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Engineering Recommendation G5

Issue 5 2018

Worked examples of Stage 1 and Stage 2 connections

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Amendments since publication

Issue	**Date**	**Amendment**
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 comprises 19 worked examples of connections to the public supply system that are subject to harmonic assessment at Stages 1 and 2.

Each connection example forms one chapter, following this introduction and list of normative references, and progresses sequentially through the logic of the flowcharts for the relevant Stage(s), as presented in ENA EREC G5 Issue 5.

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.

BS EN 61851-21-1, *Electric vehicle conductive charging system — Electric vehicle on-board charger EMC requirements for conductive connection to an AC/DC supply*

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 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)]

UN ECE-R10, *United Nations European Commission for Europe (UNECE) — Uniform provisions concerning the approval of vehicles with regard to electromagnetic compatibility*

[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 Summary of worked examples

Table E1 summarises the connection data for the 19 worked examples that are solved in this document based on application of EREC G5 to connections made at 22 kV and below.

Table E1 — Connection data for Worked Examples 1–19

Ex.	Equipment	Rating kVA	Rating A	No. of phases	Harmonic statement	PCC voltage	Service current capacity (I_{SCC})	Final stage
1	Heat Pump	3.0	13.04	1	IEC 61000-3-2 compliant	LV	< 100 A	1A
2	2 x Heat Pump	1 x 3.0	13.04	1	IEC 61000-3-2 compliant	LV	< 100 A	1A
		1 x 3.0	13.04	1	IEC 61000-3-2 compliant			
3	Heat Pump	9.2	40	1	IEC 61000-3-12 compliant	LV	< 100 A	1B-1
4	2 x Heat Pump	10	14.43	3	IEC 61000-3-12 compliant	LV	≥ 100 A	1B-1
		34	49.07	3	IEC 61000-3-12 compliant			
5	EV Charge Point	7.36	32	1	—	LV	< 100 A	1B-1
6	EV Rapid DC Output (Mode 4) Charger	50	72.17	3	IEC 61000-3-12 compliant subject to $S_{SC\ MIN}$ = 2.0 MVA	LV	≥ 100 A	1B-2
	EV Charge Point	22	32.00	3	IEC 61000-3-12 compliant			
7	Active Front-end Motor Drive	70	101.04	3	—	LV	≥ 100 A	1C-1
8	Rectifier	4	17.39	1	—	LV	< 100 A	1C-1
9	6-Pulse AC/DC Motor Drive	20	28.87	3	—	LV	≥ 100 A	1C-2
	Active Front-end Motor Drive	70	101.04	3	—			
10	Active Front-end Motor Drive	104	150	3	—	LV	≥ 100 A	1D-1
11	6-Pulse AC/DC Motor	20	28.87	3	—	LV	≥ 100 A	1D-2

	Drive							
	Active Front-end Motor Drive	70	101.04	3	—			
12	6-Pulse AC/DC Motor Drives	50	72.17	3	—	11 kV	—	2A-1
		30	43.30	3	—			
13	6-Pulse AC/DC Motor Drive	2 x 50	2 x 72.17	3	—	11 kV	—	2A-2
	Active Front-end Motor Drive	1 x 200	1 x 288.68	3	—			
14	6-Pulse AC/DC Motor Drives	2 x 50	2 x 72.17	3	—	11 kV	—	2B-1
		1 x 30	1 x 43.30	3	—			
15	6-Pulse AC/DC Motor Drive	100	144.34	3	—	11 kV	—	2B-2
	Active Front-end Motor Drive	500	721.69	3	—			
16	6-Pulse Motor Drive	80	115.47	3	Current emission data available	LV	—	2C via 1D-1
17	6-Pulse AC/DC Motor Drives	1 x 100	1 x 144.34	3	Current emission data available	6.6 kV	—	2C
		5 x 20	5 x 28.87	3	Current emission data available			
18	Professional Equipment	12	17.32	3	Current emission data available	LV	< 100 A	2C via 1C
19	Kiln	7.4	32.17	1	Current emission data available	LV	< 100 A	2C via 1C

3 Worked Example 1

Table E2 — Connection data for Worked Example 1

Example	Equipment	Rating kVA	Rating A	No. of phases	Harmonic statement	PCC voltage	Final stage
1	Heat Pump	3.0	13.04	1	IEC 61000-3-2 compliant	LV	1A

3.1 Step 1

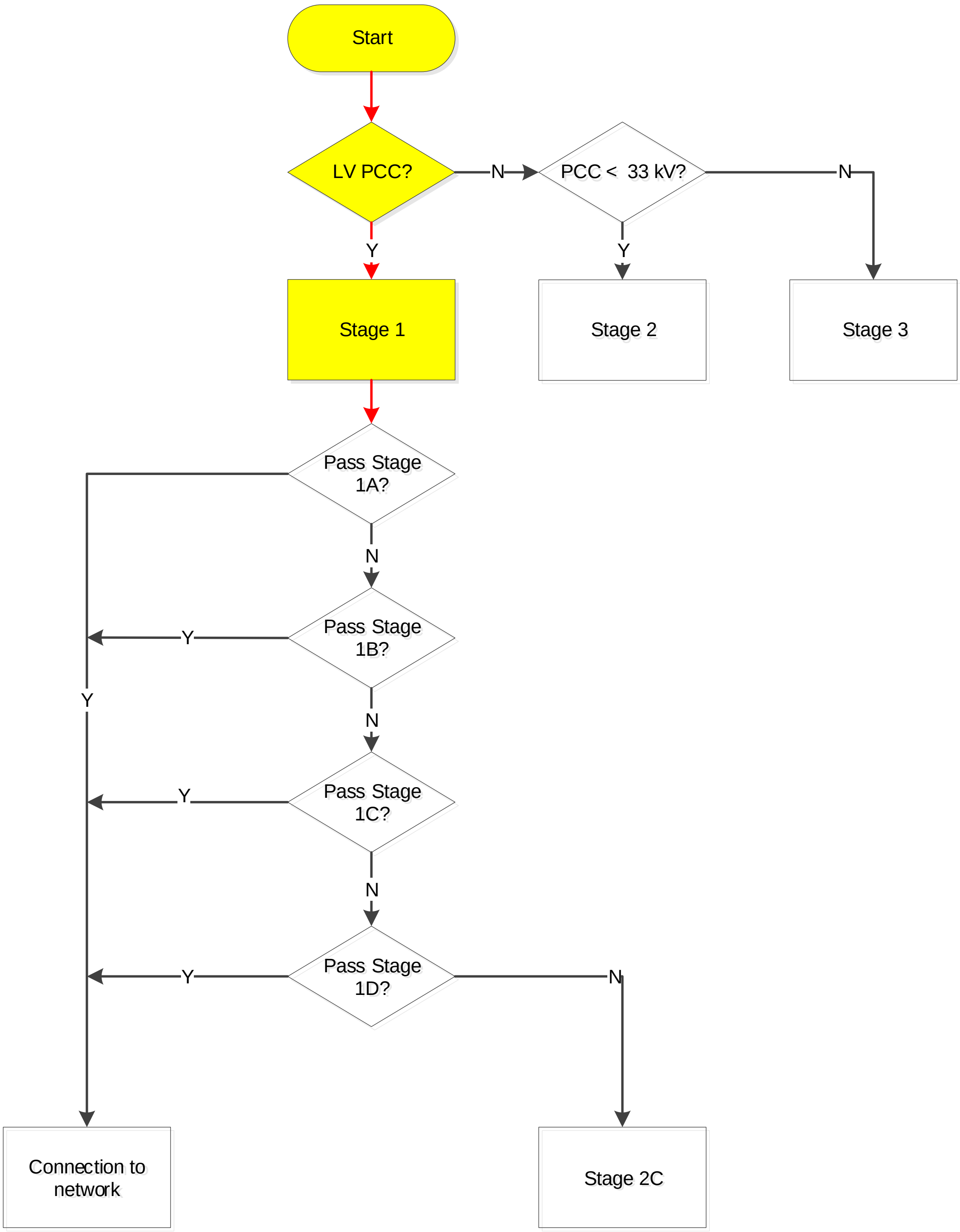

Figure E1 — Step 1 for Worked Example 1

3.2 Step 2

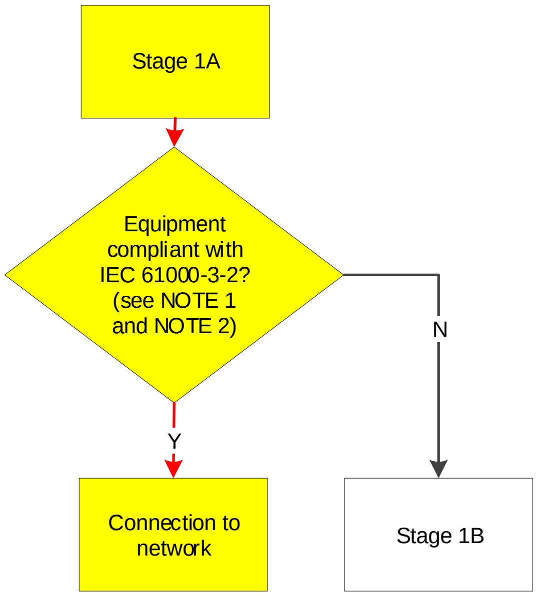

Figure E2 — Step 2 for Worked Example 1

The equipment is IEC 61000-3-2 compliant and therefore connection to the network is permitted.

4 Worked Example 2

Table E3 — Connection data for Worked Example 2

Example	Equipment	Rating kVA	Rating A	No. of phases	Harmonic statement	PCC voltage	Final stage
2	2 x Heat Pump	1 x 3.0	13.04	1	IEC 61000-3-2 compliant	LV	1A
		1 x 3.0	13.04	1	IEC 61000-3-2 compliant		

4.1 Step 1

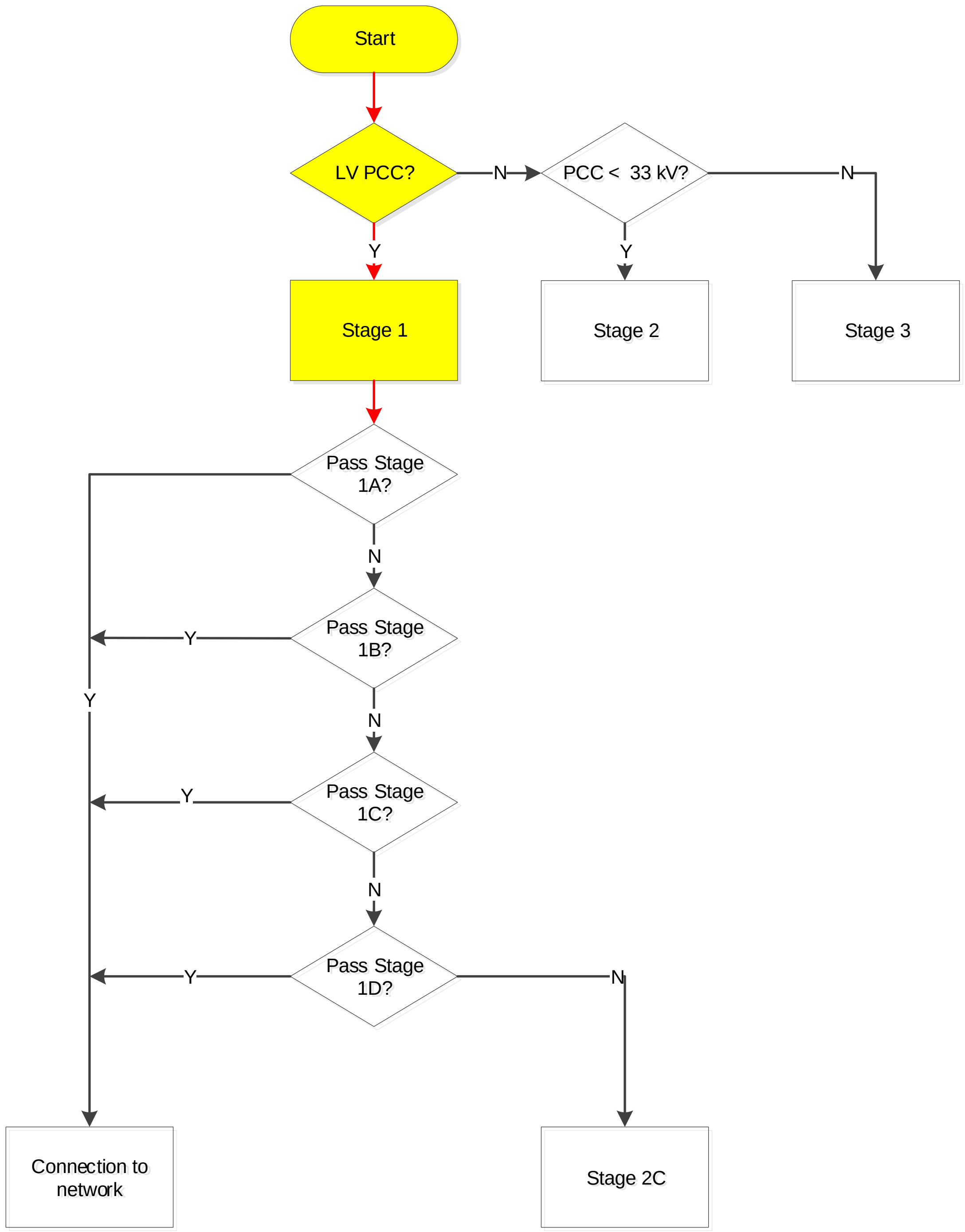

Figure E3 — Step 1 for Worked Example 2

4.2 Step 2

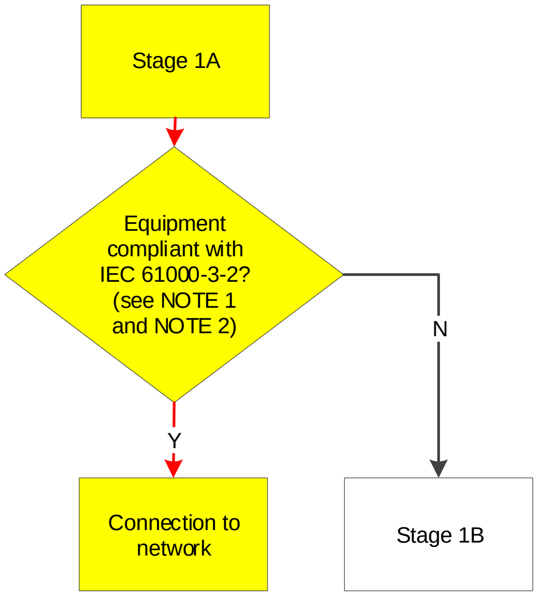

Figure E4 — Step 2 for Worked Example 2

The two items of equipment are each IEC 61000-3-2 compliant and therefore connection to the network is permitted.

5 Worked Example 3

Table E4 — Connection data for Worked Example 3

Example	Equipment	Rating kVA	Rating A	No. of phases	Harmonic statement	PCC voltage	Service current capacity (I_{SCC})	Final stage
3	Heat Pump	9.2	40	1	IEC 61000-3-12 compliant	LV	< 100 A	1B-1

The following additional data has been supplied for this connection:

- Whole current metering is used.
- Single-phase source impedance at the PCC = 0.18 Ω.

5.1 Step 1

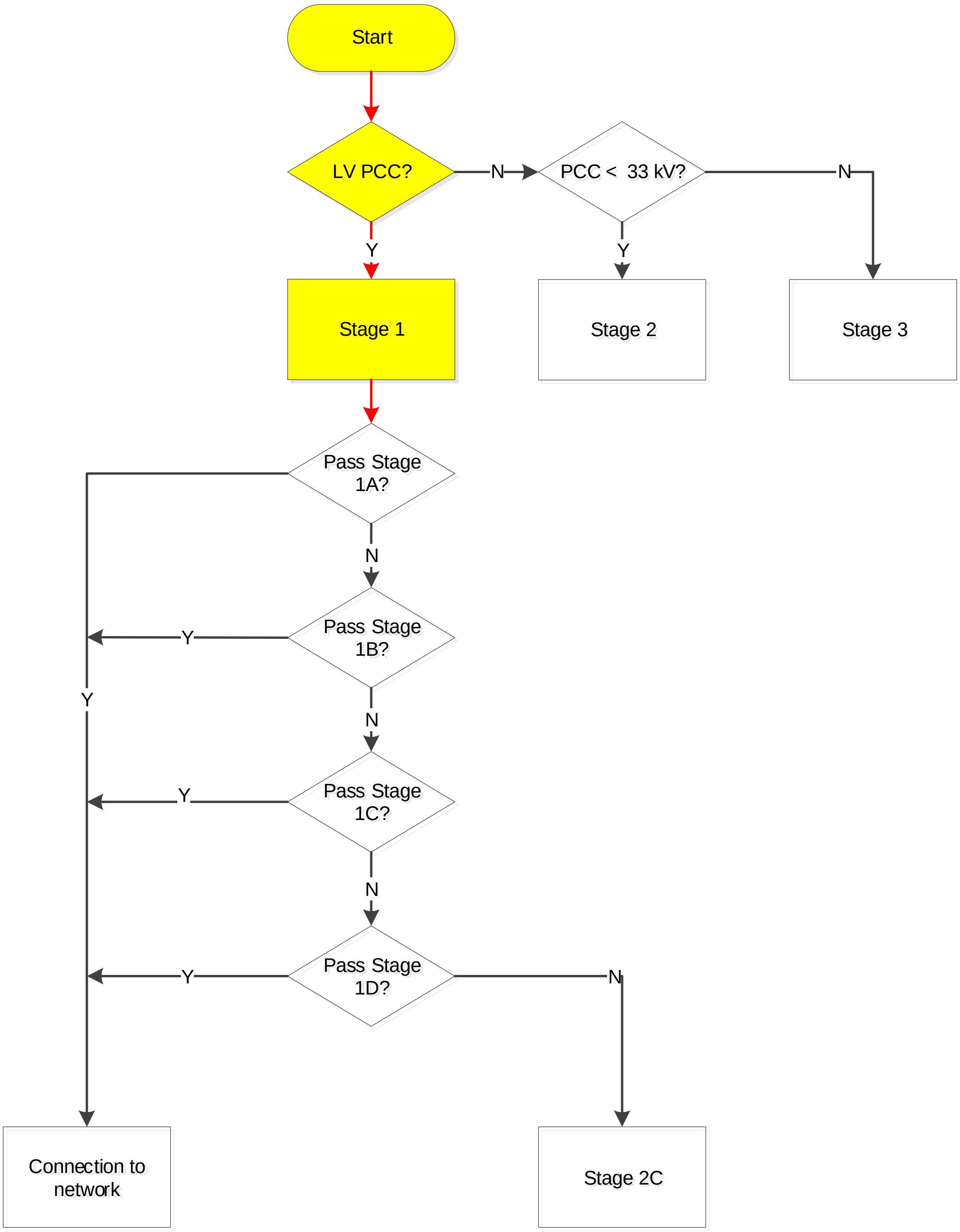

Figure E5 — Step 1 for Worked Example 3

5.2 Step 2

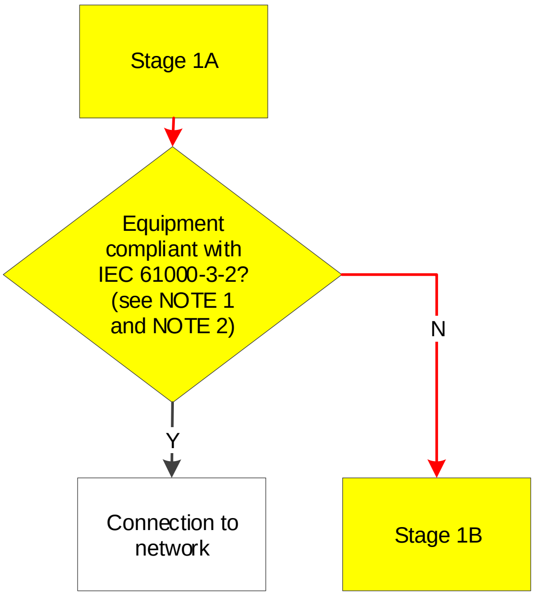

Figure E6 — Step 2 for Worked Example 3

5.3 Step 3

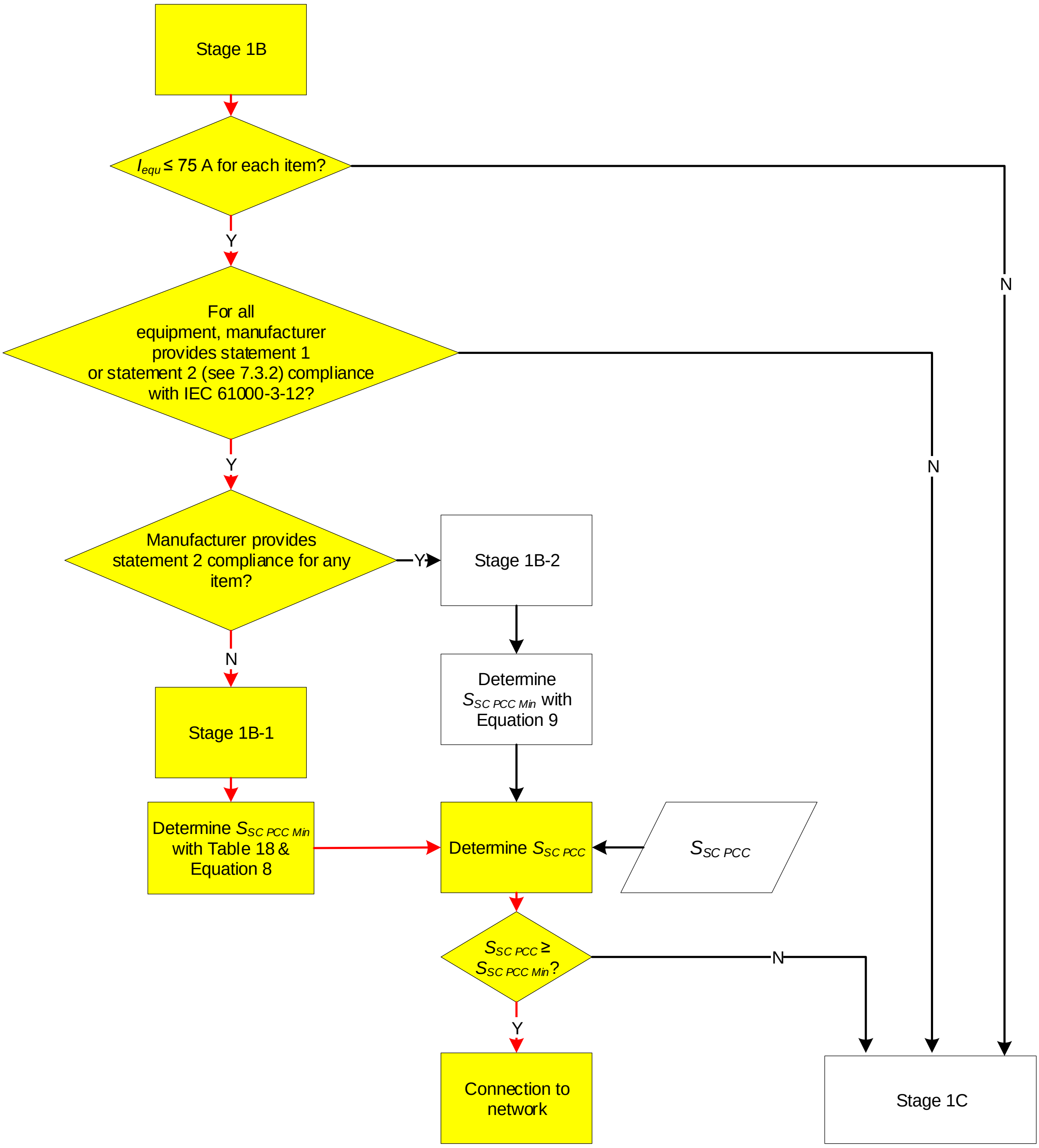

Figure E7 — Steps 3 to 8 for Worked Example 3

There is one item of equipment, with rating ($I_{equ\ 1}$) = 40 A, which is less than the 75 A threshold, so we progress to Step 4.

5.4 Step 4

There is one item of equipment with the manufacturer's statement: "Equipment complying with IEC 61000-3-12", so we progress to Step 5.

5.5 Step 5

No items of equipment carry the statement 2 compliance note: “Equipment complying with IEC 61000-3-12 subject to $S_{SC\ Min} \geq X$ kVA”, so we progress to Step 6.

5.6 Step 6

We need to determine the minimum short-circuit power (MVA) at the PCC ($S_{SC\ PCC\ Min}$).

Whole current metering has been specified as being used, therefore the service current capacity (I_{SCC}) is less than 100 A.[1]

From Table 18, for $M = 1$:

- $F_{SCE\ Min} = 29.05$ and $\alpha = 2$.
- $S_{equ\ 1} = 9.2$ kVA.

From Equation 8, reproduced below, we can solve for $S_{SC\ PCC\ Min}$.

$$S_{SC\ PCC\ Min} = \frac{F_{SCE\ Min} \sqrt[\alpha]{\sum_{m=1}^{M} \left(S_{equ\ m}\right)^{\alpha}}}{1000} = \frac{29.05 \times \sqrt[2]{9.2^2}}{1000} = 0.267 \text{ MVA} \qquad (1)$$

5.7 Step 7

We calculate the single-phase short-circuit power ($S_{SC\ PCC}$) from the single-phase source impedance at the PCC.

$S_{SC\ PCC} = V_{phase}^2 / Z_{source\ 1\text{-}ph}$

where

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

$Z_{source\ 1\text{-}ph}$ is the single-phase source impedance (Ω).

$S_{SC\ PCC} = (230)^2 / 0.18 = 0.294$ MVA

5.8 Step 8

Because the single-phase short-circuit power at the PCC ($S_{SC\ PCC}$) is greater than the minimum short-circuit power at the PCC ($S_{SC\ PCC\ Min}$), 0.294 MVA > 0.267 MVA, then the connection is compliant and is permitted.

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[1] For low voltage systems there are two distinct types of metering: whole current metering and current transformer (CT) metering. The specified rating of whole current metering is characteristically limited to a value of 80 A or 100 A. Above these values, we resort to CT metering. Consequently, if whole current metering is present then we assume, for the purposes of EREC G5, that the service current capacity is < 100 A. Conversely, when CT metering is present, we can assume, for the purposes of EREC G5, that the service current capacity is ≥ 100 A. Note that this categorisation is simply used to infer a source impedance, rather than providing an actual service current capacity value. For further information see, IEC TR 60725.

6 Worked Example 4

Table E5 — Connection data for Worked Example 4

Example	Equipment	Rating kVA	Rating A	No. of phases	Harmonic statement	PCC voltage	Service current capacity (I_{SCC})	Final stage
4	2 x Heat Pump	10	14.43	3	IEC 61000-3-12 compliant	LV	≥ 100 A	1B-1
		34	49.07	3	IEC 61000-3-12 compliant			

The following additional data has been supplied for this connection:

- Current transformer (CT) metering is used.
- Three-phase source impedance at the PCC = 0.15 Ω.

6.1 Step 1

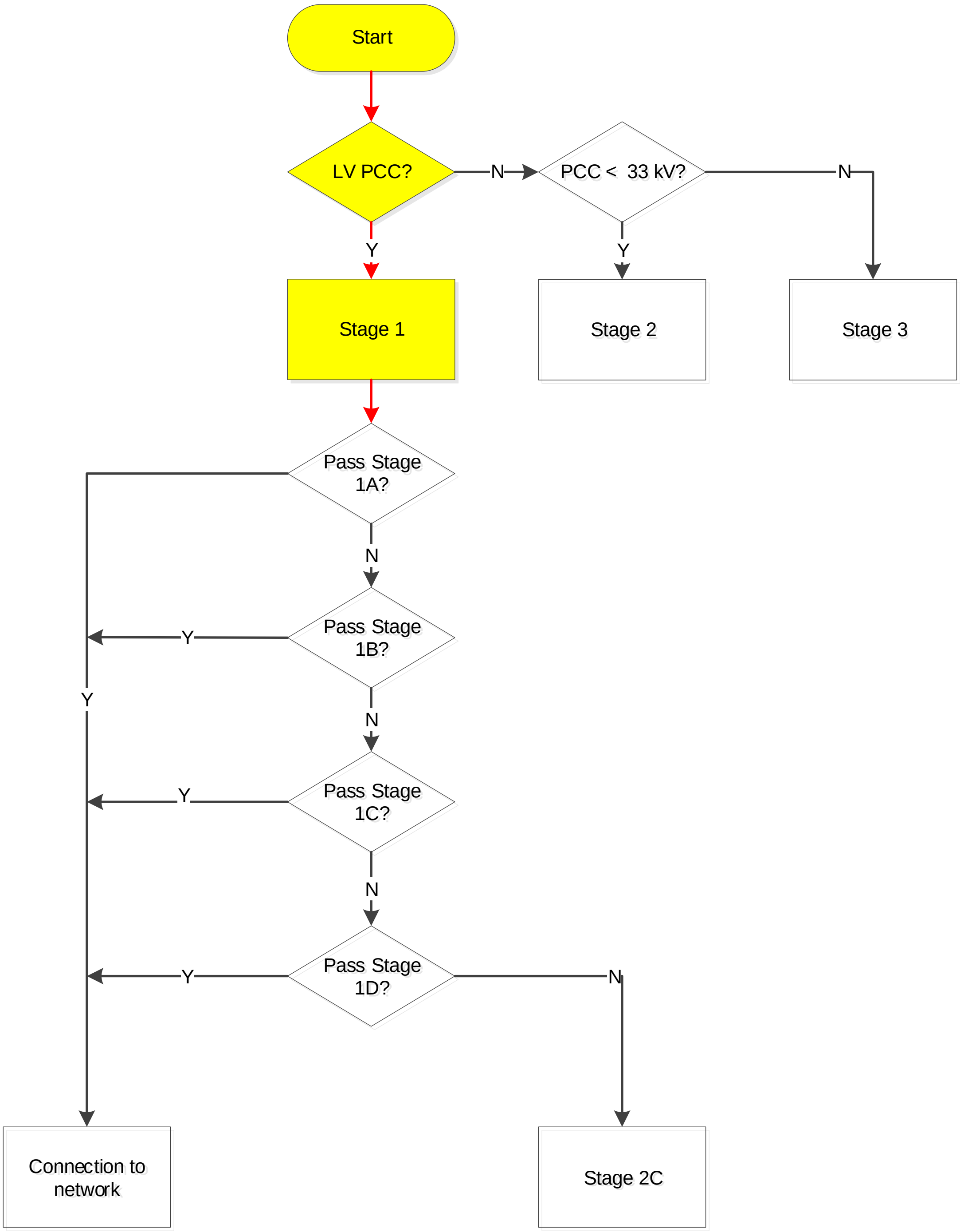

Figure E8 — Step 1 for Worked Example 4

6.2 Step 2

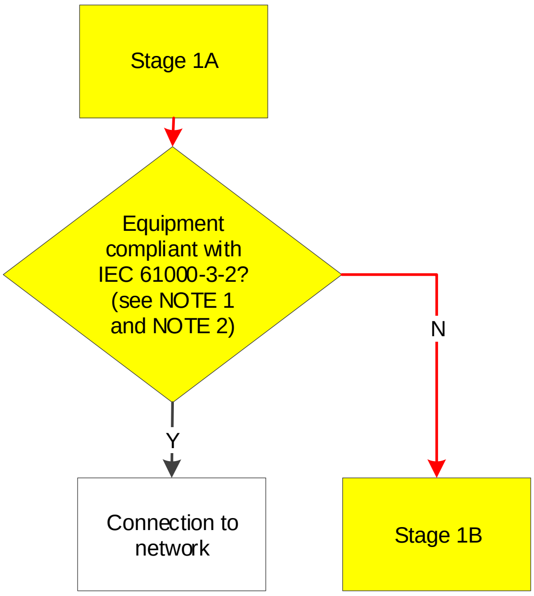

Figure E9 — Step 2 for Worked Example 4

6.3 Step 3

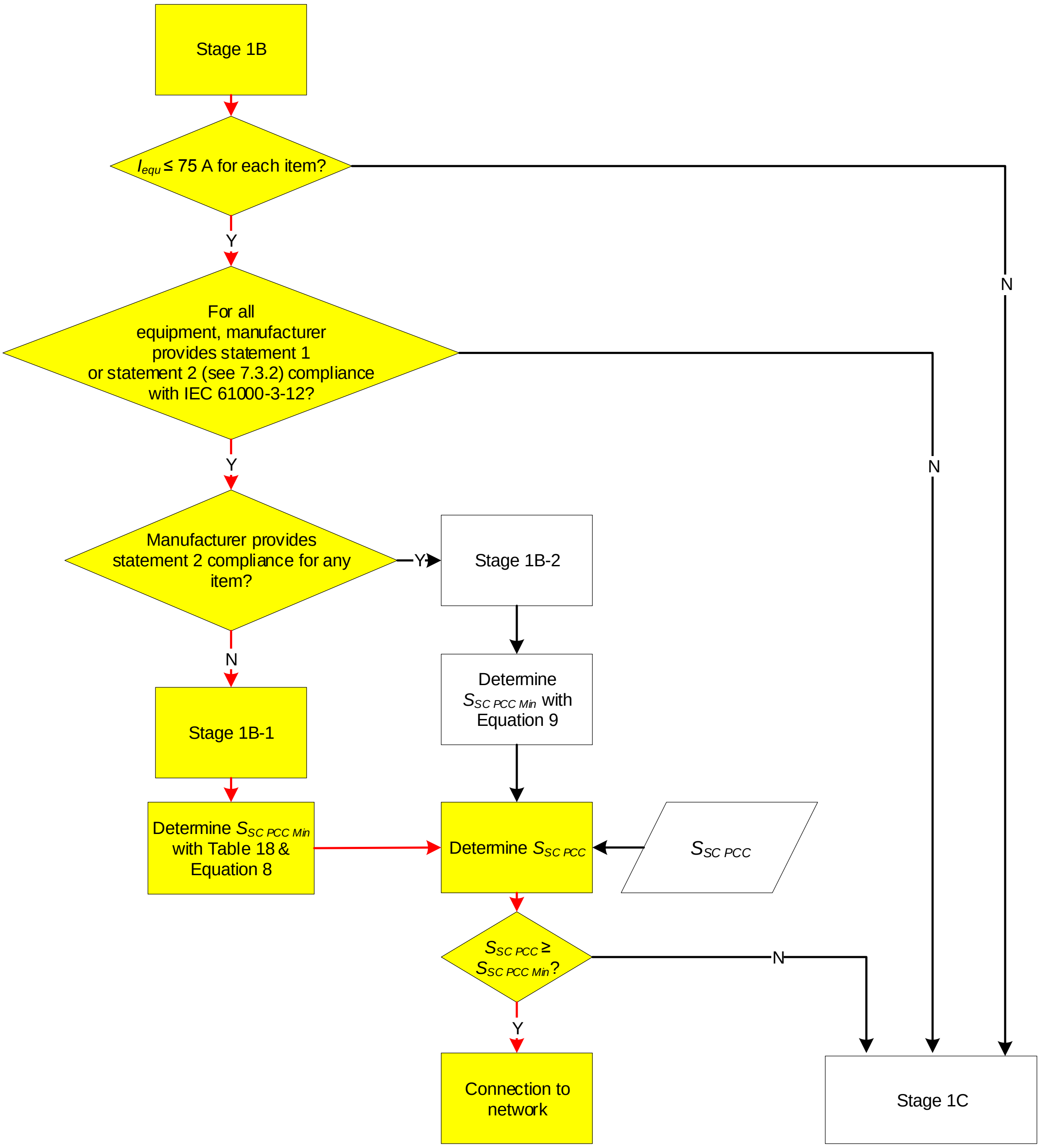

Figure E10 — Steps 3 to 8 for Worked Example 4

There are two items of equipment, with individual equipment ratings (I_{equ}) as follows:

- $I_{equ\ 1}$ = 14.43 A.
- $I_{equ\ 2}$ = 49.07 A.

