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Harmonic voltage distortion and the connection of non-linear and resonant plant and equipment to transmission systems and distribution networks in the United Kingdom

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PUBLISHING AND COPYRIGHT INFORMATION

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Foreword

This Engineering Recommendation (EREC) is published by the Energy Networks Association (ENA) and comes into effect from June, 2018. It has been prepared under the authority of the ENA Engineering Policy and Standards Manager and has been approved for publication by the ENA Electricity Networks and Futures Group (ENFG). 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, at the discretion of the network owner/operator, be connected in accordance with that recommendation.

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.

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

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

Section 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 under the relevant transmission, distribution or generation licence or the connectee connection agreement, as applicable.

Sections 7, 8, 9 and 10, detail the Stage 1, Stage 2, resonant plant, and Stage 3 assessment procedures, respectively.

The terms network owner, network operator and system operator in this EREC are intended to apply to owners and operators of transmission systems and distribution networks – referred to as NOs in this document – 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 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 the responsible party to apply sound engineering practices where such circumstances arise and to adequately document the justifications for applying alternative approaches and techniques.

Both the connection of non-linear load or generating plant and equipment and, in addition, resonant plant – cables and shunt and series reactive elements – 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 power 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 connections and to existing connections undergoing modification. In this context, modification is as defined in the terms of connection or the applicable transmission or distribution network connection code. In the case of modification, the relevant NO may, at its discretion, decide that reassessment against this EREC is not justified; for example, if the modification does not constitute a material change to the connectee's plant and equipment.

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)]

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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 non-linear or resonant plant and 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, within which the network should be operated

3.3
connectee
generator, load or any other type of connection that is connected or is being assessed for connection to the **supply system**

NOTE: There is no differentiation between load, demand, generation and any other entity that applies to connect to the public supply system, as far as this document is concerned.

3.4
distribution network operator
company responsible for making technical connection agreements with **connectee**s who are seeking connection of load, generation or any other type of connection to a distribution network

NOTE: In the context of this document, this is referred to as an NO.

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

3.6
fault level
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

3.7
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.

3.8
harmonic impedance of the PCC
impedance of the supply system when looking into the **PCC** from the **connectee** terminal. Also referred to as the self or the Thévenin impedance at the **PCC**

3.9
harmonic transfer coefficient
ratio of the harmonic voltage at node Y to the corresponding harmonic current injected at node X

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 network loading, configuration and outage conditions

3.12
incremental harmonic voltage
harmonic voltage change produced by a **connectee** at the **PCC** due to harmonic emission from its non-linear plant and equipment

3.13
incremental harmonic voltage limit
maximum permitted harmonic voltage change that a **connectee** may produce at the **PCC** due to harmonic emission from its non-linear plant and equipment

3.14
individual harmonic distortion
rms 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
rms 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
rms 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/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
network user
a generator, load or any other connection that has already been connected to the public supply system

NOTE: There is no differentiation made in this document between load, demand, generation and any other entity that has been connected to the public supply system.

3.23
normal operating conditions
the system state that may be intact or depleted but is secure outside of the post-fault switching timescale

NOTE: This includes the variation of generation, demand, plant and equipment energisation as a consequence of temporal, seasonal and operational variability, including credible planned outages, under which the system is expected to operate normally.

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 non-linear or resonant plant and equipment is assessed

3.25
point of common coupling (PCC)
point in the public **supply system**, electrically nearest to a **connectee**'s installation, at which other **network user**s' loads are, or may be, connected

NOTE: A supply system is considered as being public in relation to its use and not its ownership.

3.26
point of evaluation
point in the public **supply system** where the effect of a connection is assessed

3.27
resonant harmonic voltage limit
maximum harmonic voltage increase that can be allowed as a result of the modification of the **background harmonic level**

3.28
resonant plant
network or item of **connectee** plant or equipment, such as power factor correction capacitors, cables or active-front-end converters/inverters, that may modify the **background harmonic level** as a result of interaction with the rest of the network without emitting any harmonic current or voltage

3.29
short burst
burst in power system harmonics 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

3.30
supply system
all of the lines, switchgear and transformers operating at various voltages that make up the transmission systems and distribution systems to which **connectee**s' installations are connected

3.31
total distortion content
rms value of a time domain voltage or current signal that contains all of the frequency content, including interharmonics, except for the r.m.s. of the fundamental frequency component

3.32
total distortion ratio
ratio of the **total distortion content** to the r.m.s. of the fundamental frequency component

3.33
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*)**.

3.34
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.

3.35
total harmonic voltage limit
maximum **total harmonic voltage level** at the **PCC** that shall be allowed to exist after the **connectee**’s installation is connected

3.36
total harmonic voltage level
harmonic level at the **PCC** after the **connectee**’s installation 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 4.2.

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

4.2 Roles and responsibilities

The connection of non-linear or resonant plant and equipment will either be part of an NO’s investment strategy or be the result of a connectee’s connection to the NO’s system. The network operator is ultimately responsible for compliance under operational timescales. Under planning timescales, responsibility is delegated to the network owner (where different). In planning for harmonic compliance, when considering connectee connections, a network owner may place additional responsibilities on a connectee through the terms of a connection agreement between the connectee and network operator.

The network operator is responsible for the overall coordination of disturbance levels under normal operating conditions, in accordance with national requirements, and shall refer to the compatibility levels herein.

The network owner is responsible for assessing the impact of any connection of non-linear or resonant plant and equipment to their network. This assessment must cover all affected networks, including distribution and onshore and offshore transmission networks, and shall refer to the planning levels herein.

Where new network assets are connected, the network owner providing the connection is responsible for assessing the impact of the connectee. If the new assets are owned by another network owner, then the network owner facilitating the connection shall set harmonic limits on the network owner of the new assets. These limits shall be contractually separate from any limit the new network owner places on connectees connecting to their network.

The network owners and the network operator shall provide, where necessary and practicable, any network data, such as harmonic impedance and background harmonic level, necessary to enable the network owner hosting the connection to fully assess the impact on harmonic levels on all affected networks to ensure that the overall supply system harmonic voltage levels will not exceed the planning and compatibility levels. This harmonic assessment is to consider the effect of emissions as well as modification of existing harmonic levels due to resonance effects.

The network owner hosting the connection is the owner of the supply system that facilitates the connection. For the avoidance of doubt, a connectee requesting connection to a host network owner can be another network owner, a generator, a load or a combination of these.

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 NO (or relevant system operator) cannot control all points of the system at all times.

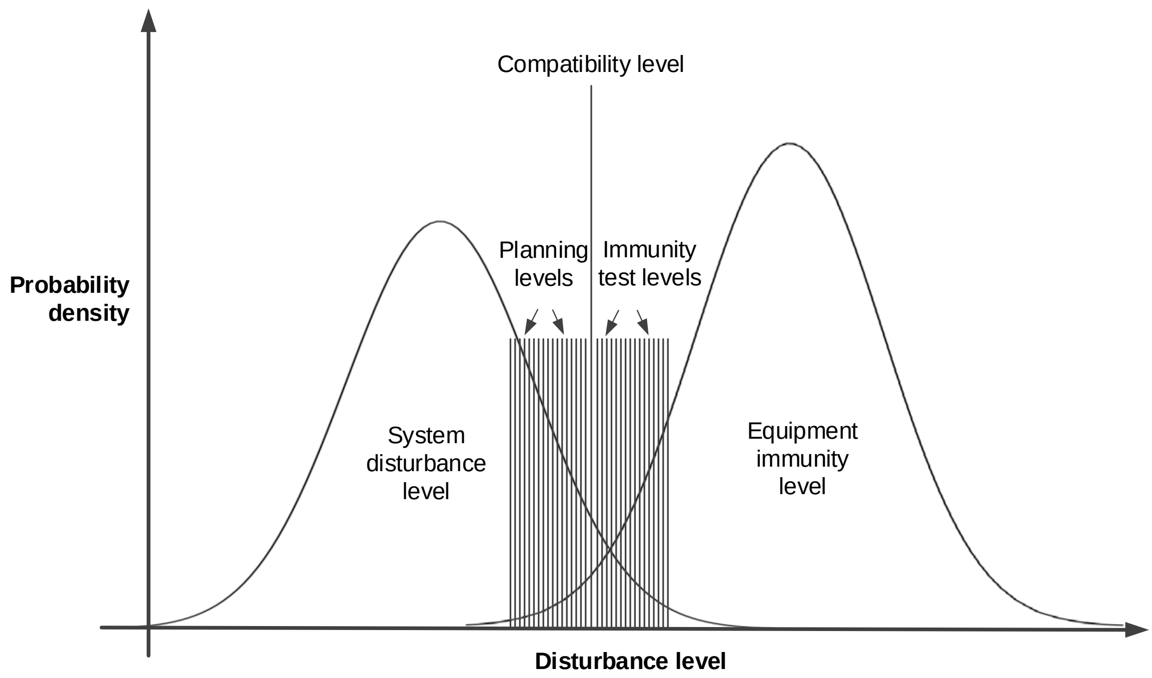


Figure 1 — Illustration of EMC concepts relevant to a supply system

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

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

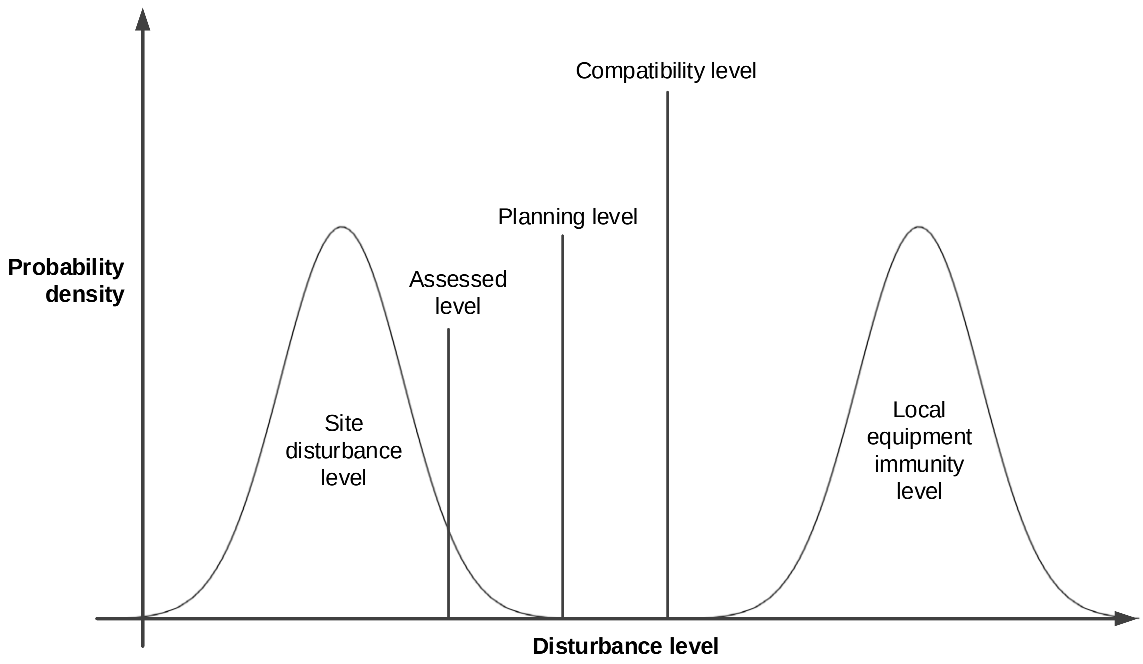


Figure 2 — Illustration of EMC concepts relevant to a local site

5 Harmonic voltage distortion levels

5.1 Introduction

Planning and compatibility levels for all voltage levels are given in Table 1 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. It is recommended to consider the assessment of these harmonics 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 measure these harmonics. It is recommended that NOs install the necessary equipment to enable measurement of harmonic voltages higher than the 50th order.

