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Background to Stage 1 and Stage 2

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Issue 1	August, 2018	Initial publication Details of all other technical, general and editorial amendments are included in the associated Document Amendment Summary for this Issue (available on request from the Operations Directorate of ENA)

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Introduction

This document provides the analytical foundation and justification for the calculations specified as part of the Stage 1 and Stage 2 assessments of ENA EREC G5 Issue 5.

Each assessment substage is considered in a separate chapter.

1 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.

ENA EREC G5 Issue 5, *Harmonic voltage distortion and the connection of non-linear and resonant plant and equipment to transmission systems and distribution networks in the United Kingdom*

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*

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* [1)]

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

[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.

2 Terms and definitions

For the purposes of this document, the following variable definitions apply:

Z_{ref} is the network reference impedance (Ω), derived from IEC TR 60725;

X_{ref} is the network reference reactance (Ω), derived from IEC TR 60725;

R_{ref} is the network reference resistance (Ω), derived from IEC TR 60725;

G_{hLV} is the permissible global harmonic voltage contribution at the PCC (% h = 1);

G_{hLVM} is the modified permissible global harmonic voltage contribution at the PCC (% h = 1);

Z_h is the network harmonic impedance (Ω) at harmonic order h, with Z_1 as the 50 Hz value;

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

k is the worst-case reactance factor (see **Error! Reference source not found.** of EREC G5 Issue 5);

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

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

I_h is the harmonic current emission of the connecting plant (A), with I_1 being the 50 Hz value;

V_{phase} is the rated phase–neutral voltage (V);

V_s is the rated phase–phase voltage at the PCC (V);

N_h is the maximum number of items of equipment that ensures that the summated voltage distortion does not exceed G_{hLVM} for each harmonic order h;

$F_{SCE\ Min}$ is the minimum short-circuit ratio factor from **Error! Reference source not found.** of EREC G5 Issue 5;

S_{SC} is the system short-circuit power (fault level) at the PCC (VA);

$S_{SC\ 3ph}$ 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);

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

I_{equ} is the equipment rated current (A);

$I_{h\ \%}$ is the harmonic current emission of the connecting plant (% h = 1);

$S_{equ\ n}$ is the equipment rated power (VA) for the *n*th item of plant or equipment;

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

$S_{SC\ Min\ n}$ is the minimum short-circuit power (MVA) at the PCC for the *n*th item of plant or equipment with a stated $S_{SC\ Min}$ as part of its compliance statement “Equipment Complying with IEC 61000-3-12 Subject to $S_{SC\ Min} \geq X$ kVA”;

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

$V_{h\ PL}$ is the planning level (% h = 1) for harmonic voltage at order h;

$V_{h\ headroom}$ is the available proportion of $V_{h\ PL}$, determined by subtracting a measured value of background harmonic voltage from the planning level or by allocating a proportion of the total planning level;

R_{sce} is the short-circuit ratio value of a piece of equipment;

T is the harmonic transfer coefficient from 11 kV to LV;

k_{sde} is the short-duration burst factor.

3 Background to Stage 1A

Under Stage 1A, equipment that is compliant with IEC 61000-3-2 is not subject to conditional connection. This is consistent with the intention behind the IEC 61000-3-2 standard and is further justified by analysis that has considered how many items compliant with the standard may connect before the voltage distortion created is excessive. The basis of this analysis is as follows.

- The PCC is LV.
- The impedance at the PCC is set at 0.8 × 0.6 of the reference impedance in IEC TR 60725, $Z_{ref} = R_{ref} + jX_{ref}$. Note that the reference impedances given in IEC TR 60725 – see Annex B of this document – refer to the supply terminals, not the PCC. The 0.8 and 0.6 factors are intended to reflect the difference between the supply terminals and the PCC as well as the distribution of equipment along the network.
- The network harmonic impedance, Z_h, envelope is derived from an impedance factor, k, equal to 1 for harmonic order $h \leq 7$ and equal to 0.5 for harmonic order $h > 7$, using the following equation:

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

where $R_1 = 0.8 \times 0.6 \times R_{ref}$ and $X_1 = 0.8 \times 0.6 \times X_{ref}$.

- Harmonic current emission is set at typical levels based on equipment type and rating – see Annex C of this document which gives one of the three emission profiles considered.
- Summation of harmonic voltages for multiple items of equipment is done using the following aggregation rule:

$$V_h = \sqrt[\alpha]{\sum_i V_{hi}^{\alpha}}$$

where α, the summation exponent, is equal to: 1 for $h < 5$; 1.4 for $5 \leq h \leq 10$; and 2 for $h > 10$.

- Permissible global emission, G_{hLV}, at the PCC is as shown in Annex A of this document.
- Modified global harmonic voltage contribution at the PCC, G_{hLVM}, is as explained in Annex A of this document.
- The voltage distortion for one item of equipment, at harmonic h, is calculated as follows:

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

- The maximum number of items of equipment, N_h, that ensures that the summated voltage distortion does not exceed G_{hLVM} for each harmonic is derived from:

$$N_h = \frac{G_{hLVM}^{\alpha}}{V_{h\,c}^{\alpha}}$$

which can be expressed as follows:

$$N_h = \frac{{G_{hLVM}}^{\alpha}}{\left(\frac{100}{230} I_h \sqrt{\left(R_1\sqrt{h}\right)^2 + k^2 h^2 X_1^2}\right)^{\alpha}}$$

Analysis of equipment with and without harmonic reduction technology indicated that the allocated voltage distortion limit is reached with 13–19 items, depending upon the assumptions made.

Calculation of N_h for each harmonic order for each harmonic current emission profile has been performed; the limiting harmonic for one case is the 3rd harmonic. This calculation is illustrated below.

$$N_h = \frac{4.0}{\left(\frac{100}{230} \times 1.48288 \times \sqrt{\left((0.8\times0.6\times0.4)\times\sqrt{3}\right)^2 + \left(1^2\times3^2\times(0.8\times0.6\times0.25)^2\right)}\right)} = 12.66 \approx 13$$

4 Background to Stage 1B

4.1 Background to Stage 1B-1

4.1.1 Derivation of Table 18 minimum short-circuit ratio factors

The following two subsections derive the equations that govern the $F_{SCE\,Min}$ factors in Table 18 of EREC G5 Issue 5 for single-phase and three-phase connections, respectively.

4.1.1.1 Single-phase

$$S_{SC} = \frac{V_{phase}{}^2}{Z_1} = \frac{V_{phase}{}^2}{\sqrt{R_1{}^2 + X_1{}^2}} = \frac{V_{phase}{}^2}{\mathrm{R}_1\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}}$$

$$R_1 = \frac{V_{phase}{}^2}{S_{SC}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}}$$

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

$$I_1 = \frac{I_{equ}}{\sqrt{1 + THD_I{}^2}}$$

$$I_h = \frac{I_{h\,\%}I_1}{100} = \frac{I_{h\,\%}I_{equ}}{100\sqrt{1 + THD_I{}^2}}$$

$$V_{h\,c} = \frac{100Z_hI_h}{V_{phase}}$$

$$V_{h\,c} = \frac{100\;\frac{V_{phase}{}^2}{S_{SC}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}}\sqrt{h + k^2h^2\left(\frac{X_1}{R_1}\right)^2}\;\frac{I_{h\,\%}I_{equ}}{100\sqrt{1 + THD_I{}^2}}}{V_{phase}} = \frac{S_{equ}I_{h\,\%}\sqrt{h + k^2h^2\left(\frac{X_1}{R_1}\right)^2}}{S_{SC}\sqrt{1 + THD_I{}^2}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}}$$

If the *j*th item of equipment complying with IEC 61000-3-12 produces voltage distortion $V_{h\,c\,j}$ (% h = 1) then, assuming each has the same $I_{h\,\%}$, X_1/R_1 and THD_I, then G_{hLVM} is given by:

$$G_{hLVM} = \sqrt[\alpha]{\sum_{j}^{M} V_{hc\,j}^{\ \alpha}} = \sqrt[\alpha]{\sum_{j}^{M}\left(\frac{S_{equ\,j}\, I_{h\,\%}\sqrt{h + k^2h^2\left(\frac{X_1}{R_1}\right)^2}}{S_{SC}\sqrt{1 + THD_I^{\,2}}\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}\right)^{\alpha}}$$

$$G_{hLVM} = \left(\frac{I_{h\,\%}\sqrt{h + k^2h^2\left(\frac{X_1}{R_1}\right)^2}}{S_{SC}\sqrt{1 + THD_I^{\,2}}\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}\right)\sqrt[\alpha]{\sum_{j}^{M} S_{equ\,j}^{\ \alpha}}\ \frac{S_{SC}}{\sqrt[\alpha]{\sum_j^M S_{equ\,j}^{\ \alpha}}}$$

$$\frac{S_{SC}}{\sqrt[\alpha]{\sum_j^M S_{equ\,j}^{\ \alpha}}} = \frac{I_{h\,\%}\sqrt{h + k^2h^2\left(\frac{X_1}{R_1}\right)^2}}{G_{hLVM\%}\sqrt{1 + THD_I^{\,2}}\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}} = \frac{F_{SCE\,Min}}{1000}$$

The above formula has been used to derive the $F_{SCE\,Min}$ factors in Table 18. In this derivation the limiting harmonic, h, for $M < 6$ is 12, for $6 \le M \le 7$ it is 6 and for $M > 7$ it is 3.