In both cases, $I_{equ} \leq 75$ A, so we progress to Step 4.

6.4 Step 4

Both items of equipment have the manufacturer's statement: "Equipment complying with IEC 61000-3-12", so we progress to Step 5.

6.5 Step 5

No items of equipment carry the statement "Equipment complying with IEC 61000-3-12 subject to $S_{SC\ Min} \geq X$ kVA", so we progress to Step 6.

6.6 Step 6

We need to determine the minimum short-circuit power (MVA) at the PCC ($S_{SC\ PCC\ Min}$).

CT metering has been specified as being used, therefore the service current capacity (I_{SCC}) is greater than 100 A.

From Table 18, for $M = 2$:

- $F_{SCE\ Min} = 24.224$ and $\alpha = 2$.
- $S_{equ\ 1} = 10$ kVA, $S_{equ\ 2} = 34$ kVA.

From Equation 8, reproduced below, we can solve for $S_{SC\ PCC\ Min}$.

$$S_{SC\ PCC\ Min} = \frac{\mathrm{F}_{\mathrm{SCE\ Min}} \sqrt[\alpha]{\sum_{m=1}^{M} \left(S_{equ\ m}\right)^{\alpha}}}{1000} = \frac{24.2245 \times \sqrt[2]{10^2 + 34^2}}{1000} = 0.859 \text{ MVA} \qquad (2)$$

6.7 Step 7

We calculate the three-phase short-circuit power ($S_{SC\ PCC}$) from the three-phase source impedance at the PCC.

$S_{SC\ PCC} = V_s^2 / Z_{source\ 3\text{-}ph}$

where

V_s	is the phase–phase voltage (V);
$Z_{source\ 3\text{-}ph}$	is the three-phase source impedance (Ω).

$S_{SC\ PCC} = (400)^2 / 0.15 = 1.067$ MVA.

6.8 Step 8

Because the single-phase short-circuit power at the PCC ($S_{SC\ PCC}$) is greater than the minimum short-circuit power at the PCC ($S_{SC\ PCC\ Min}$), 1.067 MVA > 0.859 MVA, then the connection is compliant and is permitted.

7 Worked Example 5

Table E6 — Connection data for Worked Example 5

Example	Equipment	Rating kVA	Rating A	No. of phases	Harmonic statement	PCC voltage	Service current capacity (I_{SCC})	Final stage
5	EV Charge Point	7.36	32	1	None	LV	< 100 A	1B-1

The following additional data has been supplied for this connection:

- Whole current metering is used.
- Single-phase source impedance at the PCC = 0.26 Ω = 0.233 + j0.116 Ω.
- Connection has already been made under the ENA Connect and Notify procedure.

7.1 Step 1

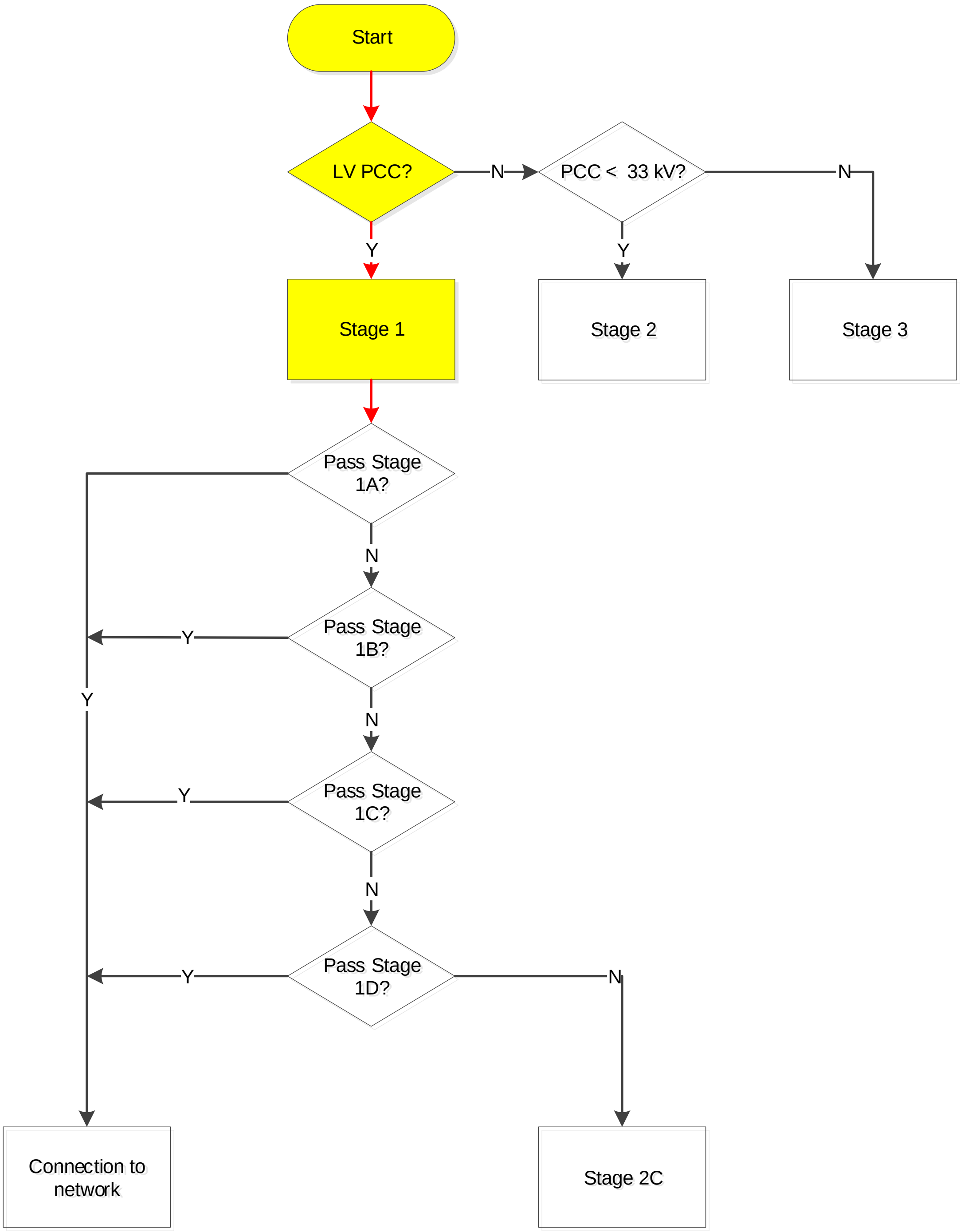

Figure E11 — Step 1 for Worked Example 5

7.2 Step 2

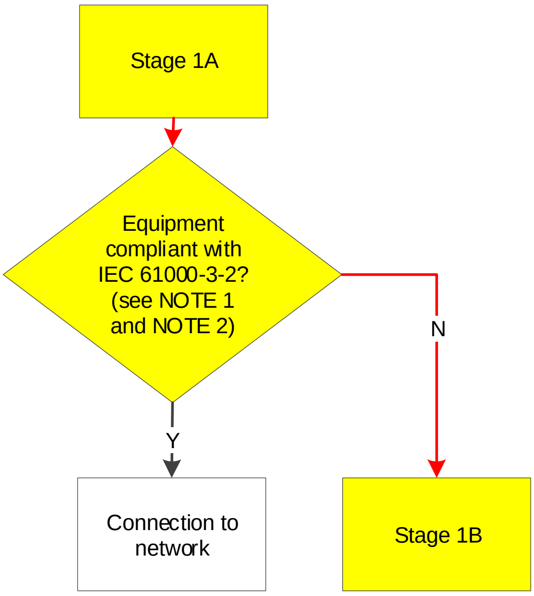

Figure E12 — Step 2 for Worked Example 5

7.3 Step 3

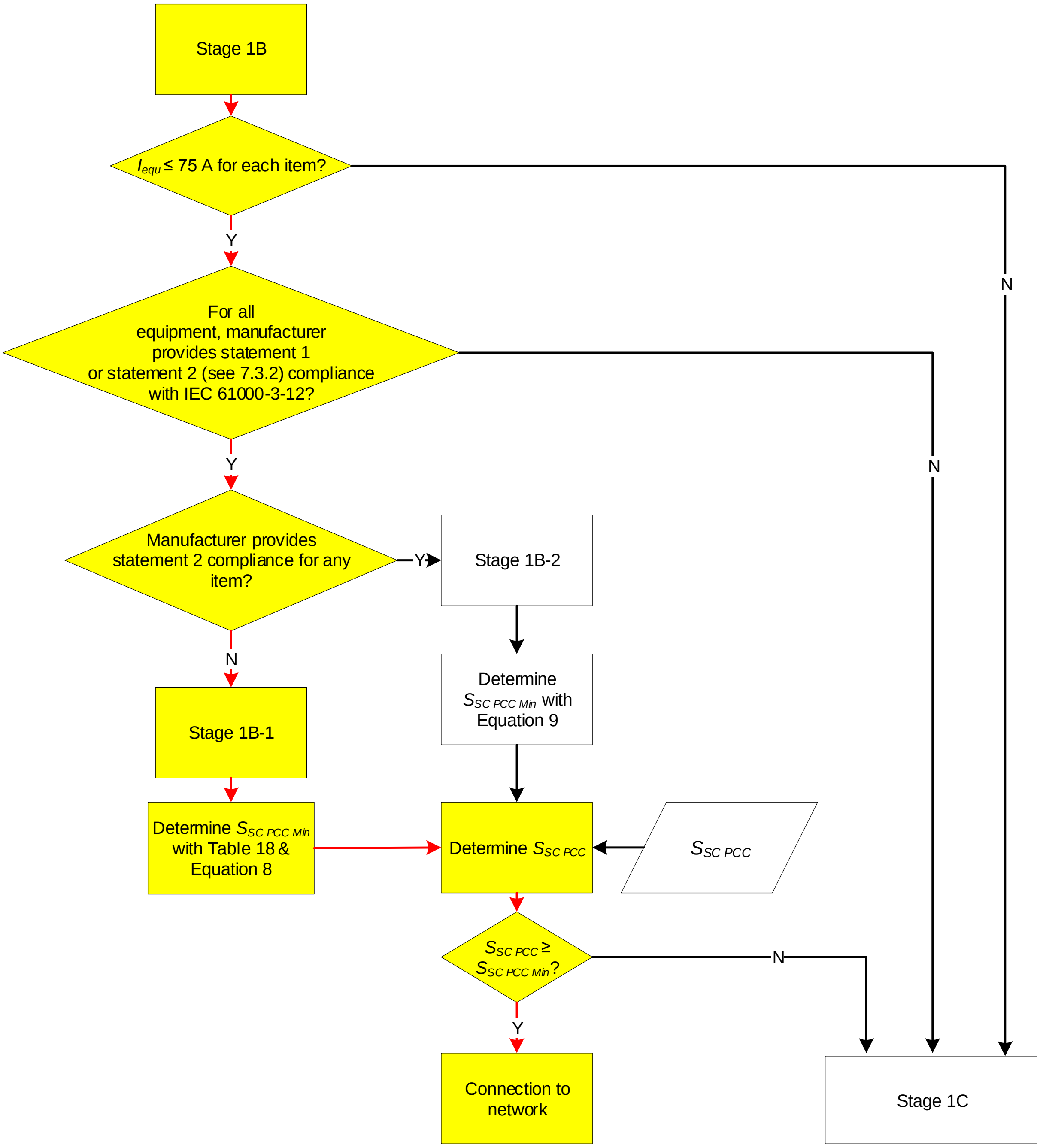

Figure E13 — Steps 3 to 9 for Worked Example 5

There is one item of equipment, with rating ($I_{equ\ 1}$) = 32 A, which is less than the 75 A threshold, so we progress to Step 4.

7.4 Step 4

As the charger is on board the electric vehicle and the specific electric vehicle that is connected to the charge point may vary – the charge point might be used by several vehicles – it is not possible to know the harmonic emission.

EMC Regulation 10 (ECE-R10) and EN 61851-21 refer to EN 61000-3-2 and EN 61000-3-12 standards. For a 32 A rated charge point, we may assume the prospective on-board chargers are all compliant with the limits in EN 61000-3-12 relating to $R_{sce} = 33$, in the absence of other information. Consequently, the corresponding manufacturer's statement would be "Equipment complying with IEC 61000-3-12".

7.5 Step 5

In this example, there are no items of equipment carrying the statement "Equipment complying with IEC 61000-3-12 subject to $S_{SC\ Min} \geq X$ kVA", so we progress to Step 6.

7.6 Step 6

We need to determine the minimum short-circuit power (MVA) at the PCC ($S_{SC\ PCC\ Min}$).

Whole current metering has been specified as being used, therefore the service current capacity (I_{SCC}) is less than 100 A.

From Table 18, for $M = 1$:

- $F_{SCE\ Min} = 29.05$ and $\alpha = 2$.
- $S_{equ\ 1} = 7.36$ kVA.

From Equation 8, reproduced below, we can solve for $S_{SC\ PCC\ Min}$:

$$S_{SC\ PCC\ Min} = \frac{F_{SCE\ Min}\sqrt[\alpha]{\sum_{m=1}^{M}\left(S_{equ\ m}\right)^{\alpha}}}{1000} = \frac{29.05 \times \sqrt[2]{7.36^2}}{1000} = 0.214 \text{ MVA} \tag{3}$$

7.7 Step 7

We calculate the single-phase short-circuit power ($S_{SC\ PCC}$) from the single-phase source impedance at the PCC.

$S_{SC\ PCC} = V_{phase}^2 / Z_{source\ 1\text{-}ph}$

where

V_{phase}	is the phase–neutral voltage (V);
$Z_{source\ 1\text{-}ph}$	is the single-phase source impedance (Ω).

$S_{SC\ PCC} = (230)^2 / 0.26 = 0.203$ MVA.

7.8 Step 8

Because 0.203 MVA is less than 0.214 MVA, then $S_{SC\ PCC} > S_{SC\ PCC\ Min}$ is not satisfied and so we progress to Step 9, which takes account of a correction to the X/R ratio.

7.9 Step 9

Since whole current metering is specified, the service current capacity is less than 100 A and so we refer to Table A1.

Source impedance = 0.26 Ω = (0.233 + j0.116) Ω.

X/*R* ratio = 0.116 / 0.233 = 0.498.

From Table A1 in EREC G5, reproduced below, for $M = 1$ and $X/R \leq 0.5$, the appropriate multiplier is 0.947.

	Multiplier											
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

We can now find a modified $S_{SC\ PCC\ Min} = M \times 0.213808$ MVA = 0.2025 MVA.

Because the single-phase short-circuit power at the PCC ($S_{SC\ PCC}$) is greater than the modified minimum short-circuit power at the PCC (modified $S_{SC\ PCC\ Min}$), 0.2035 MVA > 0.2025 MVA, then the connection is compliant and is permitted.

8 Worked Example 6

Table E7 — Connection data for Worked Example 6

Example	Equipment	Rating kVA	Rating A	No. of phases	Harmonic statement	PCC voltage	Service current capacity (I_{SCC})	Final stage
6	EV Rapid DC Output (Mode 4) Charger	50	72.17	3	IEC 61000-3-12 compliant subject to $S_{SC\ MIN}$ = 2.0 MVA	LV	≥ 100 A	1B-2
	EV Charge Point	22	32.00	3	IEC 61000-3-12 compliant			

The following additional data has been supplied for this connection:

- Current transformer (CT) metering is used.
- $S_{SC\ PCC}$ = 3.05 MVA.

8.1 Step 1

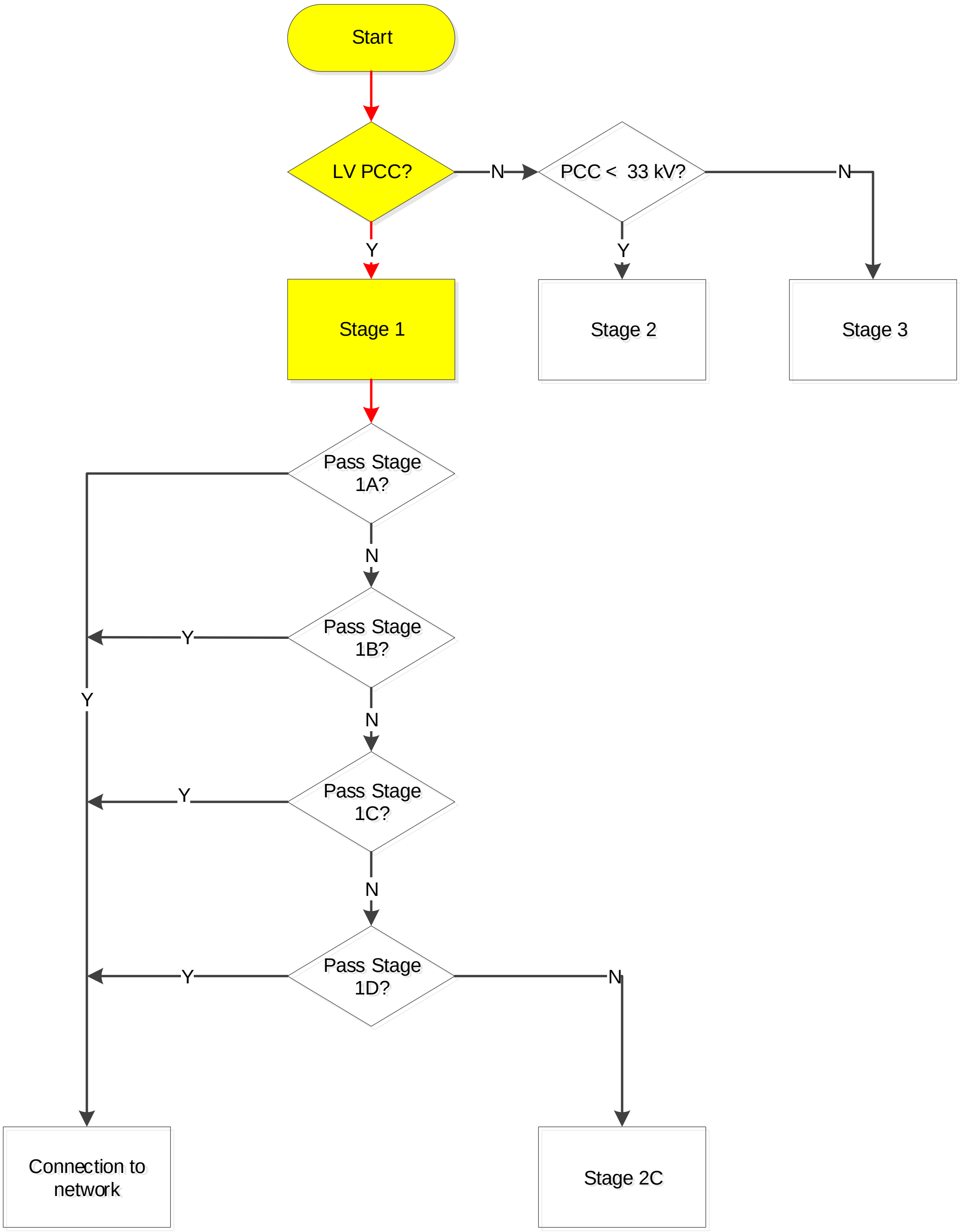

Figure E14 — Step 1 for Worked Example 6

8.2 Step 2

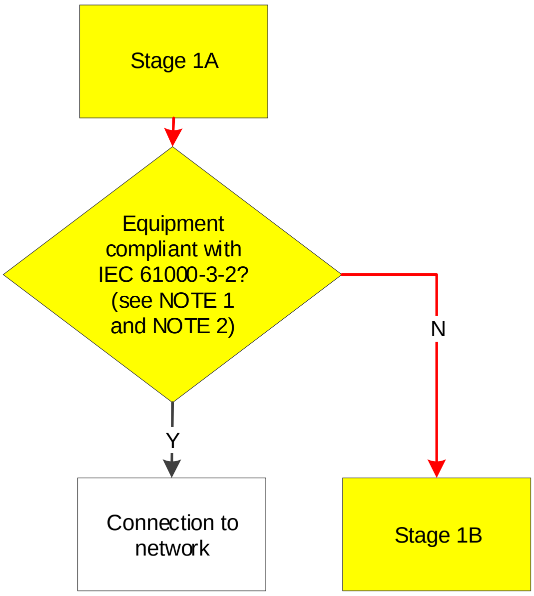

Figure E15 — Step 2 for Worked Example 6

8.3 Step 3

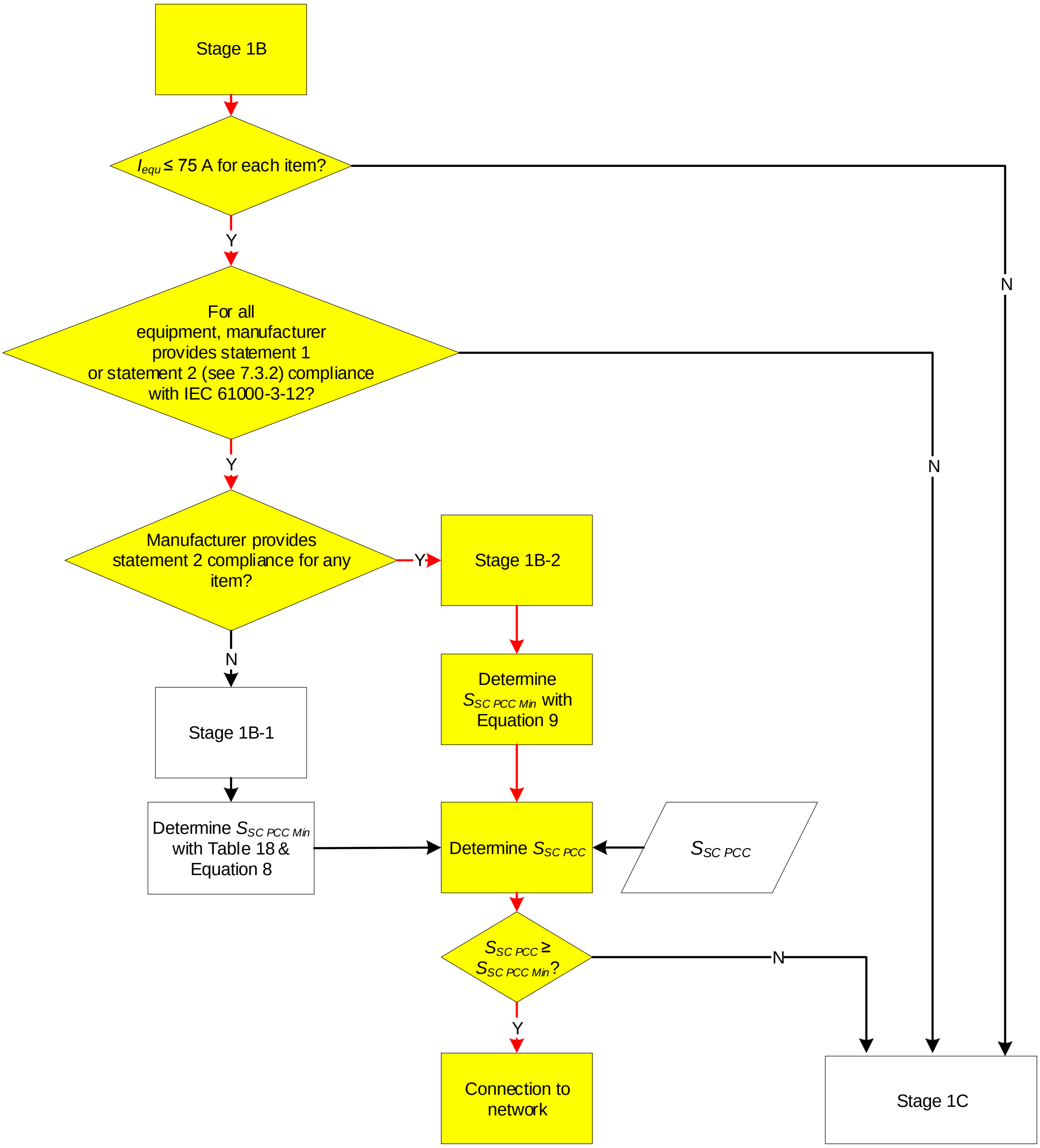

Figure E16 — Steps 3 to 7 for Worked Example 6

There are two items of equipment, with individual equipment ratings (I_{equ}) as follows:

- $I_{equ\ 1}$ = 72.17 A.
- $I_{equ\ 2}$ = 32.00 A.

In both cases, $I_{equ} \leq 75$ A, so we progress to Step 4.

8.4 Step 4

One item of equipment has the manufacturer's statement: "Equipment complying with IEC 61000-3-12".

One item of equipment carries the statement "Equipment complying with IEC 61000-3-12 subject to $S_{SC\ Min} \geq 2.0$ kVA".

Both items have a compliance statement, but one is contingent on a specified $S_{SC\ Min}$ value, so we progress to Step 5, which follows the Stage 1B-2 process.

8.5 Step 5

We need to determine the minimum short-circuit power (MVA) at the PCC ($S_{SC\ PCC\ Min}$).

From Equation 9, reproduced below, we can solve for $S_{SC\ PCC\ Min}$:

$$S_{SC\ PCC\ Min} = 33 \sum_{m=1}^{M} S_{equ\ m} + \sum_{n=1}^{N} S_{SC\ Min\ n} \tag{4}$$

The manufacturer states "Equipment complying with IEC 61000-3-12 subject to $S_{SC\ Min} = 2.0$ MVA" for one item, so $N = 1$ in Equation 9 and we can state that $S_{SC\ Min\ 1} = 2.0$ MVA and also that $\sum_{n=1}^{N} S_{SC\ Min\ n} = 2.0$ MVA.

The manufacturer states "Equipment complying with IEC 61000-3-12" for one item, so $M = 1$ in Equation 9 and we can state that $\sum_{m=1}^{M} S_{equ\ m} = S_{equ\ 1} = 22$ kVA and also that $33 \sum_{m=1}^{M} S_{equ\ m} = 33 \times 22$ kVA $= 0.726$ MVA.

Solving Equation 9:

$S_{SC\ PCC\ Min} = 2.0$ MVA $+$ 0.726 MVA = 2.726 MVA.

8.6 Step 6

The utility has provided the three-phase short-circuit power, $S_{SC\ PCC} = 3.05$ MVA.

8.7 Step 7

Because the three-phase short-circuit power at the PCC ($S_{SC\ PCC}$) is greater than the minimum short-circuit power at the PCC ($S_{SC\ PCC\ Min}$), 3.05 MVA > 2.726 MVA, then the connection is compliant and is permitted.

9 Worked Example 7

Table E8 — Connection data for Worked Example 7

Example	Equipment	Rating kVA	Rating A	No. of phases	Harmonic statement	PCC voltage	Service current capacity (I_{SCC})	Final stage
7	Active Front-end Motor Drive	70	101.04	3	—	LV	≥ 100 A	1C-1

The following additional data has been supplied for this connection:

- Current transformer (CT) metering is used.
- $S_{SC\ PCC}$ = 5.1 MVA.

9.1 Step 1

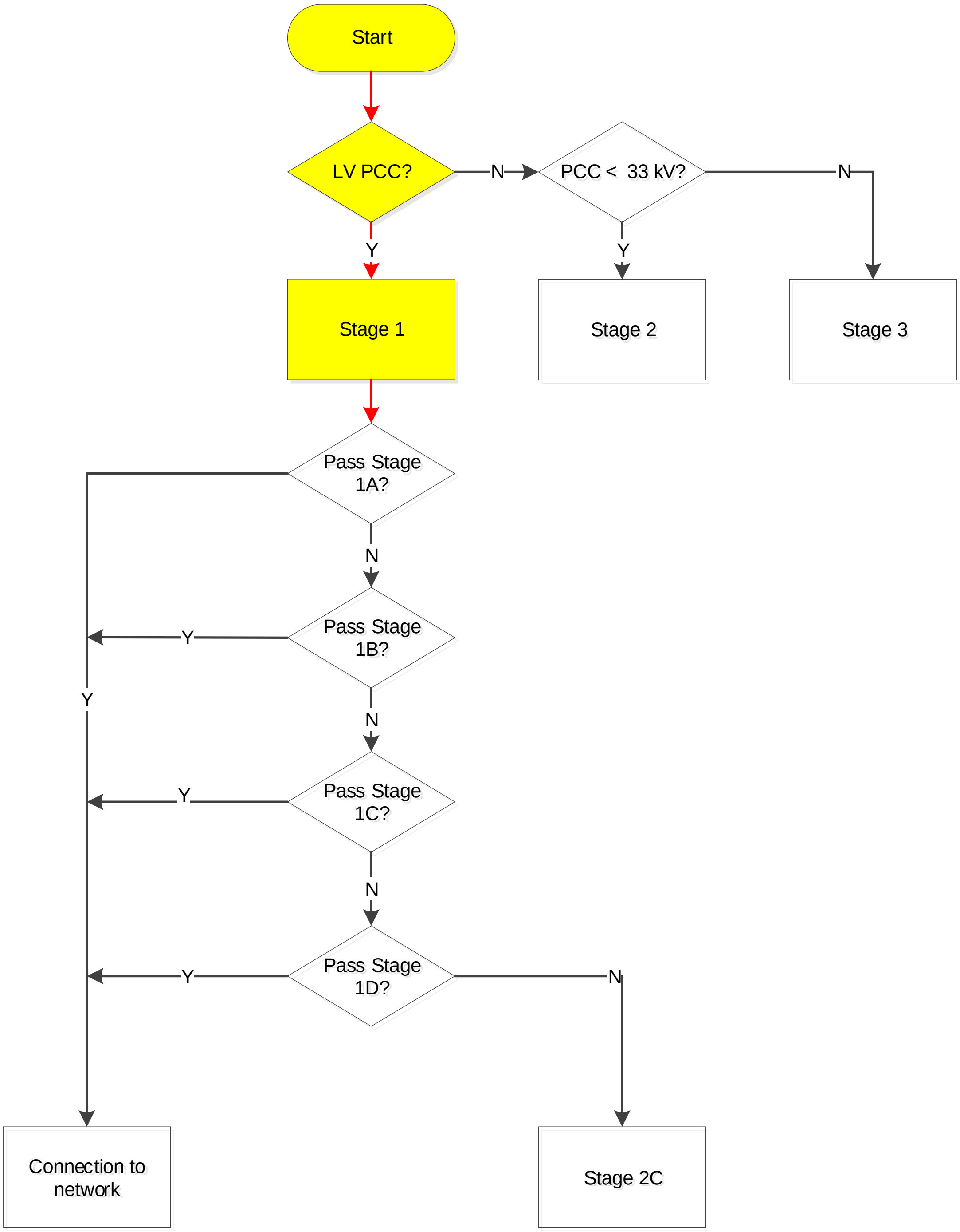

Figure E17 — Step 1 for Worked Example 7

9.2 Step 2

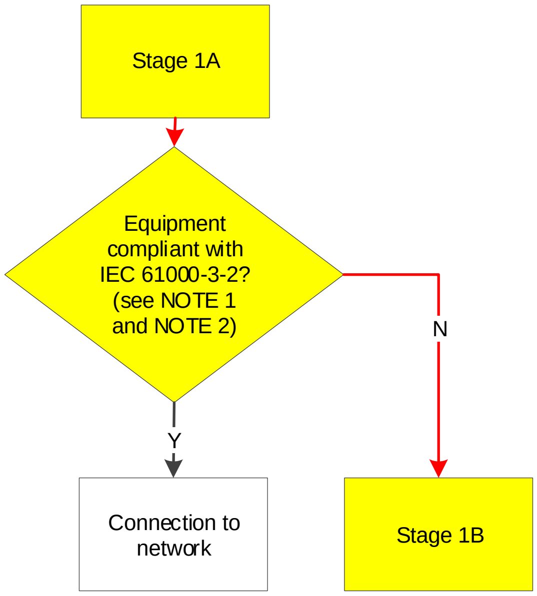

Figure E18 — Step 2 for Worked Example 7

9.3 Step 3

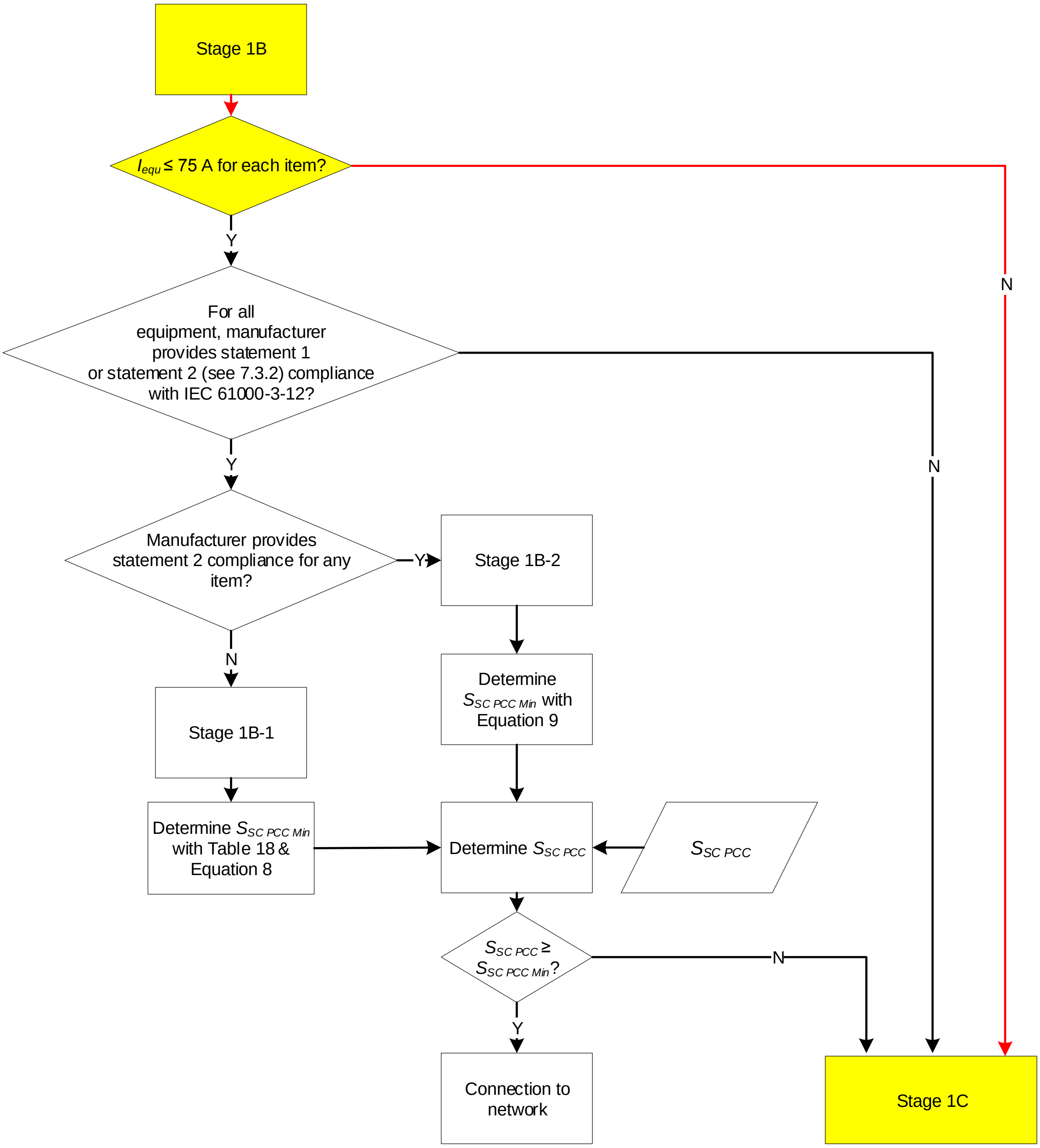

Figure E19 — Step 3 for Worked Example 7

There is one item of equipment, with rating $I_{equ\ 1}$ = 101.04 A, which is greater than the 75 A threshold, so we progress to Step 4, which follows the Stage 1C process.