For frequencies above 5 kHz relevant IEC standards, e.g. IEC 61000-2-2, applies.

It is essential that the appropriate modelling techniques for harmonic studies, such as those recommended in Electra 167 [3] and IEEE TP-125-0 [4], are followed.

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 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 connectees.

Table 1 — THD_V planning levels

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

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 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
$25 < V \leq 66$	5
$66 < V \leq 230$	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
$17 \le h \le 49$	$2.27(17/h) - 0.27$	≥ 23	0.2	≥ 10	$0.25(10/h) + 0.25$
$53 \le h \le 97$	$27/h$	—	—	—	—

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
$17 \le h \le 49$	$2.27(17/h) - 0.27$	> 21	0.2	≥ 10	$0.25(10/h) + 0.25$
$53 \le h \le 97$	$27/h$	—	—	—	—

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	1.5	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	—	—	—	—

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	—	—	—	—

NOTE: The planning and compatibility levels apply at the PCC.

5.4 Subharmonic and interharmonic distortion

The frequency of the interharmonic 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 component has an 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 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 standard, the r.m.s. value of the centred subgroup between the harmonic orders h and h + 1 is designated as $V_{h\ ig}$. For example, the centred subgroup 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).

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

where

$V_{h\ ig}$	is the interharmonic centred subgroup for order *h*;
n	is the interharmonic order between integer harmonic orders;
$V_{i,n}^{h,\ h+1}$	is the interharmonic components between harmonic orders *h* and *h* + 1.

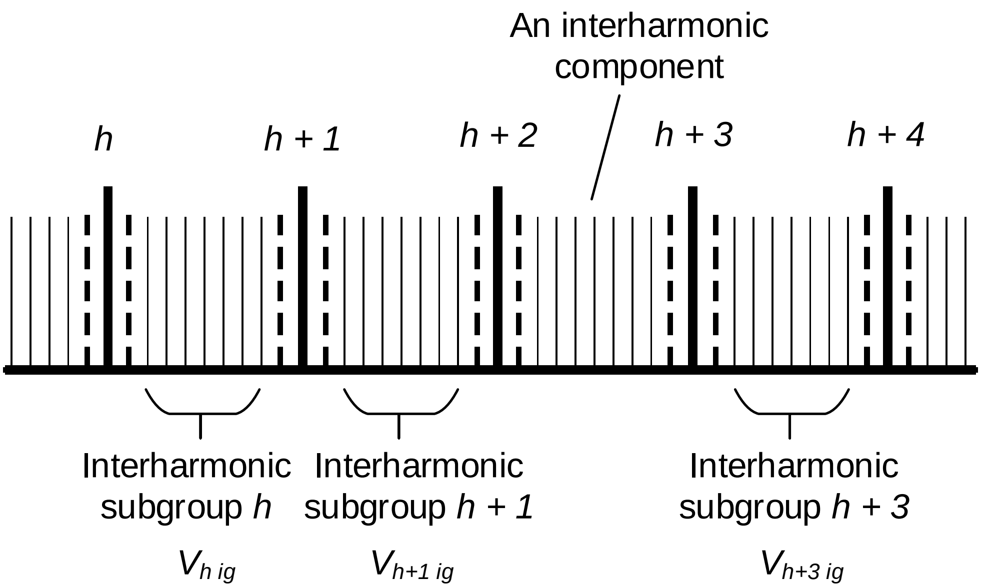


Figure 3 — Illustration of harmonics and interharmonic subgroups

Total distortion content (TDC) is defined as the r.m.s. of the time domain voltage or current signal without the r.m.s. of the fundamental frequency component. TDC_V for the voltage is given by (3).

$$TDC_V = \sqrt{(V_{rms})^2 - (V_{1\ rms})^2} \tag{3}$$

where

TDC_V	is the total voltage distortion content;
V_{rms}	is the r.m.s. of the voltage signal consisting of all frequency content, including interharmonic components;
$V_{1\ rms}$	is the r.m.s. of the fundamental frequency component.

Total distortion ratio (TDR) is defined as the ratio of the total distortion content (TDC) to the r.m.s. of the fundamental frequency component, as shown in (4) for total voltage distortion ratio (TDR_V).

$$TDR_V = \frac{TDC_V}{V_{1\ rms}} \tag{4}$$

If the predicted subharmonic and interharmonic voltage emissions from an item of plant or equipment, or from a connectee's aggregate load, are less than 0.1% of the fundamental voltage, then connections may be made without any further assessment.

In the United Kingdom, it is assumed that ripple control systems are not being used and therefore a connectee's load may be connected without assessment provided that its individual interharmonic emissions are lower than the limit values provided in Table 13.

For LV systems, 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

	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 and fluctuating harmonic distortion

Non-continuous loads that have either short-duration bursts or fluctuations, e.g. irregular motor start/stop, shall be considered by selecting a more appropriate aggregation period: either 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 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 $\sqrt{2}$.

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

Semiconductor motor controllers (e.g. soft-starters) and load controllers which fall within the scope of this section, 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, and using the limits presented in Table 14 and Table 15.

Table 14 — Maximum permitted aggregate equipment rated power at reference short-circuit power for $V \leq 0.4$ 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
LV	314 kVA

Table 15 — Maximum permitted aggregate equipment rated power at reference short-circuit power for 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.

Notching is a high-frequency event and as such it is recommended that wide-bandwidth transducers are used. Equipment that results in voltage notching 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.

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 duration shall meet the requirements of (6).

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

where

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

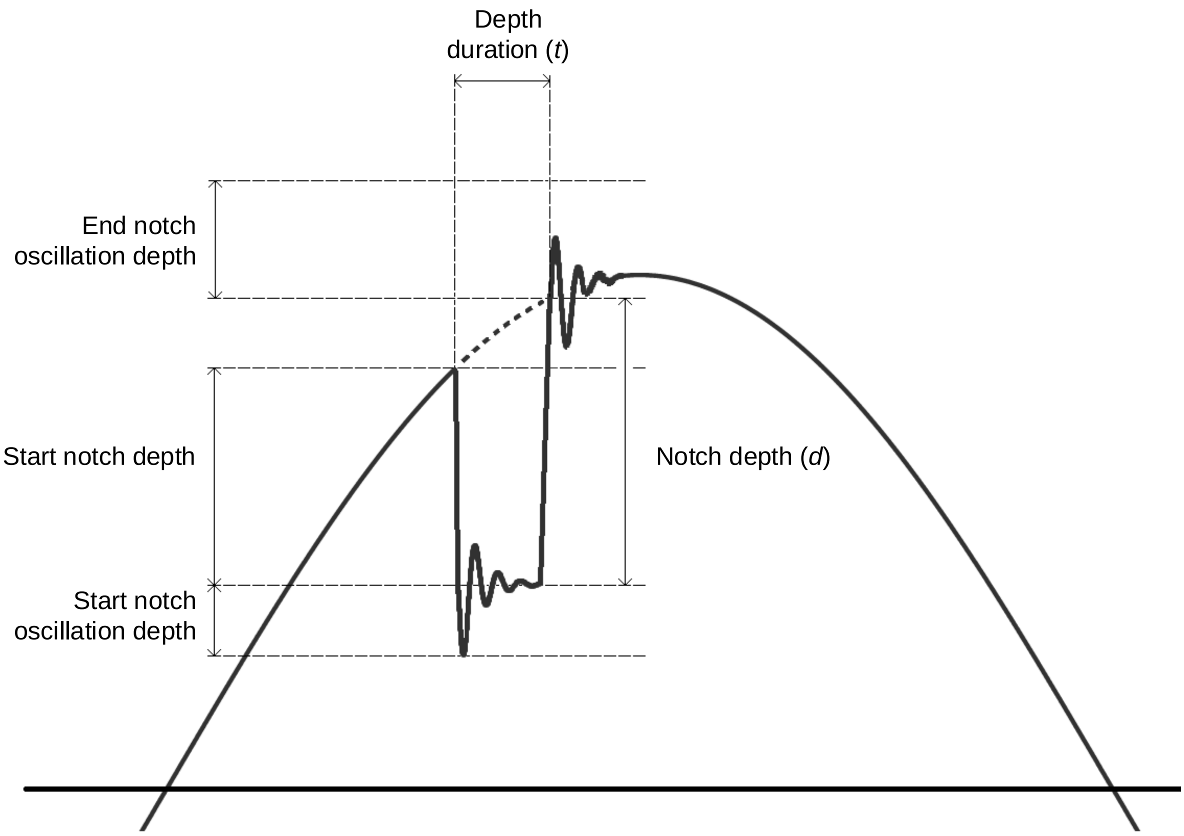


Figure 4 — Depiction of voltage notching

6 Assessment of non-linear and resonant connections

6.1 Introduction

This assessment procedure is intended to be generally applicable to:

- any non-linear plant or equipment that causes a harmonic emission into the electricity supply system, irrespective of the direction of the fundamental frequency power flow;
- any resonant plant, which may amplify the background harmonic level in the supply system.

Therefore, there is no differentiation between demand and generation as far as this procedure is concerned. Any specific reference to load, demand or generation shall be treated as implying the general case of non-linear or resonant plant and equipment.

The assessment procedure for the connection of non-linear or resonant plant and 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 network if it is connected without any mitigation measures.

Stage 1 facilitates the connection of plant and equipment to LV networks. It specifies the maximum sizes of plant and equipment that can be connected. The main basis for Stage 1 assessment is product-related international standards. Measurement of the background harmonic level may be required at the final stage of the assessment.