4.1.1.2 Three-phase

$$S_{SC} = \frac{V_s^{\,2}}{Z_1} = \frac{V_s^{\,2}}{\sqrt{R_1^{\,2} + X_1^{\,2}}} = \frac{V_s^{\,2}}{\mathrm{R}_1\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}$$

$$R_1 = \frac{V_s^{\,2}}{S_{SC}\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}$$

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

$$I_1 = \frac{I_{equ}}{\sqrt{1 + THD_I^{\,2}}}$$

$$I_h = \frac{I_{h\,\%}\, I_1}{100} = \frac{I_{h\,\%}\, I_{equ}}{100\sqrt{1 + THD_I^{\,2}}}$$

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

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

$$V_{h\,c} = \frac{100 \dfrac{{V_s}^2}{S_{SC}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}} \sqrt{h+k^2h^2\left(\frac{X_1}{R_1}\right)^2} \dfrac{I_{h\,\%} I_{equ}}{100\sqrt{1+THD_I^2}}}{V_s} = \frac{S_{equ} I_{h\,\%}\sqrt{h+k^2h^2\left(\frac{X_1}{R_1}\right)^2}}{S_{SC}\sqrt{1+THD_I^2}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}}$$

Thus, the formula is equivalent to that for single-phase equipment.

4.1.2 Example calculation

M = 6; h = 6; k = 1; α = 1.4; X_1/R_1 = 0.625 for I_{SCC} < 100 A; $G_{6LVM\,\%}$ = 0.4857; $I_{6\,\%}$ = 2.6667; THD_I = 0.23 pu.

NOTE: The $I_{6\,\%}$ and THD_I values are taken from Table 2 of IEC 61000-3-12.

$$\frac{F_{SCE\,Min}}{1000} = \frac{I_{h\,\%}\sqrt{h+k^2h^2\left(\frac{X_1}{R_1}\right)^2}}{G_{hLVM\,\%}\sqrt{1+THD_I^2}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}} = \frac{2.6667\sqrt{6+1^2 6^2 0.625^2}}{0.4857\sqrt{1+0.23^2}\sqrt{1+0.625^2}} = 20.324$$

4.2 Background to Stage 1B-2 Equation 9

The “Equipment Complying with IEC 61000-3-12” is based on $S_{SC\ PCC}$ / S_{equ} = 33, which forms the basis of the first term, $S_{SC\,PCC\,Min} = 33\sum_{m=1}^{M} S_{equ\,m}$, in Equation 9.

NOTE: The coefficient value 33 is taken from IEC 61000-3-12.

The second term in Equation 9 is derived as follows:

$$\frac{S_{SC\,Min}}{\sqrt[\alpha]{\sum_n^N {S_{equ\,n}}^{\alpha}}} = \frac{I_{h\,\%}\sqrt{h+k^2h^2\left(\frac{X_1}{R_1}\right)^2}}{G_{hLVM\,\%}\sqrt{1+THD_I^2}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}}$$

$$S_{SC\ Min} = \frac{I_{h\ \%}\sqrt{h + k^2 h^2 \left(\frac{X_1}{R_1}\right)^2}\ \sqrt[\alpha]{\sum_n^N S_{equ\ n}{}^{\alpha}}}{G_{hLVM\ \%}\sqrt{1 + THD_I{}^2}\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}$$

Assuming α = 1:

$$S_{SC\ Min} = \frac{I_{h\ \%}\sqrt{h + k^2h^2\left(\frac{X_1}{R_1}\right)^2}\ \sum_n^N S_{equ\ n}}{G_{hLVM\ \%}\sqrt{1 + THD_I^{\ 2}}\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}$$

$$S_{SC\ Min\ n} = \frac{I_{h\ \%}\sqrt{h + k^2h^2\left(\frac{X_1}{R_1}\right)^2}\ S_{equ\ n}}{G_{hLVM\ \%}\sqrt{1 + THD_I^{\ 2}}\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}$$

$$S_{SC\ Min} = \sum_{n=1}^{N} S_{SC\ Min\ n}$$

This is the second term in Equation 9.

5 Background to Stage 1C

5.1 Background to Stage 1C-1 Table 19

Assumptions:

- PCC is LV.
- Network harmonic impedance, Z_h, envelope is derived from impedance factor, k, equal to 1 for harmonic order $h \leq 7$ and 0.5 for $h > 7$:

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

  where X_1/R_1 ratio is set at 1 for three-phase converters and 0.625 for the single-phase rectifier – see Annex B for the basis of these ratios.

- Harmonic current emission is set at typical levels for each converter technology type – see Annex C of this document.
- Permissible voltage distortion emission is set at 1/4 of 25% of the LV planning levels for three-phase connections and 1/2 of 25% of the planning levels for single-phase connections. For the three-phase case, this is based on assuming 15 pieces of existing disturbing equipment resulting in voltage distortion at 75% of the planning levels, thus leaving five items to produce the remaining 25%, taken together with a coincidence factor of 0.9. With a coincidence factor of 0.9, the five pieces equate to four, based on 0.9 × 5, rounded down to four. For single-phase connections, this is based on assuming six pieces of existing disturbing equipment resulting in voltage distortion at 75% of the planning levels, leaving two items to produce the remaining 25%, taken together with a coincidence factor of 1.
- Summation of harmonic voltages for multiple items of equipment is done using a summation exponent, α, of unity:

$$V_h = \sqrt[\alpha]{\sum_i V_{hi}^{\alpha}} = \sum_i V_{hi}$$

- The aggregate permitted equipment rated power (VA), $\sum S_{equ\ permitted}$, for a three-phase connection is calculated as follows:

$$\sum S_{equ\ permitted} = \frac{\frac{1}{4}\ 25\%\ V_{h\ PL}\ S_{SC\ PCC}\sqrt{1 + THD_I^{\,2}}\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}{I_{h\ \%}\sqrt{h + k^2 h^2 \left(\frac{X_1}{R_1}\right)^2}}$$

- The corresponding single-phase aggregate permitted equipment rated power (VA), $\sum S_{equ\ permitted}$, is calculated by:

$$\sum S_{equ\ permitted} = \frac{\frac{1}{2}\ 25\%\ V_{h\ PL}\ S_{SC\ PCC}\sqrt{1+THD_I^2}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}}{I_{h\ \%}\sqrt{h+k^2h^2\left(\frac{X_1}{R_1}\right)^2}}$$

5.1.1 Derivation of Table 19 value for three-phase six-pulse converters

We will calculate the permitted aggregate equipment rated power, $\sum S_{equ\ permitted}$, for a three-phase six-pulse converter.

Calculation of $\sum S_{equ\ permitted}$ for the reference LV short-circuit power of 10 MVA has been performed for each harmonic order; the limiting harmonic has been found to be the 5th harmonic for six-pulse technology. The Table 19 value is based on the following calculation:

$$\sum S_{equ\ permitted} = \frac{\frac{1}{4}\ 25\%\ V_{h\ PL}\ S_{SC\ PCC}\sqrt{1+THD_I^2}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}}{I_{h\ \%}\sqrt{h+k^2h^2\left(\frac{X_1}{R_1}\right)^2}}$$

$$\sum S_{equ\ permitted} = \frac{\frac{1}{4}\times 0.25\times 4\%\times 10\ \text{MVA}\sqrt{1+0.3441^2}\sqrt{1+1^2}}{31.4\%\ \sqrt{5+1^2\times 5^2\times 1^2}} = 21.74\ \text{kVA}$$

5.1.2 Derivation of Table 19 value for three-phase active-front-end converters

We will calculate the permitted aggregate equipment rated power, $\sum S_{equ\ permitted}$, for a three-phase active-front-end converter.

Calculation of $\sum S_{equ\ permitted}$ for the reference LV short-circuit power of 10 MVA has been performed for each harmonic order; the limiting harmonic has been found to be the 5th harmonic for active-front-end technology. The Table 19 value is based on the following calculation:

$$\sum S_{equ\ permitted} = \frac{\frac{1}{4}\ 25\%\ V_{h\ PL}\ S_{SC\ PCC}\sqrt{1+THD_I^2}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}}{I_{h\ \%}\sqrt{h+k^2h^2\left(\frac{X_1}{R_1}\right)^2}}$$

$$\sum S_{equ\ permitted} = \frac{\frac{1}{4}\times 0.25\times 4\%\times 10\ \text{MVA}\sqrt{1+0.038067^2}\sqrt{1+1^2}}{3.37\%\ \sqrt{5+1^2\times 5^2\times 1^2}} = 191.68\ \text{kVA}$$

5.1.3 Derivation of Table 19 value for three-phase twelve-pulse converters

We will calculate the permitted aggregate equipment rated power, $\sum S_{equ\ permitted}$, for a three-phase twelve-pulse converter.