9.4 Step 4

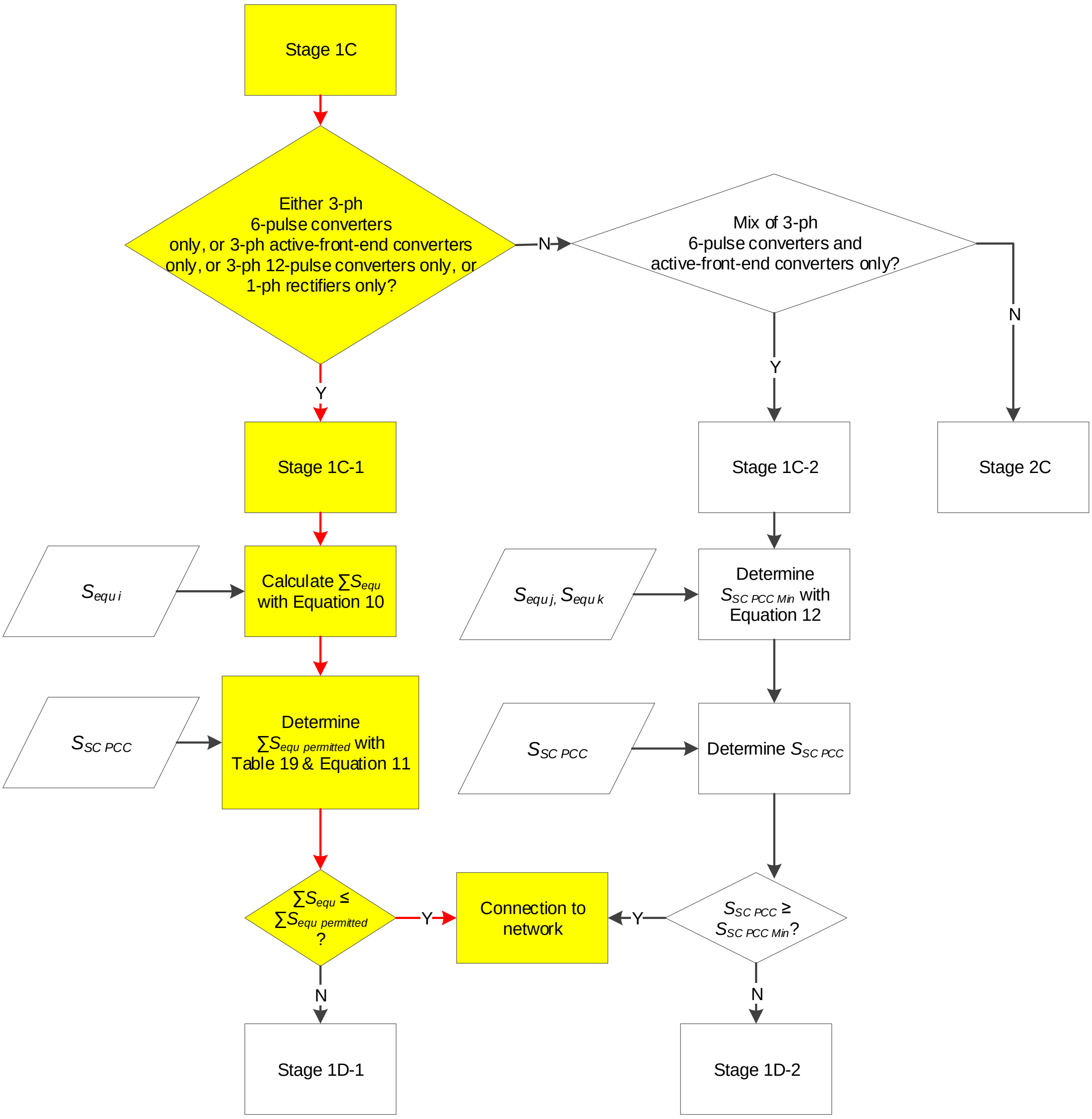

Figure E20 — Steps 4 to 7 for Worked Example 7

We are not dealing with a mix of technology types so we follow the Stage 1C-1 process.

9.5 Step 5

Since there is only one item of equipment, the aggregate equipment rated power $\sum S_{equ}$ = 70 kVA.

9.6 Step 6

The short-circuit power at the PCC ($S_{SC\,PCC}$) is given as $S_{SC\,PCC}$ = 5.1 MVA.

The permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$) for the connection is determined with reference to the Table 19 value for $\sum S_{equ\ permitted\ @\ reference\ Ssc}$, which is then scaled according to the short-circuit power at the PCC ($S_{SC\ PCC}$) as shown in Equation 11, which is reproduced and solved below.

From Table 19:

- $\sum S_{equ\ permitted\ @\ reference\ Ssc}$ = 192 kVA for a reference S_{SC} of 10 MVA.

Equation 11, reproduced below, is used to solve for the permitted aggregate equipment rated power, $\sum S_{equ\ permitted}$.

$$\sum S_{equ\ permitted} = S_{SC\ PCC}\left(\frac{\sum S_{equ\ permitted\ @\ Ssc\ reference}}{S_{SC\ reference}}\right) \tag{5}$$

$\sum S_{equ\ permitted}$ = 5.1 MVA × (192 kVA / 10 MVA) = 97.92 kVA.

9.7 Step 7

Since the aggregate equipment rated power ($\sum S_{equ}$) is less than the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$), 70 kVA < 97.92 kVA, then the connection is compliant and is permitted.

10 Worked Example 8

Table E9 — Connection data for Worked Example 8

Example	Equipment	Rating kVA	Rating A	No. of phases	Harmonic statement	PCC voltage	Service current capacity (I_{SCC})	Final stage
8	Rectifier	4	17.39	1	—	LV	< 100 A	1C-1

The following additional data has been supplied for this connection:

- Whole current metering is used.
- Single-phase source impedance at the PCC is 0.03301 Ω.

NOTE: The PCC is located at the secondary terminals of a 100 kVA single-phase transformer.

10.1 Step 1

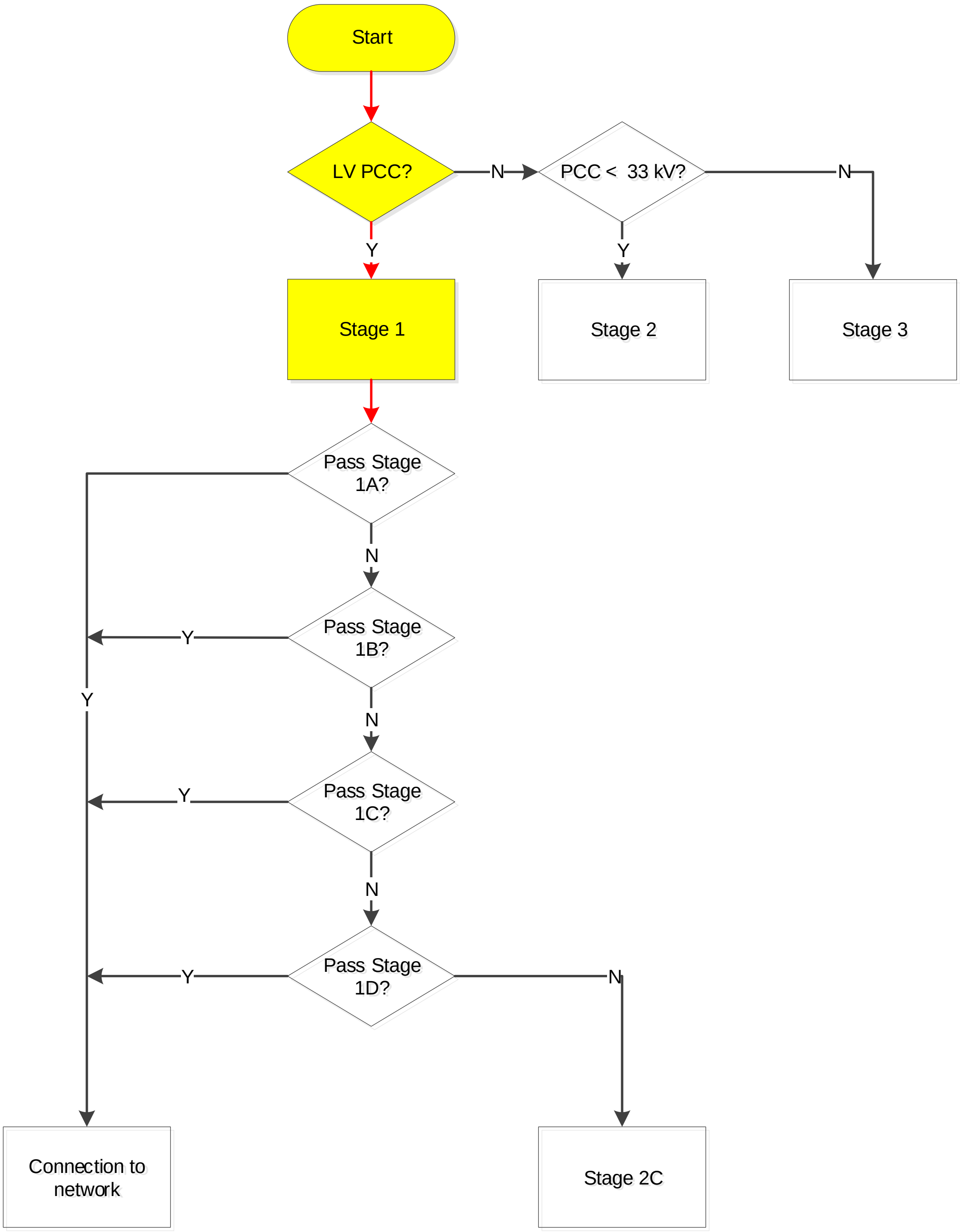

Figure E21 — Step 1 for Worked Example 8

10.2 Step 2

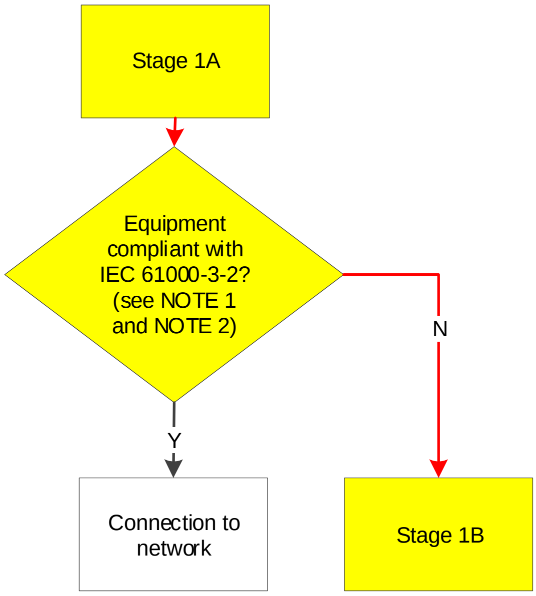

Figure E22 — Step 2 for Worked Example 8

10.3 Step 3

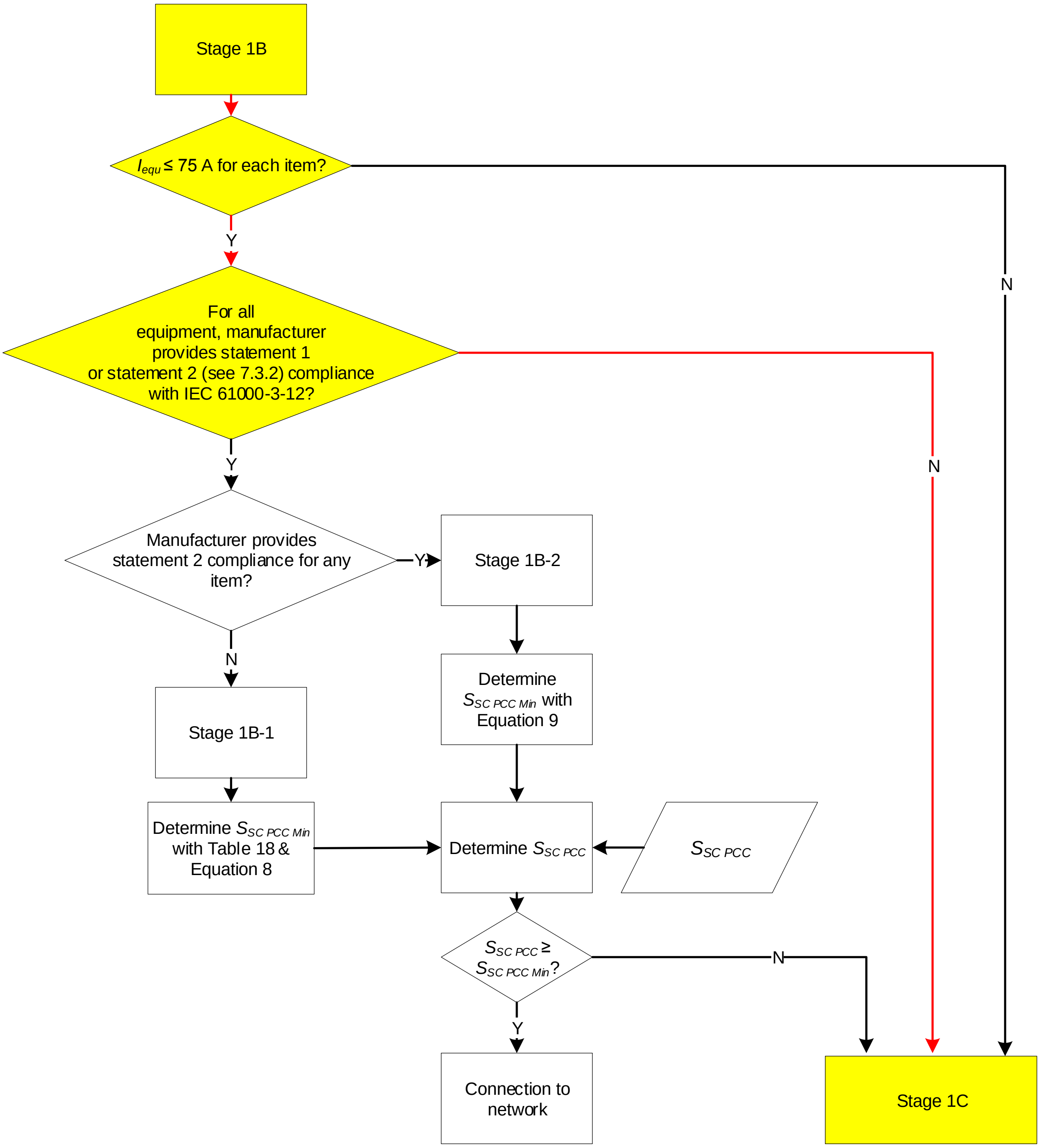

Figure E23 — Step 3 for Worked Example 8

There is one item of equipment, with rating $I_{equ\ 1}$ = 17.39 A, which is less than the 75 A threshold, so we progress to Step 4.

10.4 Step 4

No statement of compliance was provided for the item of equipment, so we proceed to Step 5, which follows the Stage 1C process.

10.5 Step 5

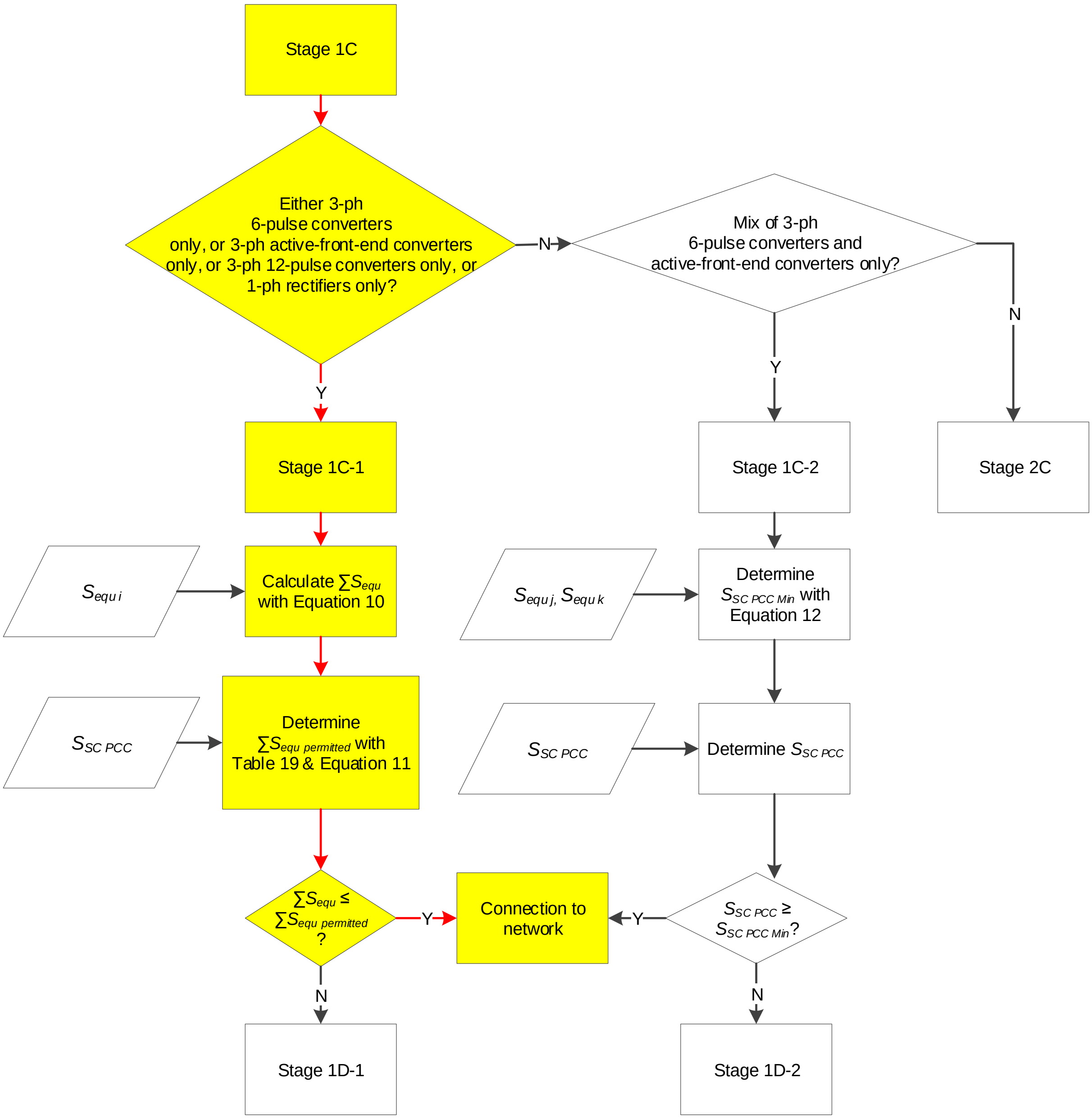

Figure E24 — Steps 5 to 9 for Worked Example 8

We are not dealing with a mix of technology types so we follow the Stage 1C-1 process.

10.6 Step 6

Since there is only one item of equipment, the aggregate equipment rated power $\sum S_{equ}$ = 4 kVA.

10.7 Step 7

The permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$) for the connection is determined with reference to the Table 19 value for $\sum S_{equ\ permitted\ @\ reference\ Ssc}$, which is then scaled according to the short-circuit power at the PCC ($S_{SC\ PCC}$) as shown in Equation 11, which is reproduced and solved below.

From Table 19:

- $\sum S_{equ\ permitted\ @\ reference\ Ssc}$ = 7.9 kVA for a reference S_{SC} of 2 MVA.

10.8 Step 8

Equation 11, reproduced below, is used to solve for the permitted aggregate equipment rated power, $\sum S_{equ\ permitted}$.

$$\sum S_{equ\ permitted} = S_{SC\ PCC}\left(\frac{\sum S_{equ\ permitted\ @\ Ssc\ reference}}{S_{SC\ reference}}\right) \tag{6}$$

The short-circuit power at the PCC ($S_{SC\ PCC}$) is calculated as $S_{SC\ PCC} = V_{phase}^2 / Z_{source\ phase-neutral}$ = $(230)^2$ / 0.03301 = 1.6025 MVA.

$\sum S_{equ\ permitted}$ = 1.6025 MVA × (7.9 kVA / 2 MVA) = 6.33 kVA.

10.9 Step 9

Since the aggregate equipment rated power ($\sum S_{equ}$) is less than the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$), 4 kVA < 6.33 kVA, then the connection is compliant and is permitted.

11 Worked Example 9

Table E10 — Connection data for Worked Example 9

Example	Equipment	Rating kVA	Rating A	No. of phases	Harmonic statement	PCC voltage	Service current capacity (I_{SCC})	Final stage
8	6-Pulse AC/DC Motor Drive	20	28.87	3	—	LV	≥ 100 A	1C-2
	Active Front-end Motor Drive	70	101.04	3	—			

The following additional data has been supplied for this connection:

- Current transformer (CT) metering is used.
- Three-phase short-circuit power at the PCC is 13.1 MVA.

11.1 Step 1

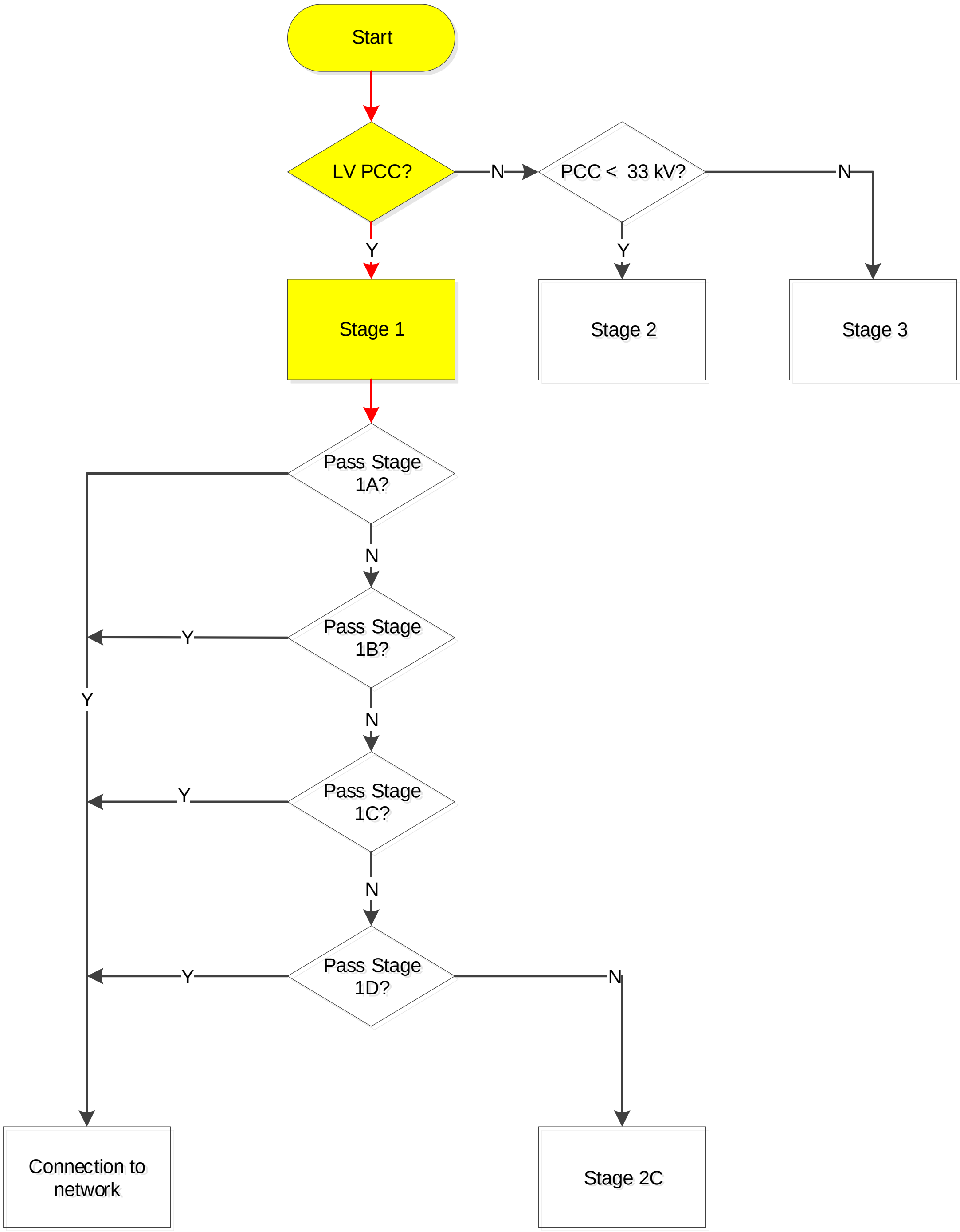

Figure E25 — Step 1 for Worked Example 9

11.2 Step 2

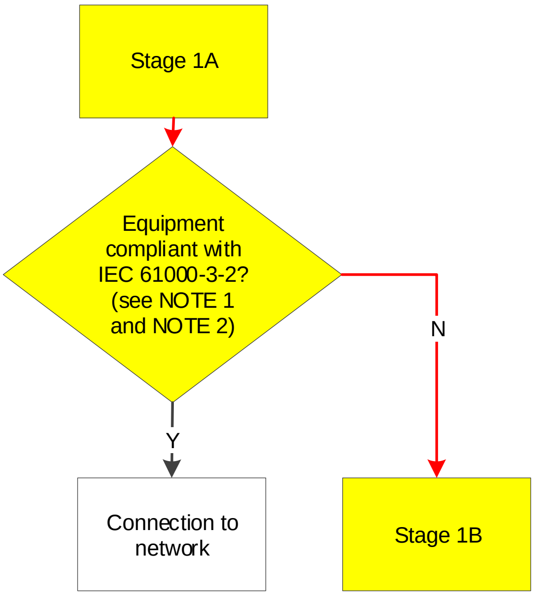

Figure E26 — Step 2 for Worked Example 9

11.3 Step 3

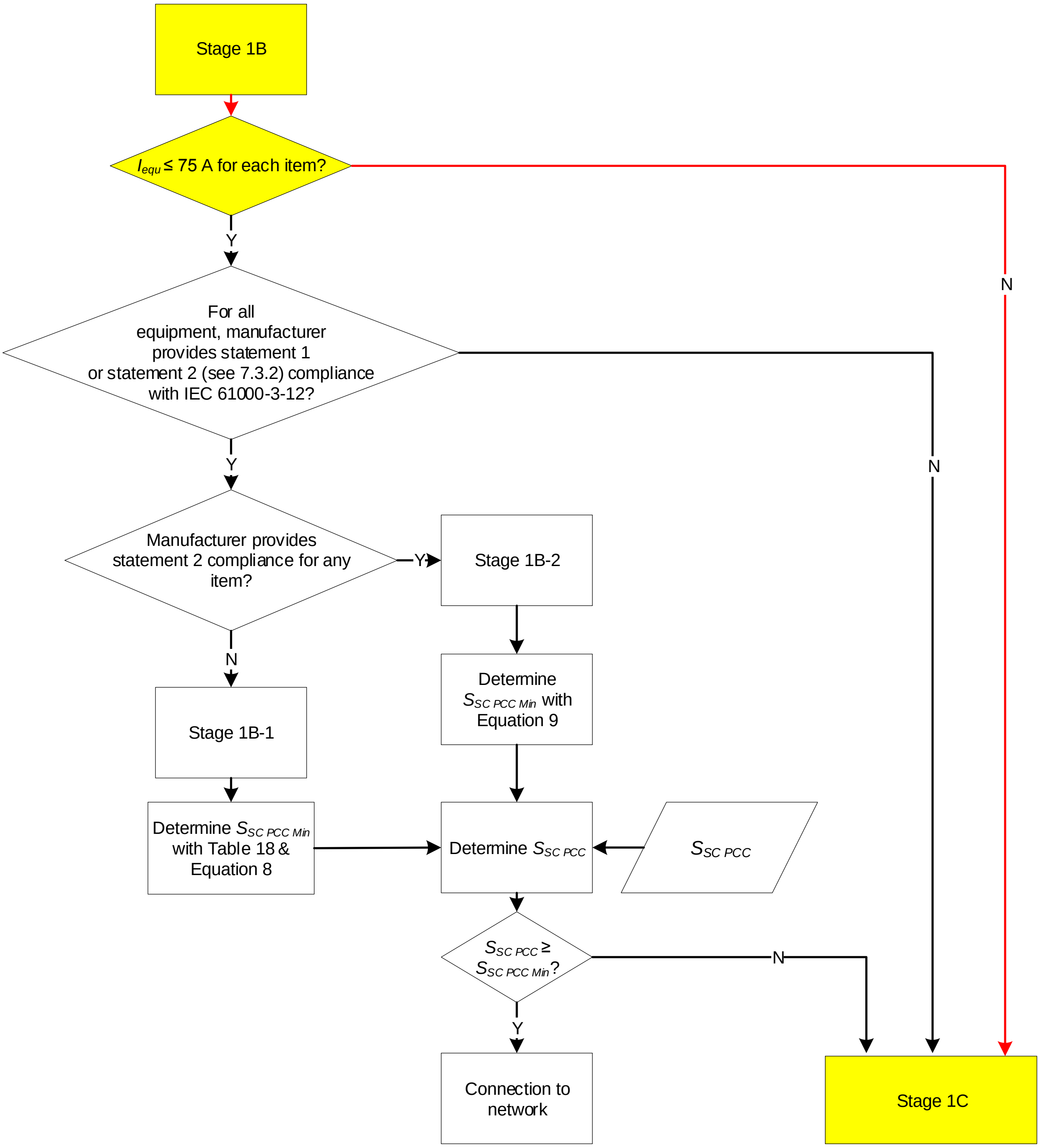

Figure E27 — Step 3 for Worked Example 9

There is one item of equipment with rating above the 75 A threshold, $I_{equ\ 2}$ = 101.04 A, so we progress to Step 4, which follows the Stage 1C process.

11.4 Step 4

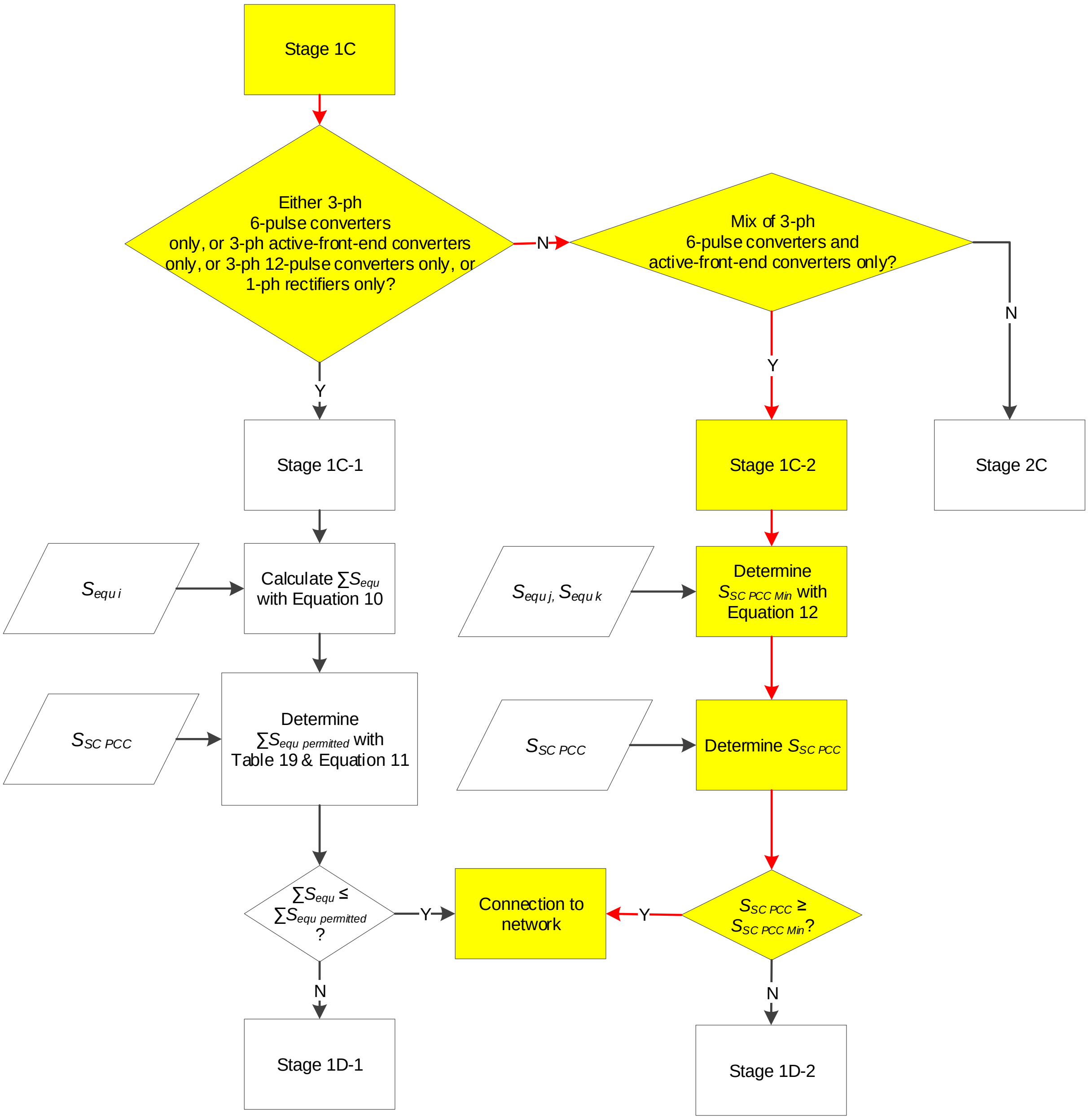

Figure E28 — Steps 4 to 7 for Worked Example 9

We have a mix of three-phase six-pulse converters and active-front-end converters, so we progress to Step 5, which follows the Stage 1C-2 process.

