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Engineering Recommendation G5

Issue 5 2020

Harmonic voltage distortion and the connection of harmonic sources and/or resonant plant to transmission systems and distribution networks in the United Kingdom

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Contents

1 Scope 10
2 Normative references 11
3 Terms and definitions 12
4 Principles of harmonic voltage distortion 17
4.1 Introduction 17
4.2 Roles and responsibilities 17
4.3 Illustration of the EMC concept 17
5 Harmonic voltage distortion levels 19
5.1 Introduction 19
5.2 Planning levels 19
5.3 Compatibility levels 22
5.4 Subharmonic and interharmonic distortion 25
5.5 Short-duration bursts or fluctuating harmonic distortion 27
5.6 Notching 28
6 Assessment of Relevant Equipment 31
6.1 Introduction 31
6.2 Situations where planning levels may be exceeded 31
6.3 Guidelines 33
6.3.1 Point of evaluation 33
6.3.2 System impedance 33
6.3.3 Aggregation and diversity 34
6.3.4 Uncertainty 34
6.3.5 Measurement 35
6.3.5.1 Instrumentation 36
6.3.5.2 Transducers 36
6.3.5.3 Temporal and seasonal variation 36
6.3.5.4 Use of grouped measurements 37
6.4 Summary description of the connection process 37
6.4.1 Stage 1 connection summary 37
6.4.2 Stage 2 connection summary 38
6.4.3 Resonant (non-emitting) plant installation summary 38
6.4.4 Stage 3 connection summary 38
7 Stage 1 assessment procedure ....**Error! Bookmark not defined.**
7.1 Applicability and substages 39
7.2 Stage 1A assessment procedure 40
7.2.1 Assessment by compliance with IEC 61000-3-2 40
7.3 Stage 1B assessment procedure 41
7.3.1 Assessment by compliance with IEC 61000-3-12 41
7.3.2 Compliance with IEC 61000-3-12 or equivalent 43
7.3.3 Stage 1B-1 assessment procedure – minimum short-circuit power 44
7.3.4 Stage 1B-2 assessment procedure – minimum short-circuit power 45

7.3.4.1 Short-circuit power at the PCC 45
7.3.4.2 Compliance with the limit of minimum short-circuit power at the PCC.....45
7.4 Stage 1C assessment procedure 45
7.4.1 Stage 1C-1 assessment procedure – identical converter technology 48
7.4.1.1 Aggregate equipment rated power.....48
7.4.1.2 Short-circuit power at the PCC 48
7.4.1.3 Permitted aggregate equipment rated power 48
7.4.1.4 Compliance with the limit of aggregate equipment rated power 50
7.4.2 Stage 1C-2 assessment procedure – mixed three-phase converter technology 50
7.4.2.1 Minimum short-circuit power at the PCC.....50
7.4.2.2 Short-circuit power at the PCC 51
7.4.2.3 Compliance with the limit of minimum short-circuit power at the PCC.....51
7.5 Stage 1D assessment procedure 51
7.5.1 Stage 1D-1 assessment procedure – identical converter technology – assessment accounting for actual headroom 52
7.5.1.1 Compliance with the limit of aggregated equipment rated power 54
7.5.2.1 Minimum short-circuit power at the PCC.....54
7.5.2.2 Short-circuit power at the PCC 55
7.5.2.3 Compliance with the limit of minimum short-circuit power at the PCC.....55
8 Stage 2 assessment procedure.....56
8.1 Applicability and substages.....56
8.2 Stage 2A assessment procedure 57
8.2.1 Stage 2A-1 assessment procedure – identical converter technology.....59
8.2.1.1 Aggregate equipment rated power.....59
8.2.1.2 Short-circuit power at the PCC 59
8.2.1.3 Permitted aggregate equipment rated power 59
8.2.1.4 Compliance with the limit of aggregate equipment rated power 61
8.2.2 Stage 2A-2 assessment procedure – mixed three-phase converter technology 61
8.2.2.1 Minimum short-circuit power at the PCC.....61
8.2.2.2 Short-circuit power at the PCC 61
8.2.2.3 Compliance with the limit of minimum short-circuit power 62
8.3 Stage 2B assessment procedure 62
8.3.1 Stage 2B-1 Assessment procedure – identical converter technology – assessment accounting for actual headroom 64
8.3.1.1 Permitted aggregate equipment rated power 64
8.3.1.2 Compliance with the limit of permitted aggregate equipment rated power 65

8.3.2 Stage 2B-2 Assessment procedure – mixed three-phase converter technology – assessment accounting for actual headroom 65
8.3.2.1 Minimum short-circuit power at the PCC.....65
8.3.2.2 Short-circuit power at the PCC 66
8.3.2.3 Compliance with the limit of short-circuit power 66
8.4 Stage 2C assessment procedure 66
8.4.1 Background harmonic level at the PCC.....67
8.4.2 Harmonic current emission.....67
8.4.3 Short-circuit power at the PCC 68
8.4.4 Harmonic impedance 68
8.4.5 Incremental increase in harmonic voltage distortion 69
8.4.6 Prediction of harmonic voltage distortion.....71
8.4.7 Compliance with planning levels 72
9 Assessment of resonant plant 73
9.1 Applicability and substages.....73
9.2 Resonant plant at 0.4 kV and below.....73
9.3 Resonant plant at voltage levels above 0.4 kV and below 33 kV.....74
10 Stage 3 assessment procedure.....77
10.1 Applicability and substages.....77
10.2 Impedance loci.....79
10.3 Measurement of the background harmonic level 79
10.4 Incremental harmonic voltage limit 79
10.4.1 Transfer coefficients.....80
10.4.2 Calculation of harmonic headroom 81
10.4.3 Apportionment multiplier for harmonic voltage headroom.....82
10.4.3.1 Apportionment multiplier for voltages of 132 kV and below.....82
10.4.3.2 Apportionment multiplier for voltages above 132 kV 82
10.5 Total harmonic voltage limit at the PCC 84
10.5.1 Total harmonic voltage change limit 84
10.5.2 Total harmonic voltage limit.....84
10.5.3 Harmonic change limit due to the modification of the background harmonic level.....85
10.6 Final harmonic voltage limit table 86
10.7 Definition of compliance.....86
10.7.1 Compliance with the incremental harmonic voltage limit 87
10.7.2 Compliance with the total harmonic voltage limit 87
10.8 Compliance report.....87
10.9 Verification of compliance 88
10.10 Connection queue and concurrent connections 89
10.10.1 Concurrent connections at the same node 89
10.10.2 Concurrent connections at electrically near nodes 90
Annex A (normative) Modification of minimum short-circuit power 92
A.1 Background.....92
A.2 Minimum short-circuit power modification factors 93

Annex B (informative) Terminology and descriptions 94

Figures

Figure 1 — Illustration of EMC concepts relevant to a supply system 18
Figure 2 — Illustration of EMC concepts relevant to a local site 18
Figure 3 — Illustration of harmonics and interharmonic subgroups 26
Figure 4 — Depiction of voltage notching 29
Figure 5 — Stage 1 assessment process flow 39
Figure 6 — Stage 1A assessment process flow 41
Figure 7 — Stage 1B assessment process flow 42
Figure 8 — Stage 1C assessment process flow 47
Figure 9 — Stage 1D assessment process flow 52
Figure 10 — Stage 2 assessment process flow 56
Figure 11 — Stage 2A assessment process flow 58
Figure 12 — Stage 2B assessment process flow 63
Figure 13 — Stage 2C assessment process flow 67
Figure 14 — Resonant plant assessment process flow 76
Figure 15 — Stage 3 assessment process flow for the setting of harmonic limits for a new user 78
Figure 16 — Apportionment multiplier (M) versus k_M 83
Figure 17 — Voltage and current source equivalents for the new user 88
Figure B.1 — Six-pulse diode rectifier 94
Figure B.2 — Six-pulse thyristor rectifier 95
Figure B.3 — Active-front-end rectifier 95
Figure B.4 — Simplified representation of active-front-end rectifier 95
Figure B.5 — Active-front-end converter 95
Figure B.6 — Six-pulse Thyristor Rectifier with Active Filter 95
Figure B.7 — Single-phase full-wave diode rectifier 95

Tables

Table 1 — THD_V planning levels 19
Table 2 — Planning levels for harmonic voltages in 0.4 kV systems and below 20
Table 3 — Planning levels for harmonic voltages above 0.4 kV and less than or equal to 25 kV 20
Table 4 — Planning levels for harmonic voltages above 25 kV and less than or equal to 66 kV 21
Table 5 — Planning levels for harmonic voltages above 66 kV and less than or equal to 230 kV 21
Table 6 — Planning levels for harmonic voltages above 230 kV 22
Table 7 — THD_V compatibility levels 22
Table 8 — Compatibility levels for harmonic voltages in 0.4 kV systems and below 23
Table 9 — Compatibility levels for harmonic voltages above 0.4 kV and less than or equal to 25 kV 23
Table 10 — Compatibility levels for harmonic voltages above 25 kV and less than or equal to 66 kV 24
Table 11 — Compatibility levels for harmonic voltages above 66 kV and less than or equal to 230 kV 24
Table 12 — Compatibility levels for harmonic voltages above 230 kV 25
Table 13 — Emission limits for subharmonics and interharmonics 27
Table 14 — Maximum permitted aggregate equipment rated power at reference short-circuit power for $V \leq 0.4$ kV 28
Table 15 — Maximum permitted aggregate equipment rated power at reference short-circuit power for 0.4 kV $< V \leq$ 25 kV 28
Table 16 — Aggregation (summation) exponents 34
Table 17 — Stage 1 assessment data requirements for substages 1A to 1D 40
Table 18 — Short-circuit ratio factor and summation exponent for varying number of items of equipment compliant with IEC 61000-3-12 44
Table 19 — Maximum permitted aggregate equipment rated power at reference short-circuit power (1C-1) 48
Table 20 — Stage 2 assessment data requirements for substages 2A to 2C 57
Table 21 — Maximum permitted aggregate equipment rated power at reference short-circuit power (2A-1) 59
Table 22 — Worst-case reactance factor for 0.4 kV and 6.6–22 kV systems 68
Table 23 — β value for voltages above 132 kV 83
Table 24 — Example limits forming part of a harmonic specification 86
Table A.1 — Minimum short-circuit power modification factors for I_{SCC} < 100 A 93
Table A.2 — Minimum short-circuit power modification factors for I_{SCC} ≥ 100 A 93

Foreword

This Engineering Recommendation (EREC) is published by the Energy Networks Association (ENA) and comes into effect from 01 March, 2020. It has been prepared under the authority of the ENA Engineering Policy and Standards Manager and has been approved for publication by the GB Distribution Code Review Panel (DCRP). The approved abbreviated title of this engineering document is “EREC G5/5”, which replaces the previously used abbreviation “ER G5/4-1”. For practical reasons, connections subject to contract specifications based on ER G5/4-1 entered into before the effective date above may be connected in accordance with that recommendation.

Where the term “shall” or “must” is used in this document it means the requirement is mandatory. The term “should” is used to express a recommendation. The term “may” is used to express permission.

NOTE: Commentary, explanation and general informative material is presented in smaller type, and does not constitute a normative element.

Introduction

The Electromagnetic Compatibility Regulations 2016 [1], which implement into UK law the Electromagnetic Compatibility Directive 2014/30/EU of the European Parliament [2], defines the interaction of equipment and fixed installations such that:

> 1. Equipment must be so designed and manufactured, having regard to the state of the art, as to ensure that—
>
> (a) the electromagnetic disturbance generated does not exceed the level above which radio and telecommunications equipment or other equipment cannot operate as intended;
>
> (b) it has a level of immunity to the electromagnetic disturbance to be expected in its intended use which allows it to operate without unacceptable degradation of its intended use.
>
> 2. A fixed installation must be installed applying good engineering practices and respecting the information on the intended use of its components, with a view to meeting the essential requirements set out in paragraph 1 of this schedule.

This Engineering Recommendation (EREC) defines the good engineering practices applicable to harmonic voltage distortion on transmission and distribution systems in the UK – being fixed installations by definition – so as to limit the disturbance levels thereon to below the immunity levels of equipment connected thereto.

Steady state disturbance levels on supply systems are defined in terms of harmonic voltage distortion and are affected by emissions of non-linear loads and generating plant and equipment as well as the connection of resonant plant, which modifies already-existing disturbance levels. This EREC provides planning and compatibility disturbance levels on UK transmission and distribution networks as well as a staged assessment plan for the connection of non-linear and resonant plant and equipment and is structured as follows.

Clause 4 defines the guiding principles of harmonic voltage distortion along with the roles and responsibilities of the various parties involved in the management of harmonics. Specifically, it covers the distinction between planning, compatibility and immunity levels.

Clause 5 defines the planning and compatibility limits applicable to the UK transmission and distribution systems.

Clause 6 describes the recommended staged approach to assessing the connection of non-linear and/or resonant plant and equipment to supply systems. This staged approach limits the level of detail of the assessment to that which is appropriate to the connection being assessed, thus enabling the pragmatic connection of plant and equipment. An assessment shall result in either a statement of compliance or harmonic voltage distortion limits, which shall inform the design of any necessary mitigation measures as required such that the resultant connection complies with the limits set out in this Engineering Recommendation.

Clauses **Error! Reference source not found.**, 8, 9 and 10, detail the Stage 1, Stage 2, resonant plant, and Stage 3 assessment procedures, respectively.

The general term Network Operator is used in this EREC which is intended to apply to owners and operators of transmission systems and distribution networks as appropriate in so far as the requirements are applicable to their statutory and regulatory duties and responsibilities.

1 Scope

This EREC provides the individual and total harmonic voltage distortion planning and compatibility levels that are applicable to UK transmission and distribution networks, and that are to be used in the process of connection assessment and/or setting limits for the connection of non-linear and resonant plant and equipment.

The general principles of electromagnetic compatibility, as applied to harmonic voltage distortion, are presented along with guidance to connection assessment and the development of harmonic distortion limits through a three-staged assessment procedure.

This EREC is focussed on conducted phenomena resulting in the development of harmonic voltages on the supply system, through the emission of harmonic currents and from the modification of the background harmonic level, in the form of:

- continuous harmonic, subharmonic and interharmonic voltage distortion within the frequency range of 0 to 5 kHz;
- harmonics above 5 kHz where relevant IEC recommendations may be applicable;
- short bursts and duration of harmonic voltage distortion;
- voltage notching.

Parts of this guidance are based on simplifications, which may not provide the optimal solution under all operating conditions. The onus is on all NOs, new users and existing users to apply sound engineering practices where such circumstances arise and to adequately document the justifications for applying alternative approaches and techniques.

All relevant equipment fall under the requirements of the connection assessment.

The levels and limits presented in this EREC are statistical in nature and are applicable to the normal temporal variations that are characteristic of a power system, including the credible outage scenarios that might prevail on the system.

This EREC applies the voltage level definitions of BS EN 50160 with the extension of HV to 230 kV and the addition of EHV covering all voltages above 230 kV, as per the terms and definitions (see 3).

This EREC does not cover the design of mitigation measures to ensure compliance with any harmonic voltage distortion or emission limits that result from the application of the assessment procedure.

This EREC takes into account the relevant harmonised equipment standards, which are applicable to particular equipment, and are a prerequisite for electromagnetic compatibility of the equipment under the terms of the UK regulations. Radiated interference that might affect communications systems is not considered in this EREC.

Harmonic voltage distortion arising from switching transients is not considered in this EREC.

The voltage of public supply systems covered by this standard does not normally have a DC component at a significant level. DC voltage can arise, however, when certain non-symmetrically controlled loads are connected. Assessing the impact of DC voltage and current on supply system is outside of the scope of this document. The final decision regarding the connection of any DC-emitting plant and equipment is at the discretion of the NO hosting the connection.

This EREC is applicable to all new users. In the case of modification, the relevant NO may, at its discretion, decide that reassessment against this EREC is not required; for example, if the modification does not constitute a material change to the new user's plant and equipment. In this context, modification is as defined in the terms of the relevant connection agreement.

2 Normative references

The following referenced documents, in whole or part, are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

BS EN 50160, *Voltage Characteristics of Electricity Supplied by Public Distribution Networks*

ENA EREC G97, *Process for the connection of non-linear and resonant plant and equipment in accordance with EREC G5, Issue 1, 2016*

IEC 60050, *International Electrotechnical Vocabulary, Chapter 161: Electromagnetic Compatibility*

IEC 61000-2-2, *Electromagnetic compatibility (EMC) — Part 2-2: Environment — Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems* [1)]

IEC 61000-3-12, *Electromagnetic compatibility (EMC) — Part 3-12: Limits — Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current > 16 A and ≤ 75 A per phase* [2)]

IEC 61000-3-2, *Electromagnetic compatibility (EMC) — Part 3-2: Limits — Limits for harmonic current emissions (equipment input current ≤ 16 A per phase)* [3)]

IEC/TR 61000-3-6, *Electromagnetic compatibility (EMC) — Part 3-6: Limits — Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems*

IEC 61000-4-30, *Electromagnetic compatibility (EMC) — Part 4-30: Testing and measurement techniques — Power quality measurement methods* [4)]

[1)] BS EN 61000-2-2 is identical to this reference.

[2)] BS EN 61000-3-12 and EN 61000-3-12 are identical to this reference.

[3)] BS EN 61000-3-2 and EN 61000-3-2 are identical to this reference.

[4)] BS EN 61000-4-30 is identical to this reference.

[5)] BS EN 61000-4-7 is identical to this reference.

IEC 61000-4-7, *Electromagnetic compatibility (EMC) — Part 4-7: Testing and measurement techniques — General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected* [5)]

IEC/TR 60725, *Consideration of reference impedances and public supply network impedances for use in determining the disturbance characteristics of electrical equipment having a rated current ≤ 75 A per phase*

3 Terms and definitions

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

3.1
background harmonic level
level of harmonic voltage distortion, defined in terms of the individual and total harmonic voltage levels, that exist before the connection of the relevant equipment under assessment

NOTE: This typically represents the pre-existing state of the network, but might also include predicted levels resulting from the effects of nearby contemporary connections.

3.2
compatibility level
level of harmonic voltage distortion, defined in terms of the individual and total harmonic levels, below which the supply system should ideally be operated

3.3
connection agreement
An agreement between the NO and the user or any customer setting out the terms relating to a connection with the NO's system

3.4
existing user
a person using the public supply system who is not classed in this document as being a new user

3.5
extra-high voltage (EHV)
nominal r.m.s. value greater than 230 kV

3.6
harmonic headroom
difference between the background harmonic level and a reference level, such as the planning level or compatibility level

NOTE: The process for calculating this difference may be linear or non-linear.

