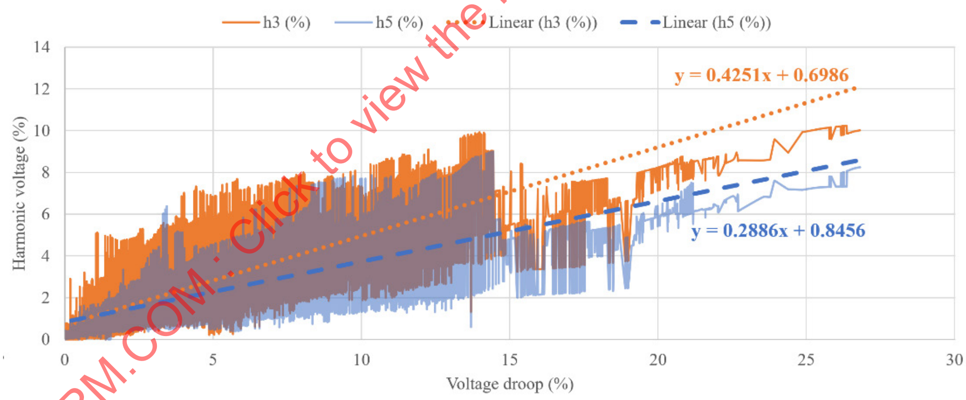

Figure A.1 – Scatter plot of voltage harmonic levels (3rd and 5th) as function of the voltage droop

The same computation was performed for each harmonic order. In this simulation, the voltage droop at the 95th percentile is equal to 7,973 %. The slope m and the y-axis zero crossing b (see Equation (A.1)) of each linear regression was computed and reported in Table A.1. It was expected that the 95th percentile of each harmonic order could be obtained by applying the straight-line function (see Equation (A.1)) where x is equal to 7,973 % and y is the harmonic level.

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5 Excel is the trade name of a product supplied by Microsoft. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the product named. Equivalent products may be used if they can be shown to lead to the same results.

$$\overline{y} = m\overline{x} + b \tag{A.1}$$

Table A.1 – Coefficients of linear regression obtained from the harmonic and droop data

h	*m*	*b*		*h*	*m*	*b*		*h*	*m*	*b*		*h*	*m*	*b*
3	0,425	0,699		13	0,1590	1,853		23	0,0192	0,924		33	0,0111	0,459
5	0,289	0,846		15	0,1436	1,680		25	0,0127	0,691		35	0,0186	0,365
7	0,252	1,206		17	0,0956	1,762		27	0,0022	0,658		37	0,0229	0,362
9	0,248	1,226		19	0,0475	1,518		29	0,0134	0,445		39	0,0164	0,473
11	0,178	1,602		21	0,0344	1,185		31	0,0117	0,409		41	0,0347	0,283

See Figure A.1 and Equation (A.1).

A.2.4 Validation of the voltage droop method

Two methods were considered to estimate the 95th percentile harmonic levels of the entire network:

a) Direct harmonic assessment used as the reference:
   1) The harmonic level at each POC of the spot loads or the customer loads is obtained from the simulation.
   2) The 95th percentile value is obtained by classification of the voltage harmonic distortion data.

b) Calculated harmonic assessment using the voltage droop approach:
   1) The voltage droop is assessed at the POC of each customer of the entire network.
   2) The linear regression for each harmonic order (y value) is carried out with the voltage droop results (x value) to obtain the slope m and the y-crossing (intercept) b of Equation (A.1).
   3) The 95th percentile value is obtained by classification of the voltage droop data.
   4) Having the voltage droop level and the linear equation, the corresponding harmonic level is computed.

Figure A.2 compares the 95th percentile harmonic level directly obtained from simulation and the 95th percentile harmonic level calculated from the linear regression of the 95th percentile voltage droop. Mitigation of the cloud of results with the linear regression did not reach the desired objective. The difference for h_3 and h_5 is about 20 %. For some harmonic orders, the difference was greater. For example, the difference for h_9 is 37 % and h_{19} reached 95 %.

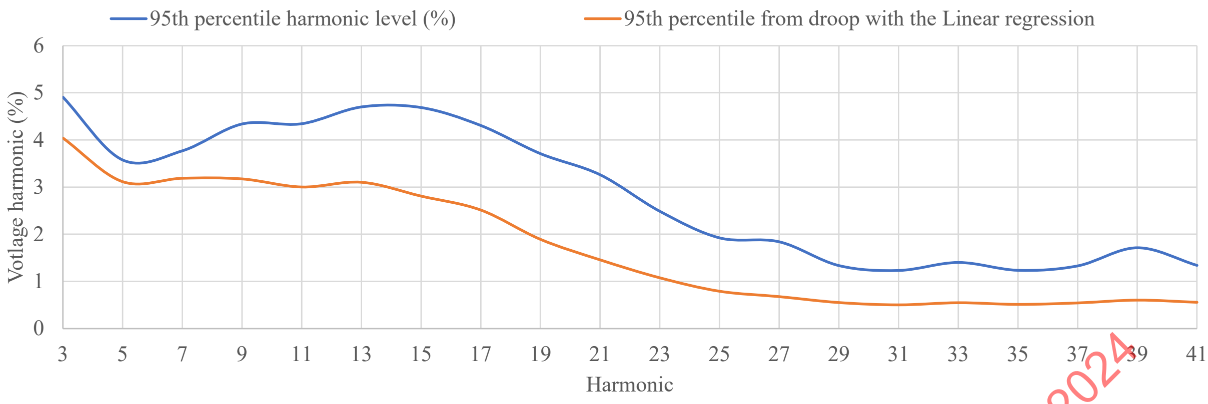

Figure A.2 – Comparison of the 95th percentile harmonic levels obtained from simulation and calculated from the voltage droop

Additional tests were performed by combining the phase conductor length and the voltage droop without success. The use of symmetrical components also failed to sufficiently reduce the uncertainty. With the additional parameters, the voltage droop method became very complicated and the decision was made to abandon the method in favour of direct modelling.

A.2.5 Clustering

A.2.5.1 General

The clustering method consists of classifying each element (feeder) of a population (distribution network) into a few groups called clusters. Many clustering algorithms exist with varying pros and cons; this study used a relatively simple clustering method called k-means clustering. The goal of the study is to find an appropriate set of feeder characteristics, that when used with the k-means algorithm, results in clusters of feeders having similar qualities with respect to harmonic sensitivity.

A.2.5.2 k-means clustering method

Clustering is a methodology translated from geographical mapping, where GPS points are often clustered based on their physical coordinates. The idea is to find a distance between points and then form clusters of points that are close together. The Minkowski equation is the most common measure of distance used for this:

$$\mathbf{d}(X,Y) = \sqrt[q]{\sum_{i=1}^{n}(x_i - y_i)^q} \tag{A.2}$$

Two special cases of the Minkowski metric are when q = 1 and q = 2, as illustrated in Figure A.3 and Figure A.4.