11.5 Step 5

We need to determine the minimum permitted short-circuit power (MVA) at the PCC ($S_{SC\ PCC\ Min}$) using Equation 12, which is reproduced below.

$$S_{SC\ PCC\ Min} = 459.977 \sum_{j=1}^{J} S_{equ\ j} + 52.170 \sum_{k=1}^{K} S_{equ\ k} \qquad (7)$$

Where J is the number of items of three-phase six-pulse plant or equipment – one in this example – and K is the number of items of three-phase active-front-end plant or equipment – also one in this example.

$$\begin{aligned} S_{SC\ PCC\ Min} &= (459.977 \times 20\ \text{kVA}) + (52.17 \times 70\ \text{kVA}) \\ &= 12.851\ \text{MVA.} \end{aligned}$$

11.6 Step 6

The three-phase short-circuit power at the PCC was given for this example as $S_{SC\ PCC} = 13.1$ MVA.

11.7 Step 7

Since the three-phase short-circuit power at the PCC ($S_{SC\ PCC}$) is greater than the minimum permitted short-circuit power ($S_{SC\ PCC\ Min}$), 13.1 MVA > 12.851 MVA, then the connection is compliant and is permitted.

12 Worked Example 10

Table E11 — Connection data for Worked Example 10

Example	Equipment	Rating kVA	Rating A	No. of phases	Harmonic statement	PCC voltage	Service current capacity (I_{SCC})	Final stage
10	Active Front-end Motor Drive	104	150	3	—	LV	≥ 100 A	1D-1

The following additional data has been supplied for this connection:

- Current transformer (CT) metering is used.
- $S_{SC\ PCC}$ = 5.1 MVA.
- $V_{5\ m}$ = 1.43%.
- $V_{5\ PL}$ = 4%.

12.1 Step 1

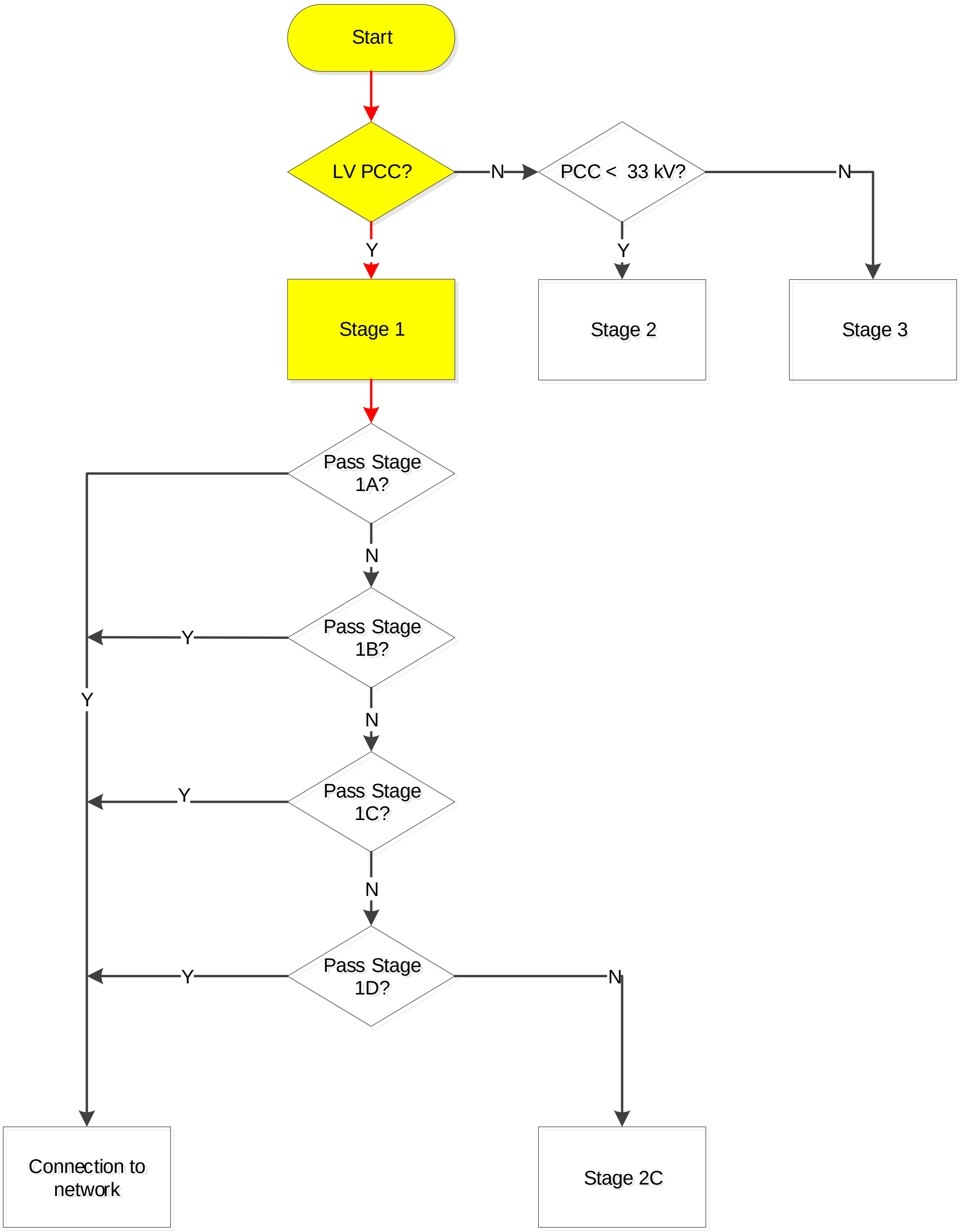

Figure E29 — Step 1 for Worked Example 10

12.2 Step 2

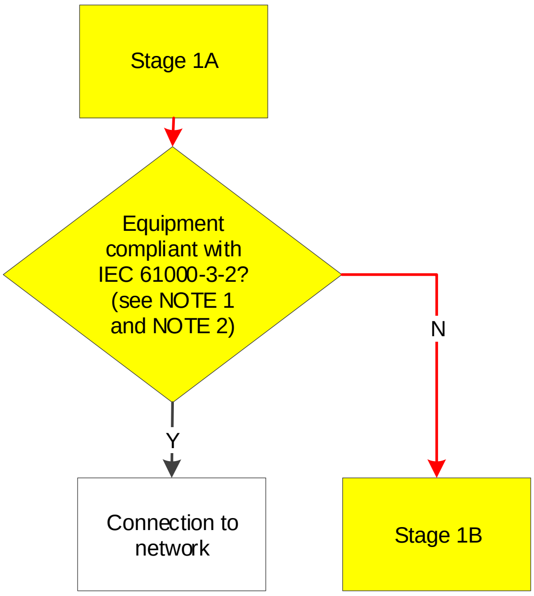

Figure E30 — Step 2 for Worked Example 10

12.3 Step 3

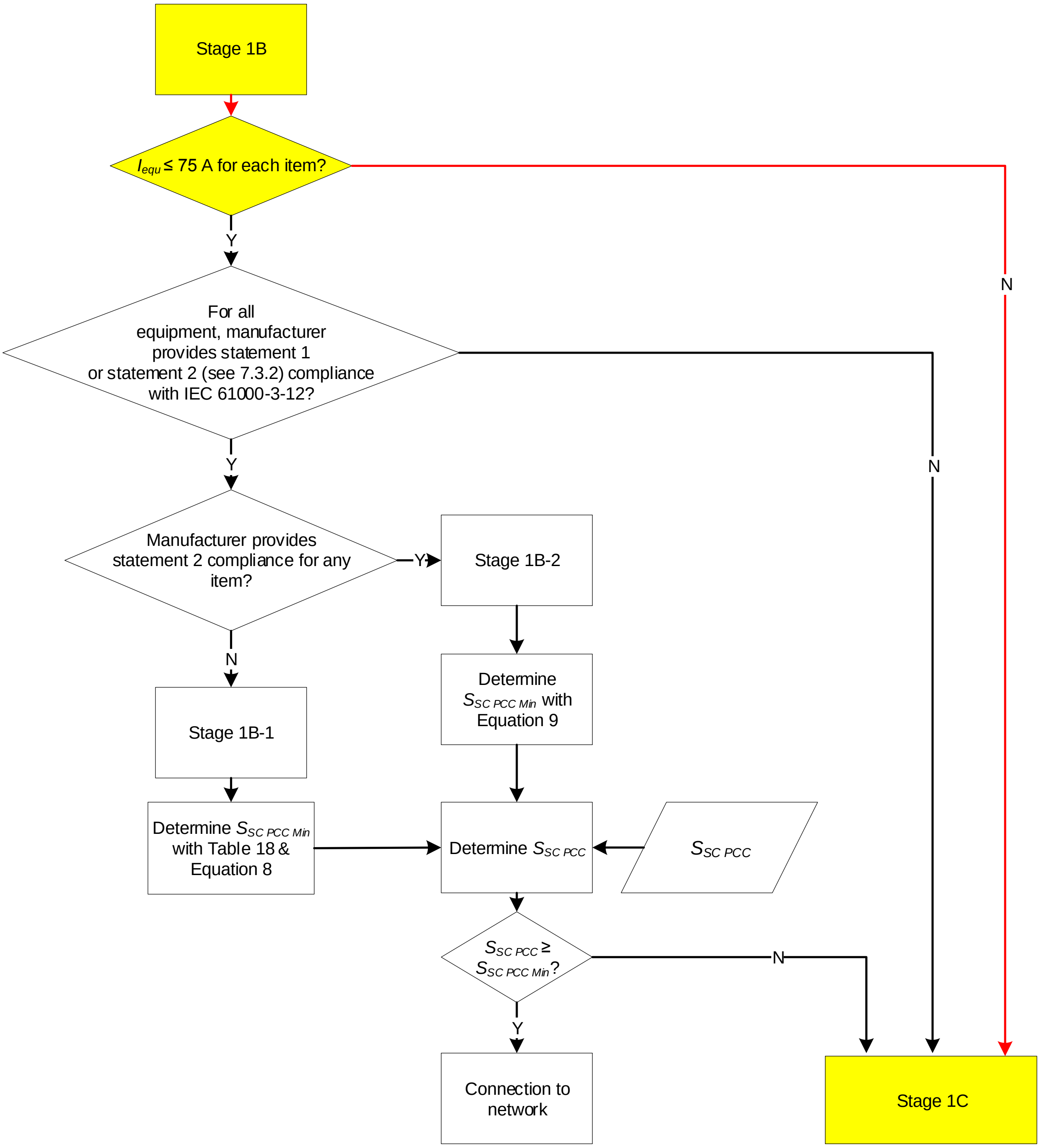

Figure E31 — Step 3 for Worked Example 10

There is one item of equipment with rating above the 75 A threshold, $I_{equ\ 1}$ = 150 A, so we progress to Step 4, which follows the Stage 1C process.

12.4 Step 4

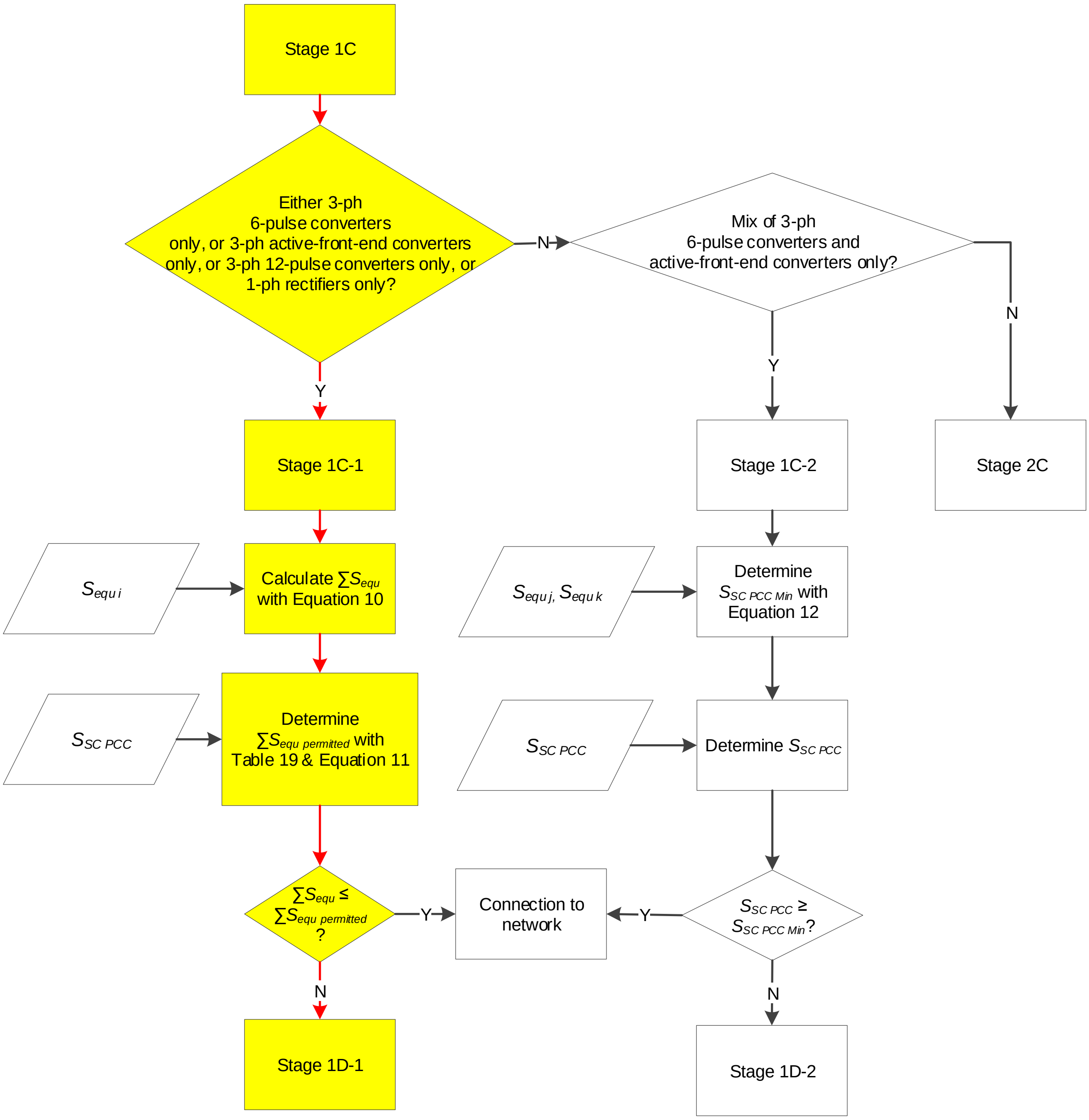

Figure E32 — Steps 4 to 7 for Worked Example 10

We are not dealing with a mix of technology types so we follow the Stage 1C-1 process.

12.5 Step 5

Since there is only one item of equipment, the aggregate equipment rated power $\sum S_{equ}$ = 104 kVA.

12.6 Step 6

The permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$) for the connection is determined with reference to the Table 19 value for $\sum S_{equ\ permitted\ @\ reference\ Ssc}$, which is then scaled according to the short-circuit power at the PCC ($S_{SC\ PCC}$) as shown in Equation 11, which is reproduced and solved below.

From Table 19:

- $\sum S_{equ\ permitted\ @\ reference\ Ssc}$ = 192 kVA for a reference S_{SC} of 10 MVA.

Equation 11, reproduced below, is used to solve for the permitted aggregate equipment rated power, $\sum S_{equ\ permitted}$.

$$\sum S_{equ\ permitted} = S_{SC\ PCC}\left(\frac{\sum S_{equ\ permitted\ @\ Ssc\ reference}}{S_{SC\ reference}}\right) \tag{8}$$

The short-circuit power at the PCC ($S_{SC\ PCC}$) is given as 5.1 MVA.

$\sum S_{equ\ permitted}$ = 5.1 MVA × (192 kVA / 10 MVA) = 97.92 kVA.

12.7 Step 7

Since the aggregate equipment rated power ($\sum S_{equ}$) is greater than the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$), 104 kVA < 97.92 kVA, then the connection must progress to Stage 1D-1.

12.8 Step 8

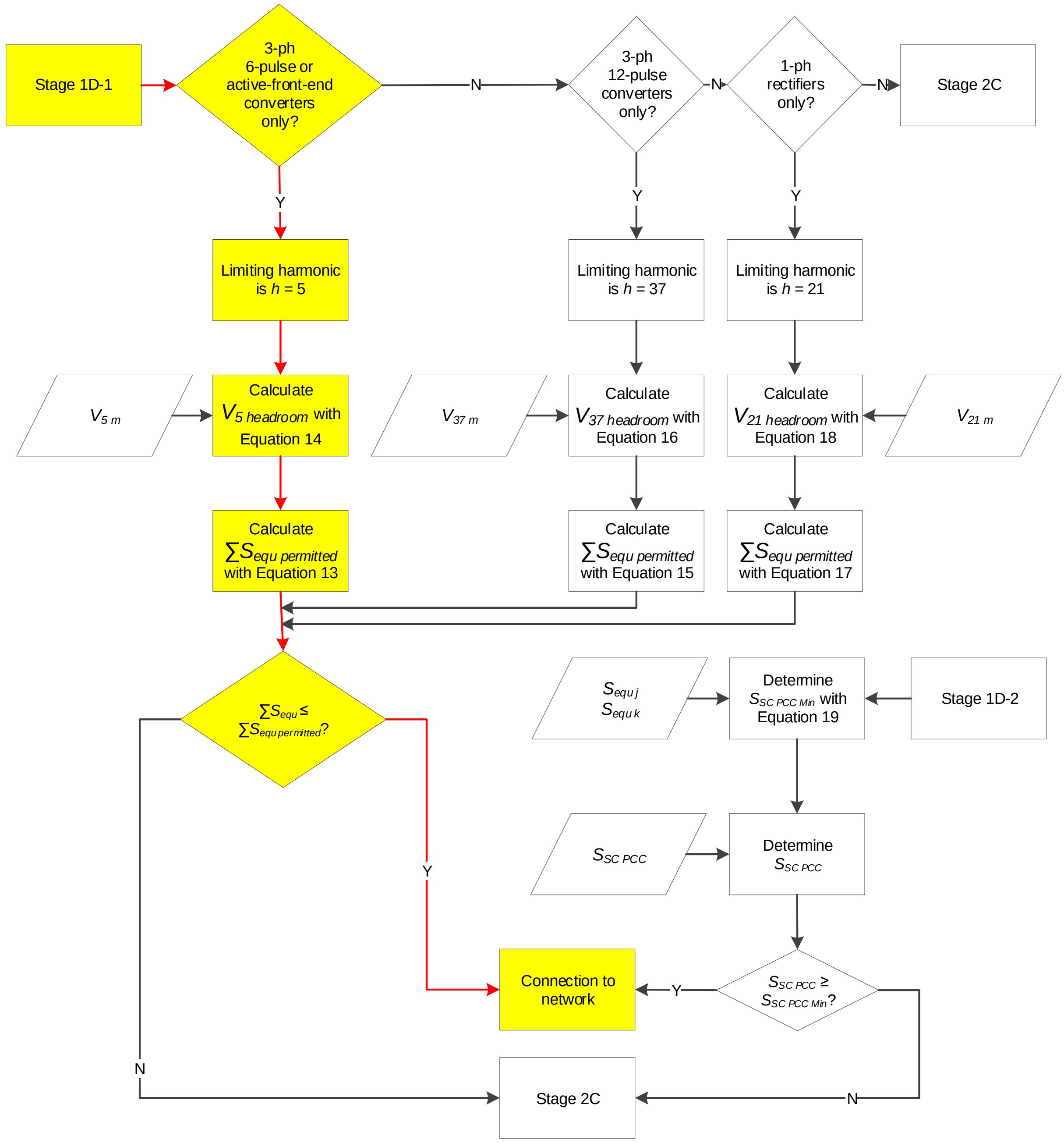

Figure E33 — Steps 8 to 11 for Worked Example 10

Since we have only one three-phase active-front-end plant item, the limiting harmonic is considered to be h = 5.

12.9 Step 9

We calculate the headroom at the limiting harmonic order using Equation 14, reproduced below.

$$V_{5\ headroom} = V_{5\ PL} - V_{5\ m} \tag{9}$$

$V_{5\ headroom}$ = 4% – 1.43% = 2.57%.

12.10 Step 10

We calculate $\sum S_{equ\ permitted}$ using Equation 13, reproduced below.

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

$$\sum S_{equ\ permitted} = \frac{5.1\ \text{MVA}}{10\ \text{MVA}} \times \frac{2.57\%}{0.25 \times 4\%} \times 192\ \text{kVA} = 251.654\ \text{kVA}.$$

12.11 Step 11

Since the aggregate equipment rated power ($\sum S_{equ}$) is less than the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$), 104 kVA < 251.654 kVA, then the connection is compliant and is permitted.

13 Worked Example 11

Table E12 — Connection data for Worked Example 11

<table>
<tr><th>Example</th><th>Equipment</th><th>Rating
kVA</th><th>Rating
A</th><th>No. of phases</th><th>Harmonic statement</th><th>PCC voltage</th><th>Service current capacity
(I_{SCC})</th><th>Final stage</th></tr>
<tr><td rowspan="2">11</td><td>6-Pulse AC/DC Motor Drive</td><td>20</td><td>28.87</td><td>3</td><td>—</td><td rowspan="2">LV</td><td rowspan="2">≥ 100 A</td><td rowspan="2">1D-2</td></tr>
<tr><td>Active Front-end Motor Drive</td><td>70</td><td>101.04</td><td>3</td><td>—</td></tr>
</table>

The following additional data has been supplied for this connection:

- Current transformer (CT) metering is used.
- $S_{SC\ PCC}$ = 6 MVA.
- $V_{5\ m}$ = 1.43%.
- $V_{5\ PL}$ = 4.0%.

13.1 Step 1

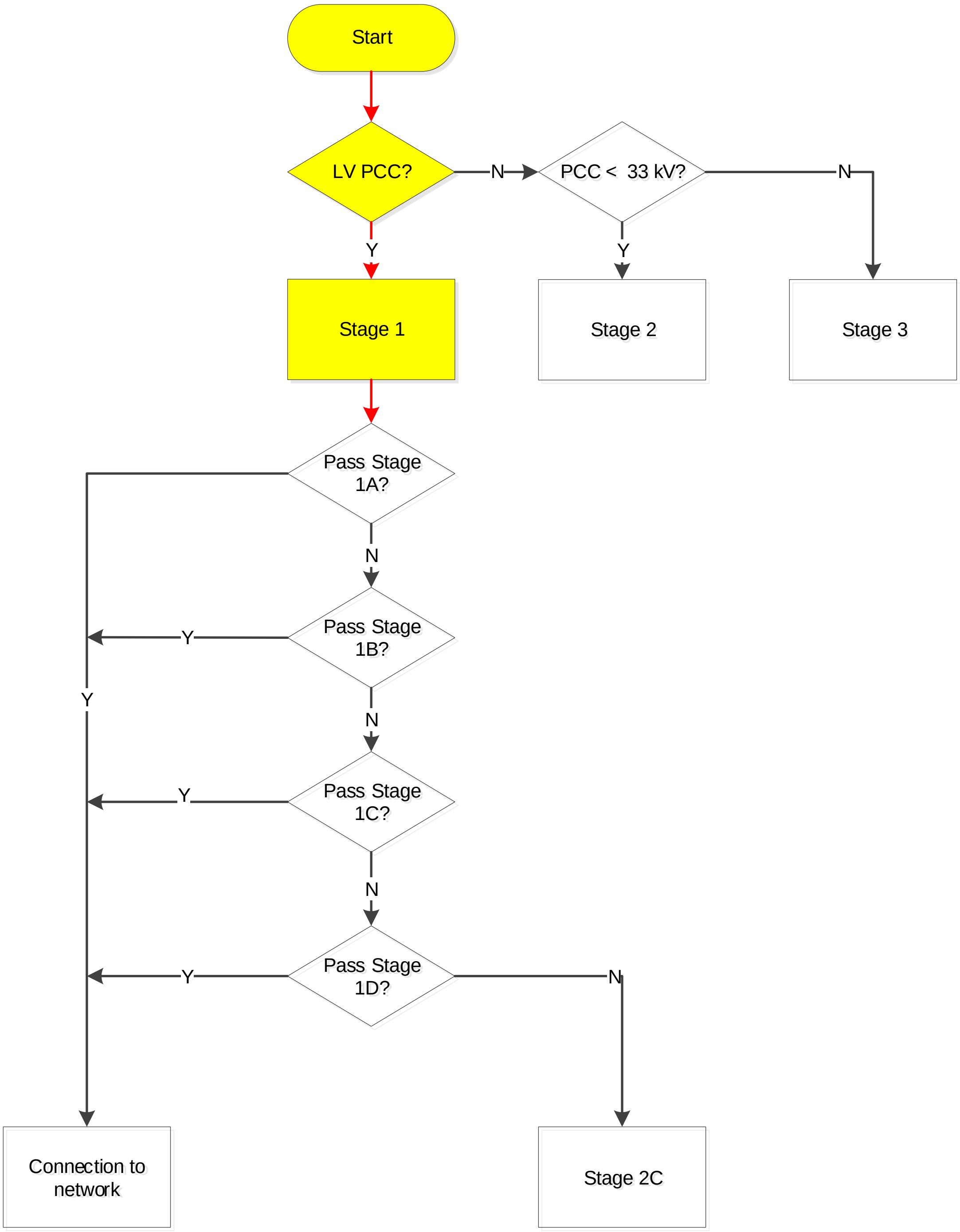

Figure E34 — Step 1 for Worked Example 11

13.2 Step 2

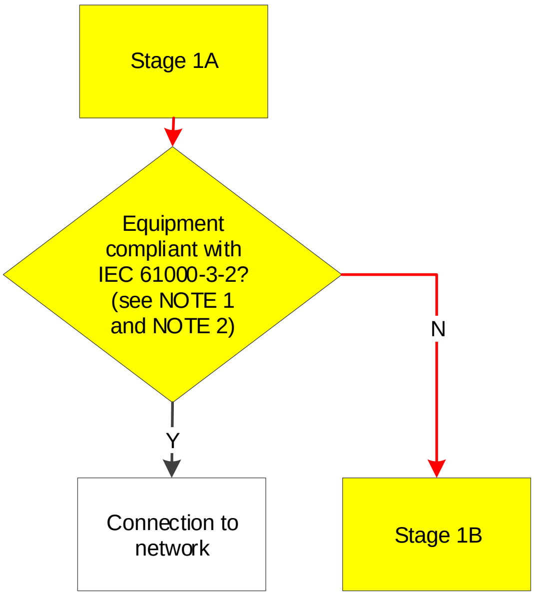

Figure E35 — Step 2 for Worked Example 11

13.3 Step 3

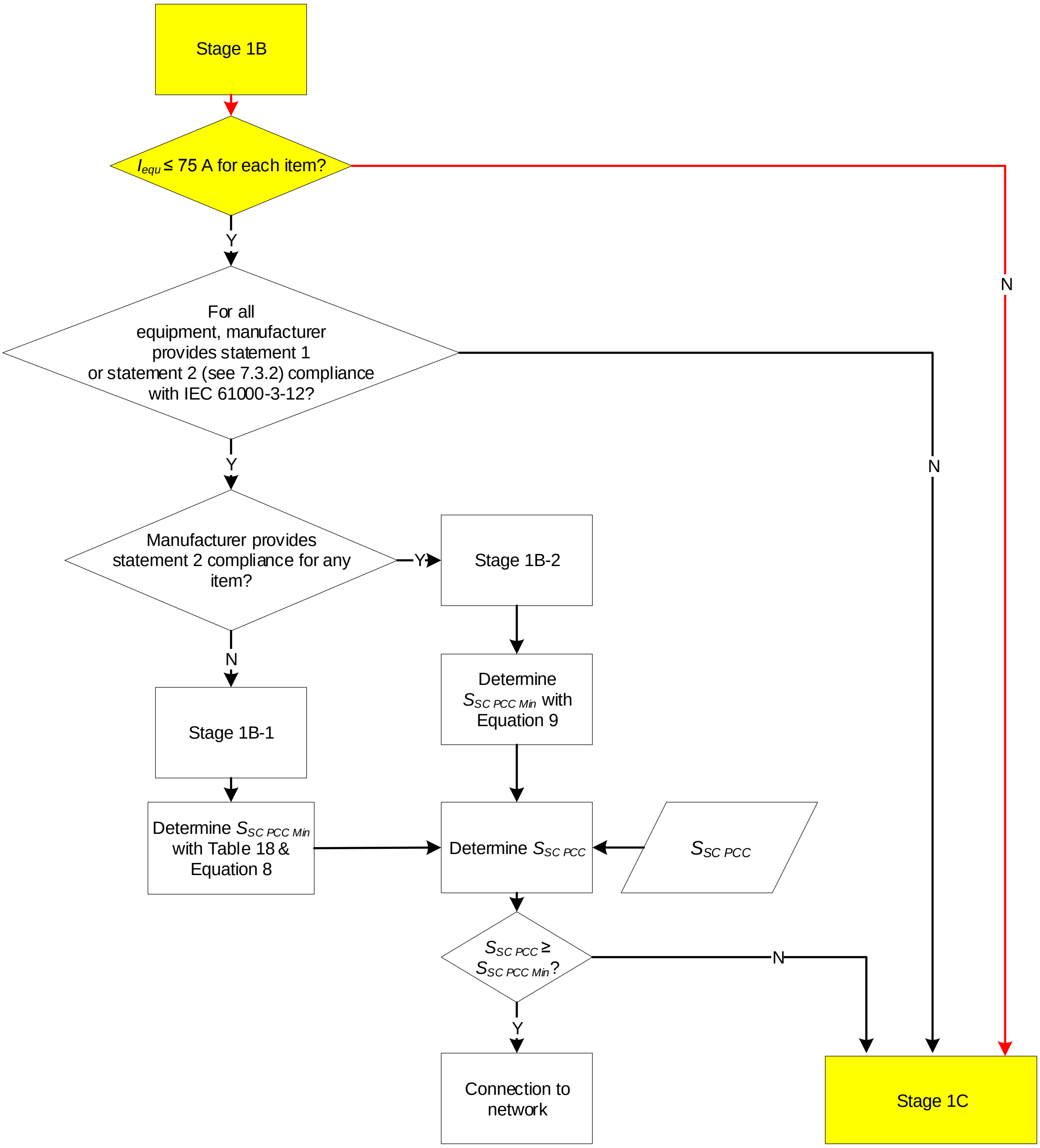

Figure E36 — Step 3 for Worked Example 11

There is one item of equipment with rating above the 75 A threshold, $I_{equ\ 2}$ = 101.04 A, so we progress to Step 4, which follows the Stage 1C process.

13.4 Step 4

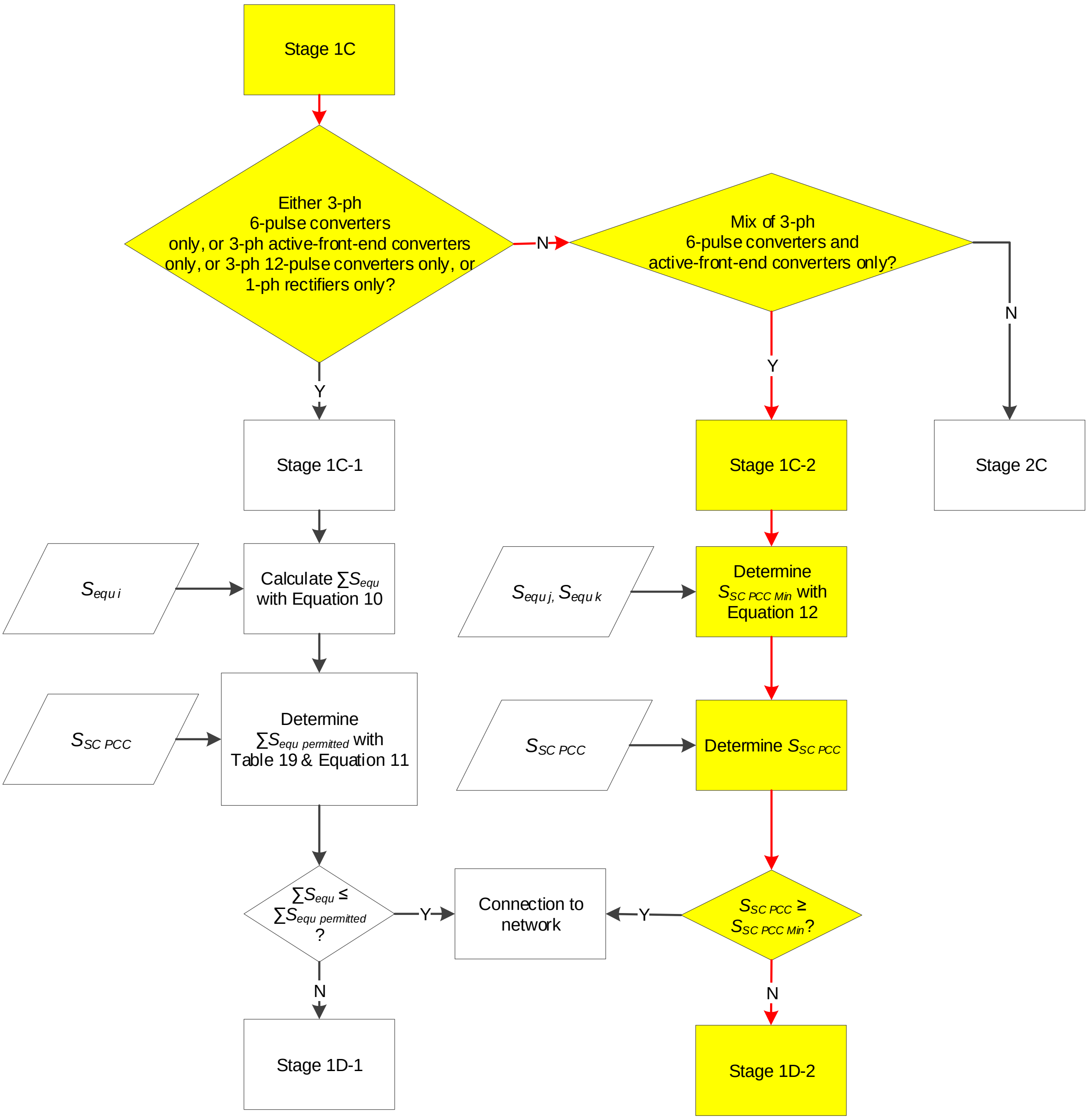

Figure E37 — Steps 4 to 7 for Worked Example 11

We have a mix of three-phase six-pulse converters and active-front-end converters, so we progress to Step 5, which follows the Stage 1C-2 process.