3.7
harmonic impedance at the PCC
impedance of the supply system when looking into the PCC from the new user's or existing user's supply terminals. Also, referred to as the self or the Thévenin impedance of the PCC

3.8
harmonic source
any plant or equipment that is connected or a new user is seeking to connect to the public supply system that may result in a harmonic distortion due to an emission of harmonic current and/ or voltage, including inter-harmonics and sub-harmonics

3.9
harmonic transfer coefficient
ratio of the harmonic voltage, in per unit, at one node in a supply system to the corresponding harmonic current, in per unit, injected at another node either in the same supply system or a customers' installation

3.10
high voltage (HV)
nominal r.m.s. value of greater than 36 kV and less than or equal to 230 kV

3.11
impedance loci
harmonic system impedance spectra under different system loading, configuration and outage conditions

3.12
incremental harmonic voltage
harmonic voltage change produced by a new user at the PCC due to harmonic current emission from its relevant equipment

3.13
incremental harmonic voltage limit
maximum permitted harmonic voltage change that a new user may produce at the PCC due to harmonic emission from its relevant equipment

3.14
individual harmonic distortion
r.m.s value of an individual harmonic voltage or current expressed as a percentage of the fundamental r.m.s. voltage or current

3.15
interharmonic frequency
any frequency that is not an integer multiple of the fundamental frequency

NOTE 1: By extension from harmonic order, the interharmonic order is the ratio (non-integer) of an interharmonic frequency to the fundamental frequency.

NOTE 2: If the ratio is less than unity, then an interharmonic frequency may be referred to as a subharmonic frequency.

3.16
interharmonic component
component of a voltage or current spectrum having an interharmonic frequency

NOTE: For brevity, such a component may be referred to simply as an interharmonic.

3.17
interharmonic component r.m.s. value
r.m.s. value of a spectral component of an electrical signal with a frequency between two consecutive harmonic frequencies

3.18
interharmonic centred subgroup r.m.s. value
r.m.s. value of all interharmonic components in the interval between two consecutive harmonic frequencies, excluding frequency components directly adjacent to the harmonic frequencies

NOTE: For brevity, such a component may be referred to simply as an interharmonic subgroup.

3.19
low voltage (LV)
nominal r.m.s. value of less than or equal to 1 kV

3.20
medium voltage (MV)
nominal r.m.s. value of greater than 1 kV and less than or equal to 36 kV

3.21
network owner (NO) and network operator (NO)
generic term embracing transmission network owner and/or operator companies and distribution network owner and/or operator companies

NOTE: This incorporates the term “NOC” from G5/4-1.

3.22
new user
a person who is either i) seeking to connect new relevant equipment or ii) seeking to modify an existing installation comprising relevant equipment

NOTE: There is no differentiation made in this document between load, generation and any other user equipment connected to the public supply system.

3.23
normal operating conditions
variation of generation/demand, the energisation/de-energisation of plant and equipment as a consequence of temporal, seasonal and operational variability, including credible outages, under which the supply system is designed to operate

3.24
planning level
level of harmonic voltage distortion, defined in terms of the individual and total harmonic voltage levels, against which the connection of relevant equipment is assessed

3.25
point of common coupling (PCC)
point in the public supply system which is electrically closest to the installation concerned and to which other customers are or might be connected

3.26
point of evaluation (PoE)
point in the public supply system where the effect of a new user is assessed. In this document a remote node included in the assessment of a new user impact is a PoE

3.27
relevant equipment
any plant or equipment that is connected or a new user is seeking to connect to the public supply system which is a harmonic source and /or resonant plant

3.28
remote node

remote nodes are defined as those substations in the public supply system that are at the same voltage level as the new user, or are at one voltage level above that of the new user and any voltage level below, excluding LV. A remote node that is included in the assessment is a PoE3.29
resonant plant
any plant or equipment that is connected or a new user is seeking to connect to the public supply system, such as power factor correction capacitors, cables or active-front-end converters/inverters, that may materially modify the background harmonic level as a result of interaction with the public supply system without emitting any harmonic current or voltage

NOTE: Active-front-end convertors/ inverters may be classified as resonant plant due to their internal impedance.

3.30
short-duration burst
burst in harmonics of the power system occurring in a time interval that is short when compared to the timescale of interest, such that its effect during the timescale of interest is unnoticeable

3.31
short-circuit power
parameter, expressed in volt–amperes, of the initial symmetrical short-circuit power at a point on the supply system. The product of the initial symmetrical short-circuit current, the nominal system voltage and, for three-phase systems, with the aperiodic component (DC) being neglected

3.32
supply system
all the lines, switchgear and transformers operating at various voltages that make up the transmission systems and distribution systems to which new users' or existing users' installations could be or are connected

3.33
total distortion content
r.m.s. value of a time domain voltage or current signal that contains all the frequency content, including interharmonics, except for the r.m.s. of the fundamental frequency component

3.34
total distortion ratio
ratio of the total distortion content to the r.m.s. of the fundamental frequency component

3.35
total harmonic current distortion (*THD_I*)
r.m.s. value of individual harmonic currents, expressed as a percentage of the fundamental r.m.s. current

NOTE: The calculation follows the same logic as that of total harmonic voltage distortion (*THD_V*).

3.36
total harmonic voltage distortion (*THD_V*)
r.m.s. value of individual harmonic voltages, expressed as a percentage of the fundamental r.m.s. voltage

NOTE 1: *THD_V* is calculated as shown in (1).

$$THD_V = \sqrt{\sum_{h=2}^{h=100} (V_h)^2} \qquad (1)$$

where

THD_V	is the total harmonic distortion; in this example, total harmonic voltage distortion;
h	represents the harmonic order;
V_h	represents the individual harmonic voltage (% h = 1).

NOTE 2: The parameter h = 100 represents the highest harmonic order under consideration. The increasing number of power electronic interfaces with supply systems has made it necessary to consider, where practicable, integer values of h up to and including 100.

3.37
total harmonic voltage limit
maximum total harmonic voltage level at the PCC that shall be allowed to exist after the new user's relevant equipment is connected

3.38
total harmonic voltage level
the expected harmonic voltage level at the PCC after the new user's relevant equipment is connected

NOTE: This includes the incremental harmonic voltage and the amplified background harmonic level.

4 Principles of harmonic voltage distortion

4.1 Introduction

Harmonic voltages, which in turn cause harmonic currents, have long been recognised as being able to interfere with telecommunications systems, to increase losses in circuits and equipment, and to cause overheating of rotating plant and capacitors; the latter being particularly susceptible to damage.

The roles and responsibilities held by the relevant parties in ensuring that the permissible levels of harmonic distortion are not exceeded are considered in Clause 4.2.

The distinction between the planning, compatibility and immunity levels of harmonic distortion, with which the relevant parties are required to comply is considered in Clause 4.3.

4.2 Roles and responsibilities

The NO is responsible for the overall coordination of disturbance levels on its network and for assessing the impact of the new user's relevant equipment. The new user is responsible for complying with conditions the NO place on them to comply with this Engineering Recommendation.

Further guidance on roles and responsibilities is provided in Engineering Recommendation G97, Process for the connection of relevant equipment in accordance with EREC G5.

4.3 Illustration of the EMC concept

Figure 1 and Figure 2 (reproduced from IEC/TR 61000-3-7) illustrate the concept of compatibility levels, planning levels and emission limits and how EMC, relating to voltage fluctuations in the supply system, is achieved.

Figure 1 shows how EMC is achieved on a supply-system-wide basis.

Figure 1 shows that there is a chance that interference might occur at certain times or certain locations in the system. This is recognition that the harmonic levels in a supply system may not remain within the planning levels at all times.

Figure 1 — Illustration of EMC concepts relevant to a supply system

Figure 2 shows conceptually that, on a local site basis, specifying a suitable planning level should ensure there is no overlap of disturbance and immunity levels.

Figure 2 — Illustration of EMC concepts relevant to a local site

For further detail, IEC 61000-2-2 and IEC/TR 61000-3-7 should be consulted

5 Harmonic voltage distortion levels

5.1 Introduction

Planning and compatibility levels for all voltage levels are given in Table 1 through to Table 12.

Plant and equipment with harmonic and interharmonic emissions above 2.5 kHz is being connected to transmission and distribution networks. It is considered prudent, based on evidence of adverse effects and the establishment of associated compatibility levels in the IEC 61000-2-X series, to manage such emissions, where reasonably practicable. Harmonic assessments should be carried out on harmonic and interharmonic emissions up to 5kHz, however it is recognised that this may not always be practicable in which case assessments may be carried out to only 2.5kHz at the discretion of the NO. In any such assessments, it is at the discretion of the relevant NO to define the harmonic limits and background harmonic level.

At present, there are technical limitations regarding the availability of suitable transducers (depending on network voltage level) to accurately measure harmonics above 2.5kHz.

Harmonic studies shall be carried out in accordance with good industry practice using appropriate modelling techniques, such as those described in Electra 167 [3] and IEEE TP-125-0 [4].

5.2 Planning levels

Table 1 provides the total harmonic voltage distortion (THD_V) planning levels. The planning levels for individual harmonic voltage distortion are presented from Table 2 through to Table 6.

Where two system voltage levels exist within a given voltage range, then different planning levels may be set for each at the discretion of the NO to enable equitable treatment for new users.

Table 1 — THD_V planning levels at supply system PCC nominal operating voltage

Nominal voltage (*V*) **kV**	**THD_V** **% *h* = 1**
$V \leq 0.4$	5
$0.4 < V \leq 25$	4.5
$25 < V \leq 66$	3.7
$66 < V \leq 230$	3
$V > 230$	3

Note 3: % h = 1 means ‘as a percentage of the voltage at the fundamental frequency’.

Table 2 — Planning levels for harmonic voltages in 0.4 kV systems and below

Odd harmonics (non-multiple of 3)		Odd harmonics (multiple of 3)		Even harmonics	
Harmonic order (*h*)	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**
5	4.0	3	4.0	2	1.6
7	4.0	9	1.2	4	1.0
11	3.0	15	0.5	6	0.5
13	2.5	≥ 21	0.2	8	0.4
17	1.6	—	—	10	0.4
19	1.5	—	—	≥ 12	0.2
23	1.2	—	—	—	—
≥ 25	25/*h*	—	—	—	—

Table 3 — Planning levels for harmonic voltages above 0.4 kV and less than or equal to 25 kV

Odd harmonics (non-multiple of 3)		Odd harmonics (multiple of 3)		Even harmonics	
Harmonic order (*h*)	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**
5	3.0	3	3.0	2	1.5
7	3.0	9	1.2	4	1.0
11	2.0	15	0.4	6	0.5
13	2.0	≥ 21	0.2	8	0.4
17	1.6	—	—	10	0.4
19	1.5	—	—	≥ 12	0.2
23	1.2	—	—	—	—
≥ 25	25/*h*	—	—	—	—

Table 4 — Planning levels for harmonic voltages above 25 kV and less than or equal to 66 kV

Odd harmonics (non-multiple of 3)		Odd harmonics (multiple of 3)		Even harmonics	
Harmonic order (*h*)	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**
5	2.8	3	2.6	2	1.3
7	2.8	9	1.1	4	0.9
11	1.9	15	0.3	6	0.5
13	1.8	≥ 21	0.2	8	0.4
17	1.4	—	—	10	0.4
19	1.3	—	—	≥ 12	0.2
23	1.0	—	—	—	—
≥ 25	0.6(25/*h*) + 0.2	—	—	—	—

Table 5 — Planning levels for harmonic voltages above 66 kV and less than or equal to 230 kV

Odd harmonics (non-multiple of 3)		Odd harmonics (multiple of 3)		Even harmonics	
Harmonic order (*h*)	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**
5	2.5	3	2.0	2	1.0
7	2	9	1.0	4	0.8
11	1.8	15	0.3	6	0.5
13	1.5	≥ 21	0.2	8	0.4
17	1.2	—	—	10	0.4
19	1.0	—	—	≥ 12	0.2
23	0.8	—	—	—	—
≥ 25	0.6(25/*h*) + 0.2	—	—	—	—

Table 6 — Planning levels for harmonic voltages above 230 kV

Odd harmonics (non-multiple of 3)		Odd harmonics (multiple of 3)		Even harmonics	
Harmonic order (*h*)	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**
5	2.0	3	1.5	2	1.0
7	2.0	9	0.5	4	0.8
11	1.5	15	0.3	6	0.5
13	1.5	≥ 21	0.2	8	0.4
17	1.2	—	—	10	0.4
19	1.0	—	—	≥ 12	0.2
23	0.8	—	—	—	—
≥ 25	0.6(25/*h*) + 0.2	—	—	—	—

5.3 Compatibility levels

Table 7 provides the total harmonic voltage distortion (THD_V) compatibility levels. The compatibility levels for individual harmonic voltage distortion are presented from Table 8 through to Table 12.

Table 7 — THD_V compatibility levels

Nominal voltage (*V*) kV	THD_V % *h* = 1
$V \leq 0.4$	8
$0.4 < V \leq 25$	8
$25 < V \leq 66$	8
$66 < V \leq 230$	4
$V > 230$	3.5

Table 8 — Compatibility levels for harmonic voltages in 0.4 kV systems and below

Odd harmonics (non-multiple of 3)		Odd harmonics (multiple of 3)		Even harmonics	
Harmonic order (*h*)	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**
5	6.0	3	5.0	2	2.0
7	5.0	9	1.5	4	1.0
11	3.5	15	0.5	6	0.5
13	3.0	21	0.3	8	0.5
$17 \leq h \leq 49$	$2.27(17/h) - 0.27$	≥ 23	0.2	≥ 10	$0.25(10/h) + 0.25$
$53 \leq h \leq 97$	$27/h$	—	—	—	—

Table 9 — Compatibility levels for harmonic voltages above 0.4 kV and less than or equal to 25 kV

Odd harmonics (non-multiple of 3)		Odd harmonics (multiple of 3)		Even harmonics	
Harmonic order (*h*)	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**
5	6.0	3	5.0	2	2.0
7	5.0	9	1.5	4	1.0
11	3.5	15	0.4	6	0.5
13	3.0	21	0.3	8	0.5
$17 \leq h \leq 49$	$2.27(17/h) - 0.27$	> 21	0.2	≥ 10	$0.25(10/h) + 0.25$
$53 \leq h \leq 97$	$27/h$	—	—	—	—

Table 10 — Compatibility levels for harmonic voltages above 25 kV and less than or equal to 66 kV

Odd harmonics (non-multiple of 3)		Odd harmonics (multiple of 3)		Even harmonics	
Harmonic order (*h*)	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**
5	5.2	3	3.1	2	1.6
7	4.7	9	1.3	4	0.9
11	2.7	15	0.4	6	0.5
13	2.4	≥ 21	0.2	8	0.5
17	1.7	—	—	10	0.5
19	1.5	—	—	≥ 12	0.2
23	1.2	—	—	—	—
≥ 25	0.6(25/*h*) + 0.2	—	—	—	—

Table 11 — Compatibility levels for harmonic voltages above 66 kV and less than or equal to 230 kV

Odd harmonics (non-multiple of 3)		Odd harmonics (multiple of 3)		Even harmonics	
Harmonic order (*h*)	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**
5	4.0	3	2.0	2	1.4
7	3.0	9	1.0	4	0.8
11	1.8	15	0.3	6	0.5
13	1.5	≥ 21	0.2	8	0.4
17	1.2	—	—	10	0.4
19	1.0	—	—	≥ 12	0.2
23	0.8	—	—	—	—
≥ 25	0.6(25/*h*) + 0.2	—	—	—	—

Table 12 — Compatibility levels for harmonic voltages above 230 kV

Odd harmonics (non-multiple of 3)		Odd harmonics (multiple of 3)		Even harmonics	
Harmonic order (*h*)	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**	**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**
5	3.0	3	1.7	2	1.4
7	2.0	9	0.5	4	0.8
11	1.5	15	0.3	6	0.5
13	1.5	≥ 21	0.2	8	0.4
17	1.2	—	—	10	0.4
19	1.0	—	—	≥ 12	0.2
23	0.8	—	—	—	—
≥ 25	0.6(25/*h*) + 0.2	—	—	—	—

5.4 Subharmonic and interharmonic distortion

The frequency of the interharmonic voltage component is given by the frequency of the spectral line, as illustrated in Figure 3 and cannot be an integer multiple of the fundamental frequency. Each interharmonic voltage component has a r.m.s. value.

Considering the window of measurement of 10 cycles (200 ms), as per IEC 61000-4-30, the frequency interval for interharmonics between two integer harmonics is 5 Hz for a system with nominal frequency of 50 Hz.

The r.m.s. value of all interharmonic voltage components in the interval between two consecutive harmonic frequencies, excluding frequency components directly adjacent to the harmonic frequencies, is denoted as shown in Figure 3. For the purposes of this Engineering Recommendation, the r.m.s. value of the centred subgroup voltage between the harmonic orders h and $h + 1$ is designated as $V_{h\,ig}$. For example, the centred subgroup voltage between $h = 5$ and $h = 6$ is designated as $V_{5\,ig}$.

The interharmonic grouping shall conform to IEC 61000-4-30 and IEC 61000-4-7, as denoted by (2).

$$V_{h\,ig} = \sqrt{\sum_{n=2}^{n=8} \left(V_{i,n}^{h,\,h+1}\right)^2} \qquad (2)$$

where:

$V_{h\,ig}$ is the interharmonic centred subgroup r.m.s. value voltage for order h;

n is the interharmonic order between integer harmonic orders;

$V_{i,n}^{h,\ h+1}$ is the interharmonic component r.m.s. value between harmonic orders *h* and *h* + 1.

Figure 3 — Illustration of harmonics and interharmonic subgroups

Total distortion content TDC_V for the voltage is given by (3).

$$TDC_V = \sqrt{\left(V_{r.m.s.}\right)^2 - \left(V_{1\ r.m.s.}\right)^2} \qquad (3)$$

where

$V_{r.m.s.}$ is the r.m.s. of the voltage signal consisting of all frequency content, including interharmonic components;

$V_{1\ r.m.s.}$ is the r.m.s. of the fundamental frequency component.

Total distortion ratio for voltage is given by (4) (TDR_V).

$$TDR_V = \frac{TDC_V}{V_{1\ r.m.s.}} \qquad (4)$$

If the predicted voltage interharmonic distortion for individual interharmonic components from a harmonic source is less than 0.1% of the fundamental voltage, then connection may be made without any further assessment of interharmonic voltage emissions. In the case of multiple harmonic sources**,** the combined distortion for individual interharmonic components shall not exceed the planning level in Table 13.

In the United Kingdom, it is assumed that ripple control systems are not being used and therefore a new user's load may be connected without assessment provided that its individual

interharmonic emissions are lower than the limit values in Table 13, further assessment of subharmonic or interharmonic voltage emissions is required.

For supply systems, less than 0.4kV, the compatibility levels for subharmonics and interharmonics above the fundamental up to 90 Hz are given in IEC 61000-2-2. For this range of frequencies, the compatibility is assessed in relation to the flicker curve. The compatibility levels apply to individual subharmonic and interharmonic components within the band and not the interharmonic subgroup.