Stage 2 facilitates the connection of plant and equipment to all systems less than or equal to 22 kV, including low-voltage plant and equipment 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 non-linear or resonant plant or equipment. The predicted harmonic voltage levels are required to be less than or equal to the specific limits. At voltages above 1 kV, the predicted values in this assessment stage are intended to be an indicator of acceptability 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 plant and equipment that is not found to be acceptable under Stage 2 assessment, and which falls outside the scope of Stages 1 and 2. It applies to any non-linear or resonant plant or equipment that has a nominal PCC voltage greater than 22 kV.

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 connectee to other connectees is increased. This concern should be reflected in a conditional connection agreement, including mitigation measures – agreed between the NO and connectee – as appropriate.

The final decision as to whether or not a particular load can be connected to a transmission system or a public electricity 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 connectee, with site-specific terms in the connection agreement. This agreement must use the connection conditions laid down in the Grid Code [5] or Distribution Code [6].

Where it is apparent that connection of a new load could impose harmonic voltage distortion on the supply system greater than the planning levels given in this document, the NO can refuse connection until agreement is reached on a solution.

In a marginal situation, or for large loads that may trigger unpredicted system resonance, a conditional connection may be agreed whereby any necessary remedial measures can be implemented within a reasonable timescale after connection.

In exceptional circumstances, for LV nodes and nodes with voltages up to 33 kV, where, for example, a connectee is located in an area remote from other connectees or network users, and it is certain that only that connectee'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 is above the planning level but below the compatibility level, then the NO may specify one or more network-specific planning levels, in the timescale given within ENA EREC G97 [7]. The temporary planning level 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 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 non-linear or resonant plant and equipment upon the levels of harmonic distortion is to be assessed against the planning levels given in 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 network operator may limit the connectee's current emissions according to the calculations in 7 and 8 respectively. For Stage 3 assessments, the network operator may limit the voltage emissions, which must be accompanied by a harmonic impedance representation of the network, created according to the calculations in 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, either directly or through calculation of the system fault level. 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 non-linear or resonant plant and equipment.

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 ER P2/6 [9]) – 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 recommended 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 non-linear plant or equipment items through the aggregation of their individual harmonic emissions. This form of aggregation is only valid based on a realistic appreciation of the plant or equipment's operational and locational diversity, without which linear addition shall be employed.

$$V_h = \sqrt[\alpha]{\sum_i \left(V_{h,\,i}\right)^{\alpha}} \qquad (7)$$

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 on the basis of 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 network and the non-linear and/or resonant connection, affecting the calculated resonances in the model;
- an absence of accurate data;
- relevant future network variations that will not be subject to their own assessment according to this EREC;
- the 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 so as 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 load, 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 will be judged by the contribution of the particular plant or equipment to the total harmonic voltage levels. For larger loads, or where fault levels are low, and/or for Stage 3 assessments (where uncertainty over the data used for the study can be significant), post-connection measurement may be required to verify compliance. 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 still be exceeded and such connections should therefore have regard to the practicality, timescale and costs of remedial measures after the connection is made. 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 non-linear plant or 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 plant or 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 network form part of Stage 1D, Stage 2B and 2C and Stage 3 assessments in order to calculate the available headroom for the connectee.

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 network(s).

These nodes could be at any voltage level and on networks not owned 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 post energisation of the connection of the non-linear or resonant plant and 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, BS EN 61000-4-30, which makes reference to the algorithm described in BS EN 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 adopts a Class A device for measurement of the background harmonic level and for pre- and post-commissioning monitoring.

Based on BS EN 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 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.

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 selection.

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 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 seasonal variation. 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 placed 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 connection summary

Stage 1 is designed for connection at LV. It is designed as a linear process such that assessments are applied in stages and substages. If a substage is passed, then the connectee can connect; if the substage is failed, then the next substage of 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 connectee 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 pass criteria.

The first substage of Stage 1 – Stage 1A – also allows for self-certification. If a connectee connects plant or equipment 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 short-circuit power level.

Under Stage 1 the final substage 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 for connectees, 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 7.

6.4.2 Stage 2 connection summary

Stage 2 is designed for connection at voltages at and below 22 kV and for those connectees that have failed Stage 1. It is also designed as a linear process, such that assessments are applied in substages.

Stage 2 includes three substages: Stage 2A and Stage 2B follow the same concept and have the same benefits as Stage 1C and Stage 1D. Those connections which fail at Stage 1 may be connected under one of the three substages at Stage 2, which each require more data from the connectee and the network. If a connection fails at Stage 2, then assessment under Stage 3 will be carried out unless the PCC is LV, in which case, no connection is possible without 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 under the Stage 2A assessment procedure. For loads where a more-detailed assessment is required, Stage 2B – a refined version of Stage 2A – is provided, which takes into account the actual background harmonic level.

Under Stage 2, the final substage of assessment 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 has indicated 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 to be within the margin of uncertainty of the assessment process.

The Stage 2 assessment procedure is given in 8.

6.4.3 Resonant (non-emitting) plant connection summary

For the assessment of the connection of resonant plant at 0.4 kV and below, and between 0.4 kV and 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 systems of 33 kV and above are assessed under Stage 3.

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

6.4.4 Stage 3 connection summary

For a Stage 3 assessment, a determination of the harmonic voltages at the PCC based on a harmonic impedance model of the network 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 10.

7 Stage 1 assessment procedure

7.1 Applicability and substages

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

Connections that fail Stage 1 advance to Stage 2C.

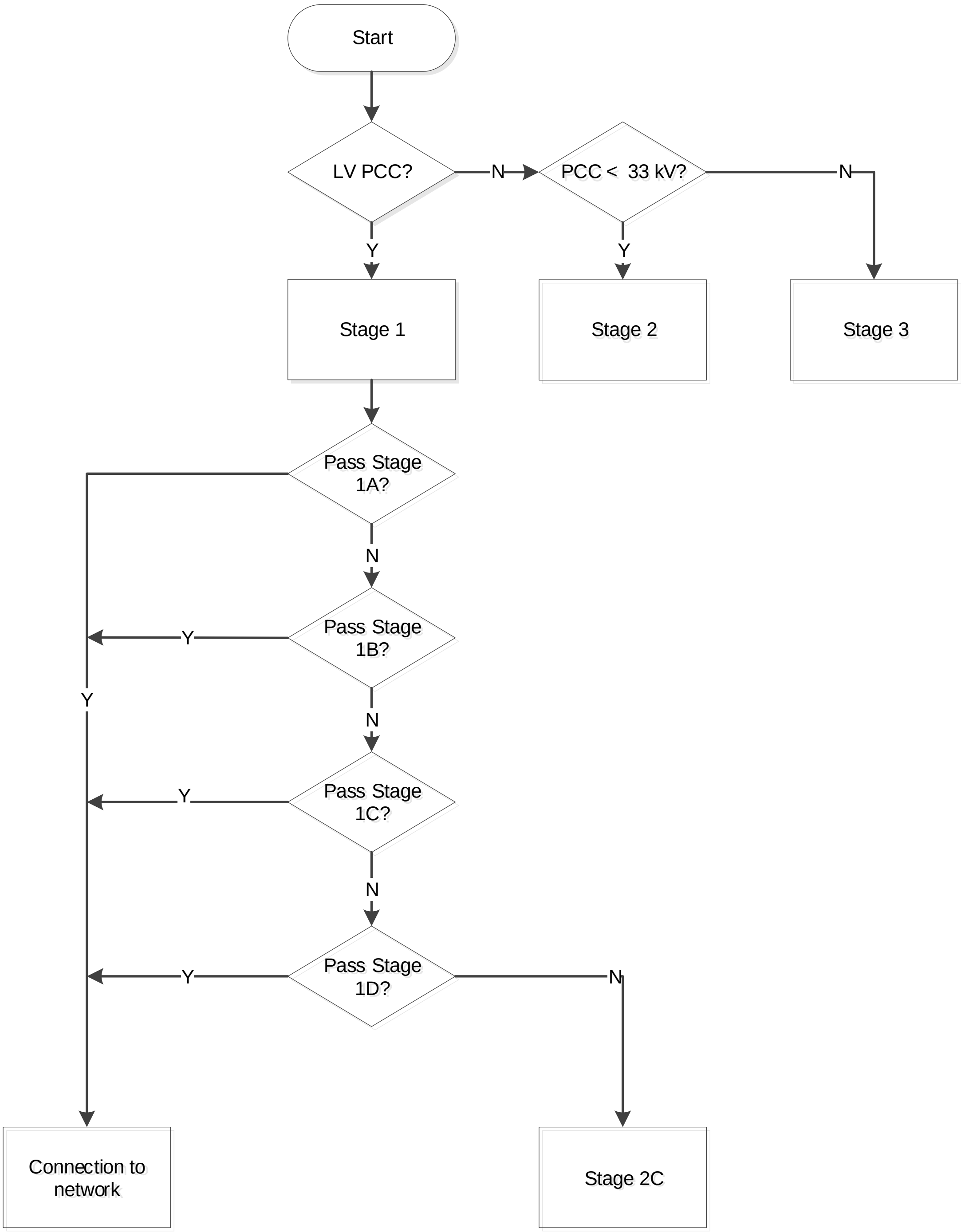


Figure 5 — Stage 1 assessment process flow

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 equivalent, can be connected without further assessment.
- If compliance cannot be verified, then the assessment advances to Stage 1B.

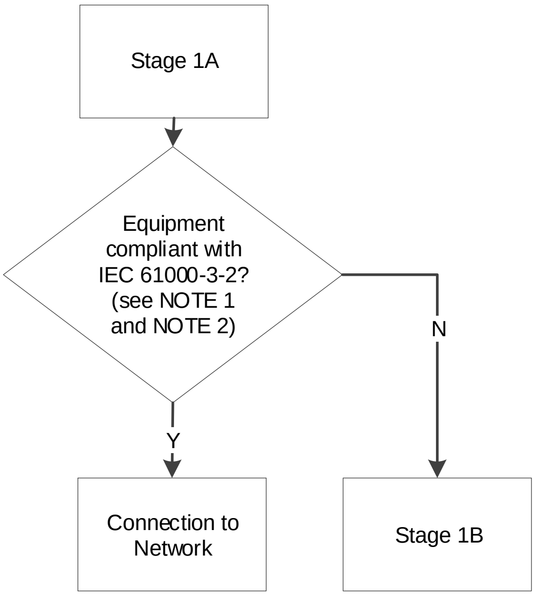


Figure 6 — Stage 1A assessment process flow

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.

- 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 $S_{SC\ PCC\ Min}$.