Distance between two points along grid lines.

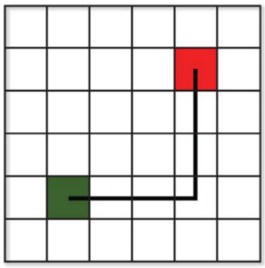

Figure A.3 – q = 1, Manhattan distance

Straight-line distance between two points.

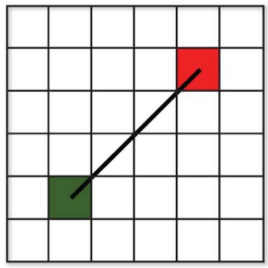

Figure A.4 – q = 2, Euclidian distance

Concerning feeder parameters, distance equations can be applied to any number of dimensions (n), thus a distance measure can be obtained for any number of feeder parameters; consider the following:

$$X\left(x1,x2,x3\ldots x_{i-1},x_i\right) \qquad Y\left(y1,y2,y3\ldots,y_{i-1},y_i\right)$$

$$\boldsymbol{d}\left(\boldsymbol{X},\boldsymbol{Y}\right)=\sqrt{\left(\boldsymbol{x}_1-\boldsymbol{y}_1\right)^2+\left(\boldsymbol{x}_2-\boldsymbol{y}_2\right)^2+\left(\boldsymbol{x}_3-\boldsymbol{y}_3\right)^2+\ldots+\left(\boldsymbol{x}_i-\boldsymbol{y}_i\right)^2} \qquad \text{(A.3)}$$

Systems clustered using one, two, or three parameters (dimensions) are more easily visualized in a chart. Figure A.5 shows an example of a network of feeders clustered using two parameters, maximum feeder length and maximum feeder load. Each small dot represents an actual feeder; colours are assigned to each cluster, and the large dots are the centroids of each cluster. The centroid is a mathematical centre of a cluster; it does not represent an actual feeder.

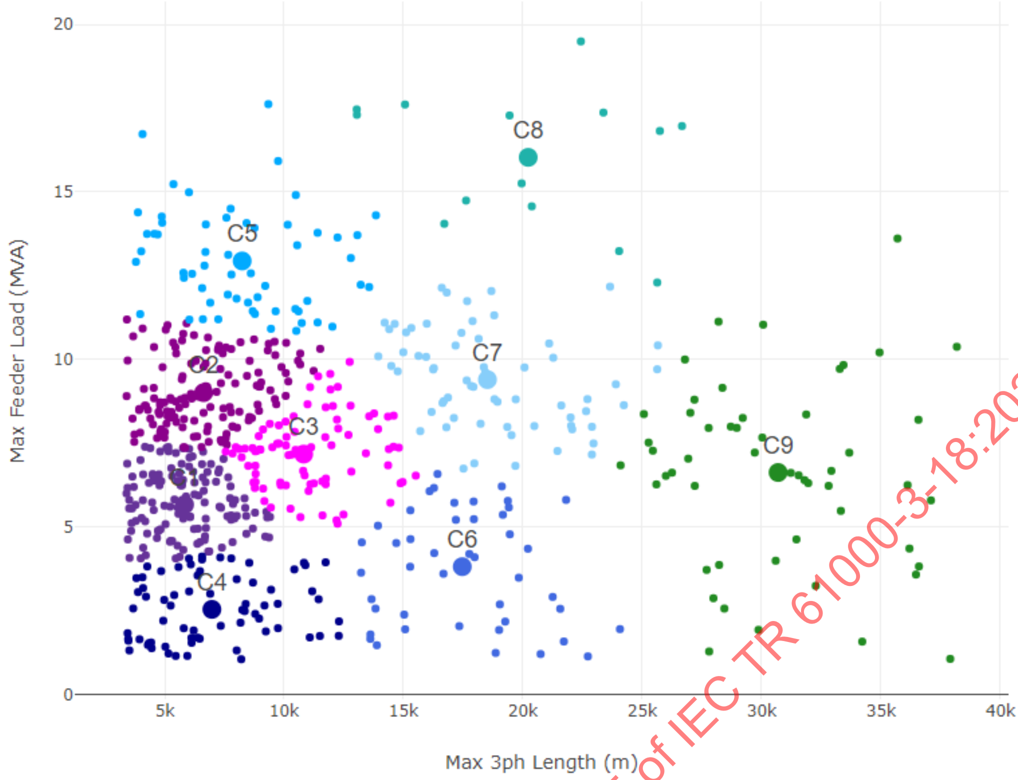

Figure A.5 – Two-parameter k-means clustering example

k-means clustering is characterized as follows:

- It is an agglomerative algorithm (bottom-up), meaning each feeder starts as its own cluster, and feeders are subsequently combined to form fewer and fewer clusters until the best result is found.
- The user initially defines the number of clusters, so iterations are usually performed to find the best result.
- Each cluster is characterized by its centre (centroid).
- k cluster centres are estimated to start the algorithm. There are many algorithms which exist for estimating the initial cluster centroids.

A k-means clustering algorithm is described as follows:

Select k observation points as the initial centroids.

Repeat the following:

a) assign each observation point to its nearest centroid to form all the clusters;

b) re-compute the centroid of each cluster after all points are assigned;

c) calculate the sum-squared-error (SSE) as described below.

Stop the loop when SSE does not change very much – this is the optimum solution.

A.2.5.3 Sum-squared-error (SSE)

A measure of cluster quality is the degree of tightness, also known as “scatter” or “distortion”, which can be quantified using a sum-squared-error (SSE illustrated in Figure A.6).

$$SSE = \sum_{i=1}^{k}\sum_{j=1}^{n_i} dist\left(C_i, X_j\right)^2$$

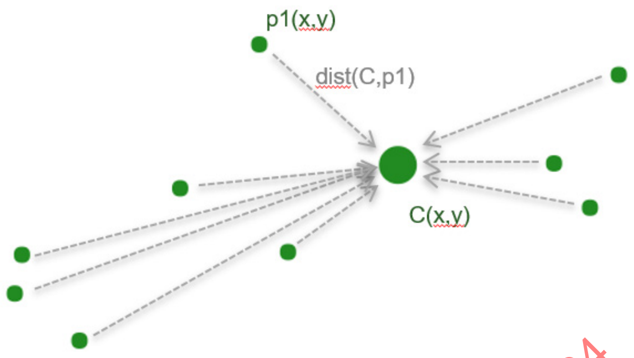

Figure A.6 – Illustration of SSE

A.2.5.4 Clustering for harmonic sensitivity

The main challenge for this study was determining which feeder characteristics are most important to use in the clustering algorithm to accurately represent harmonic distortion performance. A small list of feeder characteristics one might consider are as follows:

- maximum length from substation
- nominal voltage
- maximum impedance
- node count
- number of reclosers
- number of voltage regulators
- number of capacitors
- residential customers (number or kW)
- commercial customers (number, kW)
- industrial customers (number, kW)
- transformers (load type, kW actual and conn)
- customer dispersion factor (SSE of physical locations)
- ratios (3ph:1ph load, impedance, length)
- total load (MVA)

A.2.6 Feeder parameters

A.2.6.1 Overview

Over the course of this study, numerous combinations of feeder characteristics were tested which are known by engineering principles to have an impact on the voltage harmonic distortion of a feeder. The fine details of the study are not included here; however, the result is that the following five parameters were determined to provide the best clustering of feeders by voltage harmonic sensitivity. These calculated parameters each consist of other basic modelling characteristics.