For planning purposes, 70.7% (-3 dB) of the compatibility levels for interharmonics in IEC 61000-2-2 shall be used.

The compatibility and planning levels are given in Table 13.

Table 13 — Emission limits for subharmonics and interharmonics at supply system PCC nominal operating voltage

	Voltage ≤ 1 kV	**Voltage > 1 kV**	**All voltage levels**	
Frequency (Hz)	**≤ 95**	**≤ 90**	**110–2490**	**2510–4990**
Compatibility level (% *h* = 1)	IEC 61000-2-2 [1)]	0.2	0.5 [2) 3)]	0.3 [2) 3)]
Planning level (% *h* = 1)	70.7% of compatibility levels [1)]	0.15 [2)]	0.36 [2) 3)]	0.22 [2) 3)]
[1)] The compatibility and planning levels apply to individual subharmonic or interharmonic components.				
[2)] The compatibility and planning levels apply to the interharmonic subgroup.				
[3)] In the case where the limit defined in Table 13 exceeds the limit of the adjacent integer harmonic, the interharmonic limit shall be set equal to the lower of the adjacent integer harmonic levels.				

For all voltage levels, TDR shall be less than or equal to the relevant compatibility and planning levels for THD_V.

5.5 Short-duration bursts or fluctuating harmonic distortion

Relevant equipment that emit either short-duration bursts or fluctuating harmonic distortion (e.g. irregular motor start/stop) shall be assessed by selecting an aggregation period appropriate to the event (e.g. one minute or three seconds). The 99th percentile daily value of these measurements is to be used for the purposes of planning and compliance. IEC/TR 61000-3-7 may be consulted for further guidance.

With respect to short-duration effects on harmonic voltage distortion, compliance shall be assessed with reference to the compatibility levels for individual harmonic orders presented in Clause 5.3, multiplied by a factor k_{sde} as defined in (5) and with a corresponding increase in the THD_V compatibility level by a factor of $\sqrt{2}$.

$$k_{sde} = 1.3 + \frac{0.7}{45}(h - 5) \qquad (5)$$

Semiconductor motor controllers (e.g. soft-starters) and load controllers which fall within the scope of this Clause, and which comply with EN 60947-4-2 or EN 60947-4-3 may be assessed

under Stage 1C-1 or under 2A-1, as appropriate, using the limits presented in Table 14 and Table 15.

Table 14 — Maximum permitted aggregate equipment rated power at reference short-circuit power for supply system nominal voltages of $V \leq 0.4$ kV

PCC voltage	$\sum S_{equ\ permitted\ @\ Ssc\ reference}$ $S_{SC\ reference}$ = 10 MVA three-phase
	Semiconductor motor controllers (e.g. soft-starters) and load controllers compliant with EN 60947-4-2 or EN 60947-4-3
$V \leq 0.4$ kV	314 kVA

Note: S_{equ} permitted @ S_{sc} reference is defined in Clause 7.4

Table 15 — Maximum permitted aggregate equipment rated power at reference short-circuit power for supply system nominal voltages of 0.4 kV < $V \leq 25$ kV

PCC voltage	$\sum S_{equ\ permitted\ @\ Ssc\ reference}$ $S_{SC\ reference}$ = 60 MVA three-phase
	Semiconductor motor controllers (e.g. soft-starters) and load controllers compliant with EN 60947-4-2 or EN 60947-4-3
0.4 kV < $V \leq 25$ kV	552 kVA

5.6 Notching

Voltage notching occurs during rectifier commutation when two phases of the supply are effectively short-circuited, being connected to each other through only their commutating impedances. Figure 4 illustrates a typical voltage characteristic exhibiting commutation notching and shows the method for measuring notch parameters. Commutation notches, in so far as they contribute to harmonic levels, are covered by the compatibility levels for very-short-term effects given in IEC 61000-2-2 and IEC 61000-2-12.

NOTE: Notching is a high-frequency event and as such wide-bandwidth transducers are needed to measure notching.

Equipment that results in voltage notching, like any other relevant equipment, can only be connected if the level of harmonic distortion present at the PCC on the supply system is less than the appropriate planning level, However the following additional requirements apply at the PCC.

- The notch depth (*d*) shall not exceed 15% of the peak of the nominal fundamental voltage. For grounded systems, this is the phase–ground voltage. For ungrounded systems, the phase voltage shall be used.
- The peak amplitude of oscillations due to commutation at the start and at the end of the notch shall not exceed 10% of the peak of the nominal fundamental voltage. For grounded systems, this is the phase–ground voltage. For ungrounded systems, the phase voltage shall be used.

- The notch depth duration shall meet the requirements of (6).

$$t \leq \frac{4032}{d} \tag{6}$$

where

t is notch depth duration (μs);

d is notch depth (% of the peak of the nominal phase–ground or phase-phase voltage, depending on the grounding configuration).

Figure 4 — Depiction of voltage notching

6 Assessment of Relevant Equipment

6.1 Introduction

This assessment procedure is applicable to new users.

The assessment procedure for the connection of relevant equipment follows three stages. The objective of this three-stage approach is to balance the degree of detail required by the assessment process with the degree of risk posed by the connection of the particular installation in terms of unacceptable harmonic voltage distortion levels occurring on the supply system if it is connected without any mitigation measures.

Stage 1 facilitates the connection of harmonic sources to LV supply systems. It specifies the maximum sizes of harmonic source that can be connected under a Stage 1 assessment. Stage 1 assessment is based on harmonic sources complying with product-related international standards. Measurement of the background harmonic level may be required in some circumstances.

Stage 2 facilitates the connection of harmonic sources to all supply systems operating at a voltage of greater than LV and less than 33 kV, including any harmonic source that is too large for consideration under Stage 1, or that cannot meet the emission limits of Stage 1. Measurement of the background harmonic level may be required, before a simplified assessment is made of the predicted harmonic voltage level at the PCC that may result from the connection of the new harmonic source. The predicted harmonic voltage levels are required to be less than or equal to the specific limits. Where the voltage at the PCC is above 0.4 kV, the predicted values in this assessment stage are intended to be an indicator of acceptability, such that the connection of the harmonic source can be permitted, or of a need for more-detailed calculation under Stage 3.

Stage 3 is the final assessment at the planning stage. It applies to the connection of the harmonic sources that are not found to be acceptable under Stage 2 assessment or which fall outside the scope of Stages 1 & 2, excluding Stage 2 assessments with an LV PCC. It also applies to any harmonic sources that have a nominal PCC voltage greater than or equal to 33kV and to the assessment of relevant plant where the connection is made at system voltages of 33kV or higher.

6.2 Situations where planning levels may be exceeded

Where existing harmonic voltage levels exceed the planning levels, the risk of disturbance posed by a new user to other users is increased. This concern should be reflected in a conditional connection agreement, including mitigation measures – agreed between the NO and the new user.

The final decision as to whether or not an item of relevant equipment can be connected to the public supply system rests with the NO responsible for the connection.

Since harmonic distortion limits are not governed by statute, the enforcing document is the contractual framework between the NO and the new user, including any site-specific terms in the connection agreement.

Where demonstrated by NO system studies and/or measurement that connection of a new item of relevant equipment could impose harmonic voltage distortion on the supply system greater than the planning levels given in this document, the NO can refuse to allow the connection of the new item of relevant equipment until agreement is reached on a solution that ensures compliance with this Engineering Recommendation.

In a marginal situation, demonstrated through study and/or measurement, a conditional connection may be agreed, at the discretion of the relevant NO, whereby any necessary remedial measures are implemented within a reasonable timescale after connection of the relevant equipment.

In exceptional circumstances, for nodes with voltages up to 33 kV, where, for example, a new user is located in an area remote from other new users or existing users, and it is certain that only that new user's plant or equipment will be connected to the local network, the NO may assess new load under Stage 2 using compatibility levels appropriate to the network voltage, instead of planning levels. The use of this provision is at the discretion of the relevant NO. In these circumstances, the NO should establish procedures to ensure that no other load is connected to that part of the network with harmonic levels greater than the planning levels unless mitigation measures are adopted.

In general, and for all voltage levels, one of the following conditions prevails.

- If (as is the normal situation) the background harmonic level is below the planning level, then the harmonic headroom is determined with respect to the planning level.

- If the background harmonic level at the point of evaluation is above the planning level but below the compatibility level, then the NO may specify one or more network-specific planning levels based on measured background harmonic levels in the timescales detailed in ENA EREC G97 [7]. The specific planning level at the point of evaluation shall not exceed the compatibility level. Where remote nodes associated with other NOs are affected, then agreement on a network-specific planning level between the affected parties is required. The above change shall not affect the planning level for THD_V given in Table 1.

- Failure to comply with the timescale referenced in ENA EREC G97 [7] shall allow the NO hosting the connection to use the compatibility level in lieu of a network-specific planning level to calculate the harmonic headroom.

- If the background harmonic level is above the compatibility level, then the NO responsible for the relevant node shall be responsible for mitigation to reduce the background harmonic level to below the compatibility level. The NO hosting the connection shall assume that the background harmonic level is equal to the compatibility level – no harmonic headroom available – for the purpose of compliance with this document for the connection under consideration only. The above change shall not affect the planning level for THD_V given in Table 1.

NOTE: The rules outlined above apply to the PCC and also to remote nodes at each and every individual harmonic order h = 2 to 100.

6.3 Guidelines

6.3.1 Point of evaluation

The point of evaluation (PoE) is the point on the NO's network where the impact of the relevant equipment upon the levels of harmonic distortion is to be assessed against the planning levels given in Clause 5.2.

In most cases, the PoE will also be the PCC. For Stages 1 and 2, the PoE is always the PCC. For a Stage 3 assessment, more than one PoE might exist as a result of shifts in resonances at remote nodes, and/or the propagation of harmonics through to remote nodes in the network.

If the assessment results in limits being issued for the connection, then the PCC is the point at which the limits apply. For Stage 1 and Stage 2 assessments, the NO may limit the new user's current emissions according to the calculations in Clause **Error! Reference source not found.** and 8 respectively. For Stage 3 assessments, the NO may limit the voltage emissions, which must be accompanied by a harmonic impedance representation of the network, created according to the calculations in Clause 10.2.

6.3.2 System impedance

Connection assessments under Stages 1, 2 and 3 require the harmonic system impedance at the PCC to be taken into consideration. The system impedance at a particular frequency is needed in order to calculate the resulting harmonic voltage distortion developed at a given node due to the connection of relevant equipment.

Where system impedance is derived from short-circuit power level, the short-circuit power level may be obtained through calculation and/or measurement by the relevant NO.

For both Stage 1 and 2 assessments, the short-circuit power at the PCC is required. In order to calculate the maximum harmonic voltage distortion, the minimum short-circuit power expected for planned system conditions shall be used, taking into account maintenance and operational variations. Normal operating conditions – including outages according to transmission network requirements (as outlined in the NETS SQSS [8]), and distribution network requirements (as outlined in ENA EREC P2/7 [9] or latest version) – shall be included. Normal operating conditions is defined as the system state that may be intact or depleted but secure outside of the post-fault switching timescale.

In Stage 1, for assessment of LV systems, the short-circuit power shall be ascertained from the NO, where required.

For Stage 2 assessments, the short-circuit power shall be ascertained from the NO.

For Stage 3 assessments, detailed harmonic impedance models are required and shall be represented with minimal simplification.

For all stages of assessment, the calculation of the system harmonic impedances shall consider relevant planned outages and various generation and demand scenarios as defined by the normal operating conditions.

It is essential that appropriate modelling techniques are adopted for Stage 3 harmonic studies, e.g. those described in Electra 167 [3] and IEEE TP-125-0 [4]. BS EN 60071-4 provides guidance on power system modelling for transient studies. The same techniques used for slow- or fast-front overvoltages can be adopted for harmonic studies.

6.3.3 Aggregation and diversity

A means of aggregating multiple values for each harmonic order, based on the summation exponents in Table 16, is given by (7).

This accounts for the operation of multiple relevant equipment items through the aggregation of their individual harmonic emissions. This form of aggregation is only valid based on a declared performance of the relevant equipment's operational and locational diversity, without which linear addition shall be employed.

$$V_h = \sqrt[\alpha]{\sum_i (V_{hi})^\alpha} \qquad (7)$$

where

V_h is the aggregated (summated) harmonic voltage;

$V_{h\,i}$ is the *i*th harmonic voltage.

Table 16 — Aggregation (summation) exponents

Summation exponent (α)	Harmonic order (*h*)
1.0	$h < 5$
1.4	$5 \leq h \leq 10$
2.0	$h > 10$

The exponent is chosen based on the expected average phase angle between the harmonic sources. An exponent of 1.0 implies that they are in phase (angle 0°), while an exponent of 2.0 implies that they are at an angle of 90° to each other. An exponent of 1.4 implies an angle in the region of 70°.

6.3.4 Uncertainty

Each assessment will have inherent uncertainty associated with it; this can affect the outcome of the assessment and any limits imposed on a connection. Due diligence is required to ensure that such uncertainties are acknowledged and minimised throughout the assessment. Such uncertainties may arise from:

- the modelling of the NO's supply system and the relevant equipment's connection, affecting the calculated resonances in the model;
- an absence of accurate data;
- relevant future supply system variations that will not be subject to their own assessment according to this EREC;
- the accuracy of measurement of the background harmonic level.

Assessment of harmonic and interharmonic frequency components in the frequency range above 2.5 kHz is at the discretion of the host NO.

Where necessary, at the discretion of the NO, derived values or data may be used in lieu of actual data to better inform the assessment and limit the uncertainty. Such approaches are particularly useful for deriving values of the background harmonic level at sites from which measurements are unavailable using data obtained from adjacent sites and system impedance modelling. Similarly, in the case of measurement accuracy limitations (e.g. above 2.5 kHz), representative values of background harmonic level may be specified at the discretion of the host NO.

In the assessment and compliance process for the assessed harmonic source, the criteria given in Stages 1 and 2 are intended as a basis for simple acceptance of the connection. As the connection assessment progresses through the substages, more data is required. In the final part of a Stage 2 assessment, the acceptability of the connection will be judged by the contribution of the harmonic source to the total harmonic voltage planning levels. For Stage 3 assessments, or where uncertainty over the data used for the study can be significant, post-connection measurement may be required to verify compliance of the relevant equipment with this Engineering Recommendation. Note that it may not be practical to measure levels for all operating conditions at all potentially affected nodes. The decision as to what measurements are required rests with the NOs affected.

Where the assessment has indicated that mitigation measures may be necessary, a conditional connection may be made where the extent of the assessment's non-compliance with the limits is considered to be within the margin of uncertainty of the assessment process.

However, conditional connections involve a risk that acceptable limits of distortion may be exceeded and new users should therefore have regard to the practicality, timescale and costs of implementing remedial measures after the connection is made should they prove necessary. A combination of load restrictions with time-of-day and system operating configuration restrictions may need to be applied to the operation of the new relevant equipment until long-term mitigation measures are in place. The post-connection measurements can be used to determine the extent of any mitigation measures that are required.

However, the final decision as to whether or not particular relevant equipment can be connected to a supply system rests with the NO responsible for the connection.

6.3.5 Measurement

Measurements of the background harmonic level on the supply system form part of Stage 1D, Stage 2B and 2C and Stage 3 assessments in order to calculate the available headroom for the new user.

For Stage 2B and 2C assessment, measurements are required at the PCC. For Stage 3 assessment, measurements are required at the PCC and at remote nodes within the affected part(s) of the supply system.

These nodes could be at any voltage level and on part(s) of the supply system not owned or operated by the host NO. The selection of these remote nodes will be dependent upon the outcome of system studies identifying problematic transfer gains. It is recommended that harmonic measurements be carried out prior to and during operation of the connection of the relevant equipment. This will aid compliance monitoring and ensure that the harmonic emission limits imposed on the connection are met.

6.3.5.1 Instrumentation

Instruments for harmonic measurement are usually power quality monitors. For harmonic measurements, IEC 61000-4-30, which makes reference to the algorithm described in IEC 61000-4-7, details three classes of accuracy for measuring harmonic components: Class A, Class B and Class S. For the purpose of connection assessment and compliance monitoring, it is recommended that the NO uses a Class A device for measurement of the background harmonic level and for pre- and post-commissioning monitoring.

Based on IEC 61000-4-30, a ten-minute average characteristic should be measured and the weekly 95th percentile value from the cumulative probability function should be used in the assessment process. The use of alternative aggregation periods according to the continuity of the connection's emissions is considered in Clause 5.5.

To reduce uncertainty and facilitate full assessment in accordance with this EREC, it is desirable to have suitable instrumentation for the frequency range up to 5 kHz. Where such instrumentation is not present, NOs may be justified in installing suitable instrumentation where reasonably practicable.

Instruments may group harmonics and interharmonics above 2.5 kHz into 200 Hz bands in accordance with IEC 61000-4-7. Where the instrumentation can be configured to measure individual harmonics above the 50th, it is recommended that this option is selected to facilitate Stage 2C and Stage 3 assessment.

6.3.5.2 Transducers

Voltage transducers (VTs) are necessary when performing harmonic and interharmonic measurements at voltages above LV. For LV, it is possible to connect measuring devices directly.

VTs are typically voltage transformers, which form part of metering or protective relay circuits. VTs available on the UK supply system are typically of the electromagnetic (wound) type, capacitive voltage divider type or resistive–capacitive voltage divider type. All transformers have their limitations in terms of frequency response and careful consideration needs to be given to their suitability for harmonic assessment.

Some MV electromagnetic VTs have suitable frequency response up to 5 kHz. EHV electromagnetic VTs have limited frequency response, while resistive–capacitive voltage dividers have a suitable frequency response up to hundreds of kHz. The lower section of a capacitive voltage divider generally comprises a capacitor in parallel with an electromagnetic VT. This arrangement is tuned to 50 Hz and is not suitable for harmonic measurements. However, capacitive voltage dividers can be modified with ring-CTs on the earth links of the lower capacitor and electromagnetic VT in such a way as to extend the suitable frequency response to tens of kHz when necessary.

To reduce uncertainty and facilitate full assessment in accordance with this EREC it is desirable to have suitable transducers for the frequency range up to 5 kHz. Where such transducers are not present, or their suitability is uncertain, NOs may be justified in establishing their suitability or installing suitable transducers where reasonably practicable.

6.3.5.3 Temporal and seasonal variation

Levels of harmonic distortion on transmission systems and distribution networks vary according to loading over a 24-hour period, and between weekdays and weekends. It is

important that measurements be taken over a contiguous period of at least seven days, and in multiples of seven days (i.e. 7, 14, 21...).