13.5 Step 5

We need to determine the minimum permitted short-circuit power (MVA) at the PCC ($S_{SC\ PCC\ Min}$) using Equation 12, as shown below.

$$S_{SC\ PCC\ Min} = 459.977 \sum_{j=1}^{J} S_{equ\ j} + 52.170 \sum_{k=1}^{K} S_{equ\ k} \tag{11}$$

Where J is the number of items of three-phase six-pulse plant or equipment – one in this example – and K is the number of items of three-phase active-front-end plant or equipment – also one in this example.

$S_{SC\ PCC\ Min}$ = (459.977 × 20 kVA) + (52.17 × 70 kVA)
= 12.851 MVA.

13.6 Step 6

The three-phase short-circuit power at the PCC was given for this example as $S_{SC\ PCC}$ = 6 MVA.

13.7 Step 7

Since the three-phase short-circuit power at the PCC ($S_{SC\ PCC}$) is lower than the minimum permitted short-circuit power ($S_{SC\ PCC\ Min}$), 6 MVA < 12.851 MVA, then the connection progresses to Stage 1D-2.

13.8 Step 8

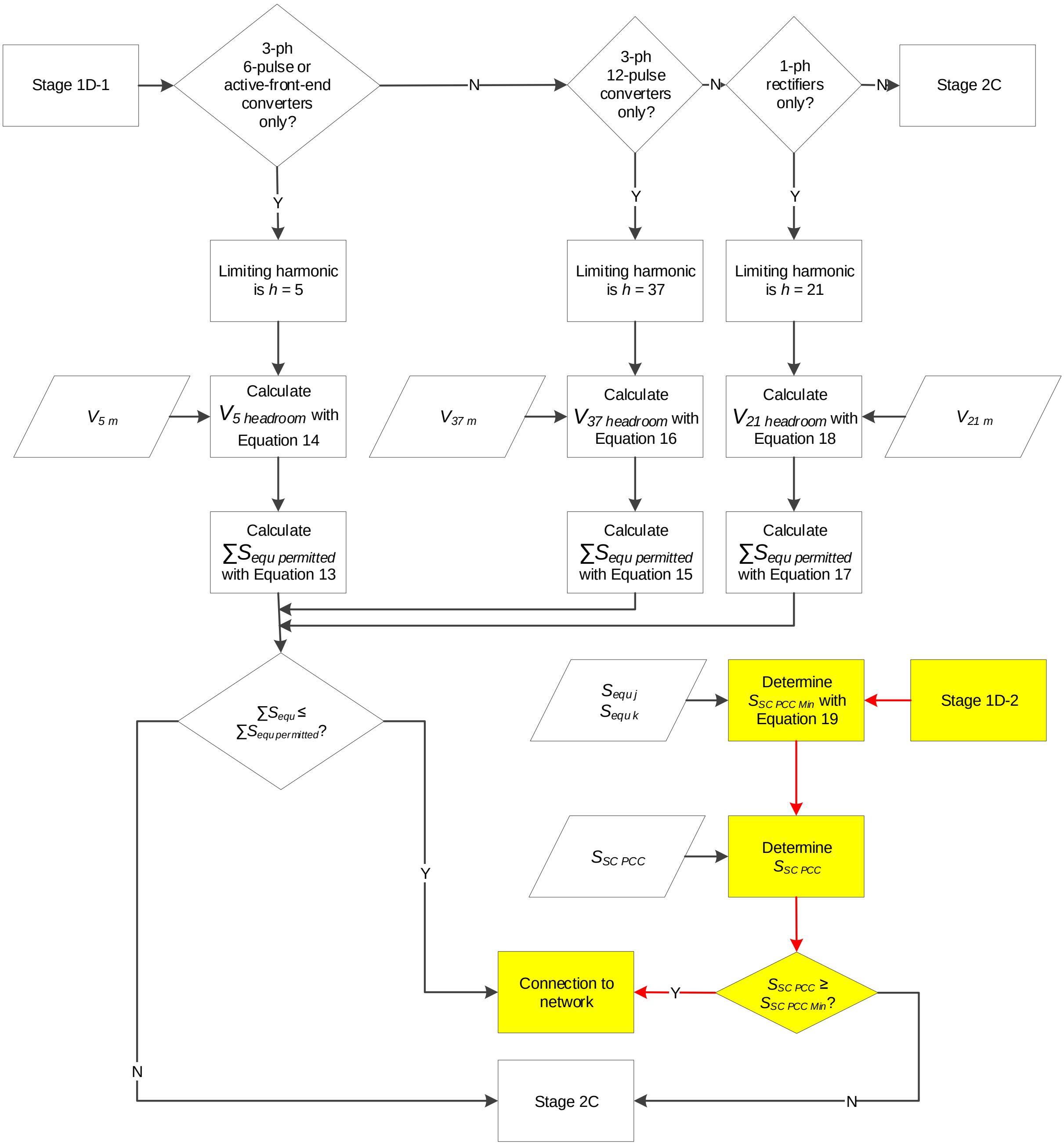

Figure E38 — Steps 8 to 10 for Worked Example 11

The minimum short-circuit power at the PCC ($S_{SC\ PCC\ Min}$), for this mixed three-phase converter technology example is calculated using Equation 19, as below.

$$S_{SC\ PCC\ Min} = \frac{459.977 \sum_{j=1}^{J} S_{equ\ j} + 52.170 \sum_{k=1}^{K} S_{equ\ k}}{V_{5\ headroom}} \qquad (12)$$

$$S_{SC\ PCC\ Min} = \frac{(459.977 \times 20\ \text{kVA}) + (52.170 \times 70\ \text{kVA})}{4\% - 1.43\%} = 5\ \text{MVA.}$$

13.9 Step 9

The three-phase short-circuit power at the PCC was given for this example as $S_{SC\ PCC}$ = 6 MVA.

13.10 Step 10

Since the three-phase short-circuit power at the PCC ($S_{SC\ PCC}$) is greater than the minimum permitted short-circuit power ($S_{SC\ PCC\ Min}$), 6 MVA > 5 MVA, then the connection is compliant and is permitted.

14 Worked Example 12

Table E13 — Connection data for Worked Example 12

Example	Equipment	Rating kVA	Rating A	No. of phases	Harmonic statement	PCC voltage	Service current capacity (I_{SCC})	Final stage
12	6-Pulse AC/DC Motor Drives	50	72.17	3	—	11 kV	—	2A-1
		30	43.30	3	—			

The following additional data has been supplied for this connection:

- $S_{SC\ PCC}$ = 100 MVA.

14.1 Step 1

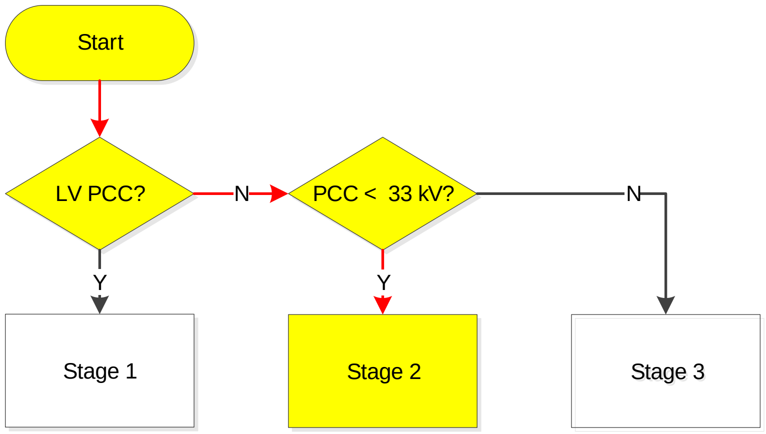

Figure E39 — Step 1 for Worked Example 12

14.2 Step 2

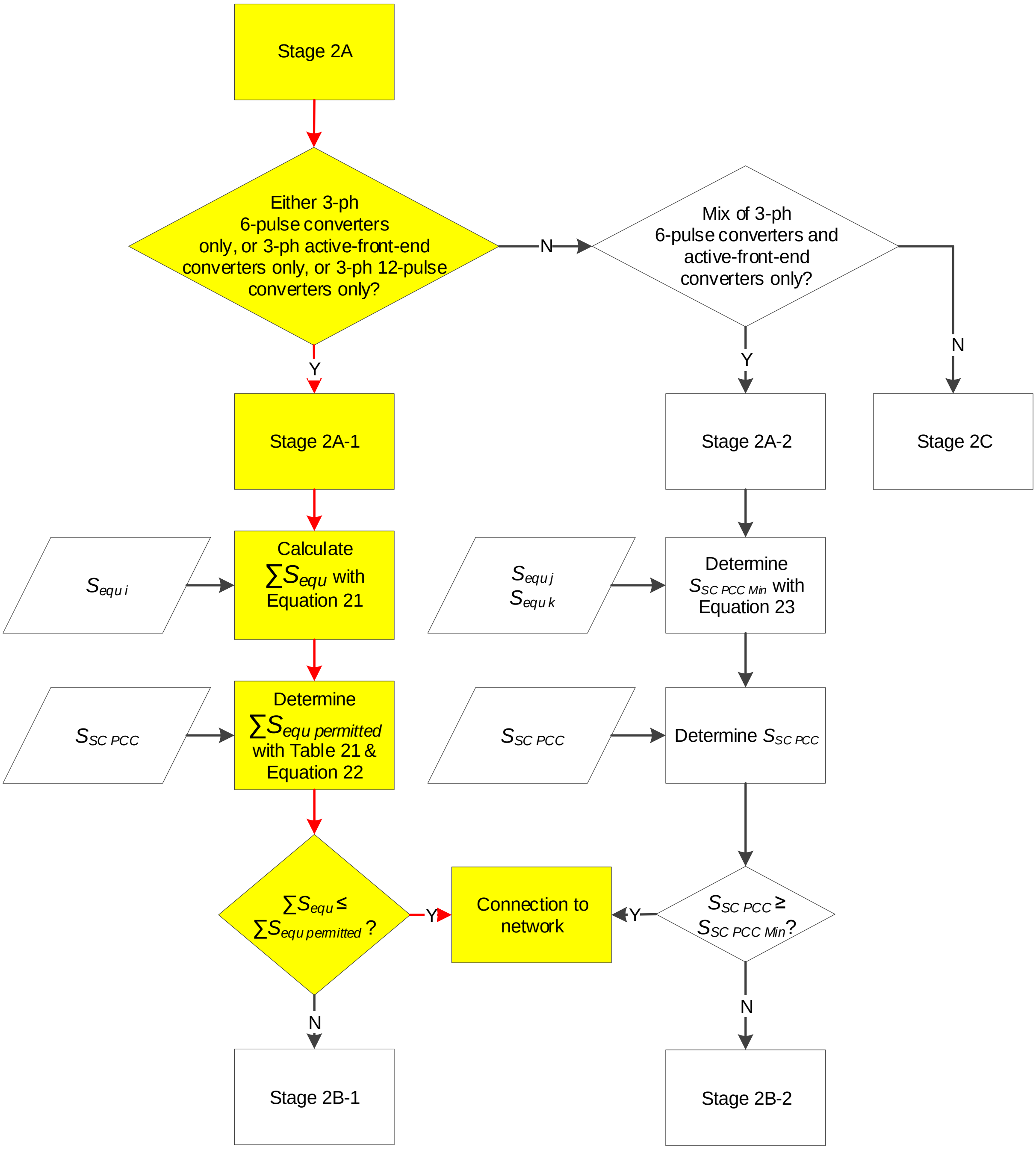

Figure E40 — Steps 2 to 6 for Worked Example 12

We are not dealing with a mix of technology types so we follow the Stage 2A-1 process.

14.3 Step 3

We determine the aggregate equipment rated power ($\sum S_{equ}$) in accordance with Equation 21, as below.

$$\sum S_{equ} = \sum_{j=1}^{J} S_{equ\,j} \tag{13}$$

$\sum S_{equ}$ = 50 kVA + 30 kVA = 80 kVA.

14.4 Step 4

The three-phase short-circuit power at the PCC was given for this example as $S_{SC\,PCC}$ = 100 MVA.

14.5 Step 5

The permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$) for the connection is determined with reference to the Table 21 value for $\sum S_{equ\ permitted\ @\ reference\ Ssc}$, which is then scaled according to the short-circuit power at the PCC ($S_{SC\,PCC}$) as shown in Equation 22, which is reproduced and solved below.

From Table 21:

- $\sum S_{equ\ permitted\ @\ 60\ MVA\ Ssc\ reference}$ = 76 kVA.

Equation 22 is used to solve for the permitted aggregate equipment rated power, $\sum S_{equ\ permitted}$.

$$\sum S_{equ\ permitted} = S_{SC\ PCC}\left(\frac{\sum S_{equ\ permitted\ @\ 60\ MVA\ Ssc\ reference}}{60\ \mathrm{MVA}}\right) \tag{14}$$

$\sum S_{equ\ permitted}$ = 100 MVA × (76 kVA / 60 MVA) = 126.7 kVA.

14.6 Step 6

Since the aggregate equipment rated power ($\sum S_{equ}$) is less than the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$), 80 kVA < 126.7 kVA, then the connection is compliant and is permitted.

15 Worked Example 13

Table E14 — Connection data for Worked Example 13

Example	Equipment	Rating kVA	Rating A	No. of phases	Harmonic statement	PCC voltage	Service current capacity (I_{SCC})	Final stage
13	6-Pulse AC/DC Motor Drive	2 x 50	2 x 72.17	3	—	11 kV	—	2A-2
	Active Front-end Motor Drive	1 x 200	1 x 288.68	3	—			

The following additional data has been supplied for this connection:

- $S_{SC\ PCC}$ = 100 MVA.

15.1 Step 1

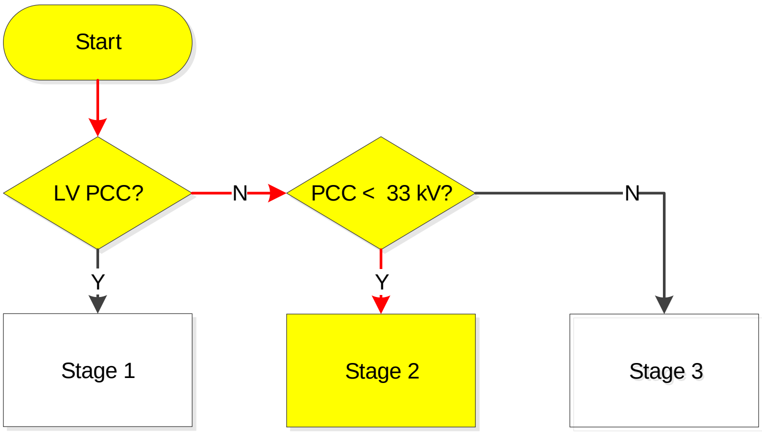

Figure E41 — Step 1 for Worked Example 13

15.2 Step 2

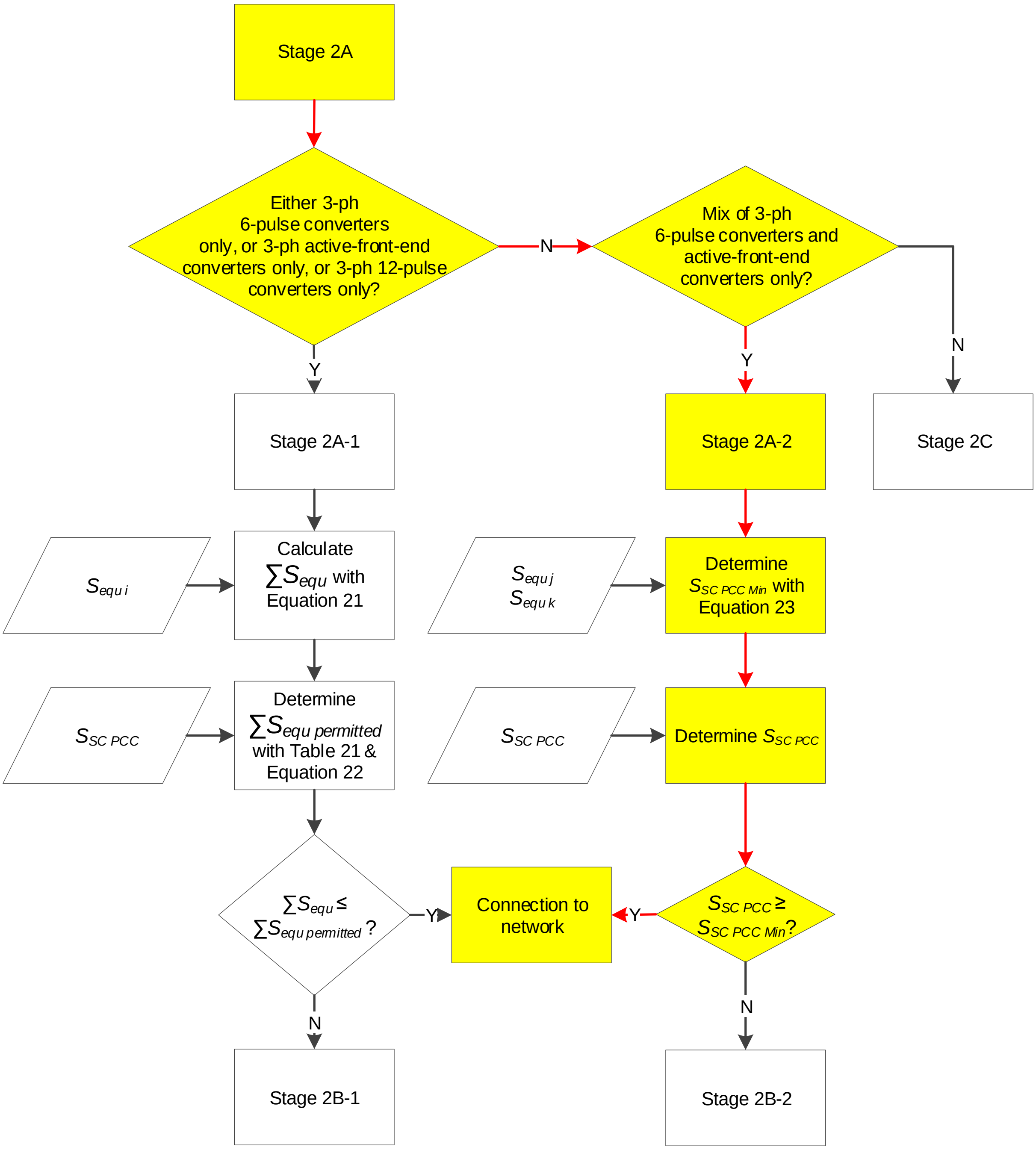

Figure E42 — Steps 2 to 5 for Worked Example 13

We have a mix of three-phase six-pulse converters and active-front-end converters, so we progress to Step 3, which follows the Stage 2A-2 process.

15.3 Step 3

We need to determine the minimum permitted short-circuit power (MVA) at the PCC ($S_{SC\ PCC\ Min}$) using Equation 23, as shown below.

$$S_{SC\ PCC\ Min} = 785.962 \sum_{j=1}^{J} S_{equ\ j} + 89.143 \sum_{k=1}^{K} S_{equ\ k} \tag{15}$$

Where J is the number of items of three-phase six-pulse plant or equipment – two in this example – and K is the number of items of three-phase active-front-end plant or equipment – one in this example.

For the three-phase six-pulse equipment:

- $S_{equ\ 1} = S_{equ\ 2} = 50$ kVA.
- $\sum_{j=1}^{J} S_{equ\ j} = 50\ \text{kVA} + 50\ \text{kVA} = 100\ \text{kVA}$.

For the three-phase active-front-end equipment:

- $\sum_{k=1}^{K} S_{equ\ k} = 200\ \text{kVA}$.

$S_{SC\ PCC\ Min} = (785.962 \times 100\ \text{kVA}) + (89.143 \times 200\ \text{kVA})$.

$S_{SC\ PCC\ Min} = 18.615$ MVA.

15.4 Step 4

The three-phase short-circuit power at the PCC was given for this example as $S_{SC\ PCC} = 100$ MVA.

15.5 Step 5

Since the three-phase short-circuit power at the PCC ($S_{SC\ PCC}$) is greater than the minimum permitted short-circuit power ($S_{SC\ PCC\ Min}$), 100 MVA > 18.615 MVA, then the connection is compliant and is permitted.

16 Worked Example 14

Table E15 — Connection data for Worked Example 14

Example	Equipment	Rating kVA	Rating A	No. of phases	Harmonic statement	PCC voltage	Service current capacity (I_{SCC})	Final stage
14	6-Pulse AC/DC Motor Drives	2 x 50	2 x 72.17	3	—	11 kV	—	2B-1
		1 x 30	1 x 43.3	3	—			

The following additional data has been supplied for this connection:

- $S_{SC\ PCC}$ = 100 MVA.
- $V_{5\ m}$ = 1.5%.
- $V_{5\ PL}$ = 3.0%.

16.1 Step 1

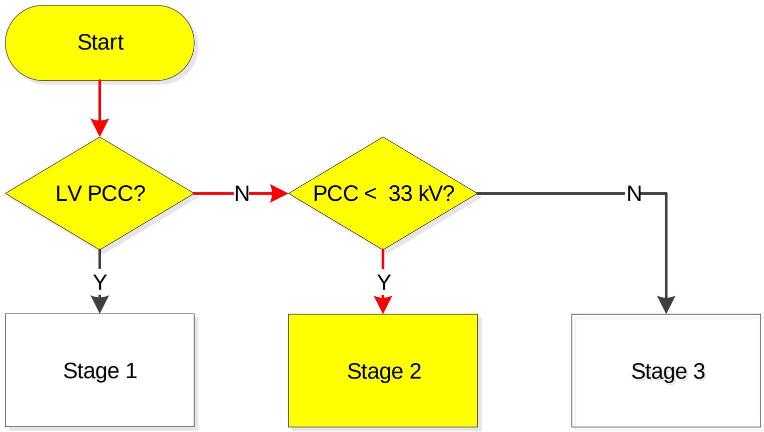

Figure E43 — Step 1 for Worked Example 14

16.2 Step 2

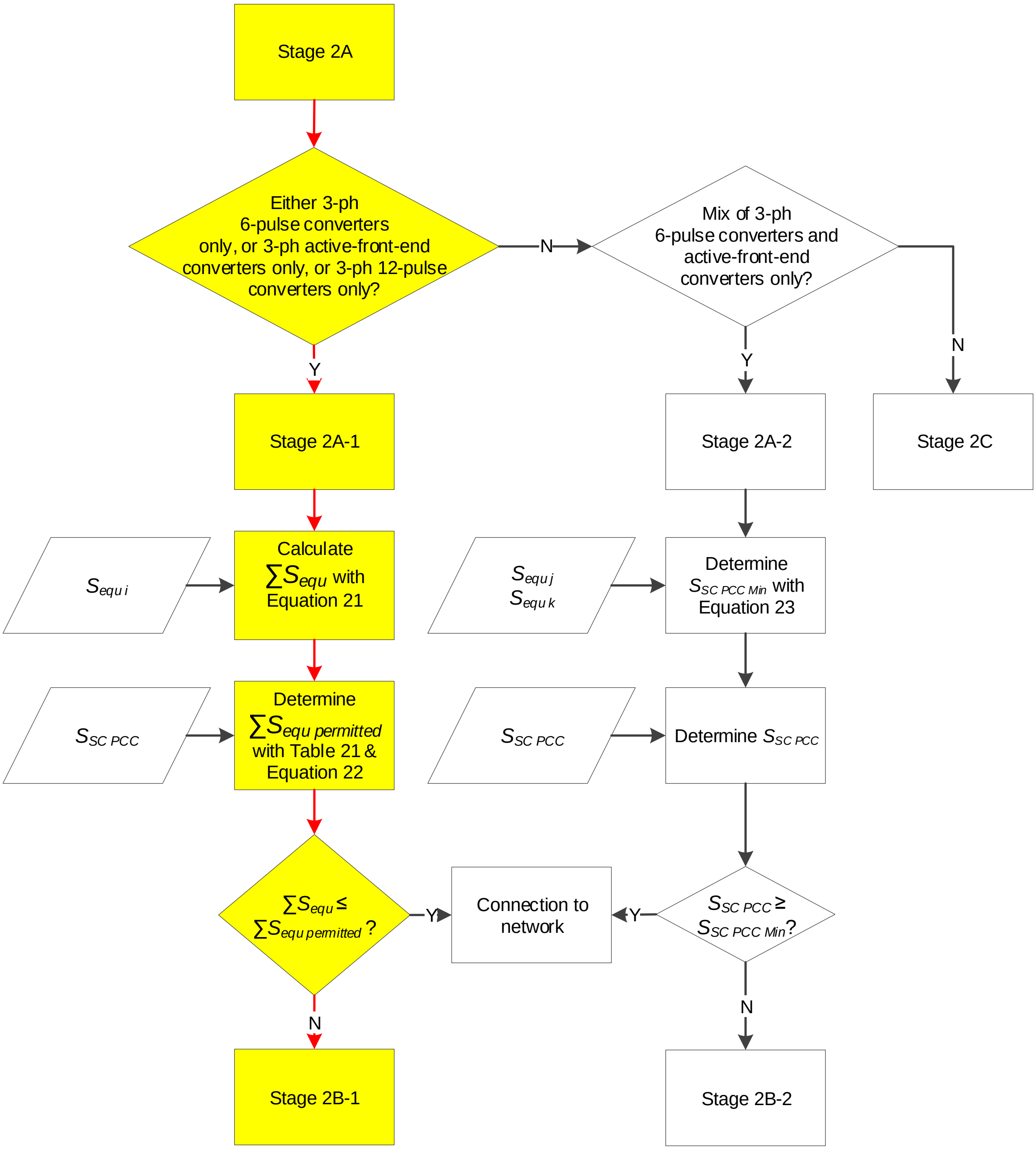

Figure E44 — Steps 2 to 6 for Worked Example 14

We are not dealing with a mix of technology types so we follow the Stage 2A-1 process.

16.3 Step 3

We determine the aggregate equipment rated power ($\sum S_{equ}$) in accordance with Equation 21, as below.

$$\sum S_{equ} = \sum_{j=1}^{J} S_{equ\ j} \tag{16}$$

$\sum S_{equ}$ = (2 × 50 kVA) + 30 kVA = 130 kVA.

16.4 Step 4

The three-phase short-circuit power at the PCC was given for this example as $S_{SC\ PCC}$ = 100 MVA.

16.5 Step 5

The permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$) for the connection is determined with reference to the Table 21 value for $\sum S_{equ\ permitted\ @\ reference\ Ssc}$, which is then scaled according to the short-circuit power at the PCC ($S_{SC\ PCC}$) as shown in Equation 22, which is reproduced and solved below.

From Table 21:

- $\sum S_{equ\ permitted\ @\ 60\ MVA\ Ssc\ reference}$ = 76 kVA.

Equation 22 is used to solve for the permitted aggregate equipment rated power, $\sum S_{equ\ permitted}$.

$$\sum S_{equ\ permitted} = S_{SC\ PCC}\left(\frac{\sum S_{equ\ permitted\ @\ 60\ MVA\ Ssc\ reference}}{60\ \text{MVA}}\right) \tag{17}$$

$\sum S_{equ\ permitted}$ = 100 MVA × (76 kVA / 60 MVA) = 126.7 kVA.

16.6 Step 6

Since the aggregate equipment rated power ($\sum S_{equ}$) is greater than the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$), 130 kVA > 126.7 kVA, then the connection progresses to Stage 2B-1.

16.7 Step 7

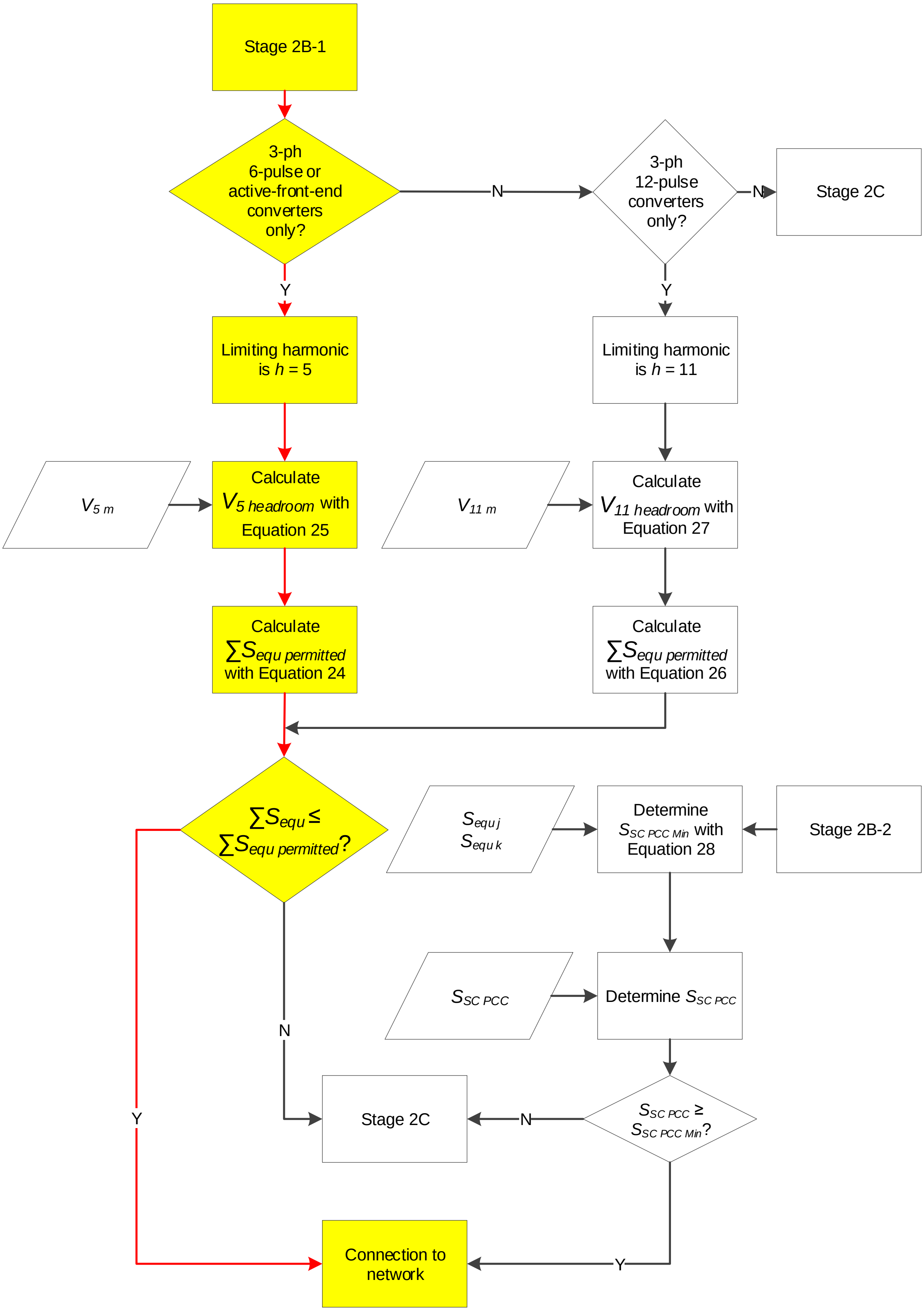

Figure E45 — Steps 7 to 10 for Worked Example 14

Since we are dealing with three-phase, six-pulse converters only, the limiting harmonic is taken to be $h = 5$.

16.8 Step 8

$V_{5\ headroom} = V_{5\ PL} - V_{5\ m}$.

$V_{5\ headroom}$ = 3% – 1.5% = 1.5%.

16.9 Step 9

The permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$) for the connection is determined with reference to the Table 21 value for $\sum S_{equ\ permitted\ @\ reference\ Ssc}$, which is then scaled according to the short-circuit power at the PCC ($S_{SC\ PCC}$) as shown in Equation 24, which is reproduced and solved below.

From Table 21:

- $\sum S_{equ\ permitted\ @\ 60\ MVA\ Ssc\ reference}$ = 76 kVA.

Equation 24 is used to solve for the permitted aggregate equipment rated power, $\sum S_{equ\ permitted}$.

$$\sum S_{equ\ permitted} = \frac{S_{SC\ PCC}}{60\text{ MVA}} \times \frac{V_{5\ headroom}}{0.25 V_{5\ PL}} \times \sum S_{equ\ permitted\ @\ 60\ MVA\ Ssc\ reference} \tag{18}$$

$$\sum S_{equ\ permitted} = \frac{100\text{ MVA}}{60\text{ MVA}} \times \frac{1.5\%}{0.25 \times 3\%} \times 76\text{ kVA} = 253.333\text{ kVA.}$$

16.10 Step 10

Since the aggregate equipment rated power ($\sum S_{equ}$) is less than the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$), 130 kVA < 253.333 kVA, then the connection is compliant and is permitted.