A.2.6.2 Average load impedance of all customers ($CustZ$)

The total load of each feeder is usually recorded at the substation and the number of customers supplied can be obtained from DSO databases. Consequently, one of the feeder characteristics to consider for the clustering parameters is the average load impedance of all the customers supplied by the feeder.

$$(1)\,CustZ = total\ customer\ count \times \frac{U^2}{Feeder\ MVA_{\mathrm{MAX}}} \tag{A.4}$$

A.2.6.3 Sum of customer count × network impedances

The portion of the harmonic current flowing through the network impedance causes the voltage harmonic distortion at the point of connection (POC) of the customer. For that reason, one of the feeder characteristics proposed for the clustering method is the sum of all network impedances at the MV side of single-phase distribution transformers times the number of customers supplied by each transformer.

$$(2)\,SumTx_{Z1} \times 1_{ph}Cust = \sum_{i=1}^{\#Tx} \left\{ Tx_{Z1_{MV}} \times \#Cust \right\}_{Tx_i} \tag{A.5}$$

A.2.6.4 Feeder branches

Consider a single-radial feeder; the harmonic current accumulates along the line as each customer contributes to the maximum voltage distortion occurring at the end of line. Feeders can also be represented like trees with multiple branches serving densely dispersed loads. Rather than offering a single path for the current to flow to the substation, the branch architecture gives multiple paths before reaching the substation. The number of feeder splits (branches) therefore reduces the maximum harmonic voltage and is thus important to the overall sensitivity.

$$(3)\,SplitCnt = \#of\ \ feeder\ branches \tag{A.6}$$

A.2.6.5 Customer dispersion factor

The $SplitCnt$ on its own is insufficient to represent the effect of very long radial portions of a feeder before starting to branch out. Rural areas can be supplied by long single-radial trunk sections before starting to have multiple branches, as opposed to urban type feeders which have numerous branches close to the substation. Simulations showed higher harmonic distortion levels for these rural feeders when supplying similar numbers of customers to what is found in urban areas. To account for this, a measure of customer dispersion is proposed, the sum squared error (SSE) of all MV/LV transformer distances to the substation.

$$(4)\,SubStraightDistSSE = \sqrt{\sum_{i=1}^{n} \left[Tx_{Dist_i} - mean\left(Tx_{Dist_i}\right) \right]^2} \tag{A.7}$$

where n = number of MV/LV transformers on the feeder.

The previous parameters were combined (Cmb) using the following equation:

$$Cmb = \frac{(1)\times(2)\times(4)}{\sqrt{(3)}} \tag{A.8}$$

The feeders are then clustered using one parameter and the centroids of the clusters are used to determine the average harmonic performance of that cluster. The details of performing this analysis are not explained here, however the results when applied to a set of feeder in Canada are as follows:

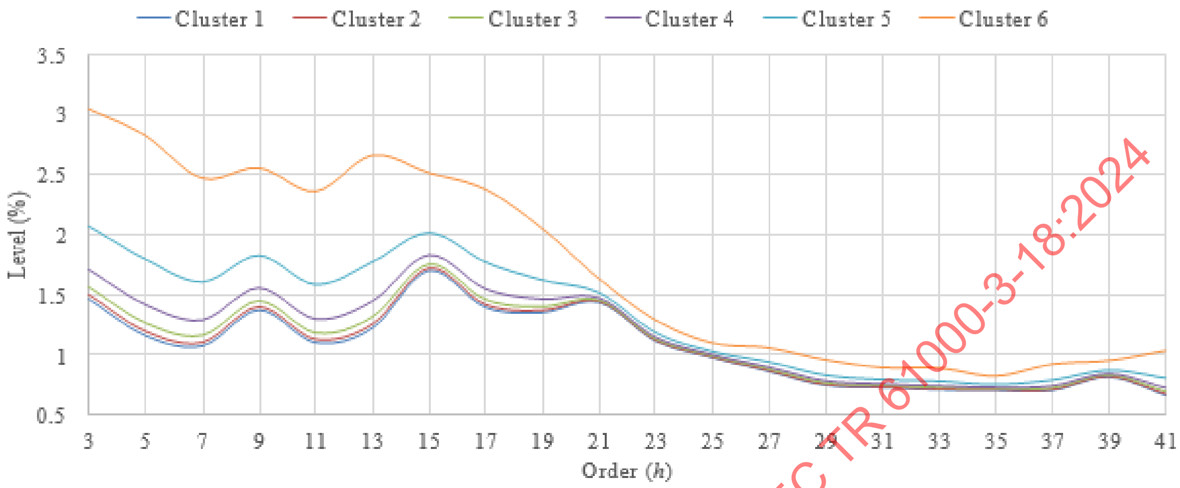

Figure A.7 – Harmonic distortion levels at cluster centroids

The cluster centroid exhibiting the highest distortion levels (orange line of Figure A.7) is then compared with the benchmark distortion levels obtained from the RNM, and the harmonic conversion factors are computed. It is noted that the clustering method also supports the conclusion that higher order harmonics do not vary significantly and thus a conversion factor of 1 can be appropriate for simplification in the upper half of the harmonic range.

The challenges of the clustering method are as follows:

a) DSO representatives can have difficulty accessing, querying, and deriving the required parameters when open and accessible feeder modelling databases are not available;

b) if the correct parameters can be obtained, DSO engineers might not have the tools or expertise required to run a clustering algorithm, such as *k*-means, to obtain the results;

c) the resulting distortion levels of the cluster centroids do not necessarily reflect the 95th percentile of harmonic distortion, thus the results might not be accurate.

Annex B
(informative)

Power distribution systems in Canada

B.1 Overview

The population density in North America (NA) is much lower than that in European countries. As a result, MV lines are considerably longer than in Europe to reach the same number of customers. The main problem for NA DSOs is serving these customers at the appropriate voltage level. The HV/MV substation regulates the voltage before powering MV feeders. Due to the feeder length being much longer than those in European countries, the voltage drop quickly becomes the limitation of these feeders in NA before reaching every customer. As a result, additional voltage regulators are often added along power lines in North America, whereas they are rare to see in Europe.

The very long MV feeders force NA DSOs to relax their design criteria. For example, the voltage drop allowance at the MV level in NA is greater than that of Europe. To relax the voltage-drop requirement at the MV level, NA DSOs prefer to limit the allowable voltage drop at the LV level. Consequently, each MV/LV transformer in NA supplies significantly fewer customers than in European countries. The challenge for DNOs is to reduce the length of the LV networks. Unlike European countries, when only 10 m of cable is needed between two customers, this length in North America can be 50 m to 100 m. As a result, instead of 100 customers per MV/LV transformer, NA DSOs design their LV networks for an average of five customers, which is about 5 % of the LV system in European countries.