Where possible and practicable, winter peak and summer minimum demand periods should be evaluated to cater for any seasonal variation in background harmonic distortion. For the purpose of planning studies, the 95th percentile value should be applied to measurements over the longest possible integer number of weeks for assessment against the planning levels. For the purpose of compliance assurance, the 95th percentile value should be applied to each week of measurement and assessed against the requirements recorded in the connection agreement on a week-by-week basis.

6.3.5.4 Use of grouped measurements

If the measured harmonics above 2.5 kHz are only available in groups of 200 Hz bands (due to the specification of the instrumentation) then it is recommended that for each measured group, with a given group centre frequency, that the measured group value is assumed to apply to each integer harmonic and interharmonic that falls within that group for the purposes of Stage 2C and Stage 3 assessment.

6.4 Summary description of the connection process

6.4.1 Stage 1 assessment summary

Stage 1 is designed for harmonic sources at LV. It is designed as a linear process such that assessments are applied in substages. If a substage assessment is passed, then the new user can connect their harmonic source; if the substage assessment is failed, then the next substage assessment is undertaken. In total, there are four substages in Stage 1.

The substages are designed such that earlier substages require less data from the **new user** but use more conservative assumptions. As the connection progresses through the substages, more data is required; however, by having more data, less-conservative assumptions can be made – effectively relaxing the success criteria.

The first substage of Stage 1 – Stage 1A – also allows for self-certification. If a new user connects a harmonic source that is compliant with the relevant international product standard, then they may connect with no assessment or referral to the NO.

The second substage of Stage 1 – Stage 1B – uses manufacturer statements concerning compliance with the relevant international product standard as the basis of assessment.

The third substage of Stage 1 – Stage 1C – is based on equipment technology type, rated power and the short-circuit power level at the PCC.

The final substage of stage 1 is Stage 1D; this is a refined version of Stage 1C that takes into account the actual background harmonic level.

The key benefit of this approach is that it will facilitate straightforward connection of harmonic sources for new users, as there are fewer requirements on them to provide data, which may be difficult for smaller parties.

The Stage 1 assessment procedure is given in Clause **Error! Reference source not found.**.

6.4.2 Stage 2 assessment summary

Stage 2 is designed for connection assessments that do not meet the requirements of Stage 1 and for the connection of harmonic sources at a PCC with voltages below 33kV. It is also designed as a linear process, such that assessments are applied in substages.

Stage 2 includes three substages. Those connection assessments that do not meet the requirements of Stage 1 may be connected under one of the three substages at Stage 2, each of which require more data from the new user and from the NO. If an assessment of the compliance of a connection with an LV PCC does not meet the requirements of Stage 2, then it will not be possible to connect the harmonic source without first implementing the agreed mitigation.

For a Stage 2 connection assessment, small converter loads may be connected on the basis of equipment technology type, rated power and short-circuit power level at the PCC under the Stage 2A assessment process. For loads where a more-detailed assessment is required, Stage 2B – a refined version of Stage 2A – is provided, which takes into account the measured background harmonic level.

The final substage of Stage 2 is Stage 2C, where a prediction of the harmonic voltage distortion post-connection is derived and compared with the planning levels. This calculation is based on a simple reactance model for the source with a multiplication factor to allow for any low-order harmonic resonance. The frequency dependency of network resistance is also considered.

Where the assessment indicates that mitigation measures may be necessary, a conditional connection may be made if the extent of the assessment's non-compliance with the limits is considered by the NO to be within the margin of uncertainty of the assessment process.

The Stage 2 assessment procedure is given in Clause 8.

6.4.3 Resonant (non-emitting) plant installation summary

For the assessment of the connection of resonant plant in a user's installation at voltages below 33 kV, a maximum modification criterion is considered. The methodology uses conservative assumptions that require a minimal amount of data to enable a quick assessment. If the assessment fails, then the connection is to be considered under Stage 3.

Connection of resonant plant to supply systems of 33 kV and above are assessed under Stage 3.

The procedure for assessment of resonant plant is given in Clause 9.

6.4.4 Stage 3 assessment summary

For a Stage 3 assessment, a determination of the harmonic voltages at the PCC based on a harmonic impedance model of the supply system is required in order to take account of any resonance that may occur. For connections at 33 kV and above, the assessment should also take into consideration the effect of such new emissions on other surrounding nodes, including connected lower-voltage networks, since the emissions can exacerbate any potential resonance conditions.

The Stage 3 assessment procedure is given in Clause 10.

7 Assessment of harmonic sources – Stage 1 procedure

7.1 Applicability and substages

A Stage 1 assessment is applicable to connections with an LV PCC.

Connection assessments that fail Stage 1 advance to Stage 2C.

Figure 5 — Stage 1 assessment process flow

Under Stage 1 there are four substages of assessment: Stage 1A through to Stage 1D. The substages are of increasing complexity from Stage 1A to Stage 1D as illustrated by Figure 5 and Table 17.

Table 17 — Stage 1 assessment data requirements for substages 1A to 1D

Data required	Stage 1A	Stage 1B	Stage 1C	Stage 1D
IEC 61000-3-2 compliance statement	✓			
IEC 61000-3-12 compliance statement	✓	✓	✓	✓
Number of IEC 61000-3-12-compliant items		✓		
Individual equipment rating(s) (I_{equ})		✓		
Service current capacity (I_{SCC})		✓		
Short-circuit power at the PCC ($S_{SC\ PCC}$)		✓	✓	✓
Manufacturer's stated minimum short-circuit power ($S_{SC\ Min}$)		✓ (1B-2)		
Technology type and number of phases			✓	✓
Aggregate equipment rated power ($\sum S_{equ}$)			✓	✓
Background harmonic level at the PCC ($V_{h\ m}$)				✓

7.2 Stage 1A assessment procedure

7.2.1 Assessment by compliance with IEC 61000-3-2

Equipment rated up to and including 16 A per phase that is compliant with IEC 61000-3-2 is assessed under Stage 1A. This assessment method involves the following steps, as shown in Figure 6.

- For each item of potentially disturbing plant or equipment, determine whether or not it is in compliance with IEC 61000-3-2.
- Equipment that is compliant with IEC 61000-3-2, EN 61000-3-2, BS EN 61000-3-2, or relevant similar standards, can be connected without further assessment.
- If compliance cannot be verified, then the assessment advances to Stage 1B.

Figure 6 — Stage 1A assessment process flow

NOTE 1: EN 61000-3-2 and BS EN 61000-3-2 are identical to IEC 61000-3-2. Compliance with the standard can be verified by a statement from the manufacturer in their product literature or in the official European Union (EU) Declaration of Conformity, listing the product and compliance with the EN 61000-3-2 standard. This requirement is deemed to be satisfied for items of plant or equipment, each rated up to and including 16 A per phase, that are compliant with any European product standard applicable to that rating that has been harmonised under the EMC Directive [1] by publication in the Official Journal of the European Union [2].

NOTE 2: The EMC Directive [1] provides requirements that govern how apparatus that forms part of a system is treated in order to prevent misapplication of the IEC 61000-3-2 standard.

> Where apparatus is capable of taking different configurations, the electromagnetic compatibility assessment should confirm whether the apparatus meets the essential requirements in the configurations foreseeable by the manufacturer as representative of normal use in the intended applications. In such cases, it should be sufficient to perform an assessment on the basis of the configuration most likely to cause maximum disturbance and the configuration most susceptible to disturbance.
>
> It is not appropriate to carry out the conformity assessment of apparatus placed on the market for incorporation into a given fixed installation, and otherwise not made available on the market, in isolation from the fixed installation into which it is to be incorporated. Such apparatus should therefore be exempted from the conformity assessment procedures normally applicable to apparatus. However, such apparatus should not be permitted to compromise the conformity of the fixed installation into which it is incorporated. Should apparatus be incorporated into more than one identical fixed installation, identifying the electromagnetic compatibility characteristics of these installations should be sufficient to ensure exemption from the conformity assessment procedure.

7.3 Stage 1B assessment procedure

7.3.1 Assessment by compliance with IEC 61000-3-12

Equipment rated up to and including 75 A per phase that is compliant with IEC 61000-3-12 is assessed under Stage 1B.

This assessment method involves the following steps, as shown in Figure 7.

Figure 7 — Stage 1B assessment process flow

- For each item of potentially disturbing plant or equipment, determine the equipment rating (I_{equ}) and the equipment number of phases.
- For each item of potentially disturbing plant or equipment, determine compliance with IEC 61000-3-12, or equivalent, including the exact statement of compliance.
- Determine the minimum required short-circuit power at the PCC ($S_{SC\ PCC\ Min}$).

- Determine short-circuit power at the PCC ($S_{SC\ PCC}$).
- Compare $S_{SC\ PCC}$ with $S_{SC\ PCC\ Min}$.

NOTE 1: EN 61000-3-12 and BS EN 61000-3-12 are identical to IEC 61000-3-12. This requirement is deemed to be satisfied for plant and equipment, each rated up to and including 75 A per phase, that is compliant with any European product standard applicable to that rating that has been harmonised under the EMC Directive [1] by publication in the Official Journal of the European Union [2].

NOTE 2: Equipment complying with IEC 61000-3-2 shall be ignored in Stage 1B.

NOTE 3: The EMC Directive [1] provides requirements that govern how apparatus that forms part of a system is treated in order to prevent misapplication of the IEC 61000-3-2 standard.

> Where apparatus is capable of taking different configurations, the electromagnetic compatibility assessment should confirm whether the apparatus meets the essential requirements in the configurations foreseeable by the manufacturer as representative of normal use in the intended applications. In such cases, it should be sufficient to perform an assessment on the basis of the configuration most likely to cause maximum disturbance and the configuration most susceptible to disturbance.
>
> It is not appropriate to carry out the conformity assessment of apparatus placed on the market for incorporation into a given fixed installation, and otherwise not made available on the market, in isolation from the fixed installation into which it is to be incorporated. Such apparatus should therefore be exempted from the conformity assessment procedures normally applicable to apparatus. However, such apparatus should not be permitted to compromise the conformity of the fixed installation into which it is incorporated. Should apparatus be incorporated into more than one identical fixed installation, identifying the electromagnetic compatibility characteristics of these installations should be sufficient to ensure exemption from the conformity assessment procedure.

7.3.2 Compliance with IEC 61000-3-12 or equivalent

Under IEC 61000-3-12, which applies to equipment rated above 16 A, up to and including 75 A, manufacturers must make one of two statements in their product documentation, either:

- statement 1: “Equipment complying with IEC 61000-3-12”; or
- statement 2: “This equipment complies with IEC 61000-3-12 provided that the short-circuit power S_{sc} [denoted $S_{SC\ Min\ n}$ herein] is greater than or equal to xx at the interface point between the new user's supply and the public system. It is the responsibility of the installer or user of the equipment to ensure, by consultation with the distribution network operator if necessary, that the equipment is connected only to a supply with a short-circuit power S_{sc} greater than or equal to xx”.

Statement 1 corresponds to plant and equipment that meets the harmonic emission limits in IEC 61000-3-12, where the ratio of short-circuit power to equipment rating is at least 33:1. Where plant and equipment does not comply with these limits, statement 2 is used and the required minimum short-circuit power is specified by the manufacturer.

As per Figure 7, the above statements are used to evaluate whether connection to the network is permissible at this stage of assessment.

NOTE 1: Compliance with EN 61000-3-12 can be verified from the official statement made by the manufacturer in their European Union (EU) Declaration of Conformity, which lists the product and its compliance with the standard. It is important to note that this alone does not provide the required detail regarding which of the two possible statements apply. If Statement 2 applies, then it does not provide the short-circuit power. Such detail must be determined by reference to the manufacturer’s literature or directly from the manufacturer.

NOTE 2: Standard BS IEC 61000-3-4 is not used in this assessment as IEC 61000-3-12 covers the same scope up to $I_{equ} \leq 75$.

7.3.3 Stage 1B-1 assessment procedure – minimum short-circuit power

The minimum short-circuit power at the PCC ($S_{SC\ PCC\ Min}$) for plant or equipment where the manufacturer states "Equipment Complying with IEC 61000-3-12" (statement 1), and where no plant or equipment is subject to statement 2, "Equipment Complying with IEC 61000-3-12 Subject to $S_{SC\ Min} \geq$ X kVA", shall be determined using Table 18 and (8).

$$S_{SC\ PCC\ Min} = \frac{F_{SCE\ Min} \sqrt[\alpha]{\sum_{m=1}^{M} \left(S_{equ\ m}\right)^{\alpha}}}{1000} \qquad (8)$$

where

$S_{SC\ PCC\ Min}$ is the minimum short-circuit power (MVA) at the PCC;

$F_{SCE\ Min}$ is the minimum short-circuit ratio factor from Table 18;

α is the summation exponent from Table 18;

M is the number of items of "Equipment Complying with IEC 61000-3-12";

$S_{equ\ m}$ is the equipment rating (kVA) for the mth item of plant or equipment.

Table 18 — Short-circuit ratio factor and summation exponent for varying number of items of equipment compliant with IEC 61000-3-12

Number of items (M)	Minimum short-circuit ratio factor ($F_{SCE\ Min}$)		Summation exponent (α)
	I_{SCC} < 100 A	$I_{SCC} \geq$ 100 A	
$M \leq 5$	29.050	24.224	2
$6 \leq M \leq 7$	20.323	16.947	1.4
$M \geq 8$	11.391	9.499	1

This table is only to be applied where the manufacturer does not state a minimum applicable short-circuit power.

This table is based on a source impedance X/R ratio of 0.625 for I_{SCC} < 100 A and 1.0 for $I_{SCC} \geq$ 100 A. These values correspond to the X/R ratios of the reference impedances in IEC/TR 60725. Where the actual X/R ratio is less than the assumed value, then the minimum short-circuit power levels derived using (8) shall be modified in accordance with Annex A.

NOTE 1: The service current capacity (I_{SCC}) is determined by reference to the network operator. For the purposes of the harmonic assessment, it is only necessary to decide which of the following categories apply to the service current capacity.

a) Less than 100 A per phase;

b) Greater than or equal to 100 A per phase.

NOTE 2: Each component of the service equipment – service cable, cut-out, meter and meter tails – has a rating, as does the environment in which the service equipment sits. The lowest of these ratings defines the service current capacity (I_{SCC}).

NOTE 3: The service current capacity category is used to infer the source X/R ratio in accordance with IEC/TR 60725.

7.3.4 Stage 1B-2 assessment procedure – minimum short-circuit power

The minimum short-circuit power at the PCC ($S_{SC\ PCC\ Min}$) for plant or equipment where the manufacturer states "Equipment Complying with IEC 61000-3-12 Subject to $S_{SC\ Min} \geq X$ kVA" for any item of plant or equipment shall be determined using (9).

$$S_{SC\ PCC\ Min} = 33 \sum_{m=1}^{M} S_{equ\ m} + \sum_{n=1}^{N} S_{SC\ Min\ n} \qquad (9)$$

where

$S_{SC\ PCC\ Min}$ is the minimum short-circuit power (MVA) at the PCC for the combination of all items of plant or equipment;

M is the number of items of plant or equipment where the manufacturer states "Equipment Complying with IEC 61000-3-12";

$S_{equ\ m}$ is the equipment rating (kVA) for the *m*th item of plant or equipment which the manufacturer states as "Equipment Complying with IEC 61000-3-12";

N is the number of items of plant or equipment with a stated $S_{SC\ Min}$;

$S_{SC\ Min\ n}$ is the minimum short-circuit power (MVA) at the PCC for the *n*th item of plant or equipment with a stated $S_{SC\ Min}$.

7.3.4.1 Short-circuit power at the PCC

Where applicable, the short-circuit power at the PCC shall be obtained from the **NO**. For three-phase plant and equipment, the three-phase short-circuit power is required. For single-phase plant and equipment, the single-phase short-circuit power is required.

7.3.4.2 Compliance with the limit of minimum short-circuit power at the PCC

The connection is acceptable if $S_{SC\ PCC} \geq S_{SC\ PCC\ Min}$. If this requirement is not satisfied, then the assessment fails Stage 1B and advances to Stage 1C.

7.4 Stage 1C assessment procedure

The Stage 1C assessment involves the use of aggregate equipment rated power ($\sum S_{equ}$), short-circuit power at the PCC ($S_{SC\ PCC}$) and technology type.

This assessment method is only applicable to the following types of plant and equipment:

- three-phase six-pulse converters;
- three-phase active-front-end converters;
- three-phase twelve-pulse converters;
- single-phase rectifiers.

This assessment method does not require the measured background harmonic level, which is instead assumed to be no higher than 75% of the planning level.

This assessment method involves the following steps, as illustrated in Figure 8.

- Determine type and mix of converter technologies.
- For the case where all items of plant and equipment have a single technology type, follow the steps of Stage 1C-1.
- For the case where a mix of three-phase six-pulse and three-phase active-front-end converter technology types is employed, follow the steps of Stage 1C-2.

Stage 1C-1

- Determine aggregate equipment rated power ($\sum S_{equ}$).
- Determine short-circuit power at the PCC ($S_{SC\ PCC}$).
- Scale Table 19 values for short-circuit power at the PCC ($S_{SC\ PCC}$) to determine the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$) for the connection.
- Compare $\sum S_{equ}$ with $\sum S_{equ\ permitted}$.

Stage 1C-2

- Determine aggregate equipment rated power ($\sum S_{equ\ j}$) for six-pulse plant and equipment.
- Determine aggregate equipment rated power ($\sum S_{equ\ k}$) for active-front-end plant and equipment.
- Calculate $S_{SC\ PCC\ Min}$ from (12).
- Determine short-circuit power at the PCC ($S_{SC\ PCC}$).
- Compare $\sum S_{SC\ PCC}$ with $\sum S_{SC\ PCC\ Min}$.

Figure 8 — Stage 1C assessment process flow

7.4.1 Stage 1C-1 assessment procedure – identical converter technology

7.4.1.1 Aggregate equipment rated power

The aggregate equipment rated power ($\sum S_{equ}$) for plant and equipment of the same type shall be determined by summation as per (10).

$$\sum S_{equ} = \sum_{j=1}^{J} S_{equ\,j} \qquad (10)$$

where

$\sum S_{equ}$ is the aggregate equipment rated power (kVA);

J is the total number of items of plant or equipment;

$S_{equ\,j}$ is the equipment rating (kVA) for the jth item of plant or equipment.

7.4.1.2 Short-circuit power at the PCC

The short-circuit power at the PCC ($S_{SC\,PCC}$) shall be obtained from the host **NO**. For three-phase plant and equipment, the three-phase short-circuit power is required. For single-phase plant and equipment, the single-phase short-circuit power is required.

7.4.1.3 Permitted aggregate equipment rated power

Table 19 gives the maximum permitted aggregate equipment rated power ($\sum S_{equ\,permitted}$) of plant and equipment at the PCC, assuming a single technology type (six-pulse only, active-front-end only or twelve-pulse only for three-phase connections or single-phase rectifier, but not a mixture).