17 Worked Example 15

Table E16 — Connection data for Worked Example 15

Example	Equipment	Rating kVA	Rating A	No. of phases	Harmonic statement	PCC voltage	Service current capacity (I_{SCC})	Final stage
15	6-Pulse AC/DC Motor Drive	100	144.34	3	—	11 kV	—	2B-2
	Active Front-end Motor Drive	500	721.69	3	—			

The following additional data has been supplied for this connection:

- $S_{SC\ PCC}$ = 62 MVA.
- $V_{5\ m}$ = 1.5%.
- $V_{5\ PL}$ = 3.0%.

17.1 Step 1

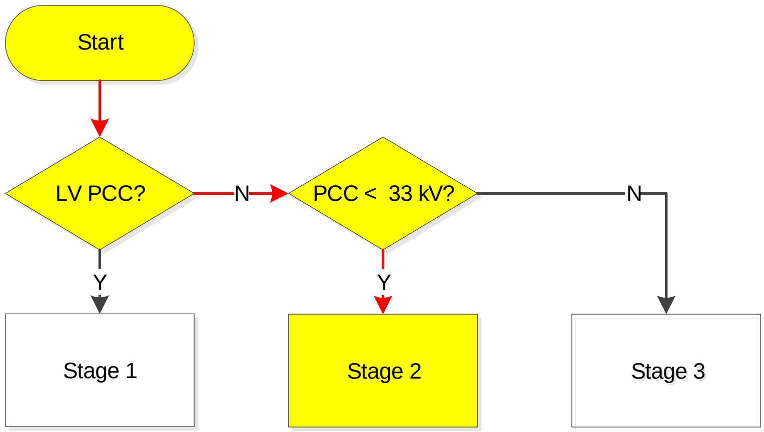

Figure E46 — Step 1 for Worked Example 15

17.2 Step 2

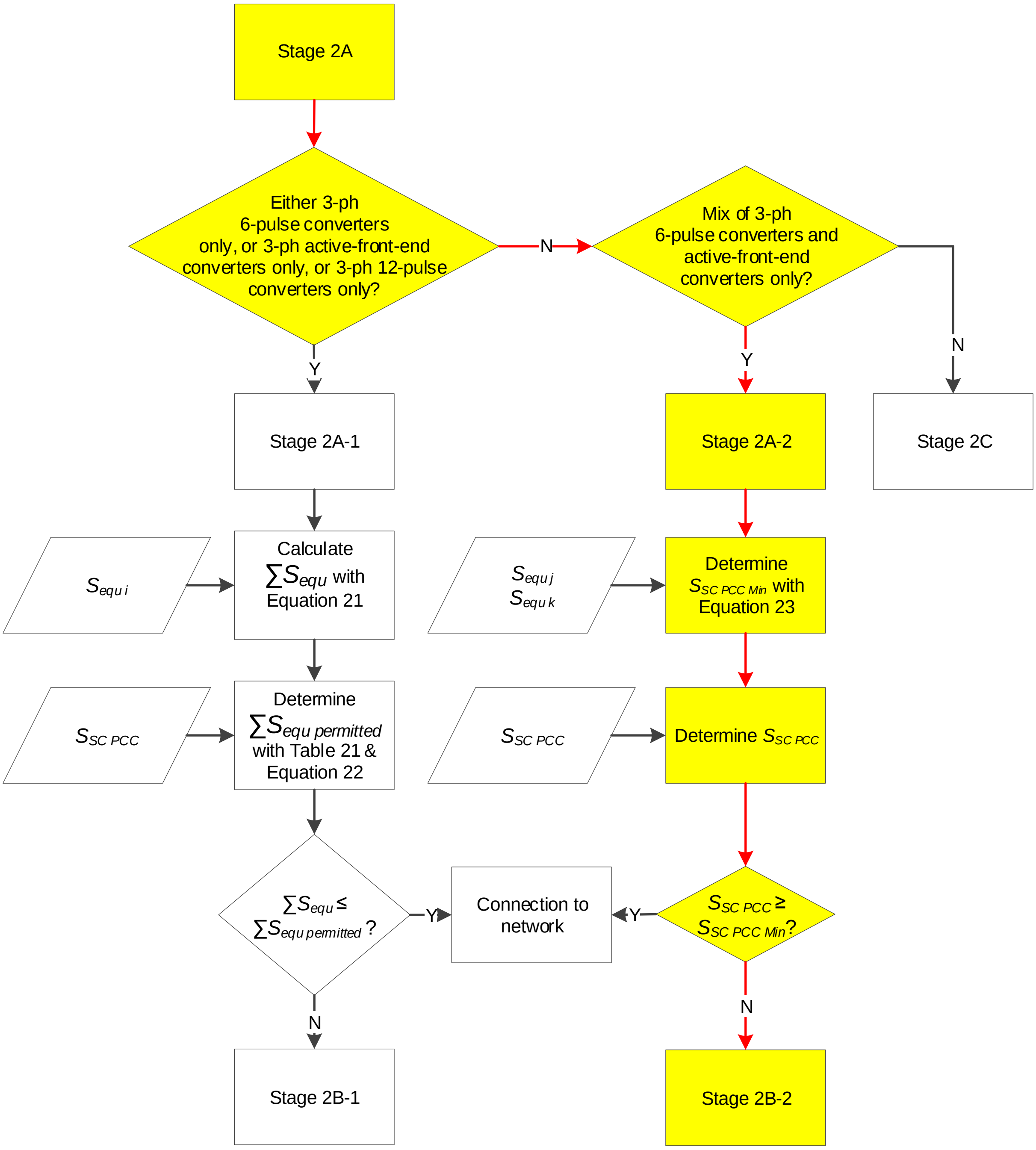

Figure E47 — Steps 2 to 5 for Worked Example 15

We have a mix of three-phase six-pulse converters and active-front-end converters, so we progress to Step 3, which follows the Stage 2A-2 process.

17.3 Step 3

We need to determine the minimum permitted short-circuit power (MVA) at the PCC ($S_{SC\ PCC\ Min}$) using Equation 23, as shown below.

$$S_{SC\ PCC\ Min} = 785.962 \sum_{j=1}^{J} S_{equ\ j} + 89.143 \sum_{k=1}^{K} S_{equ\ k} \qquad (19)$$

Where J is the number of items of three-phase six-pulse plant or equipment – one in this example – and K is the number of items of three-phase active-front-end plant or equipment – also one in this example.

For the three-phase six-pulse equipment:

- $S_{equ\ 1}$ = 100 kVA.
- $\sum_{j=1}^{J} S_{equ\ j}$ = 100 kVA.

For the three-phase active-front-end equipment:

- $S_{equ\ 1}$ = 500 kVA.
- $\sum_{k=1}^{K} S_{equ\ k}$ = 500 kVA.

$S_{SC\ PCC\ Min}$ = (785.962 × 100 kVA) + (89.143 × 500 kVA).

$S_{SC\ PCC\ Min}$ = 123.168 MVA.

17.4 Step 4

The three-phase short-circuit power at the PCC was given for this example as $S_{SC\ PCC}$ = 62 MVA.

17.5 Step 5

Since the three-phase short-circuit power at the PCC ($S_{SC\ PCC}$) is lower than the minimum permitted short-circuit power ($S_{SC\ PCC\ Min}$), 62 MVA < 123.168 MVA, then the connection progresses to Stage 2B-2.

17.6 Step 6

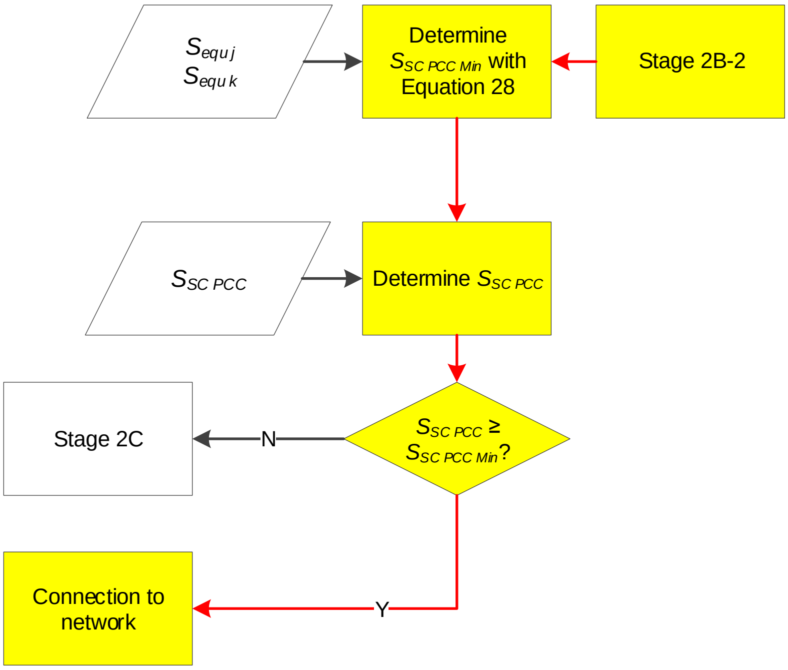

Figure E48 — Steps 6 to 9 for Worked Example 15

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) is found using Equation 28, as below.

$$S_{SC\ PCC\ Min} = \frac{589.472 \sum_{j=1}^{J} S_{equ\,j} + 66.857 \sum_{k=1}^{K} S_{equ\,k}}{V_{5\ headroom}} \tag{20}$$

17.7 Step 7

$V_{5\ headroom} = V_{5\ PL} - V_{5\ m}$.

$V_{5\ headroom} = 3\% - 1.5\% = 1.5\%$.

17.8 Step 8

$$S_{SC\ PCC\ Min} = \frac{(589.472 \times 100\ \text{MVA}) + (66.857 \times 500\ \text{MVA})}{1.5\%} = 61.584\ \text{MVA}.$$

17.9 Step 9

Since the three-phase short-circuit power at the PCC ($S_{SC\ PCC}$) is greater than the minimum permitted short-circuit power ($S_{SC\ PCC\ Min}$), 62 MVA > 61.584 MVA, then the connection is compliant and is permitted.

18 Worked Example 16

Table E17 — Connection data for Worked Example 16

Example	Equipment	Rating kVA	Rating A	No. of phases	Harmonic statement	PCC voltage	Service current capacity (I_{SCC})	Final stage
16	6-Pulse Motor Drive	80	115.47	3	Current emission data available	LV	≥ 100 A	2C via 1D-1

The following additional data has been supplied for this connection:

- Current transformer (CT) metering is used.
- $S_{SC\ PCC}$ = 5.1 MVA.
- X_1/R_1 = 1.1.
- $V_{5\ m}$ = 1.53%.
- $V_{5\ PL}$ = 4%.

18.1 Step 1

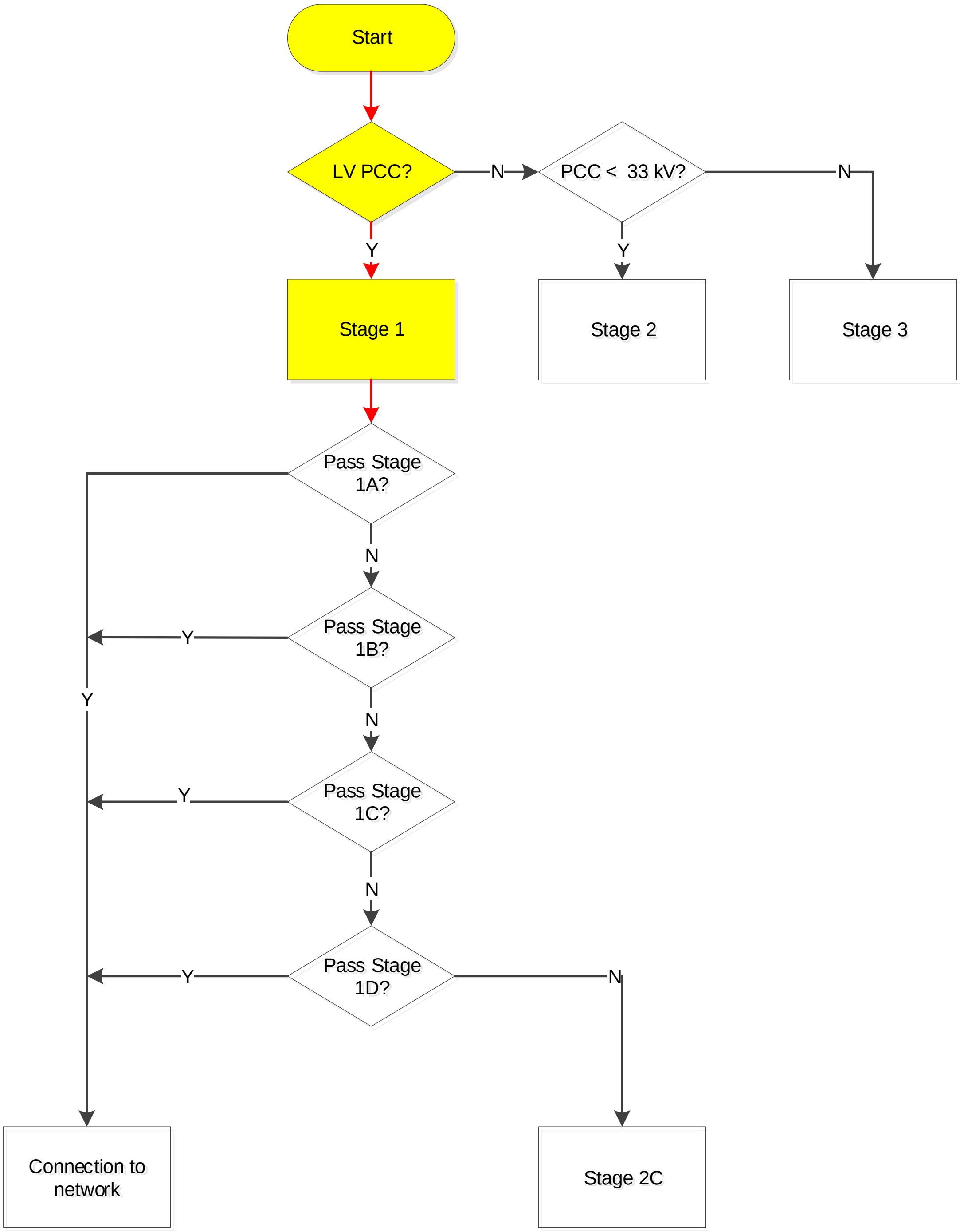

Figure E49 — Step 1 for Worked Example 16

18.2 Step 2

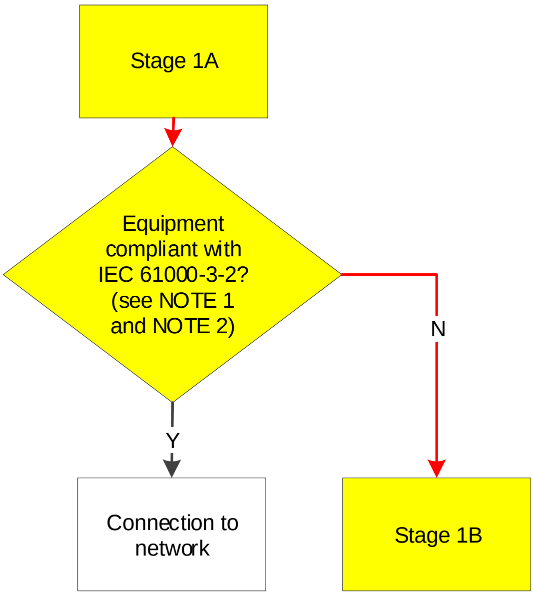

Figure E50 — Step 2 for Worked Example 16

18.3 Step 3

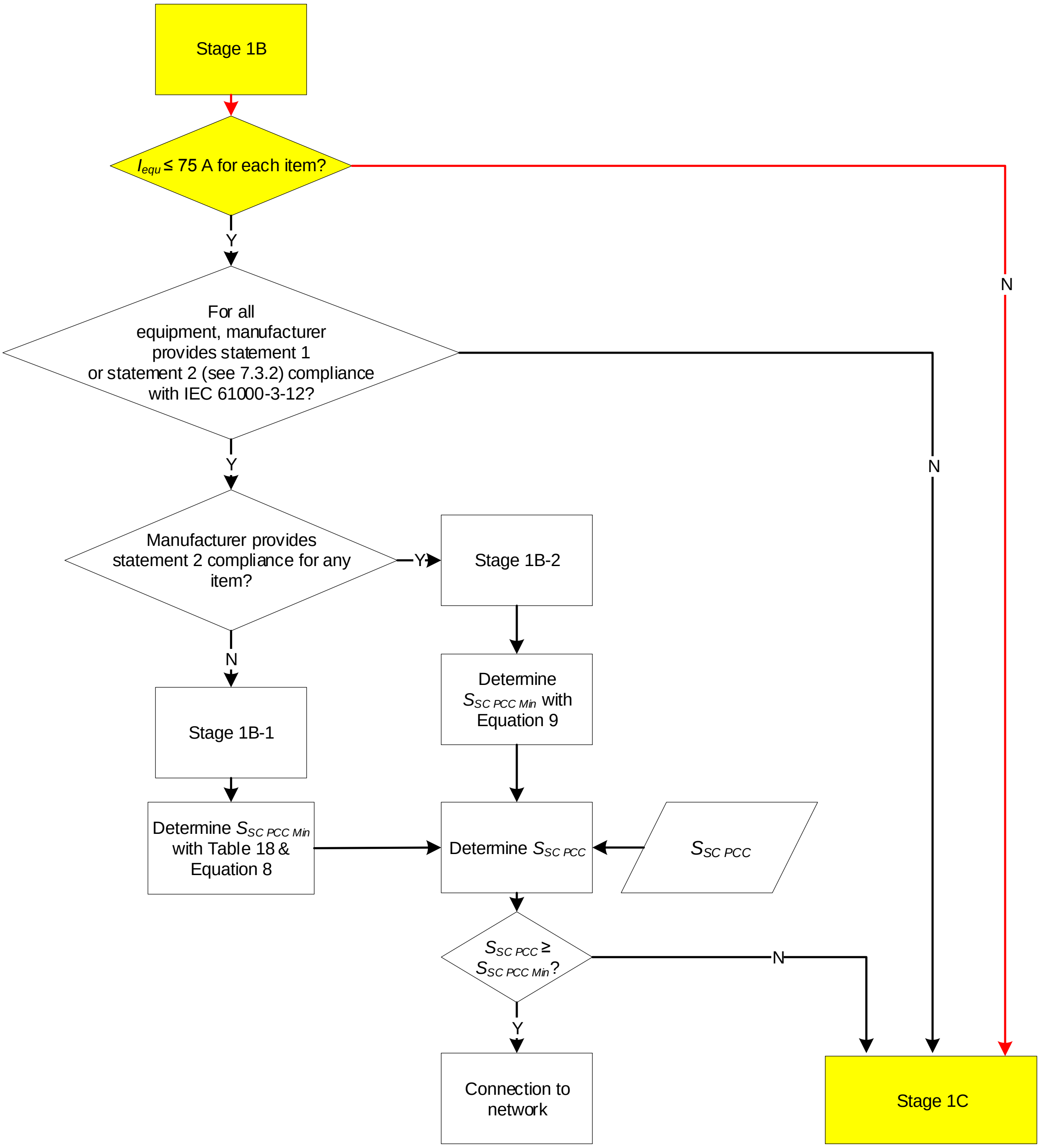

Figure E51 — Step 3 for Worked Example 16

There is one item of equipment, with rating $I_{equ\ 1}$ = 115.47 A, which is greater than the 75 A threshold, so we progress to Step 4, which follows the Stage 1C process.

18.4 Step 4

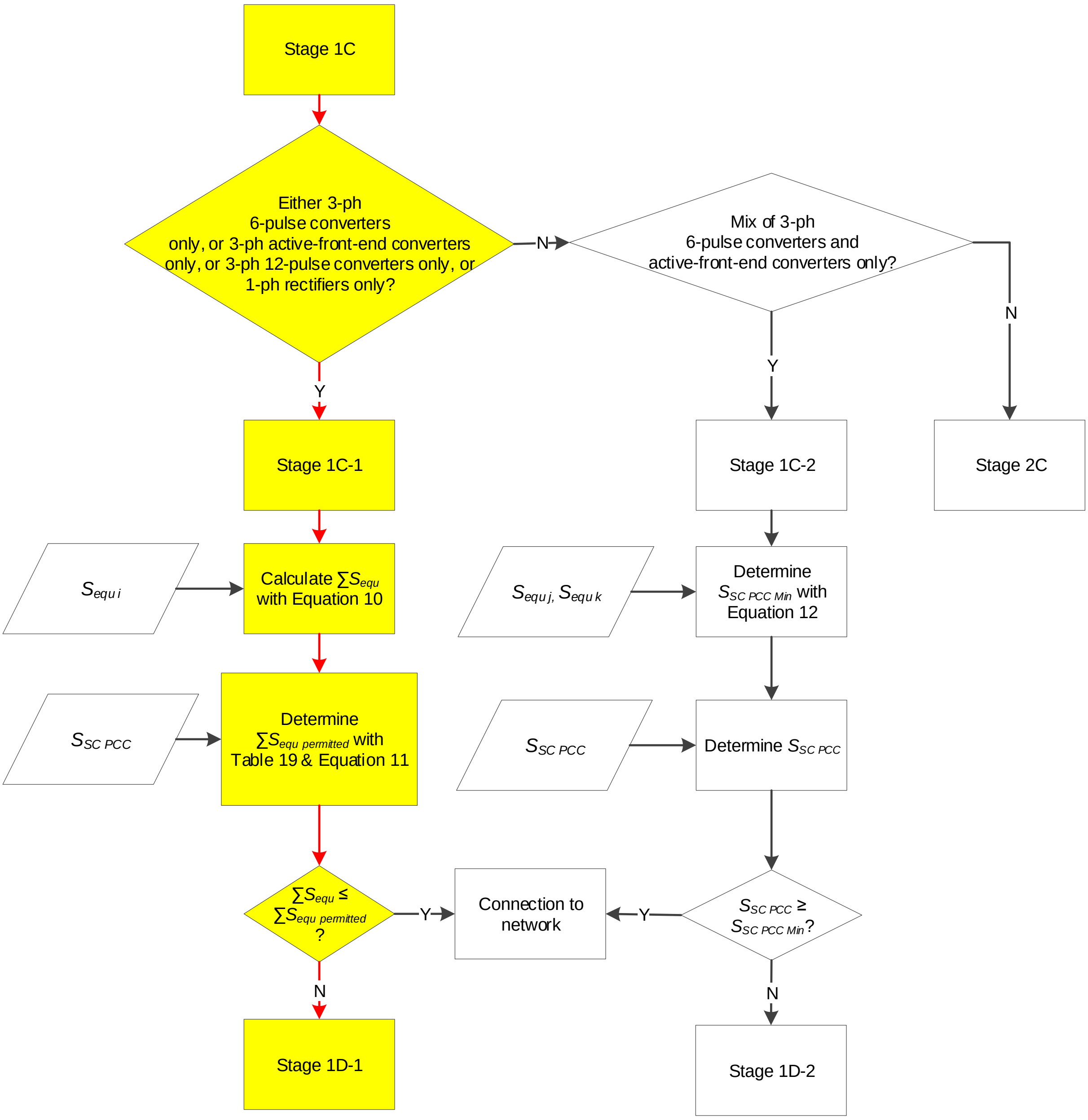

Figure E52 — Steps 4 to 9 for Worked Example 16

We are not dealing with a mix of technology types so we follow the Stage 1C-1 process.

18.5 Step 5

Since there is only one item of equipment, the aggregate equipment rated power $\sum S_{equ}$ = 80 kVA.

18.6 Step 6

The three-phase short-circuit power at the PCC was given for this example as $S_{SC\ PCC}$ = 5.1 MVA.

18.7 Step 7

The permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$) for the connection is determined with reference to the Table 19 value for $\sum S_{equ\ permitted\ @\ reference\ Ssc}$, which is then scaled according to the short-circuit power at the PCC ($S_{SC\ PCC}$) as shown in Equation 11, which is reproduced and solved below.

From Table 19:

- $\sum S_{equ\ permitted\ @\ reference\ Ssc}$ = 22 kVA for a reference S_{SC} of 10 MVA.

18.8 Step 8

Equation 11, reproduced below, is used to solve for the permitted aggregate equipment rated power, $\sum S_{equ\ permitted}$.

$$\sum S_{equ\ permitted} = S_{SC\ PCC}\left(\frac{\sum S_{equ\ permitted\ @\ Ssc\ reference}}{S_{SC\ reference}}\right) \qquad (21)$$

$\sum S_{equ\ permitted}$ = 5.1 MVA × (22 kVA / 10 MVA) = 11.22 kVA.

18.9 Step 9

Since the aggregate equipment rated power ($\sum S_{equ}$) is greater than the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$), 80 kVA > 11.22 kVA, then the connection progresses to Stage 1D-1.

18.10 Step 10

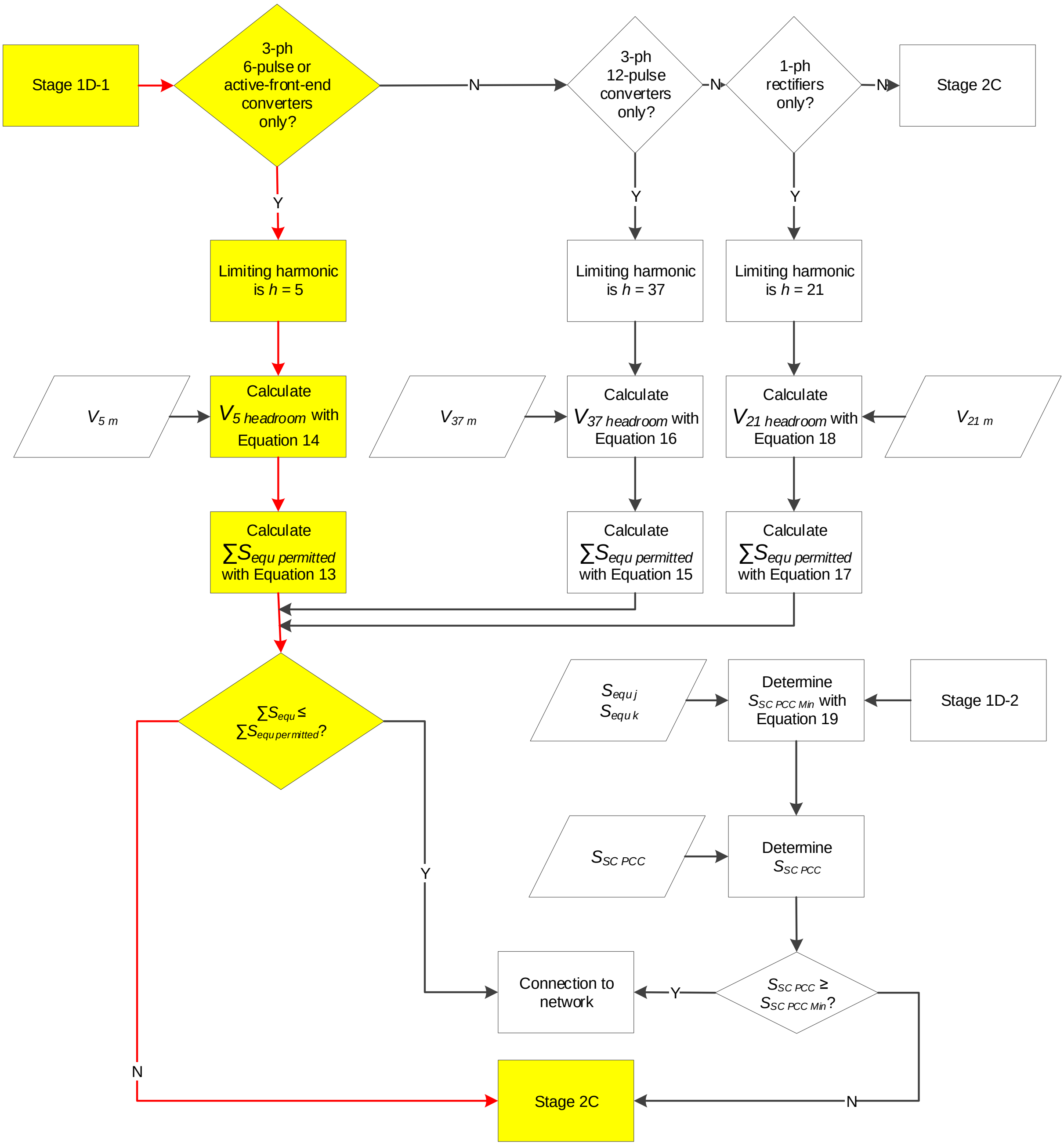

Figure E53 — Steps 10 to 13 for Worked Example 16

Since we have only one three-phase six-pulse converter, the limiting harmonic is considered to be $h = 5$.

18.11 Step 11

$V_{5\ headroom} = V_{5\ PL} - V_{5\ m}$.

$V_{5\ headroom} = 4\% - 1.53\% = 2.47\%$.

18.12 Step 12

We calculate $\sum S_{equ\ permitted}$ using Equation 13, as below.

$$\sum S_{equ\ permitted} = \frac{S_{SC\ PCC}}{10\ \text{MVA}} \times \frac{V_{5\ headroom}}{0.25 V_{5\ PL}} \times \sum S_{equ\ permitted\ @\ Ssc\ reference} \qquad (22)$$

From Table 19:

- $\sum S_{equ\ permitted\ @\ reference\ Ssc}$ = 22 kVA for a reference S_{SC} of 10 MVA.

$$\sum S_{equ\ permitted} = \frac{5.1\ \text{MVA}}{10\ \text{MVA}} \times \frac{2.47\%}{0.25 \times 4\%} \times 22\ \text{kVA} = 27.713\ \text{kVA}.$$

18.13 Step 13

Since the aggregate equipment rated power ($\sum S_{equ}$) is greater than the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$), 80 kVA > 11.22 kVA, then the connection progresses to Stage 2C.

18.14 Step 14

The connectee and DNO assemble the following harmonic current emission and background harmonic level data.

Table E18 — Harmonic current emission data at the PCC from the manufacturer for Worked Example 16

Harmonic order (*h*)	Manufacturer's stated harmonic current emission A
2	9.2
3	0
4	4.6
5	12.3
6	3.1
7	8.2
8	2.3
9	0
10	1.8
11	3.5
12	1.5
13	2.3
> 13	0.0

The DNO provided the following measured background harmonic levels:

Table E19 — Background harmonic levels at the PCC from the DNO for Worked Example 16

Harmonic order (*h*)	**Harmonic voltage % *h* = 1**		**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**
2	0.06		27	0.20
3	0.99		28	0.01
4	0.05		29	0.20
5	1.53		30	0.01
6	0.02		31	0.20
7	0.79		32	0.01
8	0.02		33	0.20
9	0.31		34	0.01
10	0.01		35	0.20
11	0.30		36	0.01
12	0.01		37	0.20
13	0.32		38	0.01
14	0.01		39	0.20
15	0.01		40	0.01
16	0.01		41	0.20
17	0.20		42	0.01
18	0.01		43	0.20
19	0.20		44	0.01
20	0.01		45	0.20
21	0.20		46	0.01
22	0.01		47	0.20
23	0.20		48	0.01
24	0.01		49	0.20
25	0.20		50	0.01
26	0.01		$THDV_m$	2.22

18.15 Step 15

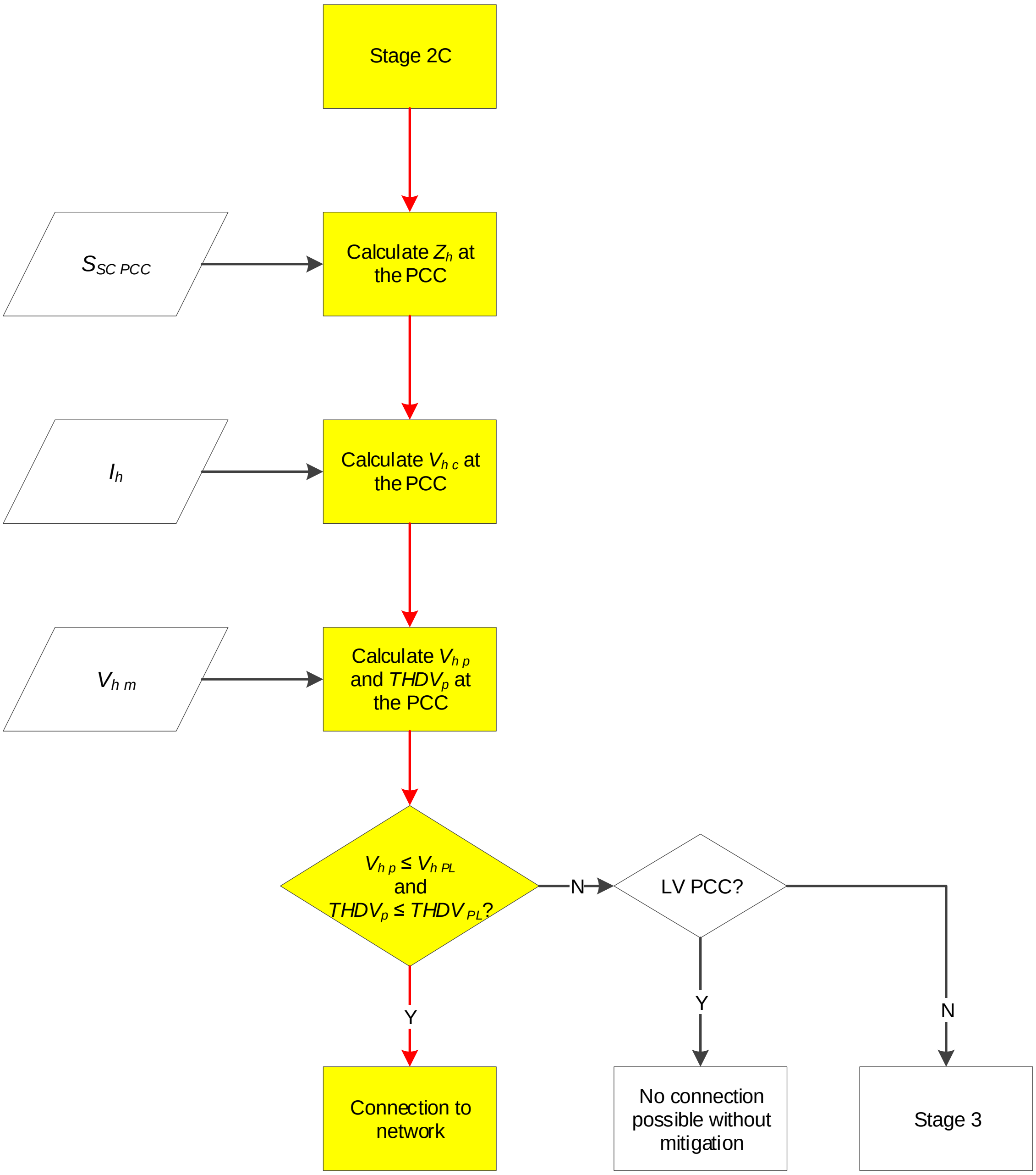

Figure E54 — Steps 14 to 19 for Worked Example 16

The goal of this process is to assess each individual harmonic order (and the $THDV_p$) against the relevant planning level to ascertain if the connection is permitted.