In North America, a split-phase 25 kVA or 50 kVA 120 V-120 V transformer commonly supplies the LV distribution system. In general, these transformers are powered by the MV system between a phase and the neutral. Their impedance averages around 1,7 % with an X/R ratio of 1,2. From the transformer, a main cable consisting of three bare conductors #3/0 ACSR (aluminium-conductor, steel reinforced) 200 mm apart from each other runs along the customer's lot line. A twisted triplex No.1/0 ACSR connects each house to the main cable. Figure B.1 illustrates the typical LV distribution system in Canada. Each load is 2,7 kVA with a power factor of 0,98.

Table B.1 – LV feeder impedance in Canada

Cable ID	Conductor type	R (Ω/km)	X_L (Ω/km)	B_C (μS/km)
Main LV	#3/0 bare ACSR	0,458 6	0,279 7	4,074
Drop lead	#1/0 insulated ACSR	0,704 9	0,109 5	30,22

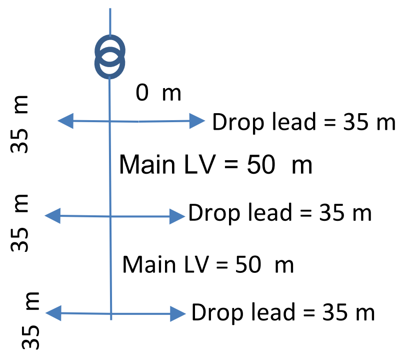

Figure B.1 – Low-voltage system in Canada

Customer harmonic currents accumulate at the MV level with those of other customers throughout the MV system. Therefore, the harmonic voltage at the POI of each customer is the sum of that of the LV system and that of the MV system. If the portion of the harmonic voltage associated with the LV system is negligible, then all the customers connected to a distribution transformer can be grouped together and considered as a single load connected to the MV system. This single load is called a spot load and is often used in NA power system models where the LV influence is a very small proportion of the voltage impact.

The power system models provided by the three Canadian participant distribution system operators (DSOs) supply more than 7,1 million customers, representing nearly 50 % of the Canadian network. More than 25 % of them are powered by dedicated single-phase distribution transformers which are often specified with low-impedance amorphous cores. Due to the voltage drop limitation, the distribution transformer generally supplies fewer than 12 single-family houses (6,7 in average), which is very popular in Canada. The case illustrated in Figure B.2 shows the transformer supplying 32 customers. The maximum number of customers supplied by a single distribution transformer reaches 1 058 (see Figure B.3). In these cases where many customers are in the same building, the DSO supplies a private network to the building that groups customers together in co-ownership. Consequently, the portion of the distortion of spot loads due to the LV impedance up to the POI is negligible. The simplification is also conservative in nature in the sense that it works against general DSO interests, since it reduces the actual distortion expected to be seen by the customers by ignoring the LV networks.

Figure B.2 – Multi-unit building of 32 customers

Figure B.3 – Buildings with > 1 000 residential customers

B.2 Conversion factor

The method explained in this document was used in Canada to estimate the conversion factor. This conversion factor considers the adjustment of the IEC triplen harmonic compatibility levels for Canada given that the MV/LV transformers do not block them like those used in Europe. The severity ratio was computed with the 95th percentile of the harmonic voltage distortion at 7,1 million of POIs in Canada and the 95th percentile of the RNM. The results are presented in Table B.2. Harmonics h_{21} and above are more sensitive to the simulation model used than those below h_{21}. It is also noted that the conversion factor above h_{21} converges to 1. Since Canada adapted the compatibility level, the increase of h_{15} and h_{21} results in a large conversion factor of 3,81. In fact, field measurement conducted by CEATI [1] showed locations with 95th percentile levels reaching 1 % for h_{15} and 0,6 % for h_{21} which significantly exceed the IEC compatibility levels.

Table B.2 – Data for assessing the Canada 240 V limits

h	$CP95_{CA}$	$CP95_{RNM}$	*CLR*	RNM_{ADJ}	*SR*	*UR*	C_{fh}	$LimitA_{IEC}$	$LimitA_{CA}$	$\Delta LimitA_{CA}$
2	1,03	2,00	1,00	2,00	1,94	0,96	1,86	1,08	2,01	86 %
3	7,22	5,03	1,19	5,97	0,70	0,96	0,79	2,30	1,82	-21 %
4	0,65	1,00	1,00	1,00	1,54	0,96	1,47	0,43	0,63	47 %
5	4,28	5,97	1,00	5,97	1,39	0,96	1,34	1,14	1,52	34 %
6	0,72	0,50	1,00	0,50	0,69	0,96	0,67	0,30	0,20	-33 %
7	4,50	4,92	1,00	4,92	1,09	0,96	1,05	0,77	0,81	5 %
8	0,50	0,50	1,00	0,50	1,00	0,96	0,96	0,23	0,22	-4 %
9	2,03	1,52	2,28	3,46	0,75	0,96	1,63	0,40	0,65	63 %
10	0,55	0,50	1,00	0,50	0,91	0,96	0,87	0,18	0,16	-13 %
11	3,86	3,46	1,00	3,46	0,90	0,96	0,86	0,33	0,28	-14 %
12	0,60	0,46	1,00	0,46	0,77	0,96	0,73	0,15	0,11	-27 %
13	3,43	2,96	1,00	2,96	0,86	0,96	0,83	0,21	0,17	-17 %
14	0,51	0,43	1,00	0,43	0,84	0,96	0,81	0,13	0,11	-19 %
15	0,51	0,40	4,93	1,97	0,78	0,96	3,70	0,15	0,56	270 %
16	0,48	0,41	1,00	0,41	0,85	0,96	0,82	0,12	0,09	-18 %
17	2,30	1,97	1,00	1,97	0,86	0,96	0,82	0,13	0,11	-18 %
18	0,47	0,39	1,00	0,39	0,83	0,96	0,80	0,10	0,08	-20 %
19	1,98	1,74	1,00	1,74	0,88	0,96	0,84	0,12	0,10	-16 %
20	0,42	0,38	1,00	0,38	0,90	0,96	0,87	0,09	0,08	-13 %
21	0,35	0,30	4,63	1,39	0,86	0,96	3,81	0,11	0,41	281 %
22	0,40	0,36	1,00	0,36	0,90	0,96	0,86	0,08	0,07	-14 %
23	1,52	1,39	1,00	1,39	0,91	0,96	0,88	0,10	0,09	-12 %
24	0,40	0,35	1,00	0,35	0,88	0,96	0,84	0,08	0,06	-16 %
25	1,35	1,26	1,00	1,26	0,93	0,96	0,89	0,09	0,08	-11 %
26	0,37	0,35	1,00	0,35	0,95	0,96	0,91	0,07	0,06	-9 %
27	0,22	0,20	1,00	0,20	0,91	0,96	0,87	0,08	0,07	-13 %
28	0,35	0,34	1,00	0,34	0,97	0,96	0,93	0,07	0,06	-7 %
29	1,08	1,04	1,00	1,04	0,96	0,96	0,92	0,08	0,07	-8 %
30	0,36	0,33	1,00	0,33	0,92	0,96	0,88	0,06	0,05	-12 %
31	0,97	0,96	1,00	0,96	0,99	0,96	0,95	0,07	0,07	-5 %
32	0,33	0,33	1,00	0,33	1,00	0,96	0,96	0,06	0,06	-4 %
33	0,21	0,20	1,00	0,20	0,95	0,96	0,91	0,07	0,06	-9 %
34	0,32	0,32	1,00	0,32	1,00	0,96	0,96	0,05	0,05	-4 %
35	0,83	0,83	1,00	0,83	1,00	0,96	0,96	0,06	0,06	-4 %
36	0,33	0,32	1,00	0,32	0,97	0,96	0,93	0,05	0,05	-7 %
37	0,76	0,77	1,00	0,77	1,01	0,96	0,97	0,06	0,06	-3 %
38	0,31	0,32	1,00	0,32	1,03	0,96	0,99	0,05	0,05	-1 %
39	0,20	0,20	1,00	0,20	1,00	0,96	0,96	0,06	0,06	-4 %
40	0,31	0,31	1,00	0,31	1,00	0,96	0,96	0,05	0,04	-4 %