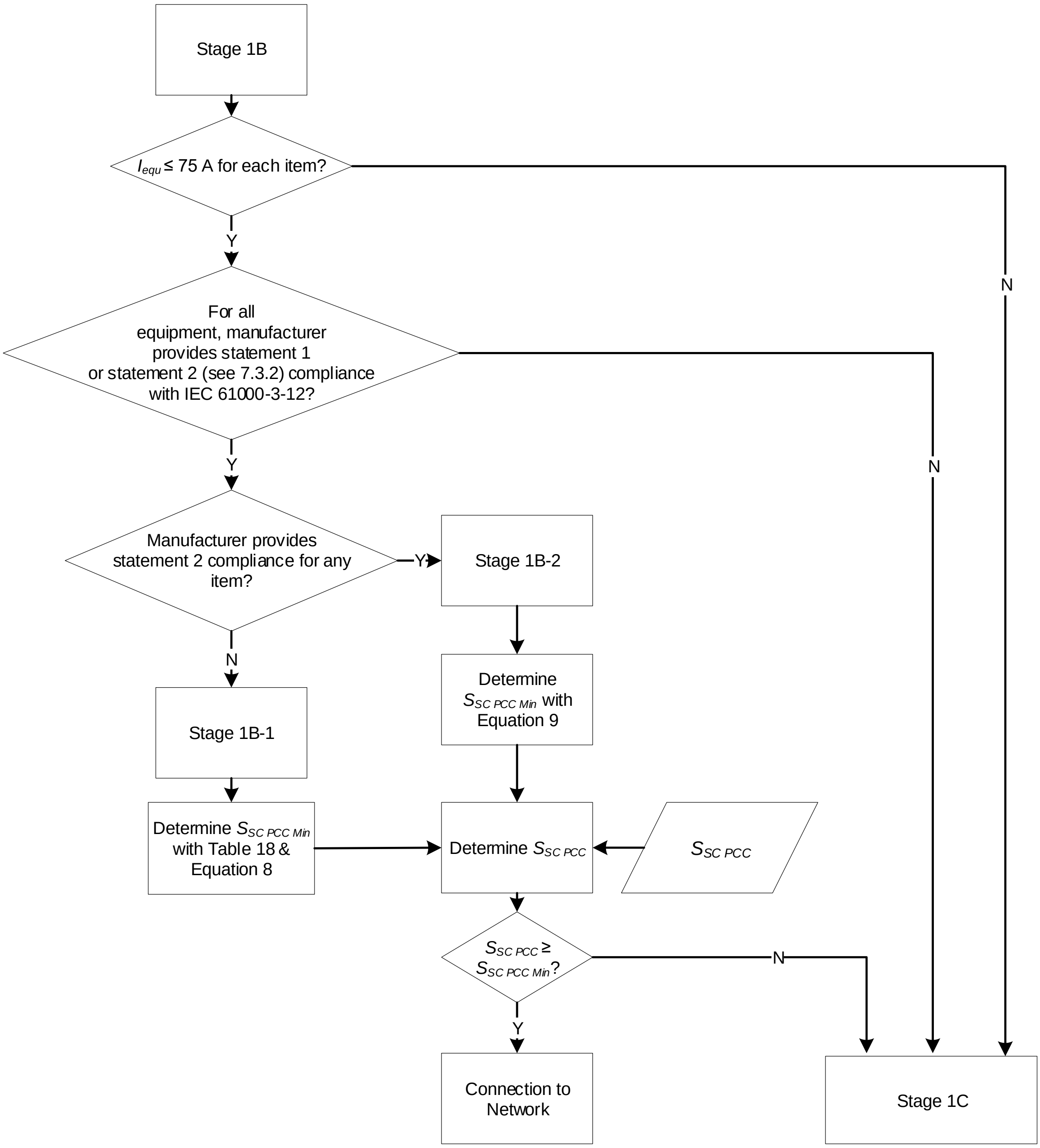


Figure 7 — Stage 1B assessment process flow

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 connectee'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 (i.e. fault level) 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 (i.e. fault level) 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).

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

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 *m*th 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} ≥ 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} ≥ 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 (i.e. fault level) 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 (i.e. fault level) 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 $\sum S_{SC\ PCC\ Min}$.

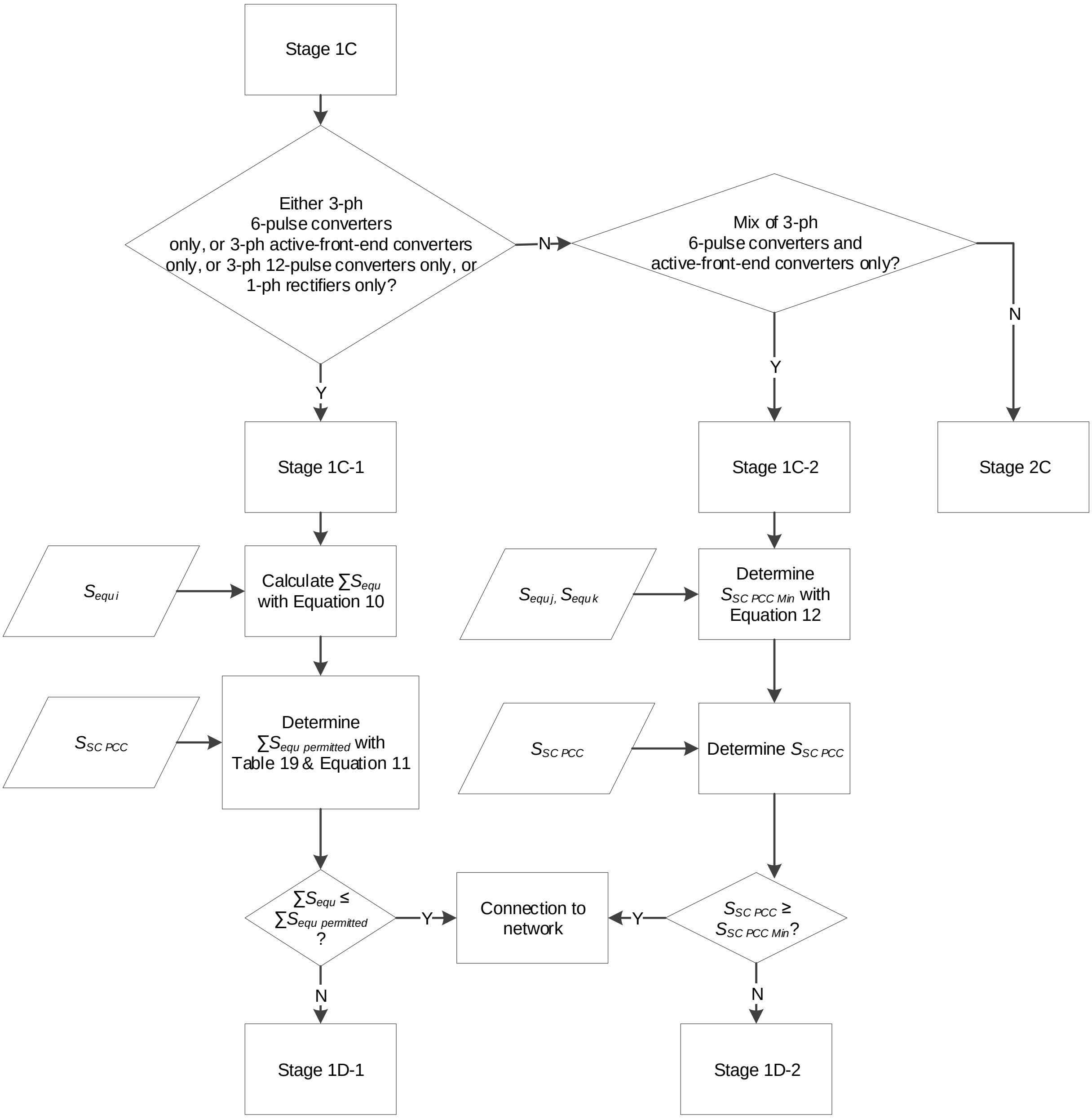


Figure 8 — Stage 1C assessment process flow

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).

$$\sum S_{equ} = \sum_{j=1}^{J} S_{equ\,j} \tag{10}$$

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 (i.e. fault level) 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.				

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).

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

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 (i.e. fault level) 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).

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

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 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.

7.4.2.2 Short-circuit power at the PCC

The three-phase short-circuit power (i.e. fault level) 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 $\sum S_{SC\ PCC\ Min}$.