Section 8.4 of EREC G5 details the process, which can be broken down into the following basic steps:

- 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 EREC G5 Section 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 $V_{h\ PL}$.

The steps outlined above will be followed for the example of the 5th harmonic, but it is recommended that a spreadsheet is used to implement calculation of the full range of applicable harmonic orders.

18.16 Step 16

An assumed worst-case harmonic impedance is used to find the incremental increase in harmonic voltage distortion (% V_{phase}) at the PCC due to the manufacturer's stated harmonic current emissions from the proposed connecting plant.

In this example, we are given the X/R ratio and so we do not need to explicitly calculate the harmonic impedance and can instead use the X/R ratio directly with Equation 35, which is reproduced and solved below for the example of the 5th harmonic.

$$V_{h\ c} = \frac{100\sqrt{3} I_h V_s \sqrt{h + k^2 h^2 \left(\frac{X_1}{R_1}\right)^2}}{S_{SC\ 3ph} \sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}} \tag{23}$$

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;

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

k is the worst-case reactance factor (see **Error! Reference source not found.**).

From Table 22:

- k = 1 for LV connection.

$$V_{5\,c} = \frac{100\ \sqrt{3}(12.3\ \text{A})(400\ \text{V})\sqrt{5 + (1^2)\ (5^2)\ (1.1^2)}}{5.1\ \text{MVA}\sqrt{1 + (1.1^2)}}$$

$V_{5\,C}$ = 5.1343 MVA / 7.5817 MVA = 0.667%.

18.17 Step 17

We know that the measured 5th harmonic level is 1.53%, so we must now aggregate the measured 5th harmonic voltage with the incremental – using the appropriate aggregation exponent (α) from Table 16 – to find the predicted harmonic voltage distortion ($V_{h\,p}$).

From Table 16 for h = 5:

- α = 1.4.

Using Equation 7 in Section 6.3.3 of EREC G5:

$$V_{h\,p} = \sqrt[\propto]{V_{h\,c}^{\ \propto} + V_{h\,m}^{\ \propto}} = \sqrt[1.4]{0.667^{1.4} + 1.53^{1.4}} = \sqrt[1.4]{0.56725 + 1.81371} = 1.858\%.$$

18.18 Step 18

A spreadsheet is used to solve for all individual harmonic orders ($V_{h\,p}$) and for the total harmonic voltage distortion ($THDV_p$).

Table E20 — Harmonic compliance assessment table for Worked Example 16

Harmonic order (*h*)	I_h at 400 V, A	k	$V_{h\,c}$ at PCC, % *h* = 1	$V_{h\,m}$ at PCC, % *h* = 1	α	$V_{h\,p}$ at PCC, % *h* = 1	$V_{h\,PL}$ at PCC, % *h* = 1	Pass/ Fail
2	9.20	1	0.220	0.060	1	0.280	1.600	Pass
3	0.00	1	0.000	0.990	1	0.990	4.000	Pass
4	4.60	1	0.203	0.050	1	0.253	1.000	Pass
5	12.30	1	0.667	1.530	1.4	1.858	4.000	Pass
6	3.10	1	0.199	0.020	1.4	0.205	0.500	Pass
7	8.20	1	0.610	0.790	1.4	1.152	4.000	Pass
8	2.30	0.5	0.110	0.020	1.4	0.117	0.400	Pass
9	0.00	0.5	0.000	0.310	1.4	0.310	1.200	Pass
10	1.80	0.5	0.104	0.010	1.4	0.107	0.400	Pass
11	3.50	0.5	0.221	0.300	2	0.372	3.000	Pass
12	1.50	0.5	0.102	0.010	2	0.103	0.200	Pass
13	2.30	0.5	0.168	0.320	2	0.362	2.500	Pass
14	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass

15	0.00	0.5	0.000	0.010	2	0.010	0.500	Pass
16	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
17	0.00	0.5	0.000	0.200	2	0.200	1.600	Pass
18	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
19	0.00	0.5	0.000	0.200	2	0.200	1.500	Pass
20	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
21	0.00	0.5	0.000	0.200	2	0.200	0.200	Pass
22	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
23	0.00	0.5	0.000	0.200	2	0.200	1.200	Pass
24	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
25	0.00	0.5	0.000	0.200	2	0.200	1.000	Pass
26	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
27	0.00	0.5	0.000	0.200	2	0.200	0.200	Pass
28	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
29	0.00	0.5	0.000	0.200	2	0.200	0.862	Pass
30	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
31	0.00	0.5	0.000	0.200	2	0.200	0.806	Pass
32	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
33	0.00	0.5	0.000	0.200	2	0.200	0.200	Pass
34	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
35	0.00	0.5	0.000	0.200	2	0.200	0.714	Pass
36	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
37	0.00	0.5	0.000	0.200	2	0.200	0.676	Pass
38	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
39	0.00	0.5	0.000	0.200	2	0.200	0.200	Pass
40	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
41	0.00	0.5	0.000	0.200	2	0.200	0.610	Pass
42	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
43	0.00	0.5	0.000	0.200	2	0.200	0.581	Pass
44	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
45	0.00	0.5	0.000	0.200	2	0.200	0.200	Pass
46	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
47	0.00	0.5	0.000	0.200	2	0.200	0.532	Pass
48	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
49	0.00	0.5	0.000	0.200	2	0.200	0.510	Pass
50	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
THD				$THDV_m$ = 2.22		$THDV_p$ = 2.651	$THDV_{PL}$ = 5	Pass

18.19 Step 19

Since all individual predicted harmonic voltage levels at the PCC, $V_{h\,p}$, are lower than the individual planning levels, V_{PL}, and the predicted total harmonic voltage distortion, $THDV_p$ is lower than the planning level for total harmonic distortion, $THDV_{PL}$, then the connection is compliant and is permitted.

19 Worked Example 17

Table E21 — Connection data for Worked Example 17

Example	Equipment	Rating kVA	Rating A	No. of phases	Harmonic statement	PCC voltage	Service current capacity (I_{SCC})	Final stage
17	6-Pulse AC/DC Motor Drives	100	144.34	3	Current emission data available	6.6 kV	—	2C
		5 x 20	5 x 28.87	3	Current emission data available			

The following additional data has been supplied for this connection:

- Current transformer (CT) metering is used.
- $S_{SC\ PCC}$ = 61 MVA.
- X_1/R_1 = 8.
- $V_{5\ m}$ = 2.1%.
- $V_{5\ PL}$ = 3%.

19.1 Step 1

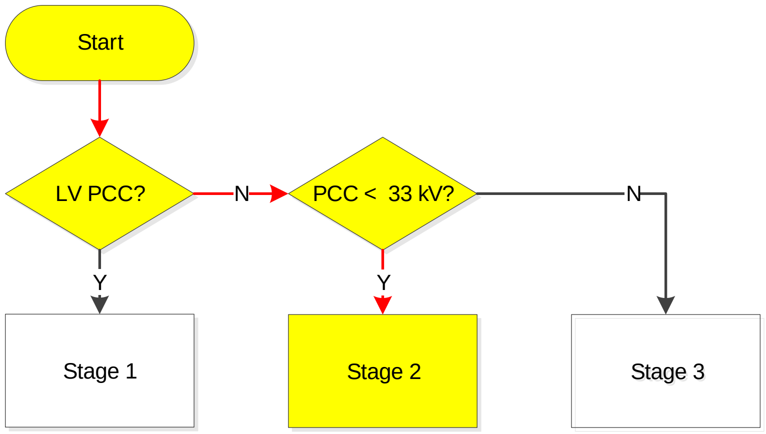

Figure E55 — Step 1 for Worked Example 17

19.2 Step 2

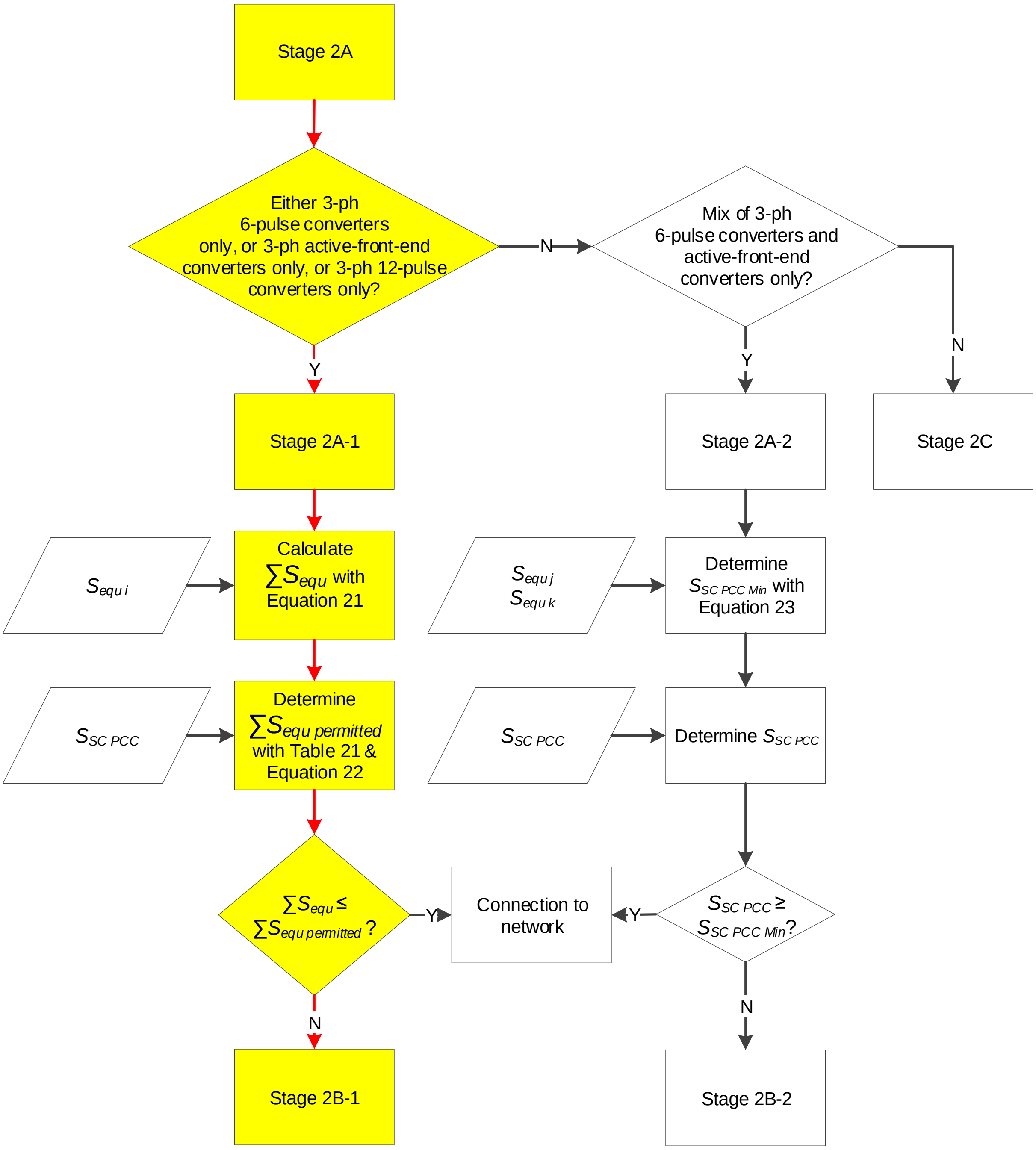

Figure E56 — Steps 2 to 6 for Worked Example 17

We are not dealing with a mix of technology types so we follow the Stage 2A-1 process.

19.3 Step 3

We determine the aggregate equipment rated power ($\sum S_{equ}$) in accordance with Equation 21, as below.

$$\sum S_{equ} = \sum_{j=1}^{J} S_{equ\,j} \tag{24}$$

$\sum S_{equ}$ = (5 × 20 kVA) + 100 kVA = 200 kVA.

19.4 Step 4

The three-phase short-circuit power at the PCC was given for this example as $S_{SC\,PCC}$ = 61 MVA.

19.5 Step 5

The permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$) for the connection is determined with reference to the Table 21 value for $\sum S_{equ\ permitted\ @\ reference\ Ssc}$, which is then scaled according to the short-circuit power at the PCC ($S_{SC\,PCC}$) as shown in Equation 22, which is reproduced and solved below.

From Table 21:

- $\sum S_{equ\ permitted\ @\ 60\ MVA\ Ssc\ reference}$ = 76 kVA.

Equation 22 is used to solve for the permitted aggregate equipment rated power, $\sum S_{equ\ permitted}$.

$$\sum S_{equ\ permitted} = S_{SC\ PCC}\left(\frac{\sum S_{equ\ permitted\ @\ 60\ MVA\ Ssc\ reference}}{60\ \mathrm{MVA}}\right) \tag{25}$$

$\sum S_{equ\ permitted}$ = 61 MVA × (76 kVA / 60 MVA) = 77.267 kVA.

19.6 Step 6

Since the aggregate equipment rated power ($\sum S_{equ}$) is greater than the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$), 200 kVA > 77.267 kVA, then the connection progresses to Stage 2B-1.

19.7 Step 7

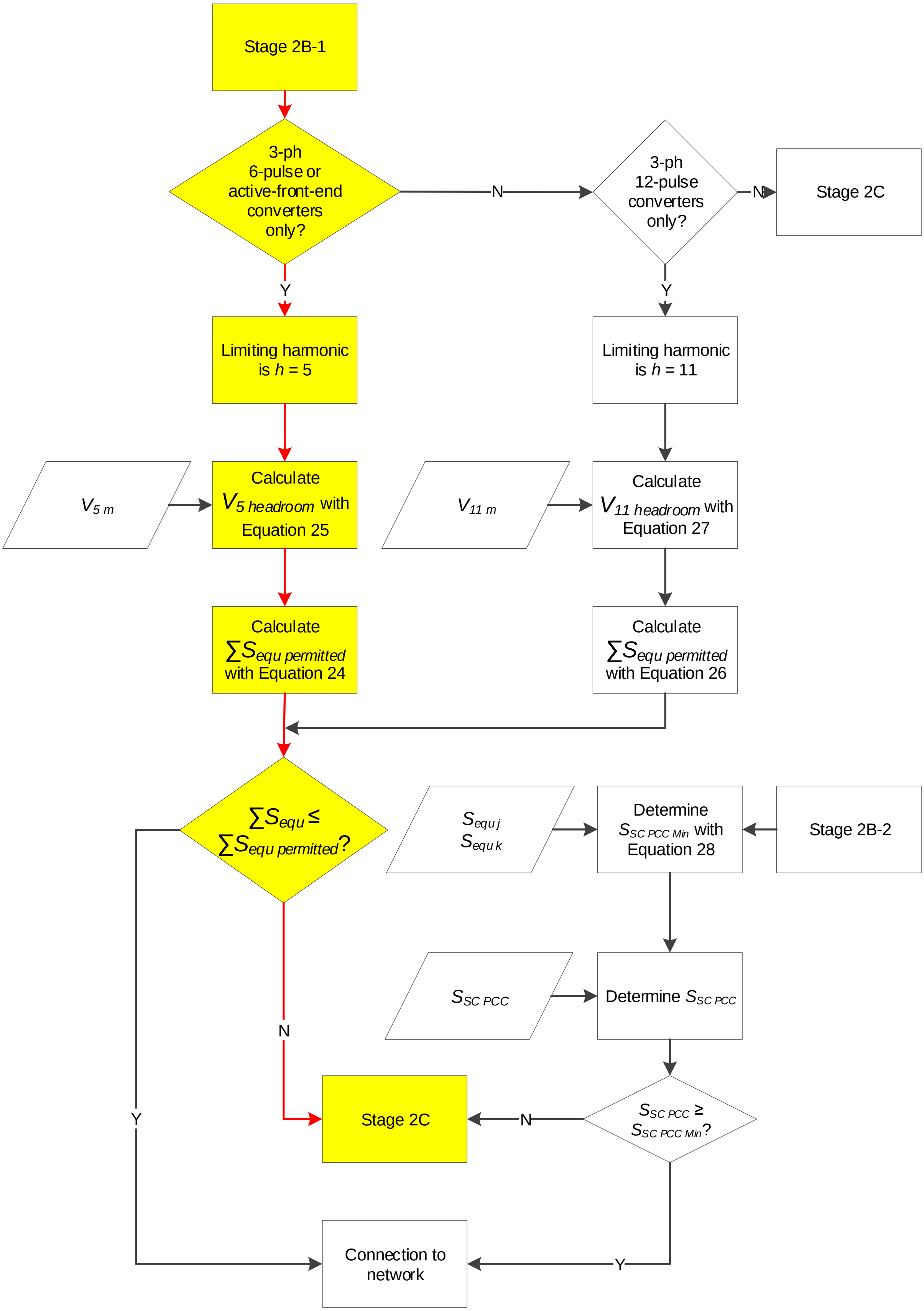

Figure E57 — Steps 7 to 10 for Worked Example 17

Since we are dealing with three-phase, six-pulse converters only, the limiting harmonic is taken to be $h = 5$.

19.8 Step 8

$V_{5\ headroom} = V_{5\ PL} - V_{5\ m}$.

$V_{5\ headroom} = 3\% - 2.1\% = 0.9\%$.

19.9 Step 9

The permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$) for the connection is determined with reference to the Table 21 value for $\sum S_{equ\ permitted\ @\ reference\ Ssc}$, which is then scaled according to the short-circuit power at the PCC ($S_{SC\ PCC}$) as shown in Equation 24, which is reproduced and solved below.

From Table 21:

- $\sum S_{equ\ permitted\ @\ 60\ MVA\ Ssc\ reference} = 76$ kVA.

Equation 24 is used to solve for the permitted aggregate equipment rated power, $\sum S_{equ\ permitted}$.

$$\sum S_{equ\ permitted} = \frac{S_{SC\ PCC}}{60\ \text{MVA}} \times \frac{V_{5\ headroom}}{0.25 V_{5\ PL}} \times \sum S_{equ\ permitted\ @\ 60\ MVA\ Ssc\ reference} \quad (26)$$

$$\sum S_{equ\ permitted} = \frac{61\ \text{MVA}}{60\ \text{MVA}} \times \frac{0.9\%}{0.25 \times 3\%} \times 76\ \text{kVA} = 92.72\ \text{kVA}.$$

19.10 Step 10

Since the aggregate equipment rated power ($\sum S_{equ}$) is greater than the permitted aggregate equipment rated power ($\sum S_{equ\ permitted}$), 200 kVA < 92.72 kVA, then the connection progresses to Stage 2C.

19.11 Step 11

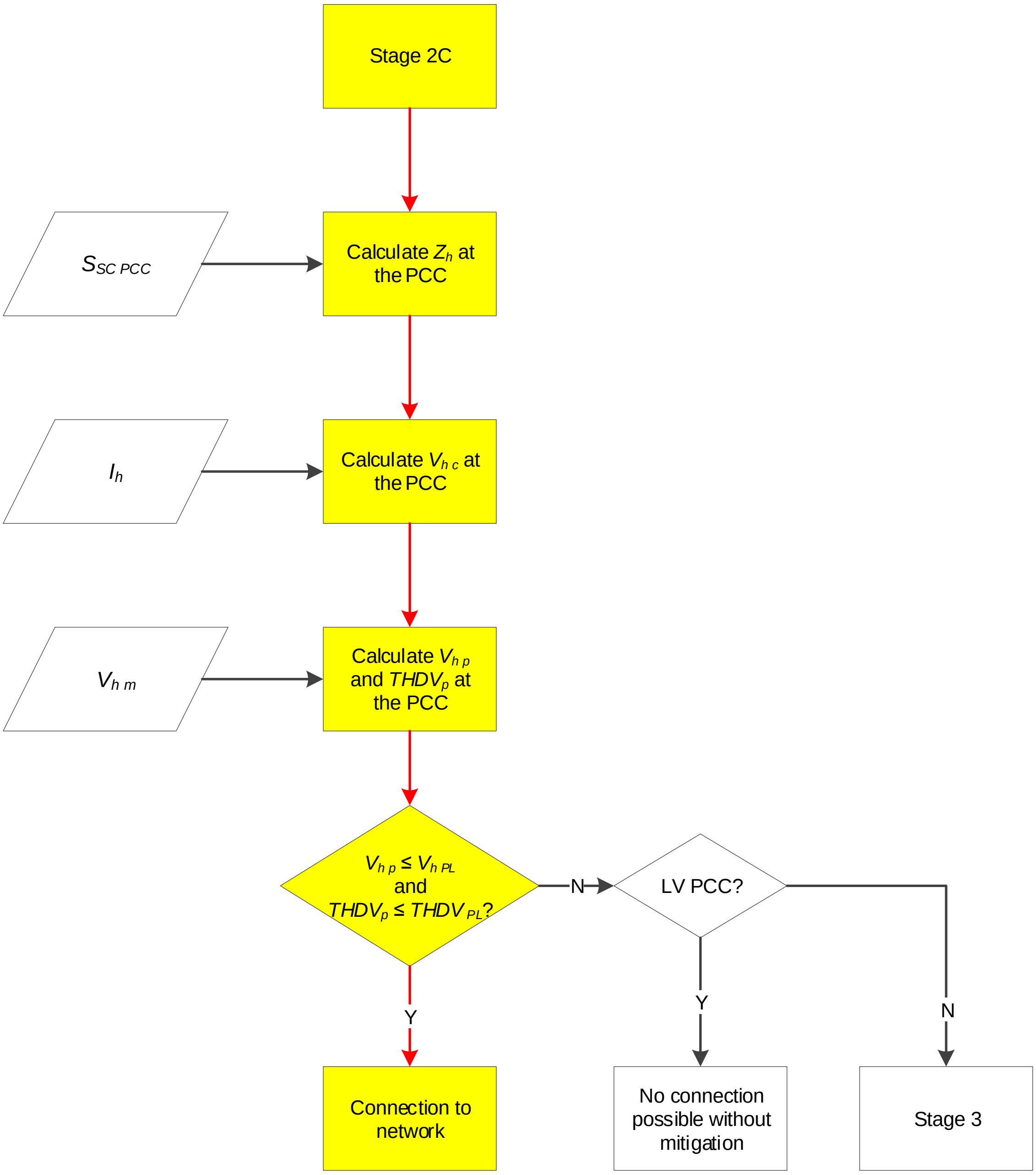

Figure E58 — Steps 11 to 15 for Worked Example 17

The following harmonic current emission data is provided by the connectee:

Table E22 — Harmonic current data taken from the manufacturer's data sheet for Worked Example 17

Harmonic order (*h*)	***20 kVA converter currents A***	***100 kVA converter currents A***	***400 V currents A***	***6.6 kV currents A***
2	—	—	—	—
3	—	—	—	—
5	8.37	37.96	65.5	4.3
7	3.2	11.9	23	1.51
9	—	—	—	—
11	1.97	9.16	13.5	0.88
13	1.13	5.37	7.8	0.51
15	—	—	—	—
17	0.98	3.78	6.2	0.41
19	0.7	2.94	4.6	0.3
21	—	—	—	—
23	0.56	1.69	3.3	0.21
25	0.47	1.55	2.8	0.18
27	—	—	—	—
29	0.33	0.91	1.9	0.12
31	0.32	0.83	1.8	0.12
33	—	—	—	—
35	0.2	0.68	1.2	0.08
37	0.21	0.57	1.2	0.08
39	—	—	—	—
41	0.13	0.54	0.8	0.06
43	0.14	0.47	0.8	0.06
45	—	—	—	—
47	0.1	0.39	0.6	0.04
49	0.1	0.36	0.6	0.04

For the group of five 20 kVA units, the aggregate harmonic current emissions are conservatively calculated using linear addition because the units are identical. The summation of these emissions with those from the larger 100 kVA unit is done using the summation exponents as detailed in Section 6.3.3 of EREC G5.

The summated LV currents are converted to currents at 6.6 kV by scaling using the 6.6 kV / 433 V transformer turns ratio of 433 / 6600.

Since the transformer has a delta winding, the triplen harmonics are ignored; balanced triplen currents are assumed, giving negligible triplen currents at 6.6 kV.

The DNO provided the following measured background harmonic levels:

Table E23 — Background harmonic levels at the PCC from the DNO for Worked Example 17

Harmonic order (*h*)	**Harmonic voltage % *h* = 1**		**Harmonic order (*h*)**	**Harmonic voltage % *h* = 1**
2	0.10		27	0.00
3	0.50		28	0.00
4	0.00		29	0.00
5	2.10		30	0.00
6	0.00		31	0.00
7	1.20		32	0.00
8	0.00		33	0.00
9	0.00		34	0.00
10	0.00		35	0.00
11	0.40		36	0.00
12	0.00		37	0.00
13	0.30		38	0.00
14	0.00		39	0.00
15	0.00		40	0.00
16	0.00		41	0.00
17	0.00		42	0.00
18	0.00		43	0.00
19	0.00		44	0.00
20	0.00		45	0.00
21	0.00		46	0.00
22	0.00		47	0.00
23	0.00		48	0.00
24	0.00		49	0.00
25	0.00		50	0.00
26	0.00		$THDV_m$	2.52

19.12 Step 12

An assumed worst-case harmonic impedance is used to find the incremental increase in harmonic voltage distortion (% V_{phase}) at the PCC due to the manufacturer's stated harmonic current emissions from the proposed connecting plant.

In this example, we are given the X/R ratio and so we do not need to explicitly calculate the harmonic impedance and can instead use the X/R ratio directly with Equation 35, which is reproduced and solved below for the example of the 5th harmonic.

$$V_{h\,c} = \frac{100\sqrt{3} I_h V_s \sqrt{h + k^2 h^2 \left(\frac{X_1}{R_1}\right)^2}}{S_{SC\,3ph}\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}} \qquad (27)$$

From Table 22:

- k = 2 for 6.6 kV connection.

$$V_{5\,c} = \frac{100\sqrt{3}(4.3\text{ A})(6600\text{ V})\sqrt{5 + (2^2)(5^2)(8^2)}}{61\text{ MVA}\sqrt{1 + (8^2)}}$$

$V_{5\,C}$ = 393.3984 MVA / 491.7977 MVA = 0.8%.

19.13 Step 13

We know that the measured 5th harmonic level is 2.1%, so we must now aggregate the measured 5th harmonic voltage with the incremental – using the appropriate aggregation exponent (α) from Table 16 – to find the predicted harmonic voltage distortion ($V_{h\,p}$).

From Table 16 for h = 5:

- α = 1.4.

Using Equation 7 in Section 6.3.3 of EREC G5:

$V_{h\,p} = \sqrt[\propto]{V_{h\,c}^{\propto} + V_{h\,m}^{\propto}} = \sqrt[1.4]{0.8^{1.4} + 2.1^{1.4}} = \sqrt[1.4]{0.7317 + 2.8256}$ = 2.475%.

19.14 Step 14

A spreadsheet is used to solve for all individual harmonic orders ($V_{h\,p}$) and for the total harmonic voltage distortion ($THDV_p$).

Table E24 — Harmonic compliance assessment table for Worked Example 17

Harmonic order (h)	I_h at 400 V, A	k	$V_{h\,c}$ at PCC, % h = 1	$V_{h\,m}$ at PCC, % h = 1	α	$V_{h\,p}$ at PCC, % h = 1	$V_{h\,PL}$ at PCC, % h = 1	Pass/ Fail
2	0.00	2	0.000	0.100	1	0.100	1.500	Pass
3	0.00	2	0.000	0.500	1	0.500	3.000	Pass
4	0.00	2	0.000	0.000	1	0.000	1.000	Pass
5	4.30	2	0.800	2.100	1.4	2.475	3.000	Pass
6	0.00	2	0.000	0.000	1.4	0.000	0.500	Pass
7	1.51	2	0.393	1.200	1.4	1.375	3.000	Pass
8	0.00	2	0.000	0.000	1.4	0.000	0.400	Pass
9	0.00	1	0.000	0.000	1.4	0.000	1.200	Pass
10	0.00	1	0.000	0.000	1.4	0.000	0.400	Pass
11	0.88	1	0.180	0.400	2	0.439	2.000	Pass
12	0.00	1	0.000	0.000	2	0.000	0.200	Pass
13	0.51	1	0.123	0.300	2	0.324	2.000	Pass
14	0.00	1	0.000	0.000	2	0.000	0.200	Pass
15	0.00	1	0.000	0.000	2	0.000	0.400	Pass
16	0.00	1	0.000	0.000	2	0.000	0.200	Pass
17	0.41	1	0.130	0.000	2	0.130	1.600	Pass
18	0.00	1	0.000	0.000	2	0.000	0.200	Pass
19	0.30	1	0.106	0.000	2	0.106	1.500	Pass
20	0.00	1	0.000	0.000	2	0.000	0.200	Pass
21	0.00	1	0.000	0.000	2	0.000	0.200	Pass
22	0.00	1	0.000	0.000	2	0.000	0.200	Pass
23	0.21	1	0.090	0.000	2	0.090	1.200	Pass
24	0.00	1	0.000	0.000	2	0.000	0.200	Pass
25	0.18	1	0.084	0.000	2	0.084	1.000	Pass
26	0.00	1	0.000	0.000	2	0.000	0.200	Pass
27	0.00	1	0.000	0.000	2	0.000	0.200	Pass
28	0.00	1	0.000	0.000	2	0.000	0.200	Pass
29	0.12	1	0.065	0.000	2	0.065	0.862	Pass
30	0.00	1	0.000	0.000	2	0.000	0.200	Pass
31	0.12	1	0.069	0.000	2	0.069	0.806	Pass
32	0.00	1	0.000	0.000	2	0.000	0.200	Pass

33	0.00	1	0.000	0.000	2	0.000	0.200	Pass
34	0.00	1	0.000	0.000	2	0.000	0.200	Pass
35	0.08	1	0.052	0.000	2	0.052	0.714	Pass
36	0.00	1	0.000	0.000	2	0.000	0.200	Pass
37	0.08	1	0.055	0.000	2	0.055	0.676	Pass
38	0.00	1	0.000	0.000	2	0.000	0.200	Pass
39	0.00	1	0.000	0.000	2	0.000	0.200	Pass
40	0.00	1	0.000	0.000	2	0.000	0.200	Pass
41	0.06	1	0.046	0.000	2	0.046	0.610	Pass
42	0.00	1	0.000	0.000	2	0.000	0.200	Pass
43	0.06	1	0.048	0.000	2	0.048	0.581	Pass
44	0.00	1	0.000	0.000	2	0.000	0.200	Pass
45	0.00	1	0.000	0.000	2	0.000	0.200	Pass
46	0.00	1	0.000	0.000	2	0.000	0.200	Pass
47	0.04	1	0.035	0.000	2	0.035	0.532	Pass
48	0.00	1	0.000	0.000	2	0.000	0.200	Pass
49	0.04	1	0.036	0.000	2	0.036	0.510	Pass
50	0.00	1	0.000	0.000	2	0.000	0.200	Pass
THD				$THDV_m$ = 2.52		$THDV_p$ = 2.939	$THDV_{PL}$ = 5	Pass

19.15 Step 15

Since all individual predicted harmonic voltage levels at the PCC, $V_{h\,p}$, are lower than the individual planning levels, V_{PL}, and the predicted total harmonic voltage distortion, $THDV_p$ is lower than the planning level for total harmonic distortion, $THDV_{PL}$, then the connection is compliant and is permitted.

20 Worked Example 18

Table E25 — Connection data for Worked Example 18

Example	Equipment	Rating kVA	Rating A	No. of phases	Harmonic statement	PCC voltage	Service current capacity (I_{SCC})	Final stage
18	Professional Equipment	12	17.32	3	Current emission data available	LV	< 100 A	2C via 1C

The following additional data has been supplied for this connection:

- Whole current metering is used.
- $S_{SC\ PCC}$ = 3.05 MVA.
- X_1/R_1 = 1.1.