NOTE 1 Column abbreviations are defined as follows:

- $CP95_{CA}$ 95th percentile distortion resulting from Canada simulation
- $CP95_{RNM}$ 95th percentile distortion resulting from RNM simulation
- CLR Compatibility level ratio
- RNM_{ADJ} 95th percentile distortion adjusted for Canada compatibility levels
- SR Sensitivity ratio
- UR Voltage ratio
- C_{fh} Conversion factor
- $LimitA_{IEC}$ IEC Class A limit
- $LimitA_{CA}$ Calculated Canada Class A limit
- $\Delta LimitA_{CA}$ Calculated Canada Class A limit difference from IEC Class A limit

NOTE 2 The computed conversion factor for 120 V equipment is twice the value in the 240 V column.

The conversion factors computed for Canada, for example, would result in the following adopted limits for Class A equipment (see Table B.3).

Table B.3 – Limits for Class A Equipment

h	IEC limit (A)	C_{fh}	CA 240 V limit (A)	CA 120 V limit (A)
Odd harmonics				
3	2,30	0,8	1,84	3,68
5	1,14	1,34	1,53	3,06
7	0,77	1,05	0,81	1,62
9	0,40	1,64	0,66	1,32
11	0,33	0,86	0,28	0,56
13	0,21	0,83	0,17	0,34
$15 \le h \le 39$	$0{,}15\ \frac{15}{h}$	1*	$0{,}15\ \frac{15}{h}$	$0{,}3\ \frac{15}{h}$
Even harmonics				
2	1,08	1,87	2,02	4,04
4	0,43	1,47	0,63	1,26
6	0,30	0,67	0,2	0,4
$8 \le h \le 40$	$0{,}23\ \frac{8}{h}$	1[a]	$0{,}23\ \frac{8}{h}$	$0{,}46\ \frac{8}{h}$

[a] There is good evidence that conversion factors for higher orders are similar across networks, and thus a simplification is proposed to use a conversion factor of 1. Individual regions might prefer to assess different conversion factors for each higher order.

Annex C
(informative)

Power distribution systems in Japan

C.1 Background for harmonics limits

In Japan, manufacturers and DSOs have been working together to comply with the guidelines and standards that were adopted in order to maintain harmonic distortion below certain levels, which is a national goal or "harmonic levels of environmental achievement", i.e. voltage THD, 5 % (6,6 kV), 3 % (> 6,6 kV). The Guideline for Electrical Appliances is enforced as JIS C 61000-3-2 [5]. The Guideline for Customers Connected to the MV and HV power system is enforced as JEAG 9702 [6].

In order to simulate voltage distortions, the following procedures were carried out:

a) deriving harmonic currents from residential customers (A/site) and MV and LV customers (A/kW);

b) developing models of MV distribution systems and HV transmission systems.

Simulations were carried out in the process of adopting the guidelines and standards, confirming the effectiveness of the translated limits. This was carried out from 1987 to 1989 by the cooperation between manufacturers, DSOs, and academics. Future situations on the voltage distortions were estimated, and from that estimation, limits for the harmonic currents were determined as 25 % for residential customers and 50 % for the MV and HV customers, compared with those of 1987 [7]. This was also equivalent to the limit translated from the IEC limits in proportion to nominal voltage.

These limits are specified in JIS C 61000-3-2 [5] mainly for residential customers and JEAG 9702 [6] mainly for MV and HV customers, contributing to maintain the harmonic levels below the required levels. JIS C 61000-3-2 [5] was created from IEC 61000-3-2, translating limits in proportion to the nominal voltage, from 230/400 V to 100/200 V, in order to align with the Japanese distribution systems. Since the JIS C 61000-3-2 [5] and JEAG 9702 [6] standards were adopted, harmonic levels have become flat or have decreased slightly, satisfying the required harmonic levels, despite the wide spread of inverter-equipped appliances [8]. This has been confirmed through system measurements [9], [10].

C.2 Outlook on a typical distribution system in Japan

The overview of the power system in Japan is shown in Figure C.1.

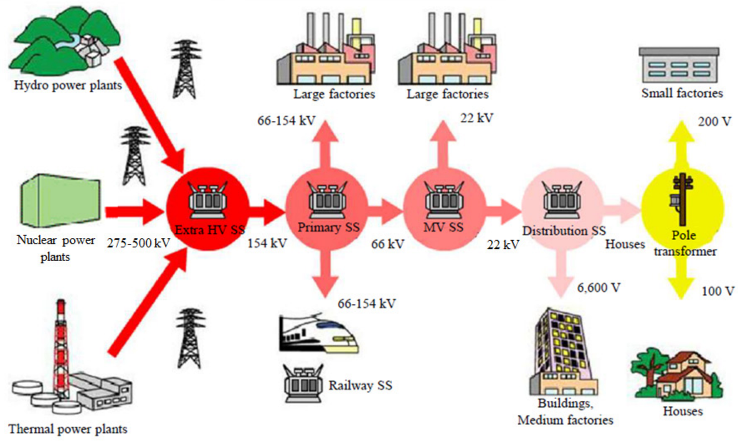

Figure C.1 – Overview of the power system in Japan [11]

In Japan, neutral grounding systems for typical Japanese HV and MV networks as shown in Figure C.2, are adopted according to the nominal system voltage.