Table 19 — Maximum permitted aggregate equipment rated power at reference short-circuit power (1C-1)

PCC voltage	$\sum S_{equ\,permitted\,@\,Ssc\,reference}$ $S_{SC\,reference}$ = 10 MVA three-phase			$\sum S_{equ\,permitted\,@\,Ssc\,reference}$ $S_{SC\,reference}$ = 2 MVA single-phase
	Six-pulse three-phase converter	Active-front-end three-phase converter	Twelve-pulse three-phase converter	Single-phase rectifier
LV	22 kVA	192 kVA	77 kVA	7.9 kVA

NOTE: An explanation of the converter technologies is provided in Annex B.

Note: An active filter in combination with six-pulse three-phase converter equipment can be treated as equivalent to active-front-end three-phase converter equipment provided that the resulting harmonic current emission does not exceed the emission profile for active-front-end three-phase converter equipment given in Table C1 of Engineering Recommendation G5 Issue 5 2018 'Background to Stage 1 and Stage 2'. The emission from the six-pulse converter may increase due to the action of the active filter on voltage distortion and affect the overall emission of the combination of equipment; consequently this needs consideration in selection of the filter rating. To achieve the required emission profile it will be necessary for the active filter to

be configured to target and adequately compensate each of the relevant harmonic orders where the emission from the six pulse converter would otherwise exceed that of Table C1 referenced above.

The values stated assume a reference short-circuit power level ($S_{SC\ reference}$). For three-phase plant and equipment, this is a three-phase short-circuit power of 10 MVA at the PCC. For single-phase plant and equipment, this is a single-phase short-circuit power of 2 MVA at the PCC.

Where $S_{SC\ PCC}$ is not equal to the assumed short-circuit power level ($S_{SC\ reference}$), the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$) shall be determined from (11).

$$\sum S_{equ\ permitted} = S_{SC\ PCC}\left(\frac{\sum S_{equ\ permitted\ @\ Ssc\ reference}}{S_{SC\ reference}}\right) \quad (11)$$

where

$\sum S_{equ\ permitted}$	is the permitted aggregate equipment rated power (kVA);
$S_{SC\ PCC}$	is the system short-circuit power at the PCC (MVA): three-phase for three-phase plant and equipment and single-phase for single-phase plant and equipment;
$\sum S_{equ\ permitted\ @\ Ssc\ reference}$	is the maximum permitted aggregate equipment rated power (kVA) at the PCC for the reference short-circuit power ($S_{SC\ reference}$);
$S_{SC\ reference}$	is the reference short-circuit power at the PCC (MVA): 10 MVA (three-phase) for three-phase plant and equipment and 2 MVA (single-phase) for single-phase plant and equipment.

7.4.1.4 Compliance with the limit of aggregate equipment rated power

The connection is acceptable if $\sum S_{equ} \leq \sum S_{equ\ permitted}$. If this requirement is not satisfied, then the assessment fails Stage 1C-1 and advances to Stage 1D-1. Note that reinforcement of the host network to increase $\sum S_{equ\ permitted}$ may also be considered.

7.4.2 Stage 1C-2 assessment procedure – mixed three-phase converter technology

7.4.2.1 Minimum short-circuit power at the PCC

The minimum short-circuit power at the PCC ($S_{SC\ PCC\ Min}$), for mixed three-phase converter technology (i.e. a mix of six-pulse and active-front-end technology types) shall be determined using (12).

$$S_{SC\ PCC\ Min} = 459.977 \sum_{j=1}^{J} S_{equ\ j} + 52.170 \sum_{k=1}^{K} S_{equ\ k} \quad (12)$$

where

$S_{SC\ PCC\ Min}$	is the minimum short-circuit power at the PCC;
J	is the number of items of three-phase six-pulse plant or equipment;
$S_{equ\ j}$	is the equipment rating (kVA) for the *j*th item of three-phase six-pulse plant or equipment;
K	is the number of items of three-phase active-front-end plant or equipment;
$S_{equ\ k}$	is the equipment rating (kVA) for the *k*th item of three-phase active-front-end plant or equipment.

7.4.2.2 Short-circuit power at the PCC

The three-phase short-circuit power at the PCC ($S_{SC\ PCC}$) shall be obtained from the host **NO**.

7.4.2.3 Compliance with the limit of minimum short-circuit power at the PCC

The connection is acceptable if $S_{SC\ PCC} \geq S_{SC\ PCC\ Min}$. If this requirement is not satisfied, then the assessment fails Stage 1C-2 and advances to Stage 1D-2.

7.5 Stage 1D assessment procedure

The Stage 1D assessment involves the use of aggregate equipment rated power ($\sum S_{equ}$), short-circuit power at the PCC ($S_{SC\ PCC}$), technology type and background harmonic level at the PCC ($V_{h\ m}$).

This assessment method is only applicable to the following types of plant and equipment:

- three-phase six-pulse converters;
- three-phase active-front-end converters;
- three-phase twelve-pulse converters;
- single-phase rectifiers.

This assessment method involves the following steps, as illustrated in Figure 9.

Stage 1D-1

- Measure the background harmonic level at the PCC ($V_{h\ m}$) for the limiting harmonic orders (h) of $h = 5$ for three-phase six-pulse converters and three-phase active-front-end converters, $h = 37$ for three-phase twelve-pulse converters and $h = 21$ for single-phase rectifiers.
- Determine the short-circuit power at the PCC ($S_{SC\ PCC}$).
- Scale Table 19 values for short-circuit power at the PCC ($S_{SC\ PCC}$), harmonic headroom ($V_{h\ headroom}$), and planning level ($V_{h\ PL}$), to determine the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$) for the connection.
- Compare $\sum S_{equ}$ with $\sum S_{equ\ permitted}$.

Stage 1D-2

- Determine the aggregate equipment rated power ($\sum S_{equ\ j}$) for six-pulse plant and equipment.
- Determine the aggregate equipment rated power ($\sum S_{equ\ k}$) for active-front-end plant and equipment.
- Calculate $S_{SC\ PCC\ Min}$ from (12).
- Determine the short-circuit power at the PCC ($S_{SC\ PCC}$).
- Compare $\sum S_{SC\ PCC}$ with $\sum S_{SC\ PCC\ Min}$.

Figure 9 — Stage 1D assessment process flow

7.5.1 Stage 1D-1 assessment procedure – identical converter technology – assessment accounting for actual headroom

This assessment requires knowledge of the measured background harmonic level at the PCC (see Clause 6.3.5), short-circuit power at the PCC ($S_{SC\ PCC}$), the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$) and the appropriate short-circuit power at the PCC, which shall be obtained from the host NO.

Table 19 in Stage 1C-1 provides the maximum permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$) of plant and equipment at the PCC assuming three-phase six-pulse only or three-phase active-front-end only or twelve-pulse only or single-phase rectifier only – but not a mixture of technology types – for a reference short-circuit power and for a measured background harmonic level equal to 75% of the planning level ($V_{h\ PL}$).

Stage 1D-1 also takes account of the measured background harmonic level at the limiting harmonic orders for each technology, in order to determine revised $\sum S_{equ\ permitted}$ values.

The $\sum S_{equ\ permitted}$ value for three-phase six-pulse converters or three-phase active-front-end converters is given by (13).

$$\sum S_{equ\ permitted} = \frac{S_{SC\ PCC}}{10\ \text{MVA}} \times \frac{V_{5\ headroom}}{0.25 V_{5\ PL}} \times \sum S_{equ\ permitted\ @\ Ssc\ reference} \tag{13}$$

where

$\sum S_{equ\ permitted}$ is the permitted aggregate equipment rated power (kVA);

$S_{SC\ PCC}$ is the system short-circuit power at the PCC (MVA): three-phase for three-phase plant and equipment and single-phase for single-phase plant and equipment;

$V_{5\ PL}$ is the LV planning level for the 5th harmonic (% h = 1);

$\sum S_{equ\ permitted\ @\ Ssc\ reference}$ is the maximum permitted aggregate equipment rated power (kVA) at the PCC for the reference short-circuit power ($S_{SC\ reference}$).

$$V_{5\ headroom} = V_{5\ PL} - V_{5\ m} \tag{14}$$

where

$V_{5\ m}$ is the measured background harmonic level at the PCC for the 5th harmonic (% h = 1).

The $\sum S_{equ\ permitted}$ value for three-phase twelve-pulse converters is given by (15).

$$\sum S_{equ\ permitted} = \frac{S_{SC\ PCC}}{10\ \text{MVA}} \times \frac{V_{37\ headroom}}{0.25 V_{37\ PL}} \times \sum S_{equ\ permitted\ @\ Ssc\ reference} \tag{15}$$

where

$$V_{37\ headroom} = V_{37\ PL} - V_{37\ m} \tag{16}$$

where

$V_{37\ PL}$ is the LV planning level for the 37th harmonic (% h = 1);

$V_{37\ m}$ is the measured background harmonic level at the PCC for the 37th harmonic (% h = 1).

The $\sum S_{equ\ permitted}$ value for single-phase rectifiers is given by (17).

$$\sum S_{equ\ permitted} = \frac{S_{SC\ PCC}}{2\ \text{MVA}} \times \frac{V_{21\ headroom}}{0.25 V_{21\ PL}} \times \sum S_{equ\ permitted\ @\ Ssc\ reference} \quad (17)$$

where

$$V_{21\ headroom} = V_{21\ PL} - V_{21\ m} \quad (18)$$

where

$V_{21\ PL}$ is the LV planning level for the 21st harmonic (% h = 1);

$V_{21\ m}$ is the measured background harmonic level at the PCC for the 21st harmonic (% h = 1).

7.5.1.1 Compliance with the limit of aggregated equipment rated power

The connection is acceptable if $\sum S_{equ} \leq \sum S_{equ\ permitted}$. If this requirement is not satisfied, then the assessment fails Stage 1D-1 and advances to Stage 2C. Note that reinforcement of the distribution network to increase $\sum S_{equ\ permitted}$ may also be considered.

7.5.2 Stage 1D-2 assessment procedure – mixed three-phase converter technology – assessment accounting for actual headroom

As with the Stage 1D-1 assessment, Stage 1D-2 requires knowledge of the measured background harmonic level at the PCC. The subsequent calculation stages are detailed below.

7.5.2.1 Minimum short-circuit power at the PCC

The minimum short-circuit power at the PCC ($S_{SC\ PCC\ Min}$), for mixed three-phase converter technology (i.e. a mix of six-pulse and active-front-end technology) shall be determined using (19).

$$S_{SC\ PCC\ Min} = \frac{459.977 \sum_{j=1}^{J} S_{equ\ j} + 52.170 \sum_{k=1}^{K} S_{equ\ k}}{V_{5\ headroom}} \quad (19)$$

where

$S_{SC\ PCC\ Min}$ is the minimum short-circuit power at the PCC;

J is the number of items of three-phase six-pulse plant or equipment;

$S_{equ\ j}$ is the equipment rating (kVA) for the jth item of three-phase six-pulse plant or equipment;

K is the number of items of three-phase active-front-end plant or equipment;

$S_{equ\ k}$ is the equipment rating (kVA) for the kth item of three-phase active-front-end plant or equipment;

$$V_{5\ headroom} = V_{5\ PL} - V_{5\ m} \quad (20)$$

where

$V_{5\ PL}$ is the LV planning level for the 5th harmonic (% h = 1);

$V_{5\ m}$ is the measured background harmonic level at the PCC for the 5th harmonic (% h = 1).

7.5.2.2 Short-circuit power at the PCC

The three-phase short-circuit power at the PCC shall be obtained from the host NO.

7.5.2.3 Compliance with the limit of minimum short-circuit power at the PCC

The connection is acceptable if $S_{SC\ PCC} \geq S_{SC\ PCC\ Min}$. If this requirement is not satisfied, then the assessment fails Stage 1D-2 and advances to Stage 2C.

8 Assessment of harmonic sources – Stage 2 procedure

8.1 Applicability and substages

Under Stage 2 there are three substages of assessment – Stage 2A through to 2C. For connections with a PCC at 6.6 kV, 11 kV, 20 kV or 22 kV, the stages increase in complexity going from Stage 2A to Stage 2C; see Figure 10 and Table 20.

For connections with an LV PCC that advance to Stage 2, only Stage 2C is applicable.

Figure 10 — Stage 2 assessment process flow

Table 20 — Stage 2 assessment data requirements for substages 2A to 2C

Data required	Stage 2A	Stage 2B	Stage 2C
Aggregate equipment rated power ($\sum S_{equ}$)	✓	✓	
Short-circuit power at the PCC ($S_{SC\ PCC}$)	✓	✓	✓
Technology type	✓	✓	
Background harmonic level at the PCC ($V_{h\ m}$)		✓	✓
Harmonic current emission (I_h)			✓

8.2 Stage 2A assessment procedure

The Stage 2A assessment involves the aggregate equipment rated power ($\sum S_{equ}$), short-circuit power at the PCC ($S_{SC\ PCC}$) and technology type.

This assessment method is only applicable to the following types of plant and equipment:

- three-phase six-pulse converters;
- three-phase active-front-end converters;
- three-phase twelve-pulse converters.

This assessment method does not require the measured background harmonic level; instead, the background harmonic level is assumed to be no higher than 75% of the planning level.

This assessment method involves the following steps, as shown in Figure 11.

- Determine the type and mix of converter technologies.
- For the case where all plant and equipment have a single technology type, follow Stage 2A-1.
- For the case where a mix of three-phase six-pulse and three-phase active-front-end converter technology types is employed, follow Stage 2A-2.

Stage 2A-1

- Determine the aggregate equipment rated power ($\sum S_{equ}$).
- Determine the short-circuit power at the PCC ($S_{SC\ PCC}$).
- Scale the Table 21 values for short-circuit power at the PCC ($S_{SC\ PCC}$) to determine the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$) for the connection.
- Compare $\sum S_{equ}$ with $\sum S_{equ\ permitted}$.

Stage 2A-2

- Determine the aggregate equipment rated power ($\sum S_{equ\ j}$) for six-pulse plant and equipment.
- Determine the aggregate equipment rated power ($\sum S_{equ\ k}$) for active-front-end plant and equipment.

- Calculate $S_{SC\ PCC\ Min}$ from (23).
- Determine the short-circuit power at the PCC ($S_{SC\ PCC}$).
- Compare $\sum S_{SC\ PCC}$ with $\sum S_{SC\ PCC\ Min}$.

Figure 11 — Stage 2A assessment process flow

8.2.1 Stage 2A-1 assessment procedure – identical converter technology

8.2.1.1 Aggregate equipment rated power

The aggregate equipment rated power ($\sum S_{equ}$) for plant and equipment of the same type shall be determined by summation as per (21).

$$\sum S_{equ} = \sum_{j=1}^{J} S_{equ\ j} \qquad (21)$$

where

$\sum S_{equ}$ is the aggregate equipment rated power (kVA);

J is the number of items of plant or equipment;

$S_{equ\ j}$ is the equipment rating (kVA) for the jth item of plant or equipment.

8.2.1.2 Short-circuit power at the PCC

The three-phase short-circuit power at the PCC ($S_{SC\ PCC}$) shall be obtained from the host NO.

8.2.1.3 Permitted aggregate equipment rated power

Table 21 gives the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$) of plant and equipment at the PCC assuming a single technology type (i.e. six-pulse only, twelve-pulse only or active-front-end only, but not a mixture).

Table 21 — Maximum permitted aggregate equipment rated power at reference short-circuit power (2A-1)

PCC voltage kV	$\sum S_{equ\ permitted\ @\ Ssc\ reference}$ $S_{SC\ reference}$ = 60 MVA three-phase		
	Six-pulse three-phase converter	Active-front-end three-phase converter	Twelve-pulse three-phase converter
6.6, 11, 20, 22	76 kVA	673 kVA	287 kVA

NOTE: The values stated assume a three-phase short-circuit power at the PCC ($S_{SC\ PCC}$) of 60 MVA.

Note: An active filter in combination with six-pulse three-phase converter equipment can be treated as equivalent to active-front-end three-phase converter equipment provided that the resulting harmonic current emission does not exceed the emission profile for active-front-end three-phase converter equipment given in Table C1 of Engineering Recommendation G5 Issue 5 2018 'Background to Stage 1 and Stage 2'. The emission from the six-pulse converter may increase due to the action of the active filter on voltage distortion and affect the overall emission of the combination of equipment; consequently this needs consideration in selection of the filter rating. To achieve the required emission profile it will be necessary for the active filter to be configured to target and adequately compensate each of the relevant harmonic orders where the emission from the six pulse converter would otherwise exceed that of Table C1 referenced above.

Where $S_{SC\ PCC}$ is not equal to 60 MVA, then the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$) shall be determined from (22).

$$\sum S_{equ\ permitted} = S_{SC\ PCC}\left(\frac{\sum S_{equ\ permitted\ @\ 60\ MVA\ Ssc\ reference}}{60\ \text{MVA}}\right) \quad (22)$$

where

$\sum S_{equ\ permitted}$ is the permitted aggregate equipment rated power (kVA) at the PCC;

$S_{SC\ PCC}$ is the system three-phase short-circuit power (MVA) at the PCC;

$\sum S_{equ\ permitted\ @\ 60\ MVA\ Ssc\ reference}$ is the maximum permitted aggregate equipment rated power at the PCC (kVA) for the reference 60 MVA three-phase short-circuit power.

8.2.1.4 Compliance with the limit of aggregate equipment rated power

The connection is acceptable if $\sum S_{equ} \leq \sum S_{equ\ permitted}$. If this requirement is not satisfied, then the assessment fails Stage 2A-1 and advances to Stage 2B-1. Note that reinforcement of the distribution network to increase $\sum S_{equ\ permitted}$ may also be considered.

8.2.2 Stage 2A-2 assessment procedure – mixed three-phase converter technology

8.2.2.1 Minimum short-circuit power at the PCC

The minimum short-circuit power at the PCC ($S_{SC\ PCC\ Min}$), for mixed three-phase converter technology (i.e. a mix of six-pulse and active-front-end technology) shall be determined using (23).

$$S_{SC\ PCC\ Min} = 785.962 \sum_{j=1}^{J} S_{equ\ j} + 89.143 \sum_{k=1}^{K} S_{equ\ k} \quad (23)$$

where

$S_{SC\ PCC\ Min}$ is the minimum short-circuit power at the PCC;

J is the number of items of three-phase six-pulse plant and equipment;

$S_{equ\ j}$ is the equipment rating (kVA) for the *j*th item of three-phase six-pulse plant and equipment;

K is the number of items of three-phase active-front-end plant and equipment;

$S_{equ\ k}$ is the equipment rating (kVA) for the *k*th item of three-phase active-front-end plant and equipment.