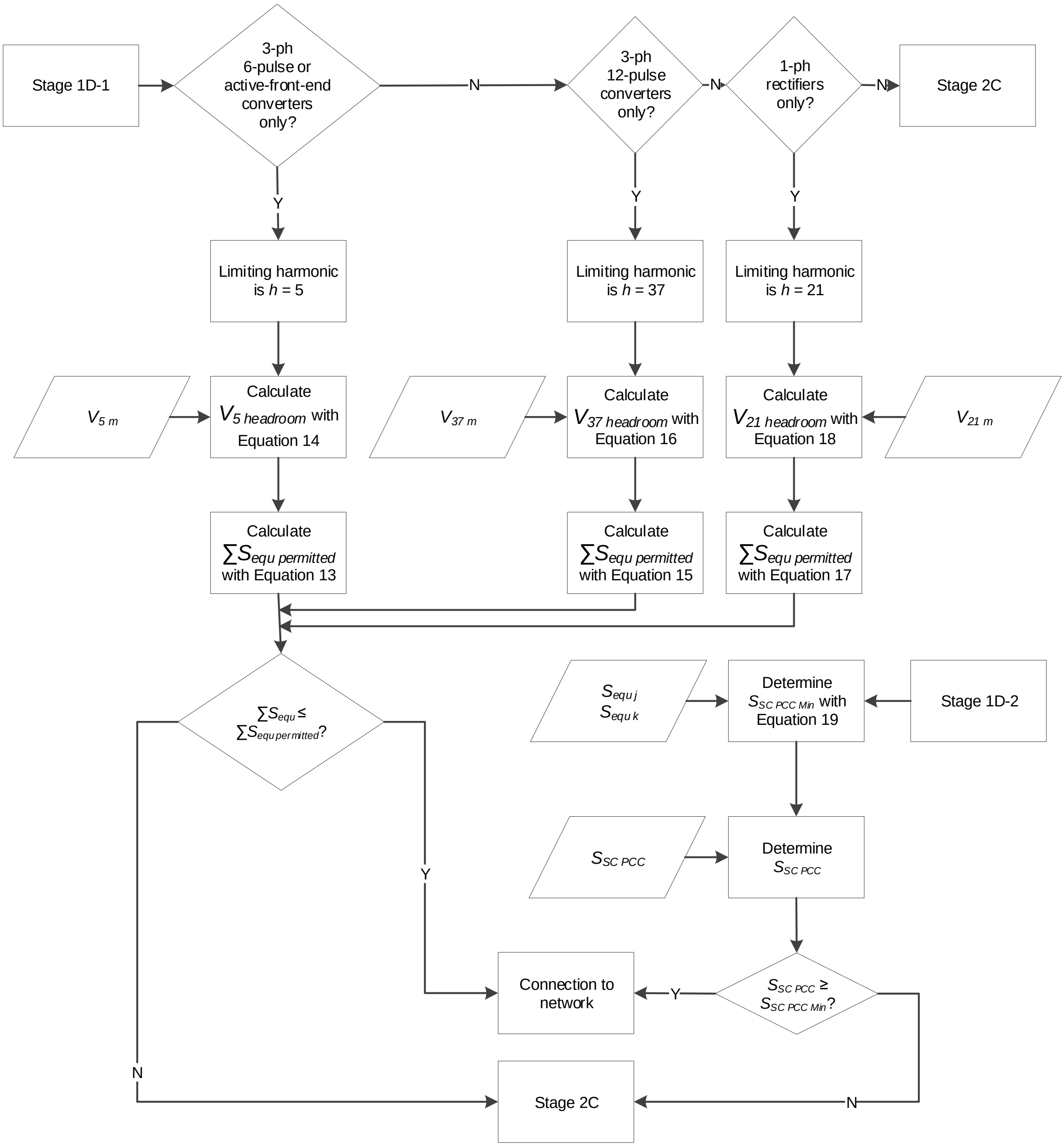


Figure 9 — Stage 1D assessment process flow

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 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 (i.e. fault level) 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).

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

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 ($S_{SC\ reference}$).

$$V_{5\ headroom} = V_{5\ PL} - V_{5\ m} \qquad (14)$$

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).

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

where

$$V_{37\ headroom} = V_{37\ PL} - V_{37\ m} \qquad (16)$$

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).

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

where

$$V_{21\ headroom} = V_{21\ PL} - V_{21\ m} \tag{18}$$

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 (i.e. fault level) 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).

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

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;

$$V_{5\ headroom} = V_{5\ PL} - V_{5\ m} \tag{20}$$

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 (i.e. fault level) 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 Stage 2 assessment 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.

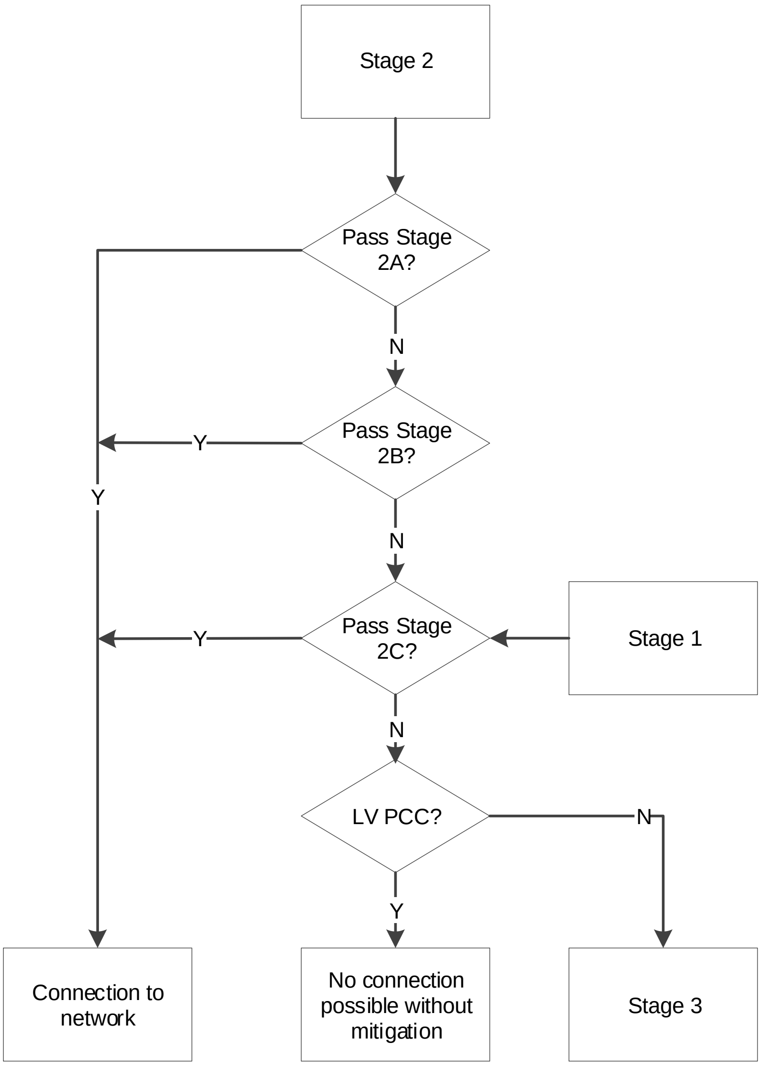


Figure 10 — Stage 2 assessment process flow

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 $\sum S_{SC\ PCC\ Min}$.

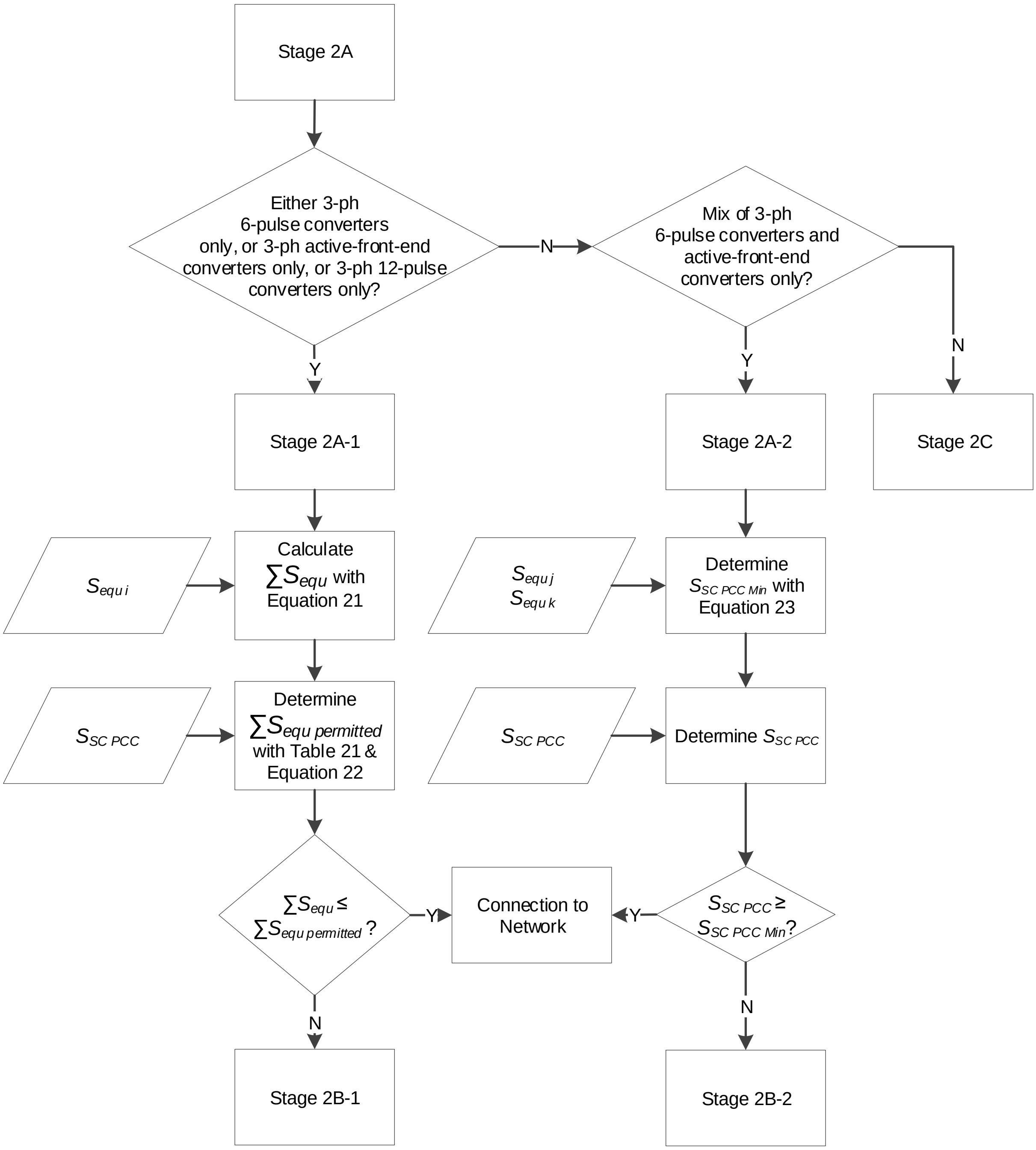


Figure 11 — Stage 2A assessment process flow

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).

$$\sum S_{equ} = \sum_{j=1}^{J} S_{equ\ j} \tag{21}$$

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 (i.e. fault level) 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.			

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).

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

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 (i.e. fault level) 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).

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

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 (i.e. fault level) 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 $\sum S_{SC\ PCC\ Min}$.