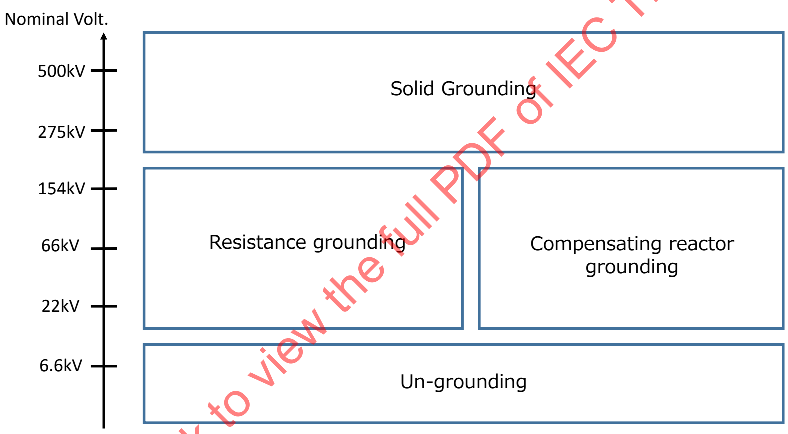

Figure C.2 – Standard neutral grounding systems for HV and MV distribution system in Japan

Therefore, Japanese DSOs are mainly responsible for operating ≤ 6,6 kV, three-phase three-wire, ungrounded distribution systems. Distribution transformer windings are mainly wye-wye, with secondary side ungrounded (Figure C.3).

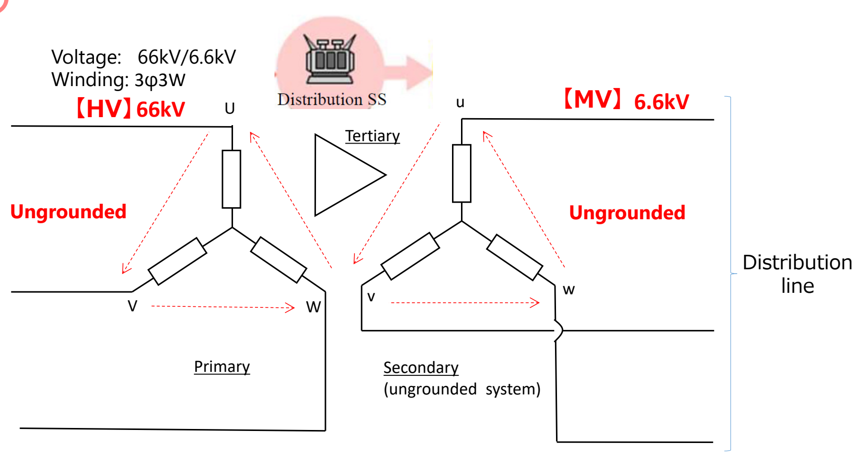

Figure C.3 – Distribution transformer for HV/MV in Japan

The three LV distribution systems shown in Figure C.4 are popular in Japan.

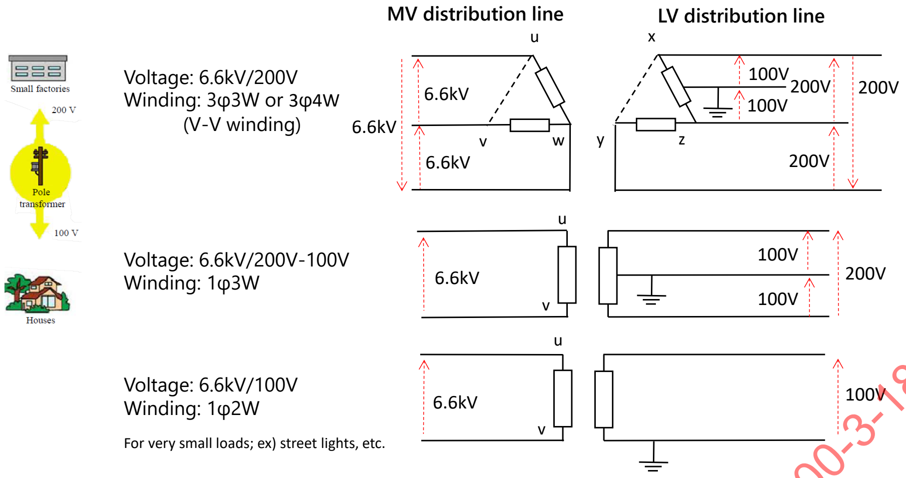

Figure C.4 – Popular LV distribution systems in Japan

C.3 Power supply to customers in Japan

The breakdown of electricity supply by voltage in the Japanese power system is as follows:

a) LV (less than 600 V) is 40 %;

b) MV (600 V to 7000 V) is 35 %;

c) HV (7 000 V or more) is 25 %.

The standard contracted power by voltage is as follows:

a) LV is less than 50 kW (general households, small condominiums, etc.);

b) MV is 50 kW to 2 000 kW (large condominiums, commercial buildings, factories, etc.);

c) HV is 2 000 kW or more (large factories, etc.).

C.4 Distribution system impedance in Japan

In past research [12], the Electric Technology Research Association conducted a sample survey of electric power companies all over Japan to investigate the impedance and length of MV distribution lines and the impedance of LV distribution lines. Among them, the 95th percentile (CP95) and the average (AVG) values are shown in Table C.1 through Table C.3.

Table C.1 – Impedance survey results for MV distribution lines (Ω)

	Downtown area		Industrial area		Residential area		Rural area		Total	
	R	X	R	X	R	X	R	X	R	X
CP95	0,708	1,157	1,960	2,394	2,849	2,786	12,336	9,036	6,084	6,258
AVG	0,263	0,415	0,525	0,828	0,888	1,142	3,682	3,703	1,446	1,629

Table C.2 – Results of long-range survey of MV distribution lines (km)

	Downtown area	Industrial area	Residential area	Rural area	Total
CP95	3,089	3,450	8,102	25,762	15,990
AVG	1,467	2,808	3,374	10,516	4,674

Table C.3 – Impedance survey results for LV distribution lines (mΩ)

	Transformer		LV distribution line		Neutral line Z_n		Service line Z_s		1 00 V circuit Z_t+Z_e+Z_n+2Z_s		200 V circuit 2Z_t+2Z_e+2Z_s	
	R	X	R	X	R	X	R	X	R	X	R	X
CP95	97,3	58,3	41,8	42,6	73,6	23,3	69,4	1,9	351,5	128,0	417,0	205,6
AVG	21,2	21,7	12,0	8,4	16,1	8,7	28,5	1,3	104,5	41,4	121,6	62,8

C.5 Case study of 95th percentile and conversion factor in Japan

The 95th percentile was calculated for 8 738 MV distribution lines belonging to Chubu Electric Power Grid Co., Inc. (CEPG) using a harmonic calculation program developed by Central Research Institute of Electric Power Industry.