8.2.2.2 Short-circuit power at the PCC

The three-phase short-circuit power at the PCC ($S_{SC\ PCC}$) shall be obtained from the host **NO**.

8.2.2.3 Compliance with the limit of minimum short-circuit power

The connection is acceptable if $S_{SC\ PCC} \geq S_{SC\ PCC\ Min}$. If this requirement is not satisfied, then the assessment fails Stage 2A-2 and advances to Stage 2B-2.

8.3 Stage 2B assessment procedure

The Stage 2B assessment involves the use of the aggregate equipment rated power ($\sum S_{equ}$), short-circuit power at the PCC ($S_{SC\ PCC}$), technology type and background harmonic level at the PCC ($V_{h\ m}$).

The assessment method is only applicable to the following types of plant and equipment:

- three-phase six-pulse converters;
- three-phase active-front-end converters;
- three-phase twelve-pulse converters.

This assessment method involves the following steps, as shown in Figure 12.

Stage 2B-1

- Measure the background harmonic level at the PCC ($V_{h\ m}$) for the limiting harmonic orders (h) of $h = 5$ for three-phase six-pulse converters and three-phase active-front-end converters and $h = 11$ for three-phase twelve-pulse converters.
- Determine the short-circuit power at the PCC ($S_{SC\ PCC}$).
- Scale the Table 21 values for the short-circuit power at the PCC ($S_{SC\ PCC}$), harmonic headroom ($V_{h\ headroom}$), and planning level ($V_{h\ PL}$), to determine the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$) for the connection.
- Compare $\sum S_{equ}$ with $\sum S_{equ\ permitted}$.

Stage 2B-2

- Determine the aggregate equipment rated power ($\sum S_{equ\ j}$) for six-pulse plant and equipment.
- Determine the aggregate equipment rated power ($\sum S_{equ\ k}$) for active-front-end plant and equipment.
- Calculate $S_{SC\ PCC\ Min}$ from (28).
- Determine the short-circuit power at the PCC ($S_{SC\ PCC}$).
- Compare $\sum S_{SC\ PCC}$ with $\sum S_{SC\ PCC\ Min}$.

Figure 12 — Stage 2B assessment process flow

8.3.1 Stage 2B-1 Assessment procedure – identical converter technology – assessment accounting for actual headroom

This assessment requires knowledge of the measured background harmonic level at the PCC (see Clause 6.3.5), the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$), the appropriate short-circuit power at the PCC, which shall be obtained from the host NO, as well as the measured background harmonic level at the PCC ($V_{h\ m}$).

8.3.1.1 Permitted aggregate equipment rated power

In Stage 2A-1, Table 21 provides the maximum permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$) of plant and equipment at the PCC assuming six-pulse only, active-front-end only or twelve-pulse only technology types – but not a mixture – for a 60 MVA three-phase reference short-circuit power, and background harmonic level at 75% of the planning level ($V_{h\ PL}$). Stage 2B-1 takes account of the measured background harmonic level at the limiting harmonics for each technology to determine revised $\sum S_{equ\ permitted}$ values.

The $\sum S_{equ\ permitted}$ value for three-phase six-pulse converters or three-phase active-front-end converters is given by (24).

$$\sum S_{equ\ permitted} = \frac{S_{SC\ PCC}}{60\ \text{MVA}} \times \frac{V_{5\ headroom}}{0.25 V_{5\ PL}} \times \sum S_{equ\ permitted\ @\ 60\ MVA\ Ssc\ reference} \qquad (24)$$

where

$\sum S_{equ\ permitted}$	is the permitted aggregate equipment rated power (kVA) at the PCC;
$S_{SC\ PCC}$	is the system three-phase short-circuit power (MVA) at the PCC;
$\sum S_{equ\ permitted\ @\ 60\ MVA\ Ssc\ reference}$	is the maximum permitted aggregate equipment rated power at the PCC (kVA) for the reference 60 MVA three-phase short-circuit power.

$$V_{5\ headroom} = V_{5\ PL} - V_{5\ m} \qquad (25)$$

where

$V_{5\ PL}$	is the LV planning level for the 5th harmonic (% h = 1);
$V_{5\ m}$	is the measured background harmonic level at the PCC for the 5th harmonic (% h = 1).

The $\sum S_{equ\ permitted}$ value for twelve-pulse converters is given by (26).

$$\sum S_{equ\ permitted} = \frac{S_{SC\ PCC}}{60\ \text{MVA}} \times \frac{V_{11\ headroom}}{0.25 V_{11\ PL}} \times \sum S_{equ\ permitted\ @\ 60\ MVA\ Ssc\ reference} \quad (26)$$

where

$$V_{11\ headroom} = V_{11\ PL} - V_{11\ m} \quad (27)$$

where

$V_{11\ PL}$ is the LV planning level for the 11th harmonic (% h = 1);

$V_{11\ m}$ is the measured background harmonic level at the PCC for the 11th harmonic (% h = 1).

8.3.1.2 Compliance with the limit of permitted aggregate equipment rated power

The connection is acceptable if $\sum S_{equ} \leq \sum S_{equ\ permitted}$. If this requirement is not satisfied, then the assessment fails Stage 2B-1 and advances to Stage 2C. Note that reinforcement of the distribution network to increase $\sum S_{equ\ permitted}$ may also be considered.

8.3.2 Stage 2B-2 Assessment procedure – mixed three-phase converter technology – assessment accounting for actual headroom

8.3.2.1 Minimum short-circuit power at the PCC

The minimum short-circuit power at the PCC ($S_{SC\ PCC\ Min}$) for mixed three-phase converter technology (i.e. a mix of six-pulse and active-front-end technology) shall be determined using (28).

$$S_{SC\ PCC\ Min} = \frac{589.472 \sum_{j=1}^{J} S_{equ\ j} + 66.857 \sum_{k=1}^{K} S_{equ\ k}}{V_{5\ headroom}} \quad (28)$$

where

$S_{SC\ PCC\ Min}$ is the minimum short-circuit power at the PCC;

J is the number of items of three-phase six-pulse plant or equipment;

$S_{equ\ j}$ is the equipment rating (kVA) for the jth item of three-phase six-pulse plant or equipment;

K is the number of items of three-phase active-front-end plant or equipment;

$S_{equ\ k}$ is the equipment rating (kVA) for the kth item of three-phase active-front-end plant or equipment.

$$V_{5\ headroom} = V_{5\ PL} - V_{5\ m} \quad (29)$$

where

$V_{5\ PL}$ is the LV planning level for the 5th harmonic (% h = 1);

$V_{5\ m}$ is the measured background harmonic level at the PCC for the 5th harmonic (% h = 1).

8.3.2.2 Short-circuit power at the PCC

The three-phase short-circuit power at the PCC ($S_{SC\ PCC}$) shall be obtained from the host NO.

8.3.2.3 Compliance with the limit of short-circuit power

The connection is acceptable if $S_{SC\ PCC} \geq S_{SC\ PCC\ Min}$. If this requirement is not satisfied, then the assessment fails Stage 2B-2 and advances to Stage 2C.

8.4 Stage 2C assessment procedure

The Stage 2C assessment involves the prediction of compliance with planning levels by using the current emissions and a worst-case harmonic impedance curve.

This assessment method involves the following steps, as shown in Figure 13.

- Measure the background harmonic level at the PCC ($V_{h\ m}$) for each harmonic order (h).
- Establish the harmonic current emission (I_h) of the proposed plant or equipment (in A or % h = 1) at each harmonic order (h).
- Determine the three-phase short-circuit power at the PCC ($S_{SC\ PCC}$).
- Calculate the harmonic impedance (Z_h) at the PCC for each harmonic order (h).
- Calculate the incremental increase in harmonic voltage distortion ($V_{h\ c}$) at the PCC for each harmonic order (h) due to the proposed harmonic current emission.
- Predict the future harmonic voltage distortion ($V_{h\ p}$) at the PCC for each harmonic order by summation of $V_{h\ m}$ and $V_{h\ c}$ (See Clause 6.3.3).
- Predict the future total harmonic voltage distortion ($THDV_p$).
- Compare the predicted $THDV_p$ and $V_{h\ p}$ with the planning limits $THDV_{PL}$ and $V_{h\ PL}$.

Figure 13 — Stage 2C assessment process flow

8.4.1 Background harmonic level at the PCC

In order to facilitate rapid assessment, it is permissible to assume that the background harmonic level at the PCC ($V_{h\ m}$) does not exceed 75% of the planning level, subject to the agreement of the relevant NO. See Clause 6.3.5 for details on measurement.

8.4.2 Harmonic current emission

The harmonic current emission (I_h) of disturbing plant or equipment will normally vary according to the power level (e.g. 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% or 100% of rated power S_{equ}).

For a Stage 2C assessment, it is the worst-case harmonic current emission at each harmonic order that shall be used.

In the case of a failure of the assessment against $THDV_p$ only (i.e. $THDV_p > THDV_{PL}$) then assessment shall be performed for each power level, as this may demonstrate compliance with $THDV_p$ at each power level.

8.4.3 Short-circuit power at the PCC

The three-phase short-circuit power at the PCC ($S_{SC\ PCC}$) shall be obtained from the host NO.

8.4.4 Harmonic impedance

The harmonic impedance (Z_h) at the PCC will vary with frequency and hence harmonic order. Determination of the actual harmonic impedance is complex and this is reserved for a Stage 3 assessment. Under Stage 2C, the assumed worst-case impedance curve is derived from the three-phase short-circuit power using (30).

$$Z_h = \sqrt{\left(R_1\sqrt{h}\right)^2 + k^2 h^2 X_1^2} \qquad (30)$$

where

Z_h is the harmonic impedance (Ω);

R_1 is the system resistance (Ω) at 50 Hz;

h is the harmonic order;

k is the worst-case reactance factor (see Table 22);

X_1 is the system reactance (Ω) at 50 Hz.

Table 22 — Worst-case reactance factor for 0.4 kV and 6.6–22 kV systems

PCC voltage	Worst-case reactance factor (*k*)			
kV	$h \leq 7$	$h \leq 8$	$h > 7$	$h > 8$
0.4	1		0.5	
6.6, 11, 20, 22		2		1

Equation (30) can be rewritten as (31) for three-phase and (32) for single-phase cases, respectively.

$$Z_h = \frac{V_s^{\,2}}{S_{SC\ 3ph}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}}\sqrt{h + h^2 k^2 \left(\frac{X_1}{R_1}\right)^2} \qquad (31)$$

$$Z_h = \frac{V_{phase}^{\ 2}}{S_{SC\ 1ph}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}}\sqrt{h + h^2k^2\left(\frac{X_1}{R_1}\right)^2} \tag{32}$$

where

V_s	is the rated phase–phase voltage (V);
V_{phase}	is the rated phase–neutral voltage (V);
$S_{SC\ 3ph}$	is the three-phase short-circuit level at the PCC (VA);
$S_{SC\ 1ph}$	is the single-phase short-circuit level at the PCC (VA).

8.4.5 Incremental increase in harmonic voltage distortion

The incremental increase in harmonic voltage distortion due to the proposed disturbing plant or equipment ($V_{h\ c}$) can be expressed as a percentage of the phase–neutral voltage at the PCC as given by (33) and (34).

$$V_{h\ c} = \frac{100\ I_h Z_h}{V_{phase}} \tag{33}$$

$$V_{h\ c} = \frac{100\ \sqrt{3} I_h Z_h}{V_s} \tag{34}$$

where

$V_{h\ c}$	is the incremental increase in harmonic voltage distortion (% V_{phase}) at the PCC;
I_h	is the harmonic current (A) at harmonic h.

Substituting (31) into (34) gives (35).

$$V_{h\ c} = \frac{100\ \sqrt{3} I_h V_s \sqrt{h + k^2h^2\left(\frac{X_1}{R_1}\right)^2}}{S_{SC\ 3ph}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}} \tag{35}$$

where

I_h	is the harmonic current (A) at harmonic h.

Equation (35) can also be expressed as shown in (36).

$$V_{h\,c} = \frac{S_{equ\ 3ph} I_h \sqrt{h + k^2 h^2 \left(\frac{X_1}{R_1}\right)^2}}{S_{SC\ 3ph} \sqrt{1 + THD_I^2} \sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}} \tag{36}$$

where

$S_{equ\ 3ph}$ is the rating (VA) of the three-phase plant or equipment;

I_h is the harmonic current (% h = 1) at harmonic h;

THD_I is the total harmonic current distortion (per unit) of the plant or equipment.

Note that if $X_1 >> R_1$ then (35) and (36) can simplify to (37) and (38), respectively.

$$V_{h\,c} = \frac{100\ \sqrt{3} I_h V_s k h}{S_{SC\ 3ph}} \tag{37}$$

where

I_h is the harmonic current (A) at harmonic h.

$$V_{h\,c} = \frac{S_{equ\ 3ph} I_h k h}{S_{SC\ 3ph} \sqrt{1 + THD_I^2}} \tag{38}$$

where

I_h is the harmonic current (% h = 1) at harmonic h.

Substituting (32) into (33) gives (39).

$$V_{h\,c} = \frac{100\ I_h V_{phase} \sqrt{h + k^2 h^2 \left(\frac{X_1}{R_1}\right)^2}}{S_{SC\ 1ph} \sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}} \tag{39}$$

where

I_h is the harmonic current (A) at harmonic h.

Equation (39) can also be expressed as shown in (40).

$$V_{h\,c} = \frac{S_{equ\ 1ph} I_h \sqrt{h + k^2 h^2 \left(\frac{X_1}{R_1}\right)^2}}{S_{SC\ 1ph} \sqrt{1 + THD_I^2} \sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}} \tag{40}$$

where

$S_{equ\ 1ph}$ is the rating (VA) of the single-phase plant or equipment;

I_h is the harmonic current (% h = 1) at harmonic h.

Note that if $X_1 >> R_1$ then (39) and (40) can simplify to (41) and (42), respectively.

$$V_{h\,c} = \frac{100\ I_h V_{phase} kh}{S_{SC\ 1ph}} \tag{41}$$

where

I_h is the harmonic current (A) at harmonic h.

$$V_{h\,c} = \frac{S_{equ\ 1ph} I_h kh}{S_{SC\ 1ph} \sqrt{1 + THD_I^2}} \tag{42}$$

where

I_h is the harmonic current (% h = 1) at harmonic h.

8.4.6 Prediction of harmonic voltage distortion

The harmonic voltage distortion ($V_{h\,p}$) resulting from adding the incremental increase in harmonic voltage distortion ($V_{h\,c}$) to the background harmonic level ($V_{h\,m}$) at the PCC is determined in accordance with Clause 6.3.3.

The predicted total harmonic voltage distortion ($THDV_p$) resulting from the predicted harmonic voltage distortion values ($V_{h\,p}$) is given by (43).

$$THDV_p = \sqrt{\sum_{h=2}^{h=100} V_{h\,p}^{\ 2}} \tag{43}$$

8.4.7 Compliance with planning levels

Under Stage 2C, compliance is assessed for all voltage planning levels, including $THDV_p$ and all individual harmonic orders.

The connection is acceptable if the predicted $THDV_p$ and all $V_{h\,p}$ remain below the planning levels of $THDV_{PL}$ and $V_{h\,PL}$, respectively. If this requirement is not satisfied, then the assessment fails Stage 2C and advances to Stage 3 unless the PCC is LV; in which case, no connection is possible without mitigation.

Reinforcement of the distribution network to increase $S_{SC\,PCC}$, and hence reduce the calculated $V_{h\,p}$ and $THDV_p$ values, may be considered, as may filter equipment.

9 Assessment of resonant plant

9.1 Applicability and substages

A resonant plant assessment is applicable to connection of any resonant plant in a user's installation, such as power factor correction capacitors, long cables or any other plant or equipment that can be considered predominately capacitive at any range of harmonic frequencies, due to their potential to magnify a background harmonic level beyond the planning level. This type of plant needs to be assessed for harmonic distortion compliance whether it is emitting harmonics or not.

For voltage levels below 33 kV, a simple assessment methodology is followed, as detailed in the following substages. All resonant plant connections at 33 kV or above are subject to a Stage 3 assessment.

The flowchart shown in Figure 14 illustrates the resonant plant assessment process.

9.2 Resonant plant at 0.4 kV and below

For resonant plant being connected at 0.4 kV or below, (44) shall be used to estimate the modification factor.

If the modification factor ($G_{h\,r}$) is less than or equal to 1.33 for a calculated resonant harmonic order (h_r) of less than or equal to 15, or if $G_{h\,r}$ is less than or equal to 2 for h_r greater than 15, then the connection is permitted.

$$G_{h\,r} = \frac{\sqrt{S_{SC\,X} Q_{rp}}}{P_d} \tag{44}$$

$$h_r = \sqrt{\frac{S_{SC\,X}}{Q_{rp}}} \tag{45}$$

where

$G_{h\,r}$ is the modification (magnification/attenuation) factor;

$S_{SC\,X}$ is the short-circuit level (kVA or MVA), based on the source impedance reactive component only, as calculated by (47);

Q_{rp} is the reactive power (kVAr or MVAr) of the new user's resonant plant;

P_d is the damping power (kW or MW), calculated according to (46).

$$P_d = P_S + 0.36 P_{PCC} \tag{46}$$

where

P_s is the static portion (i.e. non-motor type) of the new user's total active power demand (kW or MW);

P_{PCC} is the active power demand (kW or MW) at the PCC, excluding the new user. If P_{PCC} is not available, then 30% of the nameplate kVA or MVA rating of the transformer in the public network supplying the new user shall be considered instead of the factor ($0.36P_{PCC}$);

h_r is the resonant frequency – at which maximum amplification occurs.

$$S_{SC\,X} = \frac{V_L^2}{X_{SC}} \tag{47}$$

where

V_L is the phase–phase voltage (V or kV);

X_{SC} is the reactive component of the source impedance (Ω).

The rationale for selection of a magnification factor of 1.33 is that it is assumed that the background harmonic levels up to and including the 15th harmonic order are already at 75% of the planning level and that, after connection of the resonant plant, they will be amplified to be equal to the planning level.

The likelihood of the background harmonic level for voltages above the 15th harmonic order being at 75% of the planning level is assumed to be low, and hence a higher magnification factor is permitted.

If the particular connection location is known to already have harmonic distortion at the resonant frequency (calculated using (45)) that is higher than 75% of the planning level, then the assessment given by (44) automatically fails and the assessment proceeds to the next stage, given in Clause 9.3.

9.3 Resonant plant at voltage levels at or above 0.4 kV and below 33 kV

This assessment requires the use of the typical source impedance profile, with an appropriate k-factor, as given in Table 22.