Calculation of $\sum S_{equ\ permitted}$ for the reference LV short-circuit power of 10 MVA has been performed for each harmonic order; the limiting harmonic has been found to be the 37th harmonic for twelve-pulse technology. This reflects the assumed harmonic emission profile, the assumed current summation exponent, the assumed harmonic impedance and the voltage distortion planning level for each harmonic used in the calculation. Although we would expect the 11th harmonic to be the limiting case, calculation shows that this gives a less onerous value – 86 kVA compared with 77 kVA for the 37th harmonic; indeed, the 23rd, 25th, 35th harmonics are also all more onerous than the 11th harmonic case.

The Table 19 value is based on the following calculation:

$$\sum S_{equ\ permitted} = \frac{\frac{1}{4}\ 25\%\ V_{h\ PL}\ S_{SC\ PCC}\sqrt{1 + THD_I^2}\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}{I_{h\ \%}\sqrt{h + k^2 h^2 \left(\frac{X_1}{R_1}\right)^2}}$$

$$\sum S_{equ\ permitted} = \frac{\frac{1}{4} \times 0.25 \times 0.6757\% \times 10\ \text{MVA}\sqrt{1 + 0.05957^2}\sqrt{1 + 1^2}}{0.4\%\ \sqrt{37 + 0.5^2 \times 37^2 \times 1^2}} = 76.81\ \text{kVA}.$$

5.1.4 Derivation of Table 19 value for single-phase rectifiers

We will calculate the permitted aggregate equipment rated power, $\sum S_{equ\ permitted}$, for a single-phase rectifier.

Calculation of $\sum S_{equ\ permitted}$ for the reference LV short-circuit single-phase power of 2 MVA has been performed for each harmonic order; the limiting harmonic has been found to be the 21st harmonic for single-phase rectifier technology. The Table 19 value is based on the following calculation:

$$\sum S_{equ\ permitted} = \frac{\frac{1}{2}\ 25\%\ V_{h\ PL}\ S_{SC\ PCC}\sqrt{1 + THD_I^2}\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}{I_{h\ \%}\sqrt{h + k^2 h^2 \left(\frac{X_1}{R_1}\right)^2}}$$

$$\sum S_{equ\ permitted} = \frac{\frac{1}{2} \times 0.25 \times 0.2\% \times 2\ \text{MVA}\sqrt{1 + 0.87693^2}\sqrt{1 + 0.625^2}}{1.24\%\ \sqrt{21 + 0.5^2 \times 21^2 \times 0.625^2}} = 7.9\ \text{kVA}.$$

5.2 Background to Stage 1C-2 Equation 12

As per above, the limiting harmonic for six-pulse and active-front-end converters has been found to be the 5th harmonic. This has allowed the derivation of Equation 12 based on the following assumptions:

- PCC is LV.
- Network harmonic impedance, Z_h, envelope is derived from an impedance factor, k, equal to 1 for harmonic order $h \leq 7$ and 0.5 for $h > 7$:

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

  where X_1/R_1 ratio is set at 1.

- Harmonic current emission is set at typical levels for each converter technology type – see Annex C of this document.
- Permissible voltage distortion emission is set at 1/4 of 25% of the LV planning levels for three-phase connections. This is based on assuming 15 pieces of existing disturbing equipment resulting in voltage distortion at 75% of the planning level, thus leaving five items to produce the remaining 25%, taken together with a coincidence factor of 0.9. With a coincidence factor of 0.9, the five pieces equate to four, based on 0.9 × 5, rounded down to four.
- Summation of harmonic voltages for multiple items of equipment is done using a summation exponent, α, of unity:

  $$V_h = \sqrt[\alpha]{\sum_i V_{hi}^{\alpha}} = \sum_i V_{hi}$$

- The equation for calculating the minimum short-circuit power at the PCC ($S_{SC\ PCC\ Min}$), Equation 12, is derived as follows:

$$S_{SC\ PCC\ Min} = \frac{\sum_{j=1}^{J} S_{equ_j}\, I_{h_j\,\%}\sqrt{h + k^2h^2\left(\frac{X_1}{R_1}\right)^2}}{\frac{1}{4}\ 25\%\ V_{h\ PL}\sqrt{1 + THD_{I_j}{}^2}\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}} + \frac{\sum_{k=1}^{K} S_{equ_k}\, I_{h_k\,\%}\sqrt{h + k^2h^2\left(\frac{X_1}{R_1}\right)^2}}{\frac{1}{4}\ 25\%\ V_{h\ PL}\sqrt{1 + THD_{I_k}{}^2}\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}$$

$$S_{SC\ PCC\ Min} = \frac{\sum_{j=1}^{J} S_{equ_j} \times 31.4\% \times \sqrt{5 + 1^2 5^2 1^2}}{\frac{1}{4} \times 0.25 \times 4\% \sqrt{1 + 0.3441^2}\sqrt{1 + 1^2}} + \frac{\sum_{k=1}^{K} S_{equ_k} \times 3.37\% \times \sqrt{5 + 1^2 5^2 1^2}}{\frac{1}{4} \times 0.25 \times 4\% \sqrt{1 + 0.038067^2}\sqrt{1 + 1^2}}$$

$$S_{SC\ PCC\ Min} = 459.977 \sum_{j=1}^{J} S_{equ_j} + 52.170\ \sum_{k=1}^{K} S_{equ_k}$$

6 Background to Stage 1D

6.1 Background to Stage 1D-1

The following formulae have been used in the derivation of the values in Table 19.

- The aggregate permitted equipment rated power (VA), $\sum S_{equ\ permitted}$, for a three-phase connection is calculated as follows:

$$\sum S_{equ\ permitted} = \frac{\frac{1}{4}\ 25\%\ V_{h\ PL}\ S_{SC\ PCC}\sqrt{1+THD_I^2}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}}{I_{h\ \%}\sqrt{h+k^2h^2\left(\frac{X_1}{R_1}\right)^2}}$$

- The corresponding single-phase $\sum S_{equ\ permitted}$ is calculated by:

$$\sum S_{equ\ permitted} = \frac{\frac{1}{2}\ 25\%\ V_{h\ PL}\ S_{SC\ PCC}\sqrt{1+THD_I^2}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}}{I_{h\ \%}\sqrt{h+k^2h^2\left(\frac{X_1}{R_1}\right)^2}}$$

The calculations assume a reference 10 MVA value for the short-circuit power term, $S_{SC\ PCC}$, for the three-phase cases and a reference 2 MVA value for the single-phase case. So, to adjust the Table 19 values for a site-specific short-circuit power, the Table 19 value must be divided by the appropriate assumed value and multiplied by the site-specific short-circuit power.

The Table 19 calculations assume headroom of 25% of the planning level for the limiting harmonic. So, to adjust the Table 19 values for site-specific headroom, the Table 19 value must be divided by 25% of the planning level and multiplied by the site-specific headroom. This is the basis of Equations 13, 15 and 17 in Stage 1D-1, as detailed in EREC G5 Issue 5.

6.2 Background to Stage 1D-2 Equation 19

In deriving Equation 19, the headroom is set at 25% of the planning level for the 5th harmonic.

$S_{SC\ PCC\ Min}$ can be written as:

$$S_{SC\ PCC\ Min} = \frac{\sum_{j=1}^{J} S_{equ_j}\, I_{hj\ \%}\sqrt{h+k^2h^2\left(\frac{X_1}{R_1}\right)^2}}{\frac{1}{4}V_{h\ headroom}\sqrt{1+THD_{I_j}{}^2}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}} + \frac{\sum_{k=1}^{K} S_{equ_k}\, I_{hk\ \%}\sqrt{h+k^2h^2\left(\frac{X_1}{R_1}\right)^2}}{\frac{1}{4}V_{h\ headroom}\sqrt{1+THD_{I_k}{}^2}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}}$$

With h = 5 this becomes:

$$S_{SC\ PCC\ Min} = \frac{\sum_{j=1}^{J} S_{equ_j} \times 31.4\% \times \sqrt{5 + 1^2 5^2 1^2}}{\frac{1}{4} \times V_{5\ headroom} \sqrt{1 + 0.3441^2} \sqrt{1 + 1^2}} + \frac{\sum_{k=1}^{K} S_{equ_k} \times 3.37\% \times \sqrt{5 + 1^2 5^2 1^2}}{\frac{1}{4} \times V_{5\ headroom} \sqrt{1 + 0.038067^2} \sqrt{1 + 1^2}}$$

$$S_{SC\ PCC\ Min} = \frac{459.977 \sum_{j=1}^{J} S_{equ_j} + 52.170 \ \sum_{k=1}^{K} \mathrm{S}_{\mathrm{equ_k}}}{V_{5\ headroom}}$$

7 Background to Stage 2A

7.1 Background to Stage 2A-1 Table 21

Assumptions:

- PCC is 11 kV.
- Network harmonic impedance, Z_h, envelope derived from impedance factor, k, is equal to 2 for harmonic order $h \leq 8$ and 1 for $h > 8$:

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

  where X_1/R_1 ratio is set at 8.