CEPG provides about 15 % of Japan's total electricity demand (820 000 GWh). They are located in the centre of Japan and serve load centres with various demand characteristics such as downtown, industrial, and residential. CEPG's MV distribution lines have the following characteristics:

a) The length from the distribution substation to the end of their lines is several kilometres in the city and several tens of kilometres in the country.
b) The maximum size of service supplied is 4 500 kW.

A calculation result is shown in Table C.4. The EU RNM considers only the harmonics of LV single-phase customers. Therefore, the calculation results for Japan shown in Table C.4 also consider only the harmonics generated by LV customers (40 % of electricity supply). In other words, it is noted that the harmonics generated by MV and HV customers (60 % of electricity supply) are not taken into consideration. The harmonics generated by MV and HV customers are constrained with standard JEAG 9702 [6] in Japan. Here, the equipment subject to JIS C 61000-3-2 [5] is not included in the harmonic constraints for JEAG 9702 [6]. Therefore, when focused on MV and LV systems, the calculation ought to include the equipment targeted by JIS C 61000-3-2 [5] for MV customers. Unfortunately, this calculation does not include the equipment targeted by JIS C 61000-3-2 [5] for MV customers because of a lack of MV customer information.

C.6 Comparing the 95th percentile distortion level of Japan vs. EU RNM

In the case of triplen harmonics, it can be seen that the Japanese value (for example, 0,81 % for the 3rd harmonic) is smaller than the EU RNM value (for example, 5,03 % for the 3rd harmonic). This is due to many considerations: the EU MV/LV transformer has a Δ-Y connection, the capacity of the EU LV system is large with many customers connected, and the single-phase load is connected between phase and neutral. On the other hand, Japanese MV/LV transformers are single-phase transformers connected phase to phase, the capacity ranges from 20 kVA to 30 kVA, and far fewer customers are connected.

For example, in the 5th harmonic, the 95th percentile for EU RNM was 5,97 %, while the 95th percentile for Japan was 5,03 %. The sensitivity ratio SR at this time is 1,19.

In Japan, there is a national goal or "harmonic levels of environmental achievement" which is similar to the IEC compatibility level (CL). This level is set to 5 % for the MV system, but the value of individual harmonics is not provided. The maximum value of each CL in IEC is the 5th harmonic, which is 6 %. Table C.4 shows the values obtained by converting the IEC CL of each harmonic order to 5/6 so that the 6 % CL becomes 5 % for Japan

The conversion factor C_{fh} was calculated according to Equation (2). An example of the 5th harmonic is shown in Equation (C.1).

$$C_{\text{f5}} = \frac{5{,}97\ \%}{5{,}03\ \%} \times \frac{230 V}{100 V} \times \frac{5\ \%}{6\ \%} = 2{,}27 \qquad \text{(C.1)}$$

A conversion factor for the 5th harmonic is 2,27. At first glance, this is about the same as a conversion coefficient of 230 V/100 V = 2,3 currently used in JIS C 61000-3-2. However, the conversion coefficient of JIS C 61000-3-2 [5] has been discussed in consideration of the harmonics generated by MV and HV customers. It is noted that this time C_{f5} does not consider the harmonics generated by MV and HV customers.

Table C.4 – Data and calculated limits at 100 V in Japan

h	$CP95_{\text{JP}}$	$CP95_{\text{RNM}}$	CLR	RNM_{ADJ}	SR	UR	C_{fh}	$LimitA_{\text{IEC}}$	$LimitA_{\text{JP}}$	$\Delta LimitA_{\text{JP}}$
2	1,48	2,00	0,83	1,67	1,35	2,30	2,59	1,08	2,80	159 %
3	0,81	5,03	0,83	4,17	6,20	2,30	11,88	2,30	27,32	1088 %
4	0,81	1,00	0,83	0,83	1,23	2,30	2,36	0,43	1,01	136 %
5	5,03	5,97	0,83	5,00	1,19	2,30	2,27	1,14	2,59	127 %
6	0,10	0,50	0,83	0,42	5,09	2,30	9,76	0,30	2,93	876 %
7	4,38	4,92	0,83	4,17	1,12	2,30	2,15	0,77	1,66	115 %
8	0,46	0,50	0,83	0,42	1,10	2,30	2,10	0,23	0,48	110 %
9	0,35	1,52	0,83	1,25	4,29	2,30	8,22	0,40	3,29	722 %
10	0,47	0,50	0,83	0,42	1,06	2,30	2,03	0,18	0,37	103 %
11	3,32	3,46	0,83	2,92	1,04	2,30	2,00	0,33	0,66	100 %
12	0,13	0,46	0,83	0,38	3,66	2,30	7,02	0,15	1,05	602 %
13	2,90	2,96	0,83	2,50	1,02	2,30	1,96	0,21	0,41	96 %
14	0,42	0,43	0,83	0,36	1,01	2,30	1,94	0,13	0,25	94 %
15	0,13	0,40	0,83	0,33	3,12	2,30	5,99	0,15	0,90	499 %
16	0,41	0,41	0,83	0,34	1,01	2,30	1,93	0,12	0,23	93 %
17	1,98	1,97	0,83	1,67	0,99	2,30	1,90	0,13	0,25	90 %
18	0,14	0,39	0,83	0,32	2,79	2,30	5,35	0,10	0,53	435 %
19	1,77	1,74	0,83	1,47	0,98	2,30	1,89	0,12	0,23	89 %
20	0,38	0,38	0,83	0,31	0,99	2,30	1,90	0,09	0,17	90 %
21	0,12	0,30	0,83	0,25	2,48	2,30	4,76	0,11	0,52	376 %
22	0,38	0,36	0,83	0,30	0,96	2,30	1,83	0,08	0,15	83 %
23	1,44	1,39	0,83	1,17	0,96	2,30	1,85	0,10	0,18	85 %
24	0,16	0,35	0,83	0,30	2,24	2,30	4,29	0,08	0,34	329 %
25	1,31	1,26	0,83	1,06	0,96	2,30	1,84	0,09	0,17	84 %
26	0,36	0,35	0,83	0,29	0,96	2,30	1,85	0,07	0,13	85 %

h	$CP95_{JP}$	$CP95_{RNM}$	*CLR*	RNM_{ADJ}	*SR*	*UR*	C_{fh}	$LimitA_{IEC}$	$LimitA_{JP}$	$\Delta LimitA_{JP}$
27	0,10	0,20	0,83	0,17	2,10	2,30	4,02	0,08	0,32	302 %
28	0,36	0,34	0,83	0,28	0,95	2,30	1,82	0,07	0,13	82 %
29	1,11	1,04	0,83	0,88	0,94	2,30	1,80	0,08	0,14	80 %
30	0,17	0,33	0,83	0,28	1,92	2,30	3,69	0,06	0,22	269 %
31	1,03	0,96	0,83	0,81	0,93	2,30	1,79	0,07	0,13	79 %
32	0,35	0,33	0,83	0,27	0,94	2,30	1,79	0,06	0,11	79 %
33	0,11	0,20	0,83	0,17	1,85	2,30	3,55	0,07	0,25	255 %
34	0,35	0,32	0,83	0,27	0,91	2,30	1,75	0,05	0,09	75 %
35	0,91	0,83	0,83	0,69	0,91	2,30	1,75	0,06	0,11	75 %
36	0,18	0,32	0,83	0,27	1,74	2,30	3,33	0,05	0,17	233 %
37	0,84	0,77	0,83	0,64	0,91	2,30	1,75	0,06	0,10	75 %
38	0,35	0,32	0,83	0,26	0,92	2,30	1,76	0,05	0,09	76 %
39	0,12	0,20	0,83	0,17	1,68	2,30	3,23	0,06	0,19	223 %
40	0,35	0,31	0,83	0,26	0,89	2,30	1,71	0,05	0,09	71 %