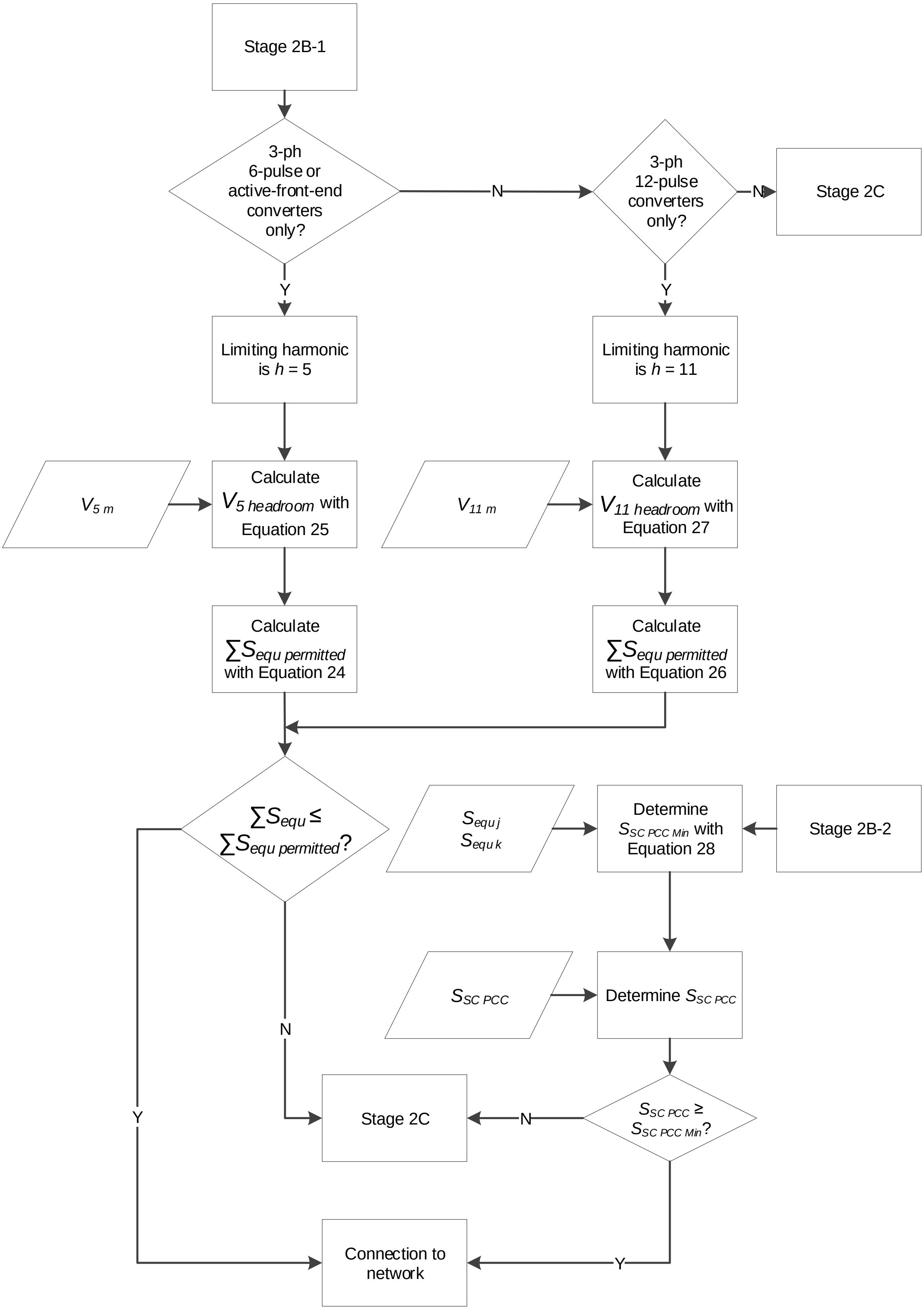


Figure 12 — Stage 2B assessment process flow

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 6.3.5), the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$), the appropriate short-circuit power (i.e. fault level) 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).

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

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.

$$V_{5\ headroom} = V_{5\ PL} - V_{5\ m} \tag{25}$$

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).

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

where

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

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 (i.e. fault level) 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).

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

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.

$$V_{5\ headroom} = V_{5\ PL} - V_{5\ m} \tag{29}$$

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 (i.e. fault level) 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 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 $V_{h\ PL}$.

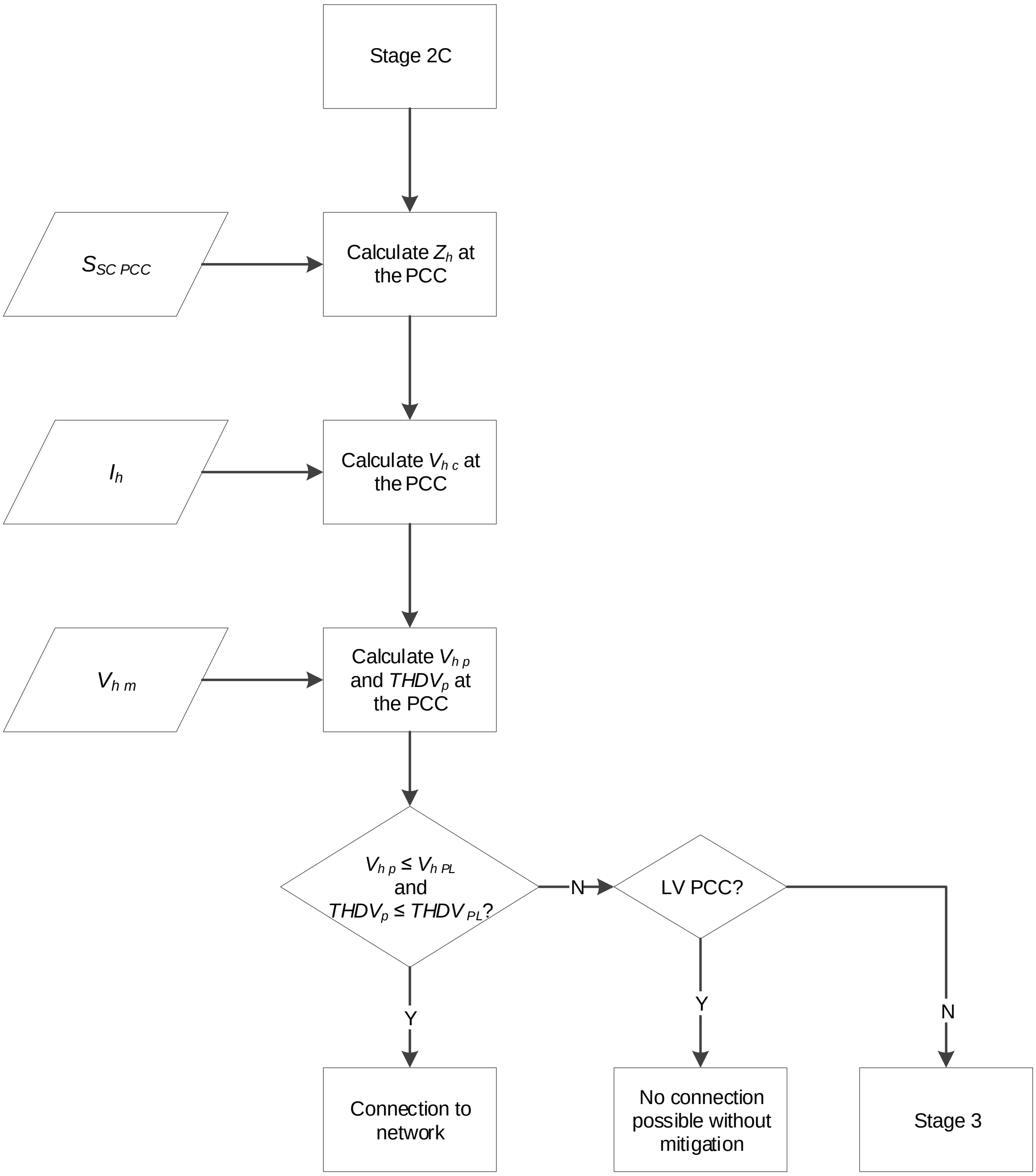


Figure 13 — Stage 2C assessment process flow

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 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 (i.e. fault level) 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	$h \le 7$	$h \le 8$	$h > 7$	$h > 8$
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.

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

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

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).

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

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.

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

where

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

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

where

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

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

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

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 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 and equipment, 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.

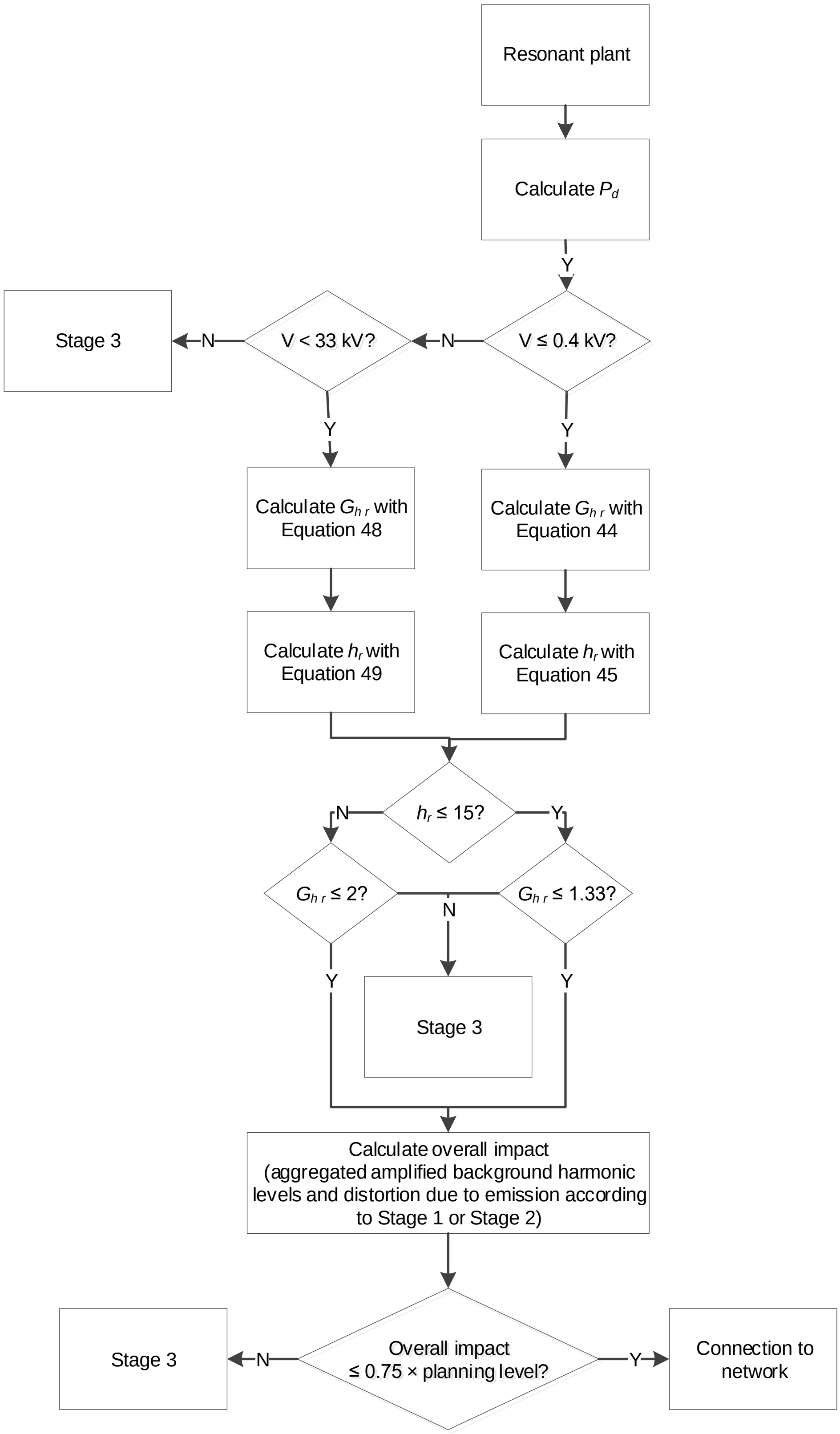


Figure 14 — Resonant plant assessment process flow

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.