- Harmonic current emission is set at typical levels for each converter technology type – see Annex C of this document.
- Permissible voltage distortion emission is set at 1/2 of 25% of the LV planning levels for a three-phase connection. This is based on assuming ten pieces of existing disturbing equipment resulting in voltage distortion at 75% of the planning level, leaving 0.25 × 10 items to give the remaining 25%, taken together with a coincidence factor of 0.9. With a 0.9 coincidence factor, the 0.25 × 10 pieces equate to two, based on 0.9 × 0.25 × 10 rounded down to two.
- Summation of harmonic voltages for multiple items of equipment is done using a summation exponent, α, of unity:

$$V_h = \sqrt[\alpha]{\sum_i V_{hi}^{\alpha}} = \sum_i V_{hi}$$

- The aggregate permitted equipment rated power (VA), $\sum S_{equ\ permitted}$, is calculated as follows:

$$\sum S_{equ\ permitted} = \frac{\frac{1}{2}\ 25\%\ V_{h\ PL}\ S_{SC\ PCC}\sqrt{1 + THD_I^2}\ \sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}{I_{h\ \%}\ \sqrt{h + k^2 h^2 \left(\frac{X_1}{R_1}\right)^2}}$$

7.1.1 Derivation of Table 21 value for three-phase six-pulse converters

We will calculate the permitted aggregate equipment rated power, $\sum S_{equ\ permitted}$, for a three-phase six-pulse converter.

Calculation of $\sum S_{equ\ permitted}$ for the 6.6/11/20/22 kV PCC with reference short-circuit power of 60 MVA has been performed for each harmonic order; the limiting harmonic has been found to be the 5th harmonic for six-pulse technology. The Table 21 value is based on the following calculation:

$$\sum S_{equ\ permitted} = \frac{\frac{1}{2}\ 25\%\ V_{h\ PL}\ S_{SC\ PCC}\sqrt{1+THD_I^2}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}}{I_{h\ \%}\sqrt{h+k^2h^2\left(\frac{X_1}{R_1}\right)^2}}$$

$$\sum S_{equ\ permitted} = \frac{\frac{1}{2}\times 0.25\times 3\%\times 60\ \text{MVA}\sqrt{1+0.3441^2}\sqrt{1+(8)^2}}{31.4\%\ \sqrt{5+2^2 5^2 (8)^2}} = 76.34\ \text{kVA}$$

7.1.2 Derivation of Table 21 value for three-phase active-front-end converters

We will calculate the permitted aggregate equipment rated power, $\sum S_{equ\ permitted}$, for a three-phase active-front-end converter.

Calculation of $\sum S_{equ\ permitted}$ for the 6.6/11/20/22 kV PCC with reference short-circuit power of 60 MVA has been performed for each harmonic order; the limiting harmonic has been found to be the 5th harmonic for active-front-end technology. The Table 21 value is based on the following calculation:

$$\sum S_{equ\ permitted} = \frac{\frac{1}{2}\ 25\%\ V_{h\ PL}\ S_{SC\ PCC}\sqrt{1+THD_I^2}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}}{I_{h\ \%}\sqrt{h+k^2h^2\left(\frac{X_1}{R_1}\right)^2}}$$

$$\sum S_{equ\ permitted} = \frac{\frac{1}{2}\times 0.25\times 3\%\times 60\ \text{MVA}\sqrt{1+0.038067^2}\sqrt{1+(8)^2}}{3.37\%\ \sqrt{5+2^2 5^2 (8)^2}} = 673\ \text{kVA}$$

7.1.3 Derivation of Table 21 value for three-phase twelve-pulse converters

We will calculate the permitted aggregate equipment rated power, $\sum S_{equ\ permitted}$, for a three-phase twelve-pulse converter.

Calculation of $\sum S_{equ\ permitted}$ for the 6.6/11/20/22 kV PCC with reference short-circuit power of 60 MVA has been performed for each harmonic order; the limiting harmonic has been found to be the 11th harmonic for twelve-pulse technology. The Table 21 value is based on the following calculation:

$$\sum S_{equ\ permitted} = \frac{\frac{1}{2}\ 25\%\ V_{h\ PL}\ S_{SC\ PCC}\sqrt{1+THD_I^2}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}}{I_{h\ \%}\sqrt{h+k^2h^2\left(\frac{X_1}{R_1}\right)^2}}$$

$$\sum S_{equ\ permitted} = \frac{\frac{1}{2}\times 0.25\times 2\%\times 60\ \text{MVA}\sqrt{1+0.05957^2}\sqrt{1+(8)^2}}{4.8\%\ \sqrt{11+1^2 11^2 (8)^2}} = 286.61\ \text{kVA}$$

7.2 Background to Stage 2A-2 Equation 23

As per Stage 1, the limiting harmonic for six-pulse and active-front-end converters has been found to be the 5th harmonic. This has allowed the derivation of Equation 23 based on the following assumptions:

- PCC is 11 kV.
- Network harmonic impedance, Z_h, envelope is derived from an impedance factor, k, equal to 2 for harmonic order $h \le 8$ and 1.0 for $h > 8$:

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

  where X_1/R_1 ratio is set at 8.
- Harmonic current emission is set at typical levels for each converter technology type – see Annex C of this document.
- Permissible voltage distortion emission is set at 1/2 of 25% of the LV planning levels for a three-phase connection. This is based on assuming ten pieces of existing disturbing equipment resulting in voltage distortion at 75% of the planning level, leaving 0.25 × 10 items to provide the remaining 25%, taken together with a coincidence factor of 0.9. With a 0.9 coincidence factor, the 0.25 × 10 pieces equate to two, based on 0.9 × 0.25 × 10 rounded down to two.
- Summation of harmonic voltages for multiple items of equipment is done using a summation exponent, α, of unity:

  $$V_h = \sqrt[\alpha]{\sum_i V_{hi}^{\alpha}} = \sum_i V_{hi}$$

- The equation for calculating the minimum short-circuit power at the PCC ($S_{SC\ PCC\ Min}$), for mixed three-phase converter technology (i.e. a mix of six-pulse and active-front-end technology), Equation 23, is derived as follows:

$$S_{SC\ PCC\ Min} = \frac{\sum_{j=1}^{J} S_{equ_j}\, I_{h_j\,\%} \sqrt{h + k^2h^2\left(\frac{X_1}{R_1}\right)^2}}{\frac{1}{2} V_{h\ PL} \sqrt{1 + THD_{I_j}{}^2} \sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}} + \frac{\sum_{k=1}^{K} S_{equ_k}\, I_{h_k\,\%} \sqrt{h + k^2h^2\left(\frac{X_1}{R_1}\right)^2}}{\frac{1}{2} V_{h\ PL} \sqrt{1 + THD_{I_k}{}^2} \sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}$$

$$S_{SC\ PCC\ Min} = \frac{\sum_{j=1}^{J} S_{equ_j} \times 31.4\% \times \sqrt{5 + 2^2 5^2 8^2}}{\frac{1}{2} \times 0.25 \times 3\% \sqrt{1 + 0.3441^2} \sqrt{1 + 8^2}} + \frac{\sum_{k=1}^{K} S_{equ_k} \times 3.37\% \times \sqrt{5 + 2^2 5^2 8^2}}{\frac{1}{2} \times 0.25 \times 3\% \sqrt{1 + 0.038067^2} \sqrt{1 + 8^2}}$$

$$S_{SC\ PCC\ Min} = 785.962 \sum_{j=1}^{J} S_{equ_j} + 89.143 \sum_{k=1}^{K} S_{equ_k}$$

8 Background to Stage 2B

8.1 Background to Stage 2B-1

The following formulae has been used to derive the values in Table 21:

$$\sum S_{equ\ permitted} = \frac{\frac{1}{2}\ 25\%\ V_{h\ PL}\ S_{SC\ PCC}\sqrt{1+THD_I^{\ 2}}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}}{I_{h\ \%}\sqrt{h+k^2h^2\left(\frac{X_1}{R_1}\right)^2}}$$

The calculations assume a reference 60 MVA value for the short-circuit power term, $S_{SC\ PCC}$. To adjust the Table 21 values for site-specific short-circuit power, the Table 21 value must be divided by the appropriate assumed value and multiplied by the site-specific short-circuit power.