20.1 Step 1

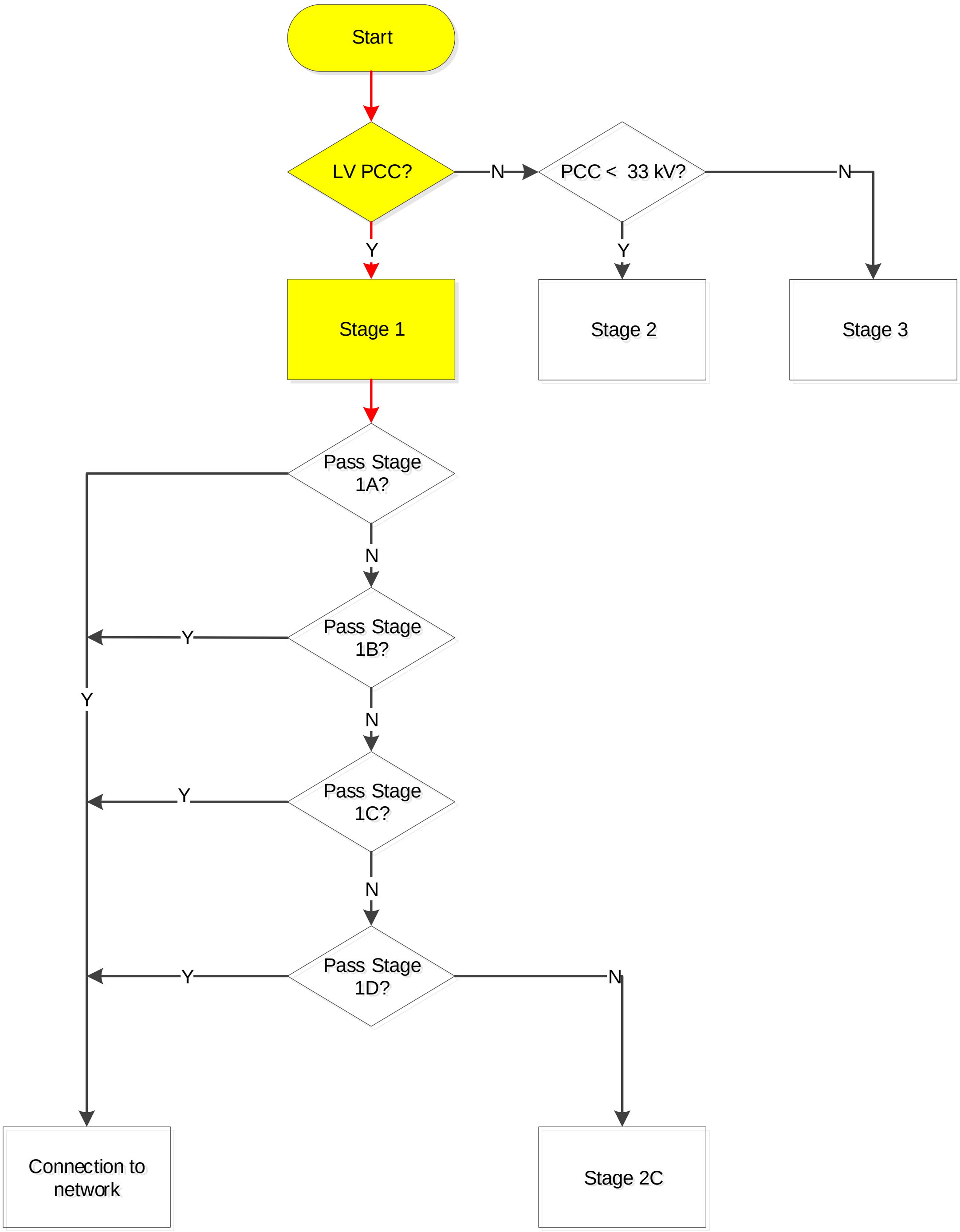

Figure E59 — Step 1 for Worked Example 18

20.2 Step 2

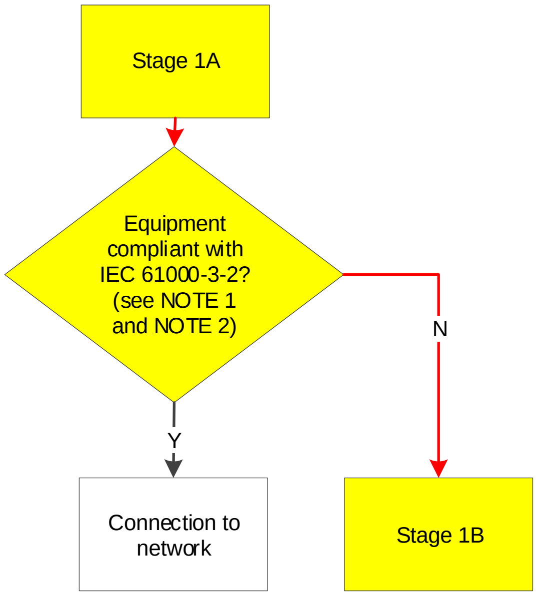

Figure E60 — Step 2 for Worked Example 18

20.3 Step 3

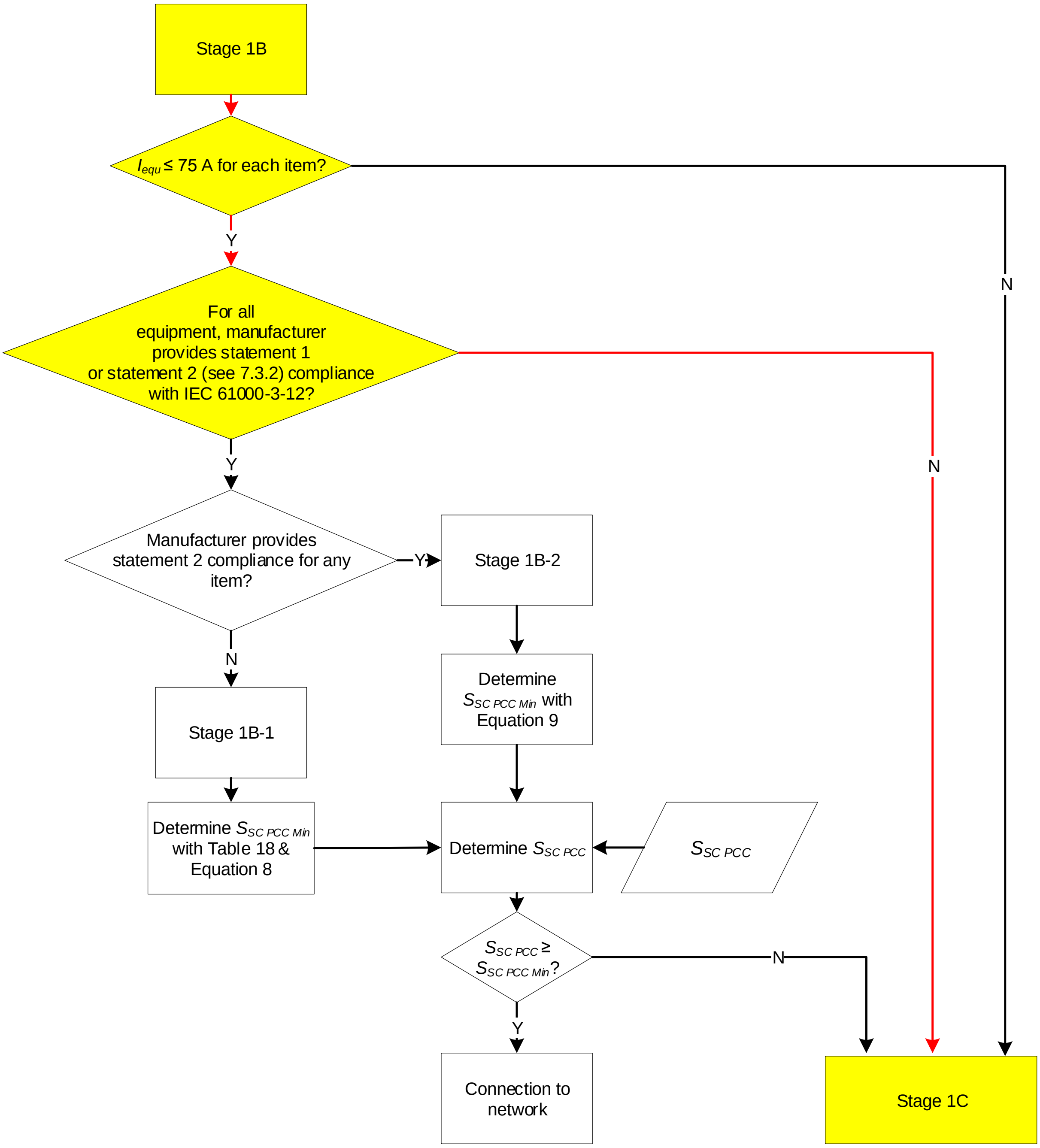

Figure E61 — Step 3 for Worked Example 18

The connectee has provided current emission data in place of a compliance statement, so we progress to Step 4, which follows the Stage 1C process.

20.4 Step 4

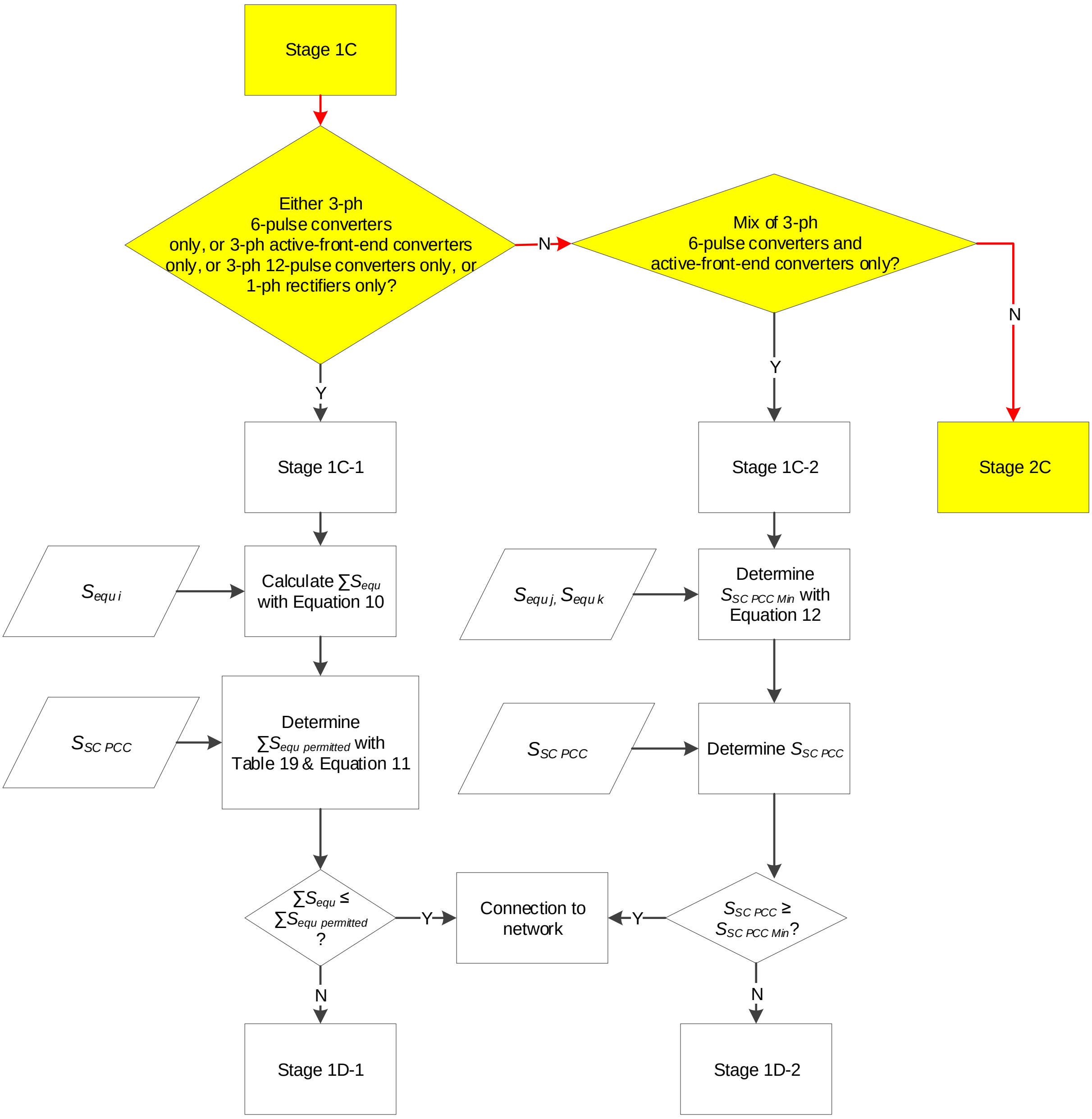

Figure E62 — Step 4 for Worked Example 18

The equipment is neither specified as a three-phase six-pulse converter, three-phase twelve-pulse converter, three-phase active-front-end converter nor single-phase rectifier technology – nor is it a mixture of these types – so we progress to Step 5, which follows the Stage 2C process.

20.5 Step 5

The connectee and DNO assemble the following harmonic current emission and background harmonic level data.

Table E26 — Harmonic current emission data at the PCC from the manufacturer for Worked Example 18

Harmonic order (*h*)	Manufacturer's stated harmonic current emission A
2	2.16
3	4.60
4	0.86
5	2.28
6	0.60
7	1.54
8	0.46
9	0.80
10	0.37
11	0.66
12	0.31
13	0.42
> 13	0.00

The DNO provided the following measured background harmonic levels:

Table E27 — Background harmonic levels at the PCC from the DNO for Worked Example 18

Harmonic order (*h*)	Harmonic voltage % *h* = 1		Harmonic order (*h*)	Harmonic voltage % *h* = 1
2	0.06		27	0.20
3	0.99		28	0.01
4	0.05		29	0.20
5	1.53		30	0.01
6	0.02		31	0.20
7	0.79		32	0.01
8	0.02		33	0.20
9	0.31		34	0.01
10	0.01		35	0.20
11	0.30		36	0.01
12	0.01		37	0.20
13	0.32		38	0.01
14	0.01		39	0.20
15	0.01		40	0.01
16	0.01		41	0.20
17	0.20		42	0.01
18	0.01		43	0.20
19	0.20		44	0.01
20	0.01		45	0.20
21	0.20		46	0.01
22	0.01		47	0.20
23	0.20		48	0.01
24	0.01		49	0.20
25	0.20		50	0.01
26	0.01		$THDV_m$	2.22

20.6 Step 6

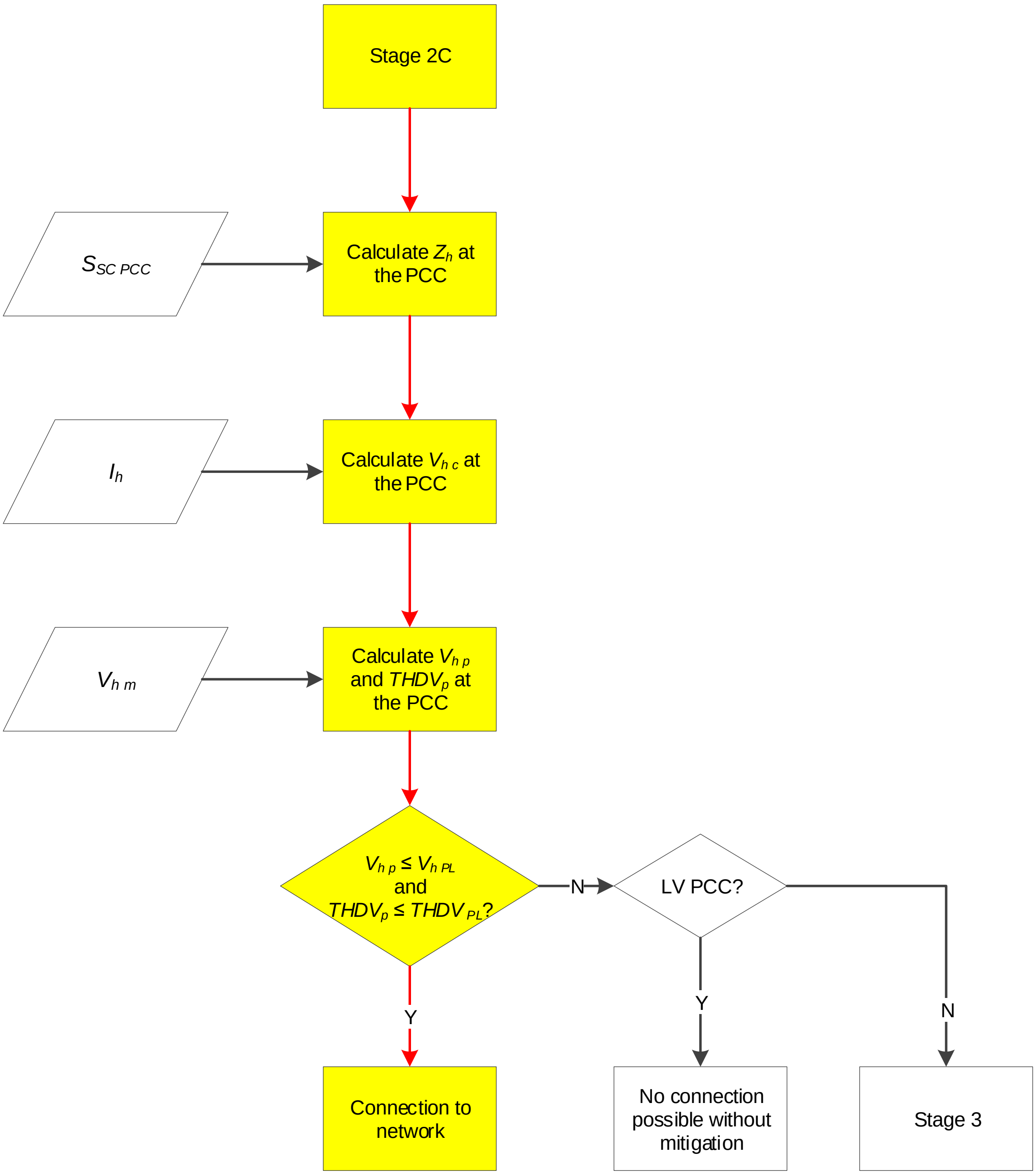

Figure E63 — Steps 6 to 9 for Worked Example 18

We are given the X/R ratio and so we do not need to explicitly calculate the harmonic impedance and can instead use the X/R ratio directly with Equation 35, which is reproduced and solved below for the example of the 5th harmonic.

$$V_{h\ c} = \frac{100\sqrt{3} I_h V_s \sqrt{h + k^2 h^2 \left(\frac{X_1}{R_1}\right)^2}}{S_{SC\ 3ph}\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}} \tag{28}$$

From Table 22:

- k = 1 for 400 V connection.

$$V_{5\,c} = \frac{100\ \sqrt{3}(2.28\text{ A})(400\text{ V})\sqrt{5 + (1^2)\ (5^2)\ (1.1^2)}}{3.05\text{ MVA}\sqrt{1 + (1.1^2)}}$$

$V_{5\,C}$ = 0.93785 MVA / 4.53415 MVA = 0.207%.

20.7 Step 7

We know that the measured 5th harmonic level is 1.53%, so we must now aggregate the measured 5th harmonic voltage with the incremental – using the appropriate aggregation exponent (α) from Table 16 – to find the predicted harmonic voltage distortion ($V_{h\,p}$).

From Table 16 for h = 5:

- α = 1.4.

Using Equation 7 in Section 6.3.3 of EREC G5:

$$V_{h\,p} = \sqrt[\propto]{V_{h\,c}^{\ \propto} + V_{h\,m}^{\ \propto}} = \sqrt[1.4]{0.207^{1.4} + 1.53^{1.4}} = \sqrt[1.4]{0.1102 + 1.8137} = 1.596\%.$$

20.8 Step 8

A spreadsheet is used to solve for all individual harmonic orders ($V_{h\,p}$) and for the total harmonic voltage distortion ($THDV_p$).

Table E28 — Harmonic compliance assessment table for Worked Example 18

Harmonic order (h)	I_h at 400 V, A	k	$V_{h\,c}$ at PCC, % h = 1	$V_{h\,m}$ at PCC, % h = 1	α	$V_{h\,p}$ at PCC, % h = 1	$V_{h\,PL}$ at PCC, % h = 1	Pass/ Fail
2	2.16	1	0.086	0.060	1	0.146	1.600	Pass
3	4.16	1	0.237	0.990	1	1.227	4.000	Pass
4	0.86	1	0.064	0.050	1	0.114	1.000	Pass
5	2.28	1	0.207	1.530	1.4	1.596	4.000	Pass
6	0.60	1	0.065	0.020	1.4	0.073	0.500	Pass
7	1.54	1	0.192	0.790	1.4	0.866	4.000	Pass
8	0.46	0.5	0.037	0.020	1.4	0.047	0.400	Pass
9	0.80	0.5	0.071	0.310	1.4	0.338	1.200	Pass
10	0.37	0.5	0.036	0.010	1.4	0.040	0.400	Pass
11	0.66	0.5	0.070	0.300	2	0.308	3.000	Pass
12	0.31	0.5	0.035	0.010	2	0.037	0.200	Pass
13	0.42	0.5	0.051	0.320	2	0.324	2.500	Pass
14	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass

15	0.00	0.5	0.000	0.010	2	0.010	0.500	Pass
16	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
17	0.00	0.5	0.000	0.200	2	0.200	1.600	Pass
18	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
19	0.00	0.5	0.000	0.200	2	0.200	1.500	Pass
20	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
21	0.00	0.5	0.000	0.200	2	0.200	0.200	Pass
22	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
23	0.00	0.5	0.000	0.200	2	0.200	1.200	Pass
24	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
25	0.00	0.5	0.000	0.200	2	0.200	1.000	Pass
26	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
27	0.00	0.5	0.000	0.200	2	0.200	0.200	Pass
28	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
29	0.00	0.5	0.000	0.200	2	0.200	0.862	Pass
30	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
31	0.00	0.5	0.000	0.200	2	0.200	0.806	Pass
32	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
33	0.00	0.5	0.000	0.200	2	0.200	0.200	Pass
34	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
35	0.00	0.5	0.000	0.200	2	0.200	0.714	Pass
36	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
37	0.00	0.5	0.000	0.200	2	0.200	0.676	Pass
38	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
39	0.00	0.5	0.000	0.200	2	0.200	0.200	Pass
40	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
41	0.00	0.5	0.000	0.200	2	0.200	0.610	Pass
42	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
43	0.00	0.5	0.000	0.200	2	0.200	0.581	Pass
44	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
45	0.00	0.5	0.000	0.200	2	0.200	0.200	Pass
46	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
47	0.00	0.5	0.000	0.200	2	0.200	0.532	Pass
48	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
49	0.00	0.5	0.000	0.200	2	0.200	0.510	Pass
50	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
THD				$THDV_m$ = 2.220		$THDV_p$ = 2.417	$THDV_{PL}$ = 5	Pass

20.9 Step 9

Since all individual predicted harmonic voltage levels at the PCC, $V_{h\,p}$, are lower than the individual planning levels, V_{PL}, and the predicted total harmonic voltage distortion, $THDV_p$ is lower than the planning level for total harmonic distortion, $THDV_{PL}$, then the connection is compliant and is permitted.

21 Worked Example 19

Table E29 — Connection data for Worked Example 19

Example	Equipment	Rating kVA	Rating A	No. of phases	Harmonic statement	PCC voltage	Service current capacity (I_{SCC})	Final stage
19	Kiln	7.4	32.17	1	Current emission data available	LV	< 100 A	2C via 1C

The following additional data has been supplied for this connection:

- Whole current metering is used.
- Single-phase fault level = 176.33 kVA.
- X_1/R_1 = 1.1.

21.1 Step 1

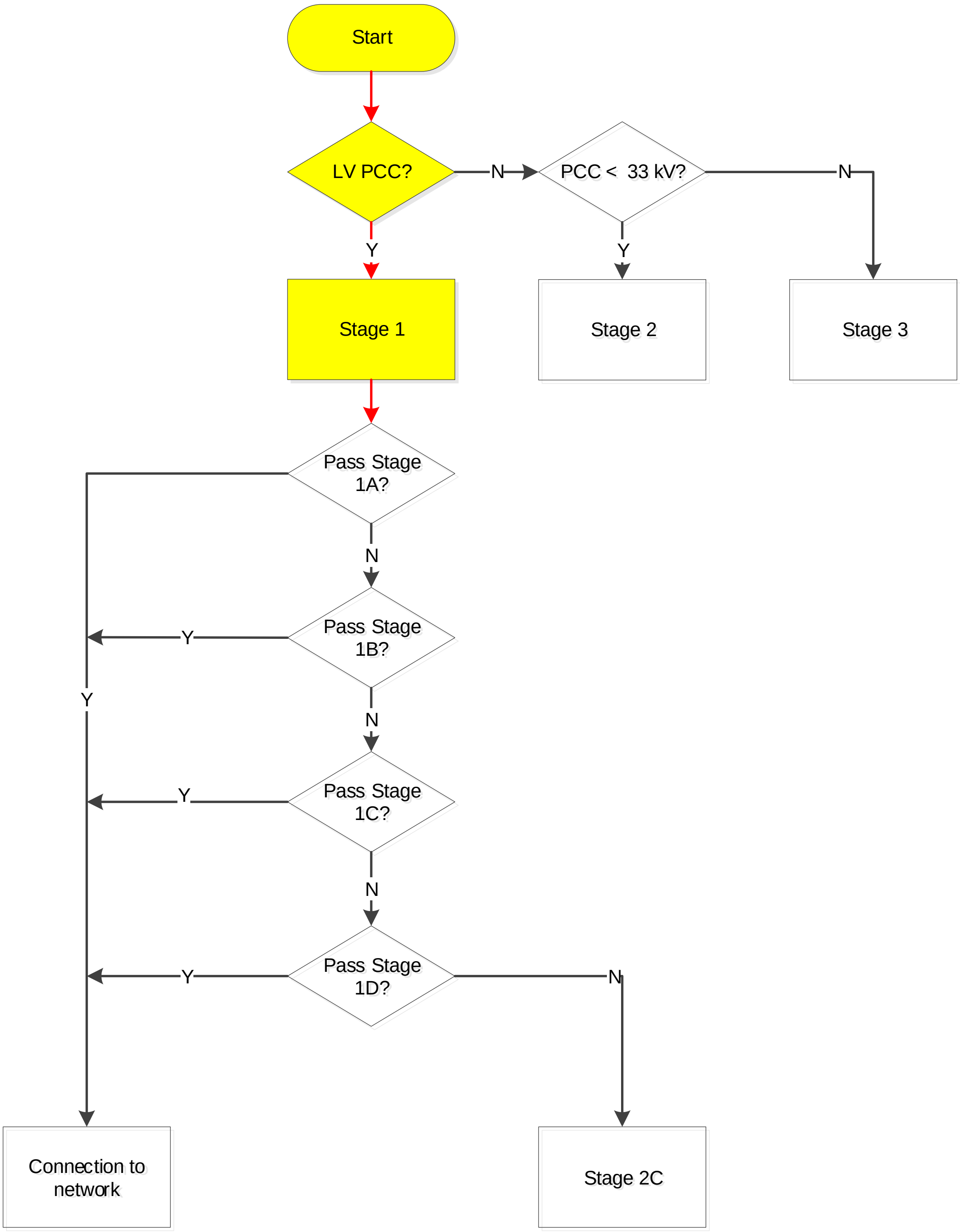

Figure E64 — Step 1 for Worked Example 19

21.2 Step 2

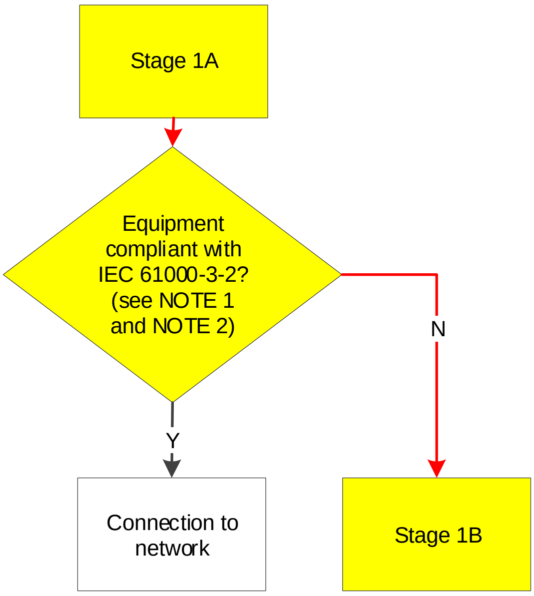

Figure E65 — Step 2 for Worked Example 19

21.3 Step 3

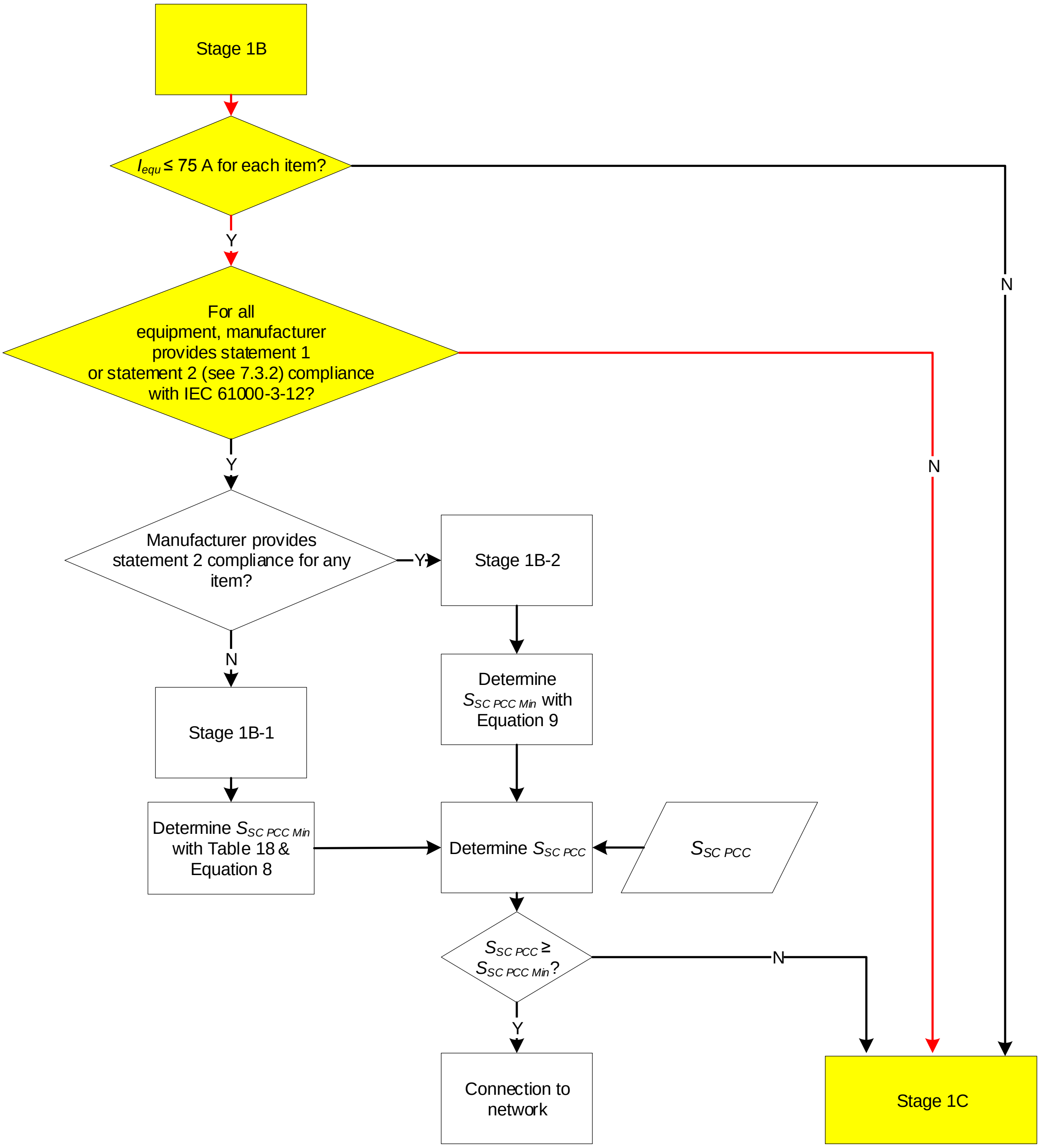

Figure E66 — Step 3 for Worked Example 19

The connectee has provided current emission data in place of a compliance statement, so we progress to Step 4, which follows the Stage 1C process.

21.4 Step 4

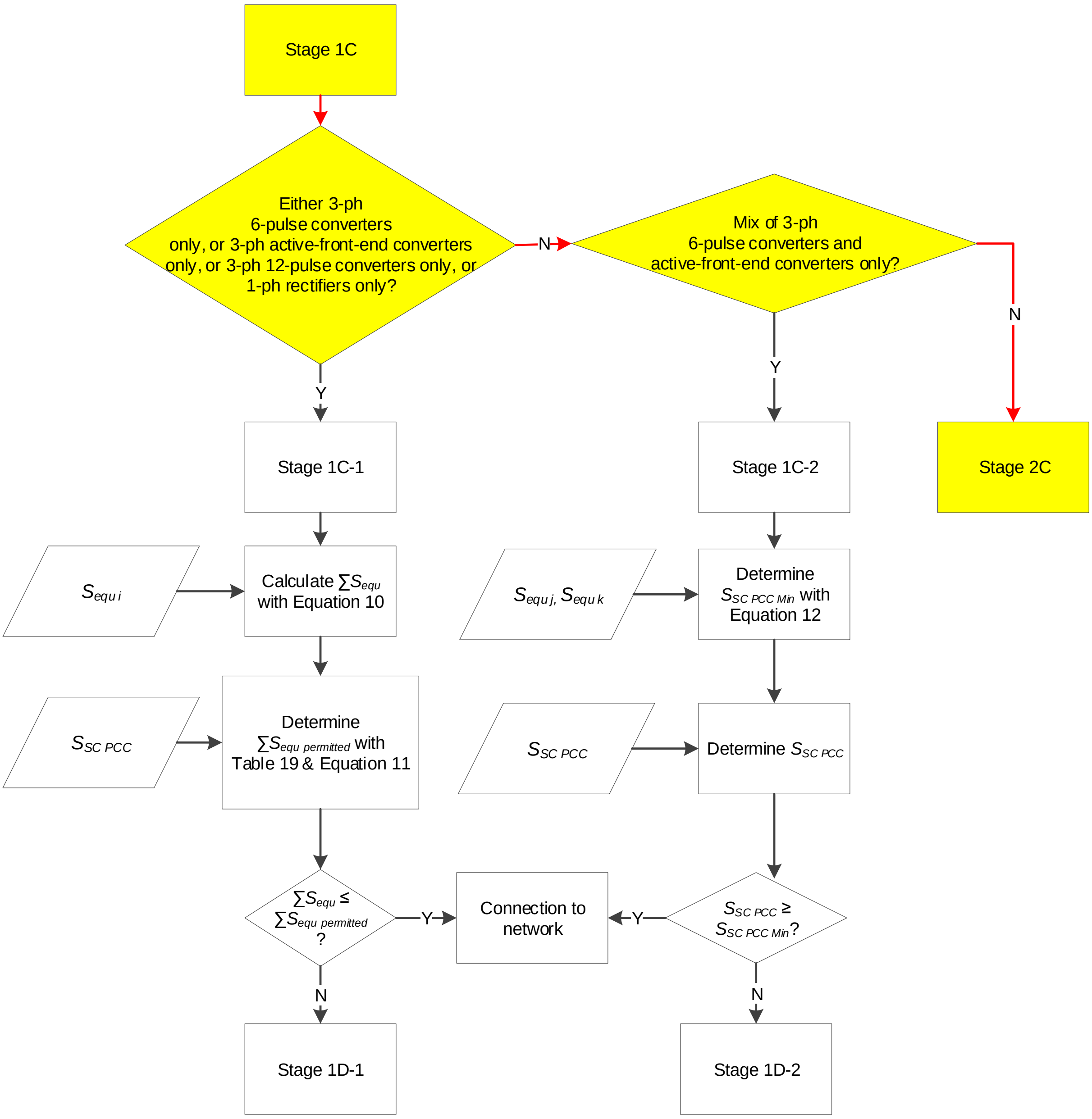

Figure E67 — Step 4 for Worked Example 19

The equipment is neither specified as a three-phase six-pulse converter, three-phase twelve-pulse converter, three-phase active-front-end converter nor single-phase rectifier technology – nor is it a mixture of these types – so we progress to Step 6, which follows the Stage 2C process.

21.5 Step 5