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

$$h_r = \sqrt{\frac{S_{SC\,X}}{Q_{rp}}} \qquad (45)$$

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 connectee's resonant plant;
P_d	is the damping power (kW or MW), calculated according to (46).

$$P_d = P_S + 0.36P_{PCC} \qquad (46)$$

where

P_s	is the static portion (i.e. non-motor type) of the connectee's total active power demand (kW or MW);
P_{PCC}	is the active power demand (kW or MW) at the PCC, excluding the connectee. If P_{PCC} is not available, then 30% of the nameplate kVA or MVA rating of the transformer in the public network supplying the connectee shall be considered instead of the factor ($0.36P_{PCC}$);
h_r	is the resonant frequency – at which maximum amplification occurs.

$$S_{SC\,X} = \frac{V_L^2}{X_{SC}} \qquad (47)$$

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 9.3.

9.3 Resonant plant at voltage levels 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 connectee'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 connectee's plant and equipment is determined by aggregating the impact of the emission from the connectee's plant and equipment and the magnification of the background harmonic level due to the connectee'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.

10 Stage 3 assessment procedure

10.1 Applicability and substages

Stage 3 assessment is applicable to all connection of non-linear or resonant plant and equipment with a PCC at 33 kV or above. The Stage 3 assessment also applies to any connection of non-linear or resonant plant and 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 connectee – 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 connectee'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 connectee's plant or equipment and the modification of the background harmonic level. This is referred to as $V_{h\ Limit\ Total}$.

The harmonic specification shall form part of the bilateral connection agreement (BCA) between the NO hosting the connection and connectee. The host NO is the company that facilitates the connection at the PCC.

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

The connectee shall carry out a harmonic compliance assessment. The purpose of the harmonic compliance assessment is to forecast harmonic levels following the connection of the new non-linear or resonant plant, 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 connectee 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 10.8.

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

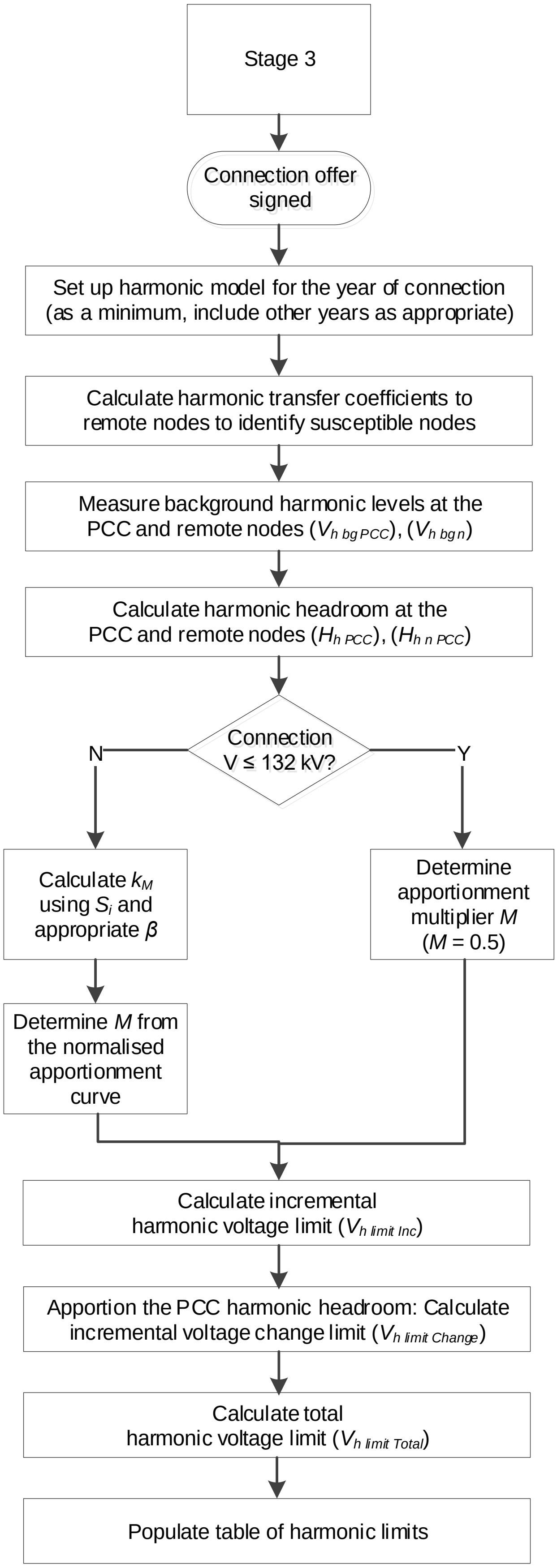


Figure 15 — Stage 3 assessment process flow for the setting of harmonic limits for a new connectee

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 connectee 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 connectee's connection, including that of other NOs and that of other connectees. 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 shall 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. Remote nodes are defined as those substations in the public supply system that are at the same voltage level as the connection, or are at one voltage level above that of the connection and any voltage level below, excluding LV. 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 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 connectee due to harmonic current or voltage emission from the connectee's non-linear plant and 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 connectee 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 10.4.1), are below 1.2 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).

$$T_{h\,PCC\,n} = \frac{V_{h\,PCC\,n}}{V_{h\,PCC}} = \frac{|Z_{h\,PCC\,n}|}{|Z_{h\,PCC}|} \tag{50}$$

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 produced by emission of harmonic current or voltage from the connectee's plant or equipment, as seen at node n;
$V_{h\,PCC}$	is the harmonic voltage produced by emission of harmonic current or voltage from the connectee's plant or equipment, as seen at the PCC;
$\|Z_{h\,PCC\,n}\|$	is the modulus of the transfer (mutual) impedance 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 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 injected into the PCC due to emission from the connectee'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.

The harmonic transfer coefficient may be used to eliminate less-susceptible nodes in the network from consideration. For example, 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.

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

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

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).

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

where

$H_{h\ n\ PCC}$	is the harmonic headroom of node *n*, transferred to the PCC, that, if fully utilised by the connectee (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 done with the goal of enabling timely allocation of harmonic limits to connectees 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 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, fault levels and 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 connectees, 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 rating of the connection, as given 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 connection size (MVA), 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

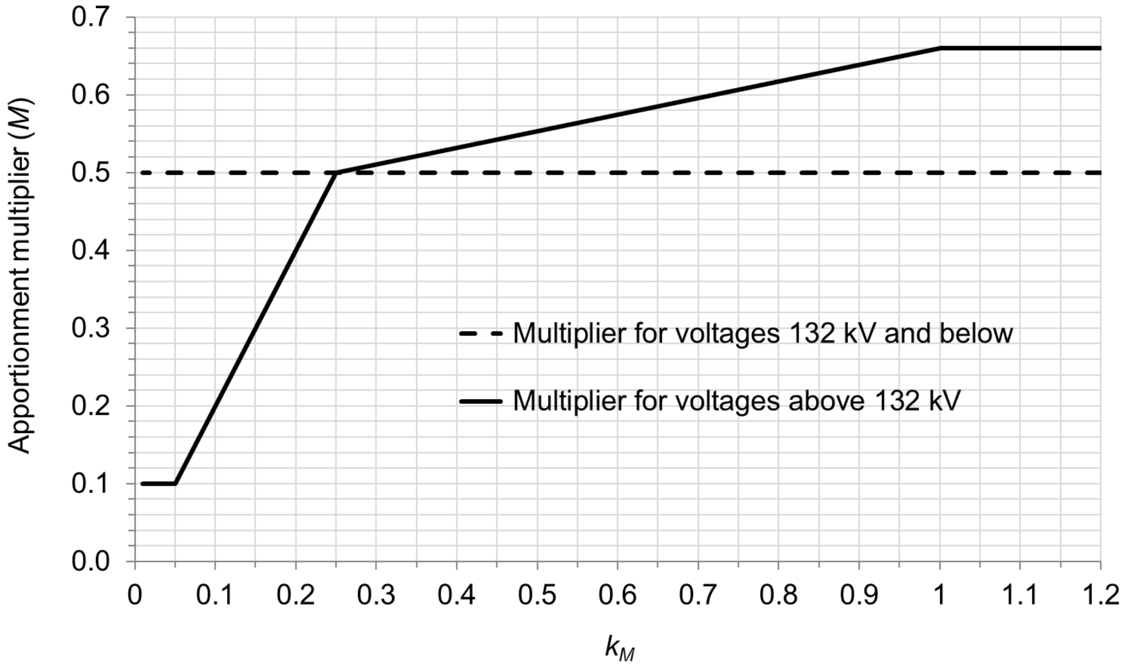


Figure 16 — Apportionment multiplier (*M*) versus k_M

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.

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

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

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

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

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 10.4.

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

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 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 connectee.

NOTE: $V_{h\ Limit\ Change}$ is inherent in the total harmonic voltage limit (see 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 connectee 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 connectee 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 connectee.

The connectee'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 connectee'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 connectee) 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 connectee'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 connectee 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 connectees 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	TBA	TBA	TBA
3	TBA	TBA	TBA
4	TBA	TBA	TBA
...	...	...	...
...	...	...	...
NOTE: All values apply at the PCC.			
[1)] Prior to connection of the connectee's plant and equipment. [2)] Due to harmonic emission of the connectee's plant and equipment.			

10.7 Definition of compliance

Compliance with the Stage 3 harmonic specification is achieved if the connectee 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 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 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 connectee 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 connectee is connected;

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

Data from the connectee'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 connectee, to a timescale agreed between the connectee 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.

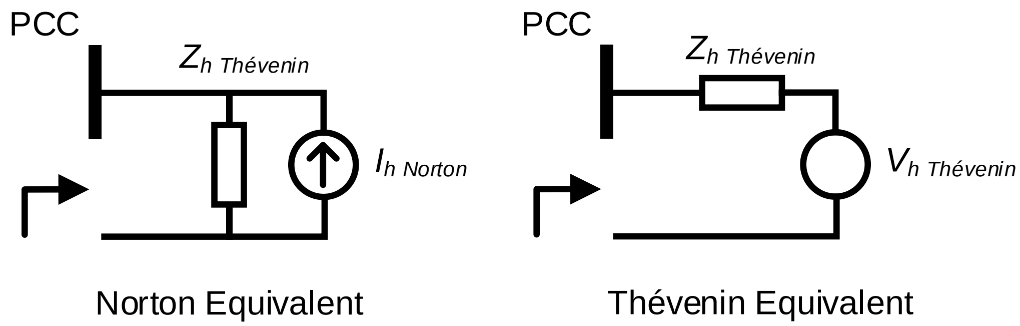


Figure 17 — Voltage and current source equivalents for the connectee

10.9 Verification of compliance

Compliance with the specified harmonic limits may be verified by harmonic measurements made by the host NO 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 connectee 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 connectee 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. 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.