The Table 21 calculations assume headroom of 25% of the planning level for the limiting harmonic. So, to adjust the Table 21 values for site-specific headroom, the Table 21 value must be divided by 25% of the planning level and multiplied by the site-specific headroom. This is the basis of Equations 24 and 26 in Stage 2B-1.

8.2 Background to Stage 2B-2 Equation 28

In deriving Equation 28 for the minimum short-circuit power at the PCC, $S_{SC\ PCC\ Min}$, the headroom is set at 25% of the planning level for the 5th harmonic.

$$S_{SC\ PCC\ Min} = \frac{\sum_{j=1}^{J} S_{equ_j}\, I_{h_j\ \%}\sqrt{h+k^2h^2\left(\frac{X_1}{R_1}\right)^2}}{\frac{1}{2}V_{h\ headroom}\sqrt{1+THD_{I_j}^{\ 2}}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}} + \frac{\sum_{k=1}^{K} S_{equ_k}\, I_{h_k\ \%}\sqrt{h+k^2h^2\left(\frac{X_1}{R_1}\right)^2}}{\frac{1}{2}V_{h\ headroom}\sqrt{1+THD_{I_k}^{\ 2}}\sqrt{1+\left(\frac{X_1}{R_1}\right)^2}}$$

With $h = 5$, current emissions at their previously assumed values and the X_1/R_1 ratio of 8, this becomes:

$$S_{SC\ PCC\ Min} = \frac{\sum_{j=1}^{J} S_{equ_j} \times 31.4\% \times \sqrt{5+2^2 5^2 8^2}}{\frac{1}{2}\times V_{5\ headroom}\sqrt{1+0.3441^2}\sqrt{1+8^2}} + \frac{\sum_{k=1}^{K} S_{equ_k} \times 3.37\% \times \sqrt{5+2^2 5^2 8^2}}{\frac{1}{2}\times V_{5\ headroom}\sqrt{1+0.038067^2}\sqrt{1+8^2}}$$

$$S_{SC\ PCC\ Min} = \frac{589.472\sum_{j=1}^{J} S_{equ_j} + 66.857\ \sum_{k=1}^{K} S_{equ_k}}{V_{5\ headroom}}$$

9 Background to Stage 2C

9.1 Background to Stage 2C Equation 30

The network impedance at the PCC will vary with frequency and hence harmonic order. The harmonic impedance, Z_h, comprises resistive and reactive components. The magnitude of the harmonic impedance is given in Equation 30 and is derived as shown below.

$$Z_h = R_h + jX_h$$

$$|Z_h| = \sqrt{R_h{}^2 + X_h{}^2}$$

$$R_h = R_1\sqrt{h}$$

NOTE: The $\sqrt{h}$ term accounts for skin effect.

$$X_h = khX_1$$

NOTE: Reactance is proportional to frequency and hence harmonic order. The reactance factor, k, accounts for possible resonance.

$$|Z_h| = \sqrt{(R_1\sqrt{h})^2 + (khX_1)^2} = \sqrt{(R_1\sqrt{h})^2 + k^2h^2X_1{}^2}$$

Figures 1 and 2 in this document, below, depict how the harmonic impedance, Z_h, (Ω) varies with harmonic order using the above equation for LV and 11 kV cases using X_1/R_1 ratios of 1 and 8, respectively.

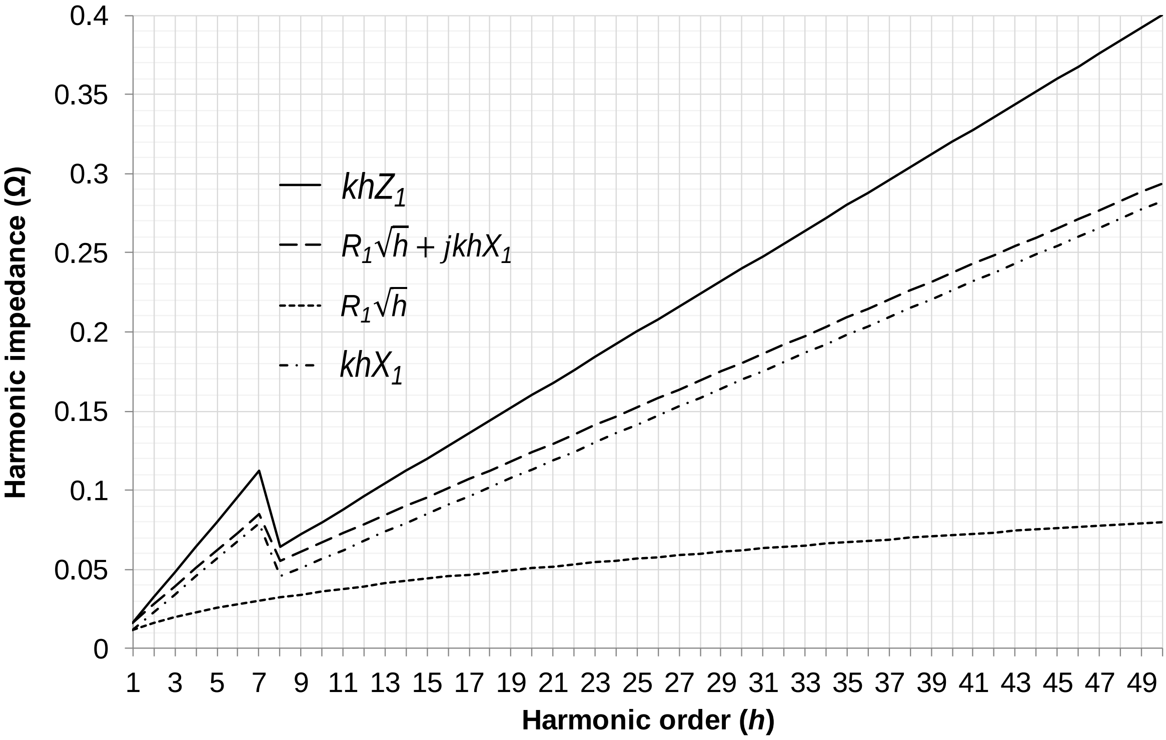

Figure 1 — Harmonic impedance versus harmonic order for LV (X_1/R_1 = 1, $S_{SC\ PCC}$ = 10 MVA)

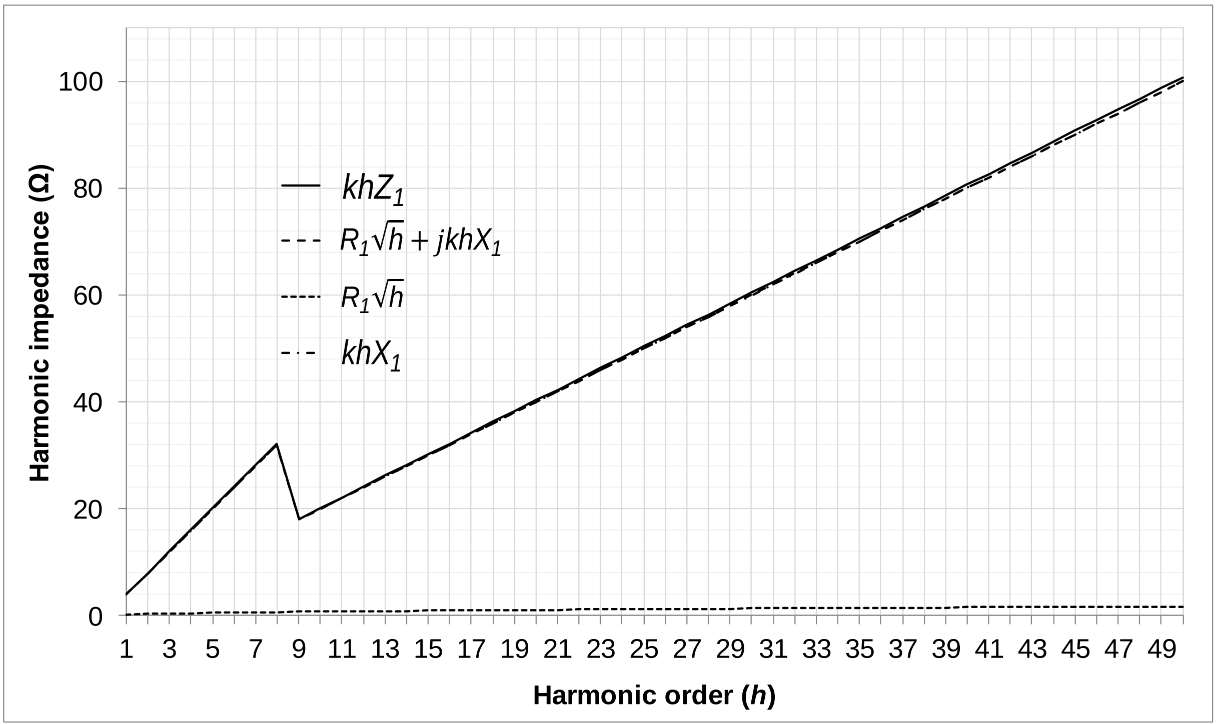

Figure 2 — Harmonic impedance versus harmonic order for 11 kV (X_1/R_1 = 8, $S_{SC\ PCC}$ = 60 MVA)

9.2 Background to Stage 2C Equations 36 and 40

The following subsections explain the derivations of Equations 36 and 40 for the incremental voltage distortion, $V_{h\,c}$, due to harmonic current I_h.