The magnification factor ($G_{h\,r}$) and the resonance frequency (h_r) are calculated according to (48) and (49).

$$G_{h\,r} = \frac{\sqrt{S_{SC\,X} Q_{rp}}}{P_d \sqrt{k}} \tag{48}$$

$$h_r = \sqrt{\frac{S_{SC\,X}}{Q_{rp} k}} \tag{49}$$

where

$G_{h\,r}$ is the modification (magnification/attenuation) factor;

Q_{rp} is the reactive power (kVAr or MVAr) of the new user's resonant plant;

$S_{SC\,X}$ is the short-circuit level (kVA or MVA), based on the source impedance reactive component only, as calculated by (47);

k is the k-factor, given by Table 22;

h_r is the resonant frequency – at which maximum amplification occurs;

P_d is the damping power, calculated according to (46).

The overall impact of the new user's plant and equipment is determined by aggregating the impact of the emission from the new user's plant and equipment and the magnification of the background harmonic level due to the new user's plant and equipment. Aggregation of the two effects is carried out by the use of an appropriate exponent, as provided in Table 16.

If the aggregated level of harmonic voltage distortion is within 75% of the planning level, then the connection is allowed. If the aggregated level of harmonic distortion exceeds 75% of the planning level, then the assessment shall proceed to Stage 3.

For resonant plant that fails the criteria given by (48) and (49) – or where the connection is made at system voltages of 33 kV or higher – a Stage 3 assessment shall be applicable, irrespective of the plant's harmonic current or voltage emissions.

Figure 14 — Resonant plant assessment process flow

10 Assessment of harmonic sources – Stage 3 procedure

10.1 Applicability and substages

Stage 3 assessment is applicable to all connection of relevant equipment with a PCC at 33 kV or above. The Stage 3 assessment also applies to any connection of relevant equipment with a PCC above LV that has failed the Stage 2 assessment.

In Stage 3, the NO that hosts the connection shall issue a harmonic specification to the new user – applicable at the PCC – which shall consist, as a minimum, of the four components outlined below.

- Impedance profile of the PCC in the form of impedance loci or tabular data.
- Background harmonic level.
- Limits for incremental harmonic voltages (% h = 1) produced by the new user's plant or equipment emission at the PCC. This is referred to as $V_{h\ Limit\ Inc}$.
- Limits for resultant total harmonic voltages at the PCC, accounting for the incremental harmonic voltages due to emission from the new user's plant or equipment and the modification of the background harmonic level. This is referred to as $V_{h\ Limit\ Total}$.

The Stage 3 harmonic specification shall form part of the connection agreement between the host of the connection and new user. The host is the company that facilitates the connection at the PCC.

The NO hosting the connection is responsible for preparing the Stage 3 harmonic specification. In accordance with ENA EREC G97 [7], the NO may allow a third party, or the new user, to prepare the harmonic specification. In such cases, the overall responsibility remains with the NO hosting the connection.

The new user shall carry out a harmonic compliance assessment to demonstrate compliance with the limits in the harmonic specification. The purpose of the harmonic compliance assessment is to forecast harmonic levels following the connection of the new relevant equipment, and to determine any harmonic mitigation measures necessary to ensure compliance with the connection limits. This assessment shall be undertaken using an appropriate power system analysis tool.

The new user shall provide the NO with a report detailing the findings of the harmonic compliance assessment and any proposed harmonic mitigation measures. The requirements of the compliance report are detailed in Clause 10.8.

The flowchart shown in Figure 15 illustrates the Stage 3 assessment process flow for the setting of harmonic limits for a new user.

All harmonic voltages are in percentage of the fundamental unless it is specified otherwise.

Figure 15 — Stage 3 assessment process flow for the setting of harmonic limits for a new user

10.2 Impedance loci

The host NO shall be responsible for the determination of the harmonic impedance of the network at the PCC and shall include this in the harmonic specification. This is usually provided in the form of impedance loci, although other forms of representation, such as tabular data, may also be acceptable.

The impedance loci represent the supply system impedance at the PCC for all harmonic frequencies that are to be included in the assessment and for which harmonic limits are issued. The impedance spectrum may be divided into different ranges of frequencies to enable analysis of impedance in narrower bands of harmonics. The harmonic impedance at the PCC is also referred to as the equivalent self-impedance or the Thévenin harmonic impedance.

The impedance loci shall be set up according to the year of connection, or to the most-appropriate time, considering other connections in the vicinity. This shall be at the discretion of the host NO. The loci shall be determined for different network conditions including, but not limited to, different network demand/generation and outage patterns under normal operating conditions (as previously defined). Seasonal variations of generation and load shall be considered.

The impedance loci of the PCC shall form the definition of the network to which the new user is to connect. Any design work, including mitigation (if needed), post-connection assessments of harmonic performance and compliance with the harmonic specification by calculation, shall refer to this definition.

Any impedance loci that form part of the harmonic specification may include all the plant and equipment that will be connected to the system at the time of the new user's connection, including that of other NOs and that of other new users. The extent of the network considered in the assessment is at the discretion of the host **NO**.

10.3 Measurement of the background harmonic level

The background harmonic level at the PCC is measured and included in the harmonic specification. The measurement shall be done according to IEC 61000-4-30 and IEC 61000-4-7 and shall be based on the 95th percentile of at least seven contiguous days of measurement. When three-phase measurement is available, the highest amongst all three phases for each harmonic order shall be included in the specification, along with the total harmonic voltage distortion (THD_V). Monitors conforming to Class A requirements in IEC 61000-4-30 should be used.

As part of the Stage 3 assessment it is a requirement to consider remote nodes, so as to ensure that the planning levels at those nodes are not exceeded. The above requirements for the PCC also apply to measurement of the background harmonic level at those remote nodes that are included in the assessment. Synchronised measurement of local (PCC) and remote nodes is desirable but not essential.

Where measurements are not possible, the background harmonic level should be estimated using measurements from electrically adjacent sites. For further guidance on measurements see Clause 6.3.5.

10.4 Incremental harmonic voltage limit

Incremental harmonic voltage is defined as the harmonic voltage that is produced, at the PCC, by the new user due to harmonic current or voltage emission from the new user's relevant equipment.

An incremental harmonic voltage limit applies to each harmonic order and to the total harmonic voltage distortion (THD_V). Each incremental harmonic voltage limit is the maximum amount of harmonic voltage that the new user may produce at the PCC due to current or voltage emission from their plant and equipment.

Due to the direct impact of incremental harmonic voltages on remote nodes, remote nodes shall be considered when setting the incremental harmonic voltage limits at the PCC.

Due to the significant volume of connections at 33 kV and below, the host NO may decide to exclude remote nodes from the Stage 3 assessment. This is recommended if the background harmonic level at the PCC is below 50% of the planning levels for all harmonics and the transfer coefficients (as defined in Clause 10.4.1), are below 1.25 for harmonics below the 5th harmonic order and below 1.8 for harmonics above and including the 5th harmonic order.

The setting of incremental limits consists of several steps, dealt with sequentially in the following subsections.

10.4.1 Transfer coefficients

The impact on remote nodes is assessed by the use of a harmonic transfer coefficient, defined by (50). This coefficient shall be calculated without consideration of the harmonic impedance of the new user's plant or equipment, and therefore no such information is required from the new user at this stage.

$$T_{h\,PCC\,n} = \frac{V_{h\,PCC\,n}}{V_{h\,PCC}} = \frac{|Z_{h\,PCC\,n}|}{|Z_{h\,PCC}|} \qquad (50)$$

where

$T_{h\,PCC\,n}$ is the harmonic transfer coefficient at order h between the PCC and node n;

$V_{h\,PCC\,n}$ is the harmonic voltage in per unit produced by emission of harmonic current or voltage from the new user's plant or equipment, as seen at node n;

$V_{h\,PCC}$ is the harmonic voltage in per unit produced by emission of harmonic current or voltage from the new user's plant or equipment, as seen at the PCC;

$|Z_{h\,PCC\,n}|$ is the modulus of the transfer (mutual) impedance in per unit at harmonic order h between the PCC and node n. It may be obtained directly from the harmonic model and is equal to the ratio of $V_{h\,PCC\,n}$ to $I_{h\,PCC}$;

$|Z_{h\,PCC}|$ is the modulus of the self (Thévenin) impedance in per unit at harmonic order h at the PCC. It may be directly obtained from the harmonic model and is equal to the ratio of $V_{h\,PCC}$ to $I_{h\,PCC}$;

$I_{h\,PCC}$ is the harmonic current in per unit injected into the PCC due to emission from the new user's plant or equipment.

Note that the self-impedance of the PCC and the transfer impedance between the PCC and remote nodes in a network are readily available through the use of harmonic analysis software. For converting impedance Ohmic values to per unit see Annex C.

The harmonic transfer coefficient in per unit, may be used to eliminate less-susceptible nodes in the network from consideration. For example, for Stage 3 the host NO may choose to consider only remote nodes in the assessment with harmonic transfer coefficients higher than

1.25. The threshold at which the less-susceptible remote nodes are eliminated from consideration shall be at the discretion of the host NO.

10.4.2 Calculation of harmonic headroom

In order to set the incremental harmonic voltage limit ($V_{h\ Limit\ Inc}$), the harmonic headroom at the PCC and at remote nodes shall be calculated according to (51) and (52), respectively.

$$H_{h\ PCC} = \sqrt[\alpha]{(V_{h\ PL})^{\alpha} - (V_{h\ bg\ PCC})^{\alpha}} \tag{51}$$

$$H_{h\ n} = \sqrt[\alpha]{(V_{h\ PL})^{\alpha} - (V_{h\ bg\ n})^{\alpha}} \tag{52}$$

where

$H_{h\ PCC}$ is the harmonic voltage headroom at the PCC;

$V_{h\ PL}$ is the planning level for harmonic voltage at order h;

$V_{h\ bg\ PCC}$ is the measured background harmonic level for order h at the PCC;

$H_{h\ n}$ is the harmonic voltage headroom at node n;

$V_{h\ bg\ n}$ is the background harmonic level for order h at node n;

α is the aggregation exponent (see Table 16).

The remote node harmonic headroom is transferred to the PCC using the harmonic transfer coefficient, as given by (53).

$$H_{h\ n\ PCC} = \frac{H_{h\ n}}{T_{h\ PCC\ n}} = \frac{\sqrt[\alpha]{(V_{h\ PL})^{\alpha} - (V_{h\ bg\ n})^{\alpha}}}{T_{h\ PCC\ n}} \tag{53}$$

where

$H_{h\ n\ PCC}$ is the harmonic headroom of node n, transferred to the PCC, that, if fully utilised by the new user (i.e. transferred to the PCC), will cause the harmonic level at node n to reach the planning level ($V_{h\ PL}$) for harmonic h.

10.4.3 Apportionment multiplier for harmonic voltage headroom

The harmonic headroom at the PCC, and all other remote nodes transferred to the PCC, is calculated with the goal of enabling timely allocation of harmonic limits to new users through the use of apportionment multipliers. The apportionment multiplier is defined according to (54) to enable the calculation of the incremental limit.

$$V_{h\ Limit\ Inc} = M \times \min(H_{h\ n\ PCC}, H_{h\ PCC}) \quad (54)$$

where

$V_{h\ Limit\ Inc}$ is the incremental harmonic voltage limit (% h=1) at the PCC;

M is the apportionment multiplier, as defined in Clauses 10.4.3.1 and 10.4.3.2.

The apportionment multiplier operates on the node with the minimum headroom, so as to ensure that all nodes will remain compliant.

Due to differences in the network topologies, typical connection size, short-circuit powerand number of connections that need to be considered under a Stage 3 assessment, the apportionment multiplier M is defined separately for distribution and transmission networks above 132 kV.

10.4.3.1 Apportionment multiplier for voltages of 132 kV and below

The apportionment multiplier (M) for voltages of 132 kV and below is 0.5.

All new users, whether generation, demand or any other entity that applies to connect to the public supply system, irrespective of their size, shall be allocated 50% of the available headroom, as per (55).

$$V_{h\ Limit\ Inc} = 0.5 \times \min(H_{h\ n\ PCC}, H_{h\ PCC}) \quad (55)$$

10.4.3.2 Apportionment multiplier for voltages above 132 kV

The apportionment multiplier (M) for voltages above 132 kV is defined in relation to the MVA import or export capacity (whichever is larger) as set out in the BCA.

The apportionment multiplier (M) is defined as a function of a parameter k_M, which is defined as the ratio of the connection size and β, as defined in (56) (where the value of β is given in Table 23 for each voltage level).

$$k_M = \frac{S_i}{\beta} \quad (56)$$

where

S_i is the MVA import or export capacity (whichever is larger), as given in the BCA;

β is a constant, defined in Table 23.

Table 23 — β value for voltages above 132 kV

Nominal phase–phase voltage (*V*) kV	β value
132 < *V* < 275	1000
275	1500
400	2000

Figure 16 — Apportionment multiplier (*M*) versus k_M

The apportionment multiplier is determined from the normalised apportionment curve shown in Figure 16, using the calculated value of k_M.

The set of analytical equations, (57) to (60), which represent Figure 16, can be used instead of the normalised curve to determine *M* for any k_M.

$$M = 0.1 \quad \text{for} \quad k_M \leq 0.05 \tag{57}$$

$$M = 2k_M \quad \text{for} \quad 0.05 \leq k_M \leq 0.25 \tag{58}$$

$$M = \frac{16}{75}k_M + \frac{67}{150} \quad \text{for} \quad 0.25 \leq k_M \leq 1 \tag{59}$$

$$M = 0.66 \quad \text{for} \quad 1 < k_M \tag{60}$$

The apportionment multiplier (*M*), as defined by (57) to (60), or by Figure 16, shall be used with (54) to allocate the headroom and subsequently set the limits for incremental harmonic voltage.

10.5 Total harmonic voltage limit at the PCC

The total harmonic voltage limit at the PCC takes into account three parameters.

a) The background harmonic level.

b) The incremental change due to harmonic emission, as described in Clause 10.4.

c) The modification of the background harmonic level due to the harmonic impedance of the new user.

10.5.1 Total harmonic voltage change limit

The total harmonic voltage change limit ($V_{h\ Limit\ Change}$) at the PCC takes into account items a) and b) in Clause 10.5.

The apportionment of the PCC harmonic voltage headroom for this purpose is given by (61).

$$V_{h\ Limit\ Change} = MH_{h\ PCC} \tag{61}$$

where

$V_{h\ Limit\ Change}$ is the total harmonic voltage change limit resulting from the apportionment of PCC headroom. This limits the total change in harmonic levels allowed at the PCC due to the new user.

NOTE: $V_{h\ Limit\ Change}$ is inherent in the total harmonic voltage limit (see Clause 10.5.2) and need not be explicitly provided in the harmonic specification.

For the purpose of calculating the total harmonic voltage change limit, only the headroom at the PCC is considered – not the transferred headroom from remote nodes. This is justified by the observation that, in a strongly meshed power system, the modification of the background harmonic level at the PCC may not have a strong impact on remote nodes in the same way as is observed for incremental changes at the PCC due to harmonic emissions from the new installation.

10.5.2 Total harmonic voltage limit

The total harmonic voltage limit ($V_{h\ Limit\ Total}$) is set by aggregating the background harmonic level ($V_{h\ bg\ PCC}$) with the total change that the new user is allowed to produce at the PCC ($V_{h\ Limit\ Change}$), defined as $V_{h\ Limit\ Total}$ and calculated as shown in (62).

$$V_{h\ Limit\ Total} = \sqrt[\alpha]{\left(V_{h\ bg\ PCC}\right)^{\alpha} + \left(V_{h\ Limit\ Change}\right)^{\alpha}} \tag{62}$$

Substituting for $V_{h\ Limit\ Change}$ gives (63).

$$V_{h\ Limit\ Total} = \sqrt[\alpha]{\left(V_{h\ bg\ PCC}\right)^{\alpha} + \left(MH_{h\ PCC}\right)^{\alpha}} \tag{63}$$

Substituting for $H_{h\ PCC}$ and rearranging (63) gives (64).

$$V_{h\ Limit\ Total} = \sqrt[\alpha]{\left(MV_{h\ PL}\right)^{\alpha} + \left(\left(1 - M^{\alpha}\right)\left(V_{h\ bg\ PCC}\right)^{\alpha}\right)} \tag{64}$$

For setting the total harmonic voltage limit, only the MVA rating of the new user and the background harmonic level at the PCC are required.

10.5.3 Harmonic change limit due to the modification of the background harmonic level

This limit is inherent in the total harmonic voltage limit and need not be explicitly specified when setting the limits. During the design stage, it can be determined by the new user.

The new user's harmonic emissions and network data are required to enable this, as this limit depends on the voltage produced at the PCC by the emissions of harmonic current and voltage from the new user's plant or equipment ($V_{h\ Inc}$).

The portion of the total harmonic voltage change limit ($V_{h\ Limit\ Change}$) that can potentially be utilised as an allowance for the change in the background harmonic level (due to the harmonic impedance of the new user) can be calculated by (65) or (66).

$$V_{h\ Limit\ Resonant} = \sqrt[\alpha]{\left(V_{h\ Limit\ Change}\right)^{\alpha} - \left(V_{h\ Inc}\right)^{\alpha}} \tag{65}$$

$$V_{h\ Limit\ Resonant} = \sqrt[\alpha]{\left(MH_{h\ PCC}\right)^{\alpha} - \left(V_{h\ Inc}\right)^{\alpha}} \tag{66}$$

where

$V_{h\ Limit\ Resonant}$ is the harmonic voltage change limit that can be utilised for the modification of the background harmonic level;

$V_{h\ Inc}$ is the incremental harmonic voltage at the PCC produced as a result of emissions of harmonic current and voltage from the new user's plant or equipment and shall always be less than or equal to $V_{h\ Limit\ Inc}$.

In practice, it is found that, for some harmonics, $V_{h\ Inc}$ may be zero and will always be equal to or less than $V_{h\ Limit\ Inc}$. The difference between $V_{h\ Limit\ Inc}$ and $V_{h\ Inc}$ may be used to accommodate for the effects of modification of the background harmonic level. However, the allowance for modification of the background harmonic level may not be used to accommodate for the incremental changes. In other words, spare incremental headroom may be used for modification, but not vice versa.

10.6 Final harmonic voltage limit table

The minimum requirements for overall limits issued to the new user are shown in Table 24.

The limiting headroom of the critical remote nodes, transferred to the PCC, $V_{h\ Limit\ Change}$ and $V_{h\ Limit\ Resonant}$, may be included in the harmonic specification. The inclusion of this additional information is at the discretion of the host NO.

In accordance with the recommendation within IEC/TR 61000-3-6 for new users having a low agreed MVA, the limits may yield impractically low values. If the voltage emission limits at some harmonic orders become smaller than 0.1%, then they may be set equal to 0.1%, except where there is a risk of interference, or if this corresponds to a remote-control frequency, for which a more-severe restriction may be justified.

Considering the tolerance of the measurement system – including voltage transducers and monitors and the noise susceptibility of the complete measurement channel – harmonic levels below 0.1% may be affected by noise and may therefore not be measured accurately. For this reason, a measured background harmonic level recorded to be below 0.05% may be set to zero and those between 0.05% and 0.1% may be set to 0.1%.