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 connectee.

Once a connectee's installation is commissioned and fully operational, the connectee 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 connectee should be issued the harmonic specification before the previous connectee in the queue is commissioned – thus before the first connection becomes part of the network – then the harmonic voltage limits issued to the first connectee may be used to estimate the background harmonic level for the next connectee. 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 connectee, taking into account the limit issued to the first connectee;

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

The harmonic headroom at the PCC for the second connectee 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 connectee;

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

All other transferred headroom values from remote nodes shall also be corrected by the incremental limit issued to the first connectee, 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 connectee;
$H_{h\ n\ PCC\ 1}$	is the harmonic headroom at remote node *n* transferred to the PCC for the first connection, calculated according to (74).

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

where

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

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

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 connectee. 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 connectee.

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

The background harmonic level at all other remote nodes shall be modified to account for the incremental harmonic voltage limit issued to the first connectee ($V_{h\ Limit\ Inc\ 1}$) at the PCC of the first connectee. The incremental harmonic voltage limit issued to the first connectee is used, together with the harmonic transfer coefficients from the PCC of the first connectee to all other nodes ($T_{h\ PCC\ 1\ n}$), including the PCC of the second connectee, 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 10.4 of this document (using the adjusted harmonic headroom values).

When the first connectee 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 connectee's proposed installation should be included in the harmonic model when the new harmonic transfer coefficients from the PCC for the second connectee are calculated. In cases where the estimated impedance of the first connectee is not known, upon agreement between the second connectee and the NO hosting the connection, the second connectee may use the harmonic data which does not include the impedance of the first connectee 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 $I_{SCC} \geq$ 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

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.

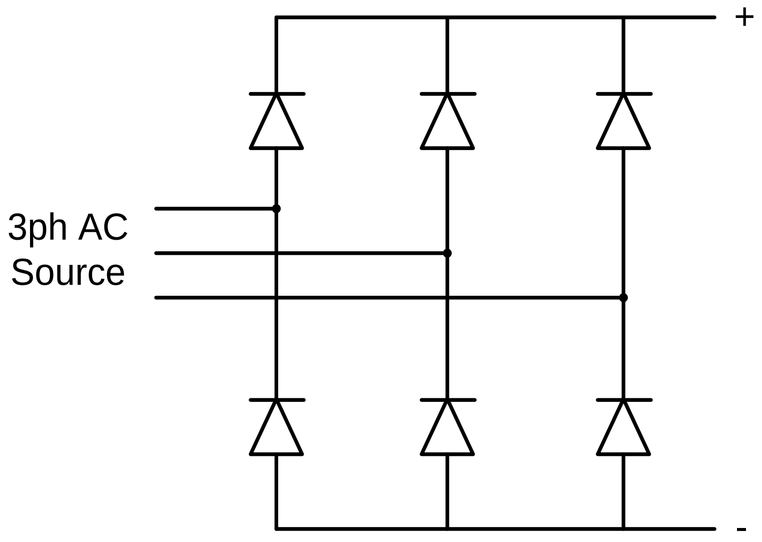


Figure B.1 — Six-pulse diode rectifier

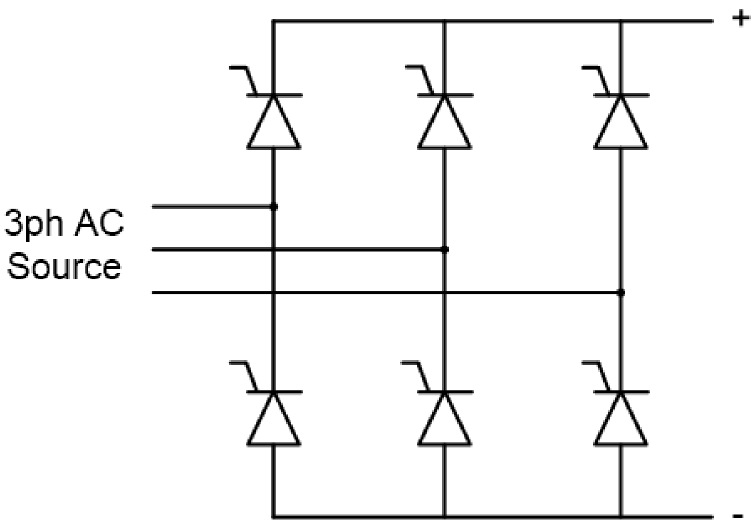


Figure B.2 — Six-pulse thyristor rectifier

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.

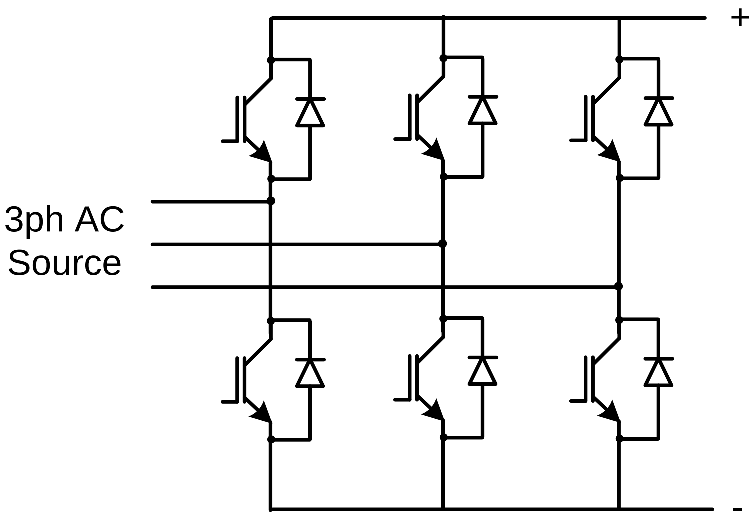


Figure B.3 — Active-front-end rectifier

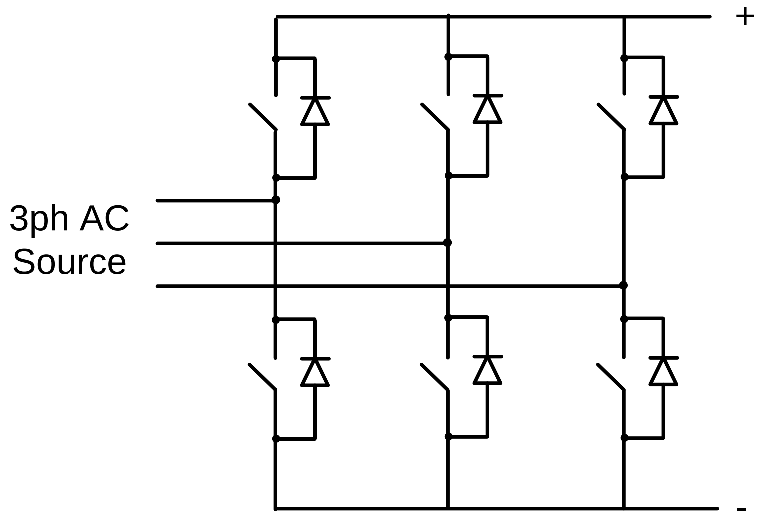


Figure B.4 — Simplified representation of active-front-end rectifier

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.

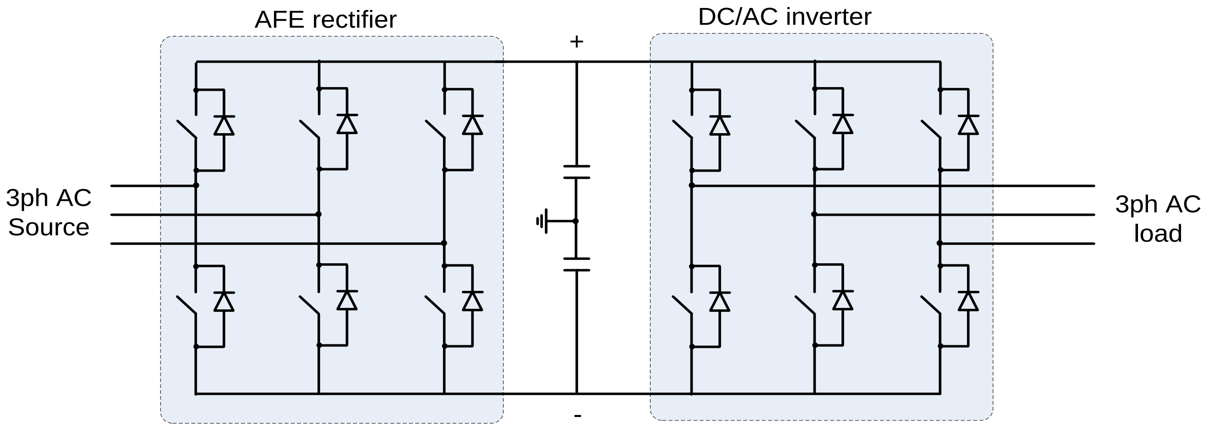


Figure B.5 — Active-front-end converter

Active-front-end converters produce currents with very low total harmonic current distortion
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.

A single-phase full-wave diode rectifier with smoothing capacitor is shown in Figure B.6. Odd harmonic emissions dominate, particularly the lower orders.

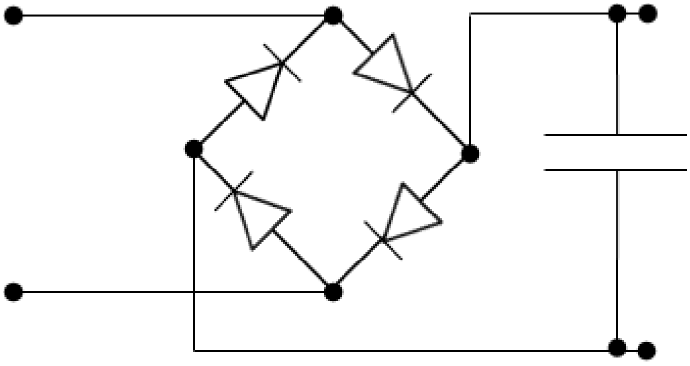
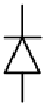
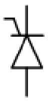
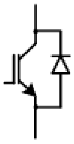


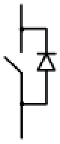
Figure B.6 — Single-phase full-wave diode rectifier

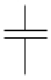
Key

 Diode

 Thyristor

 Insulated gate bipolar transistor (IGBT) with a freewheel diode

 IGBT represented as a switch

 Capacitor

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