NOTE The column abbreviations are defined as follows:

- $CP95_{JP}$ 95th percentile distortion resulting from Japan simulation
- $CP95_{RNM}$ 95th percentile distortion resulting from RNM simulation
- *CLR* Compatibility level ratio
- RNM_{ADJ} 95th percentile distortion adjusted for Japan compatibility levels
- *SR* Sensitivity ratio
- *UR* Voltage ratio
- C_{fh} Conversion factor
- $LimitA_{IEC}$ IEC Class A limit
- $LimitA_{JP}$ Calculated Japan Class A limit
- $\Delta LimitA_{JP}$ Calculated Japan Class A limit difference from IEC Class A limit

Annex D
(informative)

Example of a Python script used with CYMDIST software

The Python script presented in Annex D has been adapted for a specific power system. It can be used as a reference for various instructions needed to configure the power system. Some lines are very long and exceed the allowed formatting in a normal page. These lines continue to the next one, which violates Python formatting. Please note that some statements continue to the next line without warning.

In general, this particular DSO network model makes it possible to study feeders separately, so they are not connected to the substation bus with other feeders, as would be the normal operating conditions. The first problem to solve is to connect the feeders to the substation bus according to normal operating conditions. In addition, CYMDIST limitations relate to the version being used and might cause a need for alterations. For example, prior to the 64-bit version 9.2, CYMDIST was unable to use more than 4 GB of memory which limited the number of spot loads to be simulated. In addition, this version leaves some data in memory after each simulation which further reduces the size of the memory available for the next simulation. Due to this limitation, CYMDIST could crash if the memory allocation exceeded 4 GB. For that reason, after each simulation, the software needed to be closed and restarted. The presented script considers that limitation by splitting the networks into feeder banks using the variable "MyCount".

To avoid the memory limitation problem, CYMDIST 64-bit version 9.2 and above is recommended for simulating very large networks. This version can allocate much more than 4 GB and it clears the memory between each simulation.

```
import cympy
import cympy.db
import os
import sys
import math
import time

MyCount = 4 # set the number of feeders in bank to be processed

def GetNode(serie):
      MyNode = ""
      for i in range(0,len(serie)):
            if serie[i]=="(":
                  Str = i+1
            if serie[i]==")":
                  Stp = i
      for i in range(Str,Stp):
            MyNode += serie[i]
      return(MyNode)


def GetSub(path1):
      rdin=open(path1,'r')
      rCh = '\n'
      FList = []
      FList.append([]) # open the first dimension
      Sq3 = math.sqrt(3)
      j=0
      ret = rdin.readline()
      ret = rdin.readline()
      (a,b) = ret.split(',')
      PreviousBar = b
      while len(ret)>2:
            (a,b) = ret.split(',')
            if b==PreviousBar:
                  FList[j].append(a)
            else: # newbar
```

```
                PreviousBar=b
                j=j+1
                FList.append([])
                FList[j].append(a)
            ret=rdin.readline()
        rdin.close()
        return FList

def Set4Har():
        DevList = cympy.study.ListDevices()
        SpotLoadList = []
        for i in range(len(DevList)):# Find all device numbers
            if DevList[i].DeviceType == cympy.enums.DeviceType.SpotLoad:
                SpotLoadList.append(DevList[i].DeviceNumber)
        CustTarget=cympy.study.ListCustomerTypes()
        for i in range(len(SpotLoadList)):# find Spot loads
            CustPhase =
cympy.study.QueryInfoDevice("Phase",SpotLoadList[i],cympy.enums.DeviceType.SpotLoad)
            load = cympy.study.GetLoad(SpotLoadList[i],cympy.enums.LoadType.Spot)
            CustNumber=load.ListCustomers()
            for j in range(0,len(CustNumber)):# find and remame Customers in spot
loads
                CustType =
cympy.study.GetValueDevice('CustomerLoads[{0}].CustomerType'.format(j),
SpotLoadList[i], cympy.enums.DeviceType.SpotLoad)
                if CustPhase == "A" or CustPhase == "B" or CustPhase == "C":
                    if CustType==CustTarget[0]:

        cympy.study.SetValueDevice(CustTarget[1],'CustomerLoads[{0}].CustomerType'.forma
t(j),SpotLoadList[i], cympy.enums.DeviceType.SpotLoad)
                if CustPhase == "AB" or CustPhase == "BC" or CustPhase == "AC":
                    if CustType==CustTarget[0]:

        cympy.study.SetValueDevice(CustTarget[2],'CustomerLoads[{0}].CustomerType'.forma
t(j),SpotLoadList[i], cympy.enums.DeviceType.SpotLoad)
def SetSim():
        har = cympy.sim.Harmonic()
        har.SetValue('ThreePhase', 'AnalysisType')
        har.SetValue("NominalPI","OverheadLineModel")
        har.SetValue("NominalPI","CableModel")
        har.SetValue("ParallelRL","LoadModelEnum")
        har.SetValue("false","DoubleCircuitCoupling")
        har.SetValue("false","VoltageReport")
        har.SetValue("false","VoltageDistortionReport")
        har.SetValue("false","CurrentReport")
        har.SetValue("false","CurrentDistortionReport")
        har.SetValue("false","VoltageDisplayTag")
        har.SetValue("false","CurrentDisplayTag")

def SetSQLDatabase(DataBase):
        conn_info = cympy.db.ConnectionInformation()
        conn_info.Network = cympy.db.SQLServerDataSource()
        conn_info.Network.ServerName = "ROGER_P17"
        conn_info.Network.DatabaseName = DataBase
        conn_info.Network.WindowsAuthentication=True
        conn_info.Equipment = cympy.db.SQLServerDataSource()
        conn_info.Equipment.ServerName = "ROGER_P17"
        conn_info.Equipment.DatabaseName = DataBase
        conn_info.Equipment.WindowsAuthentication=True
        return conn_info

def FindLoadProportion():
        DevList = cympy.study.ListDevices()
        SpotLoadList = []
        OnePhLoad=0
        ThreePhLoad=0
        for i in range(len(DevList)):
            if DevList[i].DeviceType == cympy.enums.DeviceType.SpotLoad:
                SpotLoadList.append(DevList[i].DeviceNumber)
        for i in range(len(SpotLoadList)):
```