9.2.1 Three-phase connection

We derive the incremental increase in harmonic voltage distortion due to the proposed disturbing plant or equipment ($V_{h\,c}$) as a percentage of the phase–phase voltage (V_s) for a three-phase connection at the PCC as follows.

$$S_{SC\ 3ph} = \frac{V_s^{\,2}}{Z_1} = \frac{V_s^{\,2}}{\sqrt{R_1^{\,2} + X_1^{\,2}}} = \frac{V_s^{\,2}}{R_1\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}$$

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

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

$$I_1 = \frac{I_{equ}}{\sqrt{1+THD_I^{\,2}}}$$

$$I_h = \frac{I_{h\,\%}\, I_1}{100} = \frac{I_{h\,\%}\, I_{equ}}{100\sqrt{1+THD_I^{\,2}}}$$

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

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

$$V_{h\,c} = \frac{100\sqrt{3}\,\dfrac{V_s^{\,2}}{S_{SC\,3ph}\sqrt{1+\left(\dfrac{X_1}{R_1}\right)^2}}\sqrt{h+k^2h^2\left(\dfrac{X_1}{R_1}\right)^2}\,\dfrac{I_{h\,\%}\, I_{equ}}{100\sqrt{1+THD_I^{\,2}}}}{V_s}$$

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

9.2.2 Single-phase connection

We derive the incremental increase in harmonic voltage distortion due to the proposed disturbing plant or equipment ($V_{h\,c}$) as a percentage of the phase–neutral voltage (V_{phase}) for a single-phase connection at the PCC as follows.

$$S_{SC\,1ph} = \frac{V_{phase}^{\,2}}{Z_1} = \frac{V_{phase}^{\,2}}{\sqrt{R_1^{\,2}+X_1^{\,2}}} = \frac{V_{phase}^{\,2}}{R_1\sqrt{1+\left(\dfrac{X_1}{R_1}\right)^2}}$$

$$R_1 = \frac{V_{phase}^{\,2}}{S_{SC\,1ph}\sqrt{1+\left(\dfrac{X_1}{R_1}\right)^2}}$$

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

$$I_1 = \frac{I_{equ}}{\sqrt{1+THD_I^2}}$$

$$I_h = \frac{I_{h\ \%}\ I_1}{100} = \frac{I_{h\ \%}\ I_{equ}}{100\sqrt{1+THD_I^2}}$$

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

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

$$V_{h\ c} = \frac{100\sqrt{3}\ \dfrac{V_{phase}^{\ 2}}{S_{SC\ 1ph}\sqrt{1+\left(\dfrac{X_1}{R_1}\right)^2}}\sqrt{h+k^2h^2\left(\dfrac{X_1}{R_1}\right)^2}\ \dfrac{I_{h\ \%}\ I_{equ}}{100\sqrt{1+THD_I^2}}}{V_{phase}}$$

$$V_{h\ c} = \frac{S_{equ\ 1ph} I_{h\ \%}\sqrt{h+k^2h^2\left(\dfrac{X_1}{R_1}\right)^2}}{S_{SC\ 1ph}\sqrt{1+THD_I^2}\sqrt{1+\left(\dfrac{X_1}{R_1}\right)^2}}$$

10 Background to Table 14 and Table 15

10.1 Background to Table 14

Assumptions:

- The PCC is LV.
- The short-duration burst factor, k_{sde}, is given by Equation 5 of EREC G5 Issue 5, where it is defined as equal to $1.3 + 0.7/45 \times (h - 5)$.
- The network harmonic impedance, Z_h, envelope is derived using an impedance factor, k, equal to 1 for harmonic order $h \leq 7$ and 0.5 for $h > 7$:

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

  X_1/R_1 ratio set is at 1.
- Harmonic current emission levels are set at typical values for soft-starter technology – see Annex C of this document.
- Permissible voltage distortion emission is set at k_{sde} minus 0.75 times the LV planning level; this equates to the difference between the short-duration planning level and an assumed background of 75% of the planning level. It is assumed that short-duration harmonics will not coincide with those from other customers.
- Summation of harmonic voltages for multiple items of equipment is done using a summation exponent, α, of unity:

  $$V_h = \sqrt[\alpha]{\sum_i V_{hi}^{\alpha}} = \sum_i V_{hi}$$
- The aggregate permitted equipment rated power (VA), $\sum S_{equ\ permitted}$, is calculated as follows:

  $$\sum S_{equ\ permitted} = \frac{(k_{sde} - 0.75)\ V_{h\ PL}\ S_{SC\ PCC}\sqrt{1 + THD_I^{\,2}}\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}{I_{h\ \%}\sqrt{h + k^2h^2\left(\frac{X_1}{R_1}\right)^2}}$$

Calculation of $\sum S_{equ\ permitted}$ for the reference LV short-circuit power of 10 MVA has been performed for each harmonic order; the limiting harmonic for soft-starter technology has been found to be the 5th harmonic. The Table 14 value is based on the following calculation:

$$\sum S_{equ\ permitted} = \frac{(k_{sde} - 0.75)V_{h\ PL}\ S_{SC\ PCC}\sqrt{1 + THD_I^{\,2}}\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}{I_{h\ \%}\sqrt{h + k^2h^2\left(\frac{X_1}{R_1}\right)^2}}$$

$$\sum S_{equ\ permitted} = \frac{(1.3 + 0.7/45 \times (h - 5) - 0.75) V_{h\ PL}\ S_{SC\ PCC} \sqrt{1 + THD_I^2} \sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}{I_{h\ \%} \sqrt{h + k^2 h^2 \left(\frac{X_1}{R_1}\right)^2}}$$

$$\sum S_{equ\ permitted} = \frac{(1.3 + 0.7/45 \times (5 - 5) - 0.75) \times 4\% \times 10\ \text{MVA} \sqrt{1 + 0.1961^2} \sqrt{1 + (1)^2}}{18.43\%\ \sqrt{5 + 1^2 5^2 1^2}}$$

$$\sum S_{equ\ permitted} = 314\ \text{kVA}$$

10.2 Background to Table 15

Assumptions:

- The PCC voltage is greater than 0.4 kV and less than or equal to 25 kV.
- The short-duration burst factor, k_{sde}, is given by Equation 5 of EREC G5 Issue 5, where it is defined as equal to 1.3 + 0.7/45 × (h – 5).
- The network harmonic impedance, Z_h, envelope is derived using an impedance factor, k, equal to 2 for harmonic order $h \leq 8$ and 1 for $h > 8$:

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

  X_1/R_1 ratio set is at 8.
- Harmonic current emission levels are set at typical values for soft-starter technology – see Annex C of this document.
- Permissible voltage distortion emission is set at k_{sde} – 0.75 times the LV planning level; this equates to the difference between the short-duration planning level and an assumed background of 75% of the planning level. It is assumed that short-duration harmonics will not coincide with those from other customers.
- Summation of harmonic voltages for multiple items of equipment is done using a summation exponent, α, of unity:

  $$V_h = \sqrt[\alpha]{\sum_i V_{hi}^{\alpha}} = \sum_i V_{hi}$$
- The aggregate permitted equipment rated power (VA), $\sum S_{equ\ permitted}$, is calculated as follows:

$$\sum S_{equ\ permitted} = \frac{(k_{sde} - 0.75)\ V_{h\ PL}\ S_{SC\ PCC} \sqrt{1 + THD_I^2} \sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}{I_{h\ \%} \sqrt{h + k^2 h^2 \left(\frac{X_1}{R_1}\right)^2}}$$

Calculation of $\sum S_{equ\ permitted}$ for the reference short-circuit power of 60 MVA, for PCC voltage greater than 0.4 kV and less than or equal to 25 kV, has been performed for each harmonic order; the limiting harmonic for soft-starter technology has been found to be the 5th harmonic. The Table 15 value is based on the following calculation:

$$\sum S_{equ\ permitted} = \frac{(k_{sde} - 0.75)V_{h\ PL}\ S_{SC\ PCC}\sqrt{1 + THD_I^2}\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}{I_{h\ \%}\sqrt{h + k^2h^2\left(\frac{X_1}{R_1}\right)^2}}$$

$$\sum S_{equ\ permitted} = \frac{(1.3 + 0.7/45 \times (h - 5) - 0.75)V_{h\ PL}\ S_{SC\ PCC}\sqrt{1 + THD_I^2}\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}{I_{h\ \%}\sqrt{h + k^2h^2\left(\frac{X_1}{R_1}\right)^2}}$$

$$\sum S_{equ\ permitted} = \frac{(1.3 + 0.7/45 \times (5 - 5) - 0.75) \times 3\% \times 60\ \text{MVA}\sqrt{1 + 0.1961^2}\sqrt{1 + (8)^2}}{18.43\%\ \sqrt{5 + 2^2 5^2 8^2}}$$

$$\sum S_{equ\ permitted} = 552\ \text{kVA}$$

Annex A
(informative)

Derivation of modified global harmonic voltage contribution, G_{hLVM}

The global harmonic voltage contribution, G_{hLV}, after consideration of transfer from upstream, is given by:

$$G_{hLV} = \sqrt[\alpha]{PL_{hLV}^{\alpha} - (T \cdot PL_{h11\,kV})^{\alpha}}$$

where the harmonic transfer coefficient, T, from 11 kV to LV is assumed to be unity.