The use of the above is at the discretion of the host NO.

Table 24 — Example limits forming part of a harmonic specification

Harmonic order (***h***)	**Background harmonic level** [1)] % ***h=1***	**Incremental harmonic voltage limit** [2)] % ***h=1***	**Total harmonic voltage limit** % ***h=1***
2			
3			
4			
...	...	...	...
...	...	...	...
NOTE: All values apply at the PCC.			
[1)] Prior to connection of the new user's plant and equipment. [2)] Due to harmonic emission of the new user's plant and equipment.			

10.7 Definition of compliance

Compliance with the Stage 3 harmonic specification is achieved if the new user satisfies the following two requirements.

- Compliance with the incremental harmonic voltage limits ($V_{h\ Limit\ Inc}$).
- Compliance with the total harmonic voltage limits ($V_{h\ Limit\ Total}$).

10.7.1 Compliance with the incremental harmonic voltage limit

The incremental harmonic voltage change ($V_{h\ Inc}$) due to the emission from the new installation shall be less than or equal to the incremental harmonic voltage limit described in Clause 10.4 and by (67).

$$V_{h\ Inc} \leq V_{h\ Limit\ Inc} \tag{67}$$

10.7.2 Compliance with the total harmonic voltage limit

The total harmonic voltage at the PCC shall be less than or equal to the total harmonic voltage limit ($V_{h\ Limit\ Total}$), as described in Clause 10.5 and by (68).

$$V_{h\ Total} \leq V_{h\ Limit\ Total} \tag{68}$$

where

$V_{h\ Total}$ is the total harmonic level at the PCC due to the new user and is given by the aggregation of the incremental harmonic voltage produced by the new connection at the PCC and the modified background harmonic level at the PCC.

$$V_{h\ Total} = \sqrt[\alpha]{(V_{h\ Inc})^{\alpha} + \left(\frac{|Z_{h\ PCC\ Post}|}{|Z_{h\ PCC\ Pre}|} V_{h\ bg\ PCC}\right)^{\alpha}} \tag{69}$$

where

$|Z_{h\ PCC\ Post}|$ is the modulus of the self-impedance at the PCC after the new user is connected;

$|Z_{h\ PCC\ Pre}|$ is the modulus of the self-impedance at the PCC before the new connection.

Data from the new user's installation is required to enable calculation of the post-connection self-impedance at the PCC.

10.8 Compliance report

The post-design compliance report, which is to be submitted to the host NO by the new user, to a timescale agreed between the new user and the host NO, shall include but not be limited to the following.

- Demonstration of compliance with the harmonic specification, which contains, as a minimum, compliance with the incremental harmonic voltage limit and total harmonic voltage limit at the PCC.
- Presentation of $V_{h\ Inc}$, taking into account all operating conditions and configurations of the new installation, and presentation of the corresponding $V_{h\ Limit\ Resonant}$ value.
- Presentation of $V_{h\ Total}$, considering all operating conditions and configurations of the new installation.

- Equivalent Thévenin harmonic impedance of the proposed installation as seen from the PCC, with different values, as applicable, to cover the various operating conditions and configurations of the installation.

- Equivalent Thévenin voltage or Norton current source harmonic emission model at the PCC, with different values, as applicable, to cover the various operating conditions and configurations of the installation in relation to the corresponding abovementioned equivalent Thévenin harmonic impedance.

For the avoidance of doubt, the equivalent Thévenin/Norton models, seen from the PCC, are to be determined without the inclusion of the new installation's connection to the supply system, as shown in Figure 17.

Figure 17 — Voltage and current source equivalents for the new user

10.9 Verification of compliance

Compliance with the specified harmonic limits may be verified by harmonic measurements made by the host NO, the User, or their representatives before, during and after commissioning is complete, including full normal operation. The decision as to what measurements are required should rest with the NOs affected.

It is desirable that at least four weeks of harmonic measurement is carried out before the commissioning begins, allowing the background harmonic level of the supply system at the PCC to be established, immediately before the new user is connected to the supply system, prior to connection during the commissioning stages, which should also be monitored. The continuous monitoring during commissioning, and afterwards, will show the changes that the new user causes at the PCC, for the supply system configuration at the time of commissioning.

It must be recognised, however, that an installation could be correctly designed according to a host NO's harmonic specification and yet result in measured harmonic voltages above the specified limits. Some of the possible reasons for this include the following.

- The actual network impedance at the time of measurement may fall outside of the impedance loci provided by the host NO for design purposes. This may be due to changes in the network itself that were not considered during the Stage 3 assessment.

- The actual phasor addition of a background harmonic level with that resulting from the new connection may be aggregated in a more linear manner than is given by the aggregation rule and corresponding exponent used in the harmonic specification.

If this situation arises, usually the NO and new user will work together to determine root causes, which also depends on the severity of the non-compliance and find solutions depending on the

location of the connection in the network and other parameters, including other concurrent or potential future connections.

10.10 Connection queue and concurrent connections

In the cases where multiple connections are expected to connect within similar timescales, the order of allocating limits and issuing the harmonic specification is determined by the date at which the connection offer is signed by the new user.

Once a new user's installation is commissioned and fully operational, the new user is considered to be part of the background harmonic level and new measurements shall be taken for the next connection application.

In cases where the next new user should be issued the harmonic specification before the previous new user in the queue is commissioned – thus before the first connection becomes part of the network – then the harmonic voltage limits issued to the first new user may be used to estimate the background harmonic level for the next new user. The process is presented in the following two subsections.

10.10.1 Concurrent connections at the same node

In cases where two connections in the queue are connecting to the same node within a relatively short time of each other, the background harmonic level for the second connection must be estimated to account for the previous connection, whose limits have already been calculated. It is assumed that the harmonic voltage level at the PCC will rise to the total harmonic voltage limit level that was assigned to the first connection, as per (70).

$$V_{h\ bg\ PCC\ 2} = V_{h\ Limit\ Total\ 1} \tag{70}$$

where

$V_{h\ bg\ PCC\ 2}$ is the updated background harmonic level for the second new user, taking into account the limit issued to the first new user;

$V_{h\ Limit\ Total\ 1}$ is the total harmonic voltage limit issued to the first new user.

The harmonic headroom at the PCC for the second new user can be calculated using the background harmonic level given by (70), resulting in (71).

$$H_{h\ PCC\ 2} = \sqrt[\alpha]{(V_{h\ PL})^{\alpha} - (V_{h\ Limit\ Total\ 1})^{\alpha}} \tag{71}$$

where

$H_{h\ PCC\ 2}$ is the harmonic headroom at the PCC for the second new user;

$V_{h\ Limit\ Total\ 1}$ is the total harmonic voltage limit issued to the first new user.

All other transferred headroom values from remote nodes shall also be corrected by the incremental limit issued to the first new user, in accordance with (72), which can also be expressed in the form of (73).

$$H_{h\,n\,PCC\,2} = \sqrt[\alpha]{(H_{h\,n\,PCC\,1})^{\alpha} - (V_{h\,Limit\,Inc\,1})^{\alpha}} \tag{72}$$

$$H_{h\,n\,PCC\,2} = \sqrt[\alpha]{\left(\frac{(V_{h\,PL})^{\alpha} - \left(V_{h\,bg\,n\,1}\right)^{\alpha}}{T_{h\,PCC\,n}}\right)^{\alpha} - (V_{h\,Limit\,Inc\,1})^{\alpha}} \tag{73}$$

where

$H_{h\,n\,PCC\,2}$ is the harmonic headroom at remote node *n* transferred to the PCC and modified by the incremental harmonic voltage limit issued to the first new user;

$H_{h\,n\,PCC\,1}$ is the harmonic headroom at remote node *n* transferred to the PCC for the first connection, calculated according to (74).

$$H_{h\,n\,PCC\,1} = \frac{\sqrt[\alpha]{(V_{h\,PL})^{\alpha} - \left(V_{h\,bg\,n\,1}\right)^{\alpha}}}{T_{h\,PCC\,n}} \tag{74}$$

where

$V_{h\,bg\,n\,1}$ is the background harmonic level for order *h* at node *n*, considered for the first new user.

For the avoidance of doubt, the appearance of a concurrent connection cannot change the limits issued to any existing user.

10.10.2 Concurrent connections at electrically near nodes

In cases where two connections in the queue are connecting to nodes electrically close within a relatively short time of each other, the background harmonic level for the second connection must be estimated to account for the previous connection, whose limits were already calculated.

The background harmonic level at all nodes within the study shall be modified by the incremental harmonic voltage limit ($V_{h\,Limit\,Inc\,1}$) issued to the first new user. It is assumed that the background harmonic level at the first PCC will rise to the total harmonic voltage limit that was assigned to the first new user.

The harmonic headroom at the PCC of the first new user ($H_{h\,PCC\,1}$) is modified by the total harmonic voltage limit for the first new user ($V_{h\,Limit\,Total\,1}$) as described by (71). This headroom is then transferred to the PCC for the second new user by using the harmonic transfer coefficient from the PCC of the second new user to the PCC of the first new user ($T_{h\,PCC\,2\,PCC\,1}$). Note that the harmonic transfer coefficient from the PCC of the second new user to that of the first may not be equal to the harmonic transfer coefficient from the PCC of the first new user to the PCC of the second new user.

The background harmonic level at all other remote nodes shall be modified to account for the incremental harmonic voltage limit issued to the first new user ($V_{h\ Limit\ Inc\ 1}$) at the PCC of the first new user. The incremental harmonic voltage limit issued to the first new user is used, together with the harmonic transfer coefficients from the PCC of the first new user to all other nodes ($T_{h\ PCC\ 1\ n}$), including the PCC of the second new user, to modify the background harmonic level at those nodes – resulting in a new set of harmonic headroom values at all nodes ($H_{h\ n\ adj}$). Once the new, adjusted, harmonic headroom values are determined, the apportionment of the newly calculated adjusted harmonic headroom values is carried out as described in Clause 10.4 of this document (using the adjusted harmonic headroom values).

When the first new user is issued their harmonic specification, the full design may not be yet known. It is, however, recommended that the estimated harmonic impedance of the first new user's proposed installation should be included in the harmonic model when the new harmonic transfer coefficients from the PCC for the second new user are calculated. In cases where the estimated impedance of the first new user is not known, upon agreement between the second new user and the NO hosting the connection, the second new user may use the harmonic data which does not include the impedance of the first new user when calculating the transfer coefficients.

Annex A
(normative)
Modification of minimum short-circuit power

A.1 Background

In practice, X/R ratios in distribution systems vary depending on the particular distribution network. Specific values can typically vary from 0.5 to 1.5 or more. The exact values depend, in general, on transformer capacity and the amount, and type, of LV main and service used; in the case of large capacity transformers, the HV network also has an impact.

Table 18 is based on a source impedance X/R ratio of 0.625 for I_{SCC} < 100 A and 1.0 for I_{SCC} ≥ 100 A. These values correspond to the X/R ratios of the reference impedances in IEC/TR 60725. To adjust the minimum short-circuit power ($S_{SC\ PCC\ Min}$), as derived using (8) for a known source impedance X/R ratio, multiply the $S_{SC\ PCC\ Min}$ value by the corresponding modification factor in Table A.1 or Table A.2, as appropriate.

A.2 Minimum short-circuit power modification factors

Table A.1 — Minimum short-circuit power modification factors for I_{SCC} < 100 A

—	Modification factor											
M	***X/R* = 0.5**	***X/R* = 0.6**	***X/R* = 0.625**	***X/R* = 0.7**	***X/R* = 0.8**	***X/R* = 0.9**	***X/R* = 1.0**	***X/R* = 1.1**	***X/R* = 1.2**	***X/R* = 1.3**	***X/R* = 1.4**	***X/R* = 1.5**
1	0.947	0.990	1.000	1.030	1.068	1.102	1.132	1.158	1.182	1.202	1.220	1.236
2	0.947	0.990	1.000	1.030	1.068	1.102	1.132	1.158	1.182	1.202	1.220	1.236
3	0.947	0.990	1.000	1.030	1.068	1.102	1.132	1.158	1.182	1.202	1.220	1.236
4	0.947	0.990	1.000	1.030	1.068	1.102	1.132	1.158	1.182	1.202	1.220	1.236
5	0.947	0.990	1.000	1.030	1.068	1.102	1.132	1.158	1.182	1.202	1.220	1.236
6	0.912	0.983	1.000	1.049	1.108	1.160	1.206	1.247	1.282	1.312	1.339	1.362
7	0.912	0.983	1.000	1.049	1.108	1.160	1.206	1.247	1.282	1.312	1.339	1.362
8	0.947	0.990	1.000	1.030	1.068	1.102	1.132	1.158	1.182	1.202	1.220	1.236
9	0.947	0.990	1.000	1.030	1.068	1.102	1.132	1.158	1.182	1.202	1.220	1.236
10	0.947	0.990	1.000	1.030	1.068	1.102	1.132	1.158	1.182	1.202	1.220	1.236

Table A.2 — Minimum short-circuit power modification factors for I_{SCC} ≥ 100 A

—	Modification factor											
M	***X/R* = 0.5**	***X/R* = 0.6**	***X/R* = 0.625**	***X/R* = 0.7**	***X/R* = 0.8**	***X/R* = 0.9**	***X/R* = 1.0**	***X/R* = 1.1**	***X/R* = 1.2**	***X/R* = 1.3**	***X/R* = 1.4**	***X/R* = 1.5**
1	0.837	0.874	0.884	0.910	0.994	0.973	1.000	1.023	1.044	1.062	1.078	1.092
2	0.837	0.874	0.884	0.910	0.994	0.973	1.000	1.023	1.044	1.062	1.078	1.092
3	0.837	0.874	0.884	0.910	0.994	0.973	1.000	1.023	1.044	1.062	1.078	1.092
4	0.837	0.874	0.884	0.910	0.994	0.973	1.000	1.023	1.044	1.062	1.078	1.092
5	0.837	0.874	0.884	0.910	0.994	0.973	1.000	1.023	1.044	1.062	1.078	1.092
6	0.756	0.815	0.829	0.869	0.918	0.962	1.000	1.033	1.062	1.088	1.110	1.129
7	0.756	0.815	0.829	0.869	0.918	0.962	1.000	1.033	1.062	1.088	1.110	1.129
8	0.837	0.874	0.884	0.910	0.944	0.973	1.000	1.023	1.044	1.062	1.078	1.092
9	0.837	0.874	0.884	0.910	0.944	0.973	1.000	1.023	1.044	1.062	1.078	1.092
10	0.837	0.874	0.884	0.910	0.944	0.973	1.000	1.023	1.044	1.062	1.078	1.092

NOTE: definition of M is as per Table 18 and Clause 7.3.3

Annex B
(informative)

Terminology and descriptions

A converter is a term used to refer to a power electronic device that changes voltage from a.c. to d.c. or d.c. to a.c. There are also other forms of converters that convert d.c. to d.c. or a.c. to a.c.

A rectifier is a power electronic device that converts an input a.c. voltage to an output d.c. voltage. An inverter is a power electronic device that converts an input d.c. voltage to an output a.c. voltage.

A six-pulse diode rectifier is shown in Figure B.1. The same can be realised by replacing the diodes with thyristors as shown in Figure B.2. These rectifiers produce odd harmonic ($h = (6 \times n) \pm 1$, $n = 1, 2....$) voltages and currents that are not divisible by three on the a.c. side. The diode rectifier is often referred to as uncontrolled, whereas the implementation with thyristors is called a controlled rectifier; this is because the conduction of the thyristor is initiated by the application of a gate pulse.

Figure B.1 — Six-pulse diode rectifier

Figure B.2 — Six-pulse thyristor rectifier

In an active-front-end converter, the diode bridge rectifier is replaced by self-commutated insulated gate bipolar transistor (IGBT) modules, as shown in Figure B.3. Active-front-end converters have the ability to transfer power both ways (from a.c. side to d.c. side or vice versa). It is called self-commutated because the IGBT modules can be switched on and off as required. The IGBTs can be represented with switches, as shown in Figure B.4.

Figure B.3 — Active-front-end rectifier

Figure B.4 — Simplified representation of active-front-end rectifier

The IGBTs are switched on and off at a frequency of a few kHz and, depending on the switching frequency, produce harmonic current and voltage emissions into the a.c. supply. In contrast to six-pulse converters with diode rectifiers, active-front-end converters can produce both odd and even harmonics, depending upon the switching frequency used. Figure B.5 shows a typical arrangement of an active-front-end rectifier and an inverter.

Figure B.5 — Active-front-end converter

Active-front-end converters produce currents with very low total harmonic current distortion (~3%) compared to diode bridge rectifiers (~30%). In addition, active-front-end converters have the ability to produce reactive power, whereas diode bridge rectifiers have to be supplied with reactive power.

Figure B.6 — Six-pulse Thyristor Rectifier with Active Filter

Figure B.7 shows an active harmonic filter in conjunction with a six-pulse thyristor rectifier. Such a filter can be configured to reduce harmonic current emissions into the network. If suitable arranged such a combination can be effectively equivalent to an active front-end converter.

A single-phase full-wave diode rectifier with smoothing capacitor is shown in Figure B.7. Odd harmonic emissions dominate, particularly the lower orders.

Figure B.7 — Single-phase full-wave diode rectifier

Key

Diode

Thyristor

Insulated gate bipolar transistor (IGBT) with a freewheel diode

IGBT represented as a switch

Capacitor

Annex C
(informative)

A power system analysis software may only give Ohmic values of the self (Thévenin) impedance of a node and transfer (mutual) impedance between two nodes. In the Stage 3 assessment converting the impedance Ohmic values to per unit values is carried out by using the base impedance for the self and mutual impedances. The per unit values are calculated by dividing the impedances Ohmic values by the relevant base impedances. The base voltages, impedances and MVA are set for the fundamental frequency component. The same values are used to convert the relevant harmonic quantities to per unit values.

The base impedance for the self impedance is calculated as given by (755).

$$Z_{self\ base} = \frac{(V_{PCC\ base})^2}{S_{base}} \qquad (755)$$

where:

$Z_{self\ base}$ is the base impedance for the PCC, i.e. for the entire network at the voltage level where the PCC is;

$V_{PCC\ base}$ is the base voltage for the entire network at the voltage level where the PCC is;

S_{base} is the study base MVA.

The base impedance for the transfer (mutual) impedance is given by (766)

$$Z_{transfer\ base} = \frac{V_{PCC\ base}\ V_{n\ base}}{S_{base}} \qquad (766)$$

where:

$Z_{transfer\ base}$ is the base impedance between two voltage levels, i.e. the PCC and a remote node which is situated at a different voltage level;

$V_{n\ base}$ is the base voltage for the part of network where the remote node is situated.

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