Table A1 shows the global harmonic voltage contribution, G_{hLV}, together with the modified global harmonic voltage contribution, G_{hLVM}, which has been increased in order to, where possible, take account of factors that may allow for a higher contribution (e.g. for triplens trapped by a delta winding or where 11 kV levels are unlikely to reach planning levels).

Table A1 — Three-phase derivation of allocated G_{hLV}

h	PL_{LV} %	$PL_{11\,kV}$ %	G_{hLV} V	G_{hLV} % PL_{LV}	Allocated G_{hLV} % PL_{LV}	Reason	Modified G_{hLV} (G_{hLVM})
3	4	3	1.000	25.00	100.00	Delta winding	4.00
5	4	3	1.818	45.45	45.45		1.82
7	4	3	1.818	45.45	45.45		1.82
9	1.2	1.2	0.000	0.00	100.00	Delta winding	1.20
11	3	2	2.236	74.54	74.54		2.24
13	2.5	2	1.500	60.00	60.00		1.50
15	0.3	0.3	0.000	0.00	100.00	Delta winding	0.30
17	1.6	1.6	0.000	0.00	25.00	Assumes we can have LV at 1.66%	0.40
19	1.2	1.2	0.000	0.00	25.00	Assumes we can have LV at 1.24%	0.30
21	0.2	0.2	0.000	0.00	100.00	Delta winding	0.20
23	1.2	1.2	0.000	0.00	25.00	Assumes we can have LV at 1.24%	0.30
25	0.7	0.7	0.000	0.00	25.00	Assumes we can have LV at 0.723%	0.18
27	0.2	0.2	0.000	0.00	100.00	Delta winding	0.20
29	0.6810345	0.6310345	0.256	37.61	37.61		0.26
31	0.6532258	0.6032258	0.251	38.37	38.37		0.25
33	0.2	0.2	0.000	0.00	100.00	Delta winding	0.20
35	0.6071429	0.5571429	0.241	39.74	39.74		0.24
37	0.5878378	0.5378378	0.237	40.36	40.36		0.24

39	0.2	0.2	0.000	0.00	100.00	Delta winding	0.20
2	1.5	1.5	0.000	96.67	96.67	Assumes $V_{h\,c}$ from upstream of 0.05%	1.45
4	1	1	0.000	95.00	95.00	Assumes $V_{h\,c}$ from upstream of 0.05%	0.95
6	0.5	0.5	0.000	97.14	97.14	Assumes $V_{h\,c}$ from upstream of 0.05%	0.49
8	0.4	0.4	0.000	96.08	96.08	Assumes $V_{h\,c}$ from upstream of 0.05%	0.38
10	0.4	0.4	0.000	96.08	96.08	Assumes $V_{h\,c}$ from upstream of 0.05%	0.38
12	0.2	0.2	0.000	96.82	96.82	Assumes $V_{h\,c}$ from upstream of 0.05%	0.19
14	0.2	0.2	0.000	96.82	96.82	Assumes $V_{h\,c}$ from upstream of 0.05%	0.19
16	0.2	0.2	0.000	96.82	96.82	Assumes $V_{h\,c}$ from upstream of 0.05%	0.19
18	0.2	0.2	0.000	96.82	96.82	Assumes $V_{h\,c}$ from upstream of 0.05%	0.19
20	0.2	0.2	0.000	96.82	96.82	Assumes $V_{h\,c}$ from upstream of 0.05%	0.19
22	0.2	0.2	0.000	96.82	96.82	Assumes $V_{h\,c}$ from upstream of 0.05%	0.19
24	0.2	0.2	0.000	96.82	96.82	Assumes $V_{h\,c}$ from upstream of 0.05%	0.19
26	0.2	0.2	0.000	96.82	96.82	Assumes $V_{h\,c}$ from upstream of 0.05%	0.19
28	0.2	0.2	0.000	96.82	96.82	Assumes $V_{h\,c}$ from upstream of 0.05%	0.19
30	0.2	0.2	0.000	96.82	96.82	Assumes $V_{h\,c}$ from upstream of 0.05%	0.19
32	0.2	0.2	0.000	96.82	96.82	Assumes $V_{h\,c}$ from upstream of 0.05%	0.19
34	0.2	0.2	0.000	96.82	96.82	Assumes $V_{h\,c}$ from upstream of 0.05%	0.19
36	0.2	0.2	0.000	96.82	96.82	Assumes $V_{h\,c}$ from upstream of 0.05%	0.19
38	0.2	0.2	0.000	96.82	96.82	Assumes $V_{h\,c}$ from upstream of 0.05%	0.19
40	0.2	0.2	0.000	96.82	96.82	Assumes $V_{h\,c}$ from upstream of 0.05%	0.19

Annex B
(informative)

Reference impedances

Table B1 — LV network reference impedances, Z_{ref}, based on IEC TR 60725 values

Connection phases	Reference source impedance, Z_{ref}	
	< 100 A service capacity	≥ 100 A service capacity
1	0.4 + j0.25 Ω	0.25 + j0.25 Ω
3	0.24 + j0.15 Ω	0.15 + j0.15 Ω

Annex C
(informative)

Current emission assumptions

C.1 Three-phase equipment

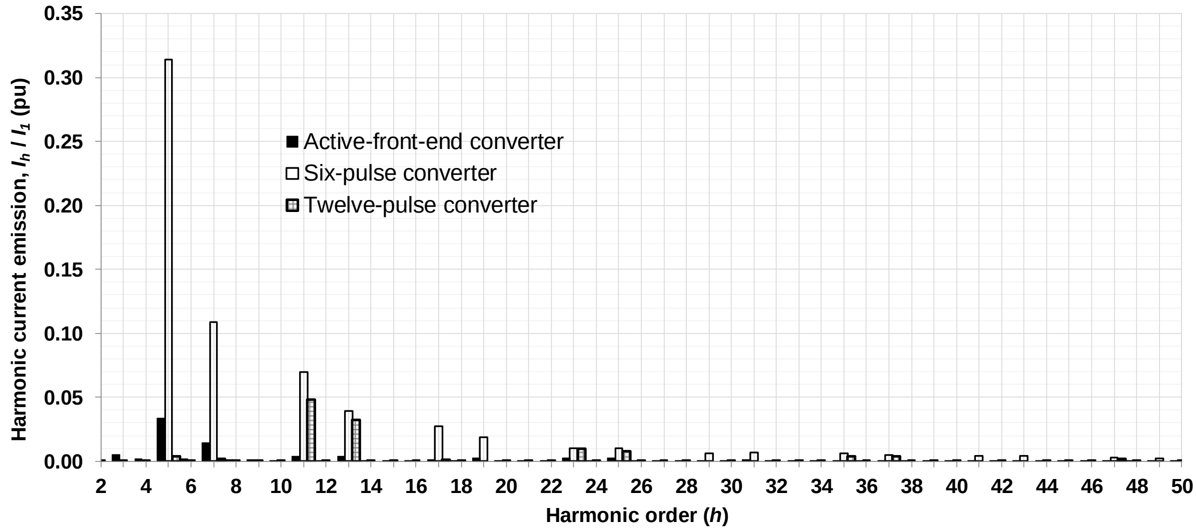

Figure C1 — Chart of current emission assumptions for three-phase equipment types

Table C1 — Harmonic current emission assumptions for three-phase equipment types

Harmonic *order* (*h*)	Active-front-end (I_h/I_1) pu	Six-pulse (I_h/I_1) pu	Twelve-pulse (I_h/I_1) pu
2	0.004	0.000	0.000
3	0.005	0.000	0.000
4	0.002	0.000	0.000
5	0.034	0.314	0.004
6	0.002	0.000	0.000
7	0.015	0.109	0.002
8	0.001	0.000	0.000
9	0.001	0.000	0.000
10	0.001	0.000	0.000
11	0.004	0.070	0.048
12	0.001	0.000	0.000
13	0.004	0.039	0.032
14	0.000	0.000	0.000
15	0.001	0.000	0.000
16	0.000	0.000	0.000

17	0.001	0.027	0.001
18	0.000	0.000	0.000
19	0.002	0.019	0.000
20	0.000	0.000	0.000
21	0.001	0.000	0.000
22	0.001	0.000	0.000
23	0.002	0.010	0.010
24	0.000	0.000	0.000
25	0.002	0.010	0.008
26	0.001	0.000	0.000
27	0.001	0.000	0.000
28	0.001	0.000	0.000
29	0.001	0.006	0.000
30	0.000	0.000	0.000
31	0.001	0.007	0.000
32	0.000	0.000	0.000
33	0.000	0.000	0.000
34	0.000	0.000	0.000
35	0.001	0.006	0.004
36	0.000	0.000	0.000
37	0.001	0.005	0.004
38	0.000	0.000	0.000
39	0.000	0.000	0.000
40	0.000	0.000	0.000
41	0.000	0.004	0.000
42	0.000	0.000	0.000
43	0.000	0.004	0.000
44	0.000	0.000	0.000
45	0.000	0.000	0.000
46	0.000	0.000	0.000
47	0.000	0.003	0.002
48	0.000	0.000	0.000
49	0.000	0.002	0.000
50	0.000	0.000	0.000
THD_I	0.0381	0.3441	0.0596

C.2 Single-phase equipment

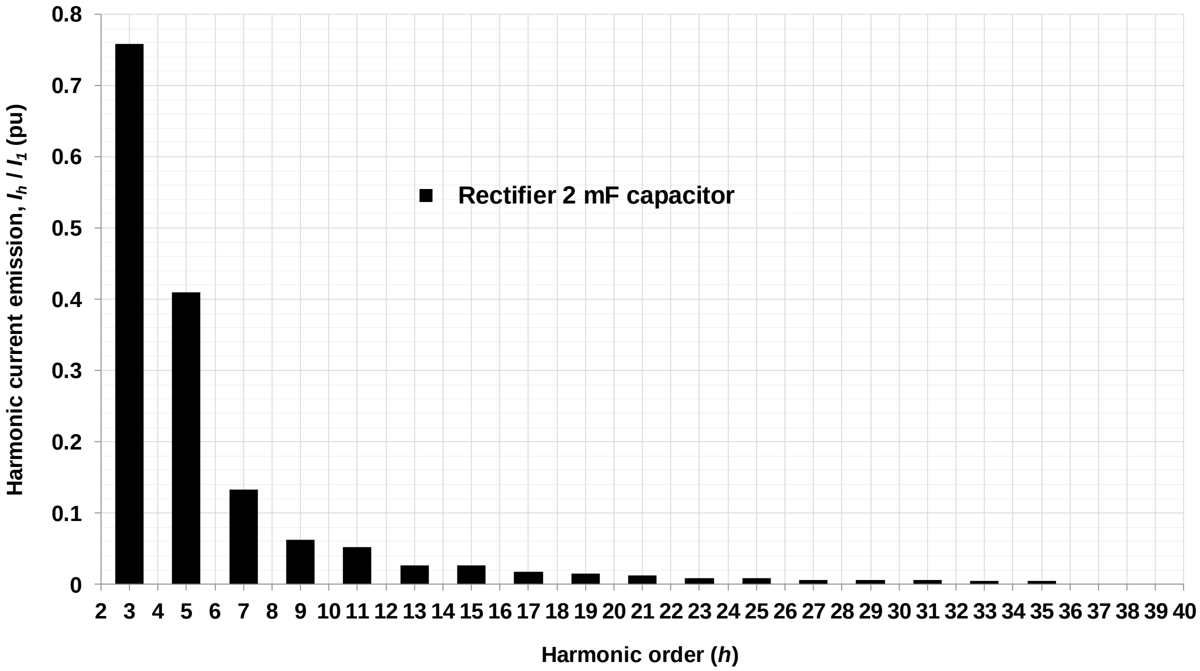

Figure C2 — Chart of current emission assumptions for a single-phase rectifier

Table C2 — Harmonic current emission assumptions for a single-phase rectifier

Harmonic order (*h*)	**Rectifier (2 mF capacitor) I_h/I_1 pu**	**Harmonic order (*h*)**	**Rectifier (2 mF capacitor) I_h/I_1 pu**
2	—	20	—
3	0.7578	21	0.0124
4	—	22	—
5	0.4097	23	0.009
6	—	24	—
7	0.1329	25	0.0089
8	—	26	—
9	0.0622	27	0.0066
10	—	28	—
11	0.0526	29	0.0063
12	—	30	—
13	0.0265	31	0.0054
14	—	32	—
15	0.0261	33	0.0046
16	—	34	—
17	0.0172	35	0.0044
18	—	36–50	—
19	0.0144		
20	—	THD_I	0.8769

C.3 Soft-starters

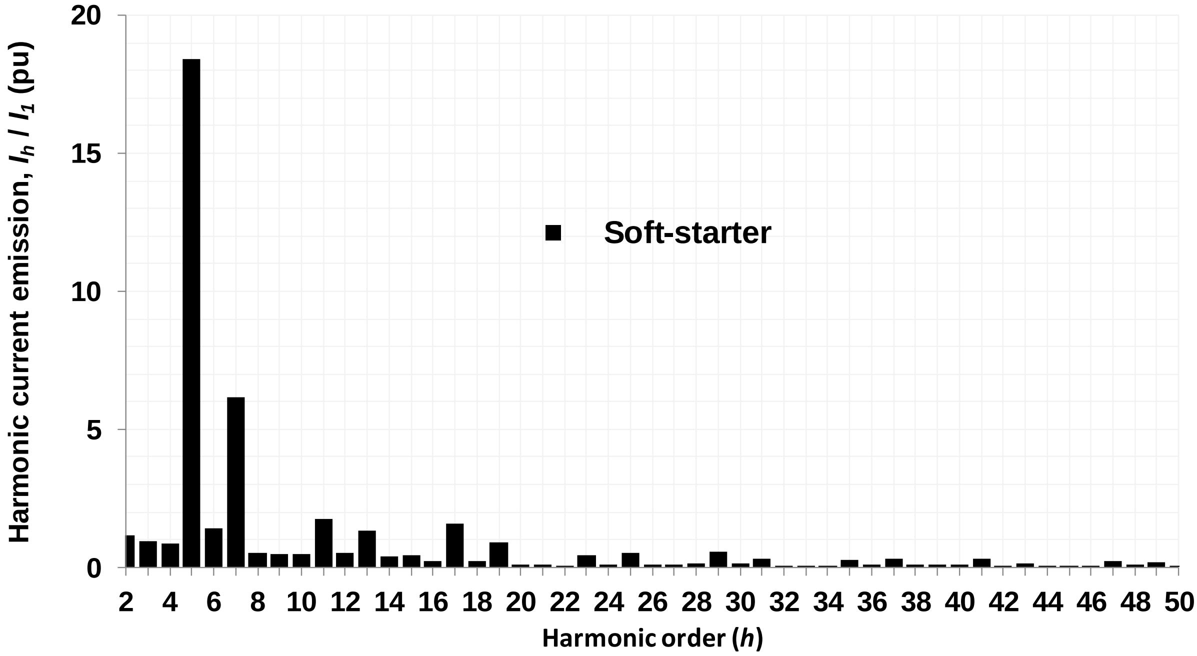

Figure C3 — Chart of current emission assumptions for a soft-starter

Table C3 — Harmonic current emission assumptions for a soft-starter

Harmonic order (h)	Soft-starter I_h/I_1 pu	Harmonic order (h)	Soft-starter I_h/I_1 pu
2	0.011652	27	0.001004
3	0.009489	28	0.001344
4	0.008451	29	0.005735
5	0.184253	30	0.001216
6	0.014341	31	0.003028
7	0.061543	32	0.000448
8	0.005412	33	0.00073
9	0.004961	34	0.000384
10	0.004622	35	0.002831
11	0.017488	36	0.001024
12	0.005085	37	0.002962
13	0.013174	38	0.000832
14	0.003775	39	0.000821
15	0.004314	40	0.00096
16	0.002241	41	0.003028
17	0.015747	42	0.000768
18	0.002305	43	0.001418
19	0.009021	44	0.000575
20	0.00096	45	0.000547
21	0.000912	46	0.000448
22	0.000512	47	0.002059
23	0.004545	48	0.000832
24	0.001152	49	0.001802
25	0.005405	50	0.000704
26	0.001152	THD_I	0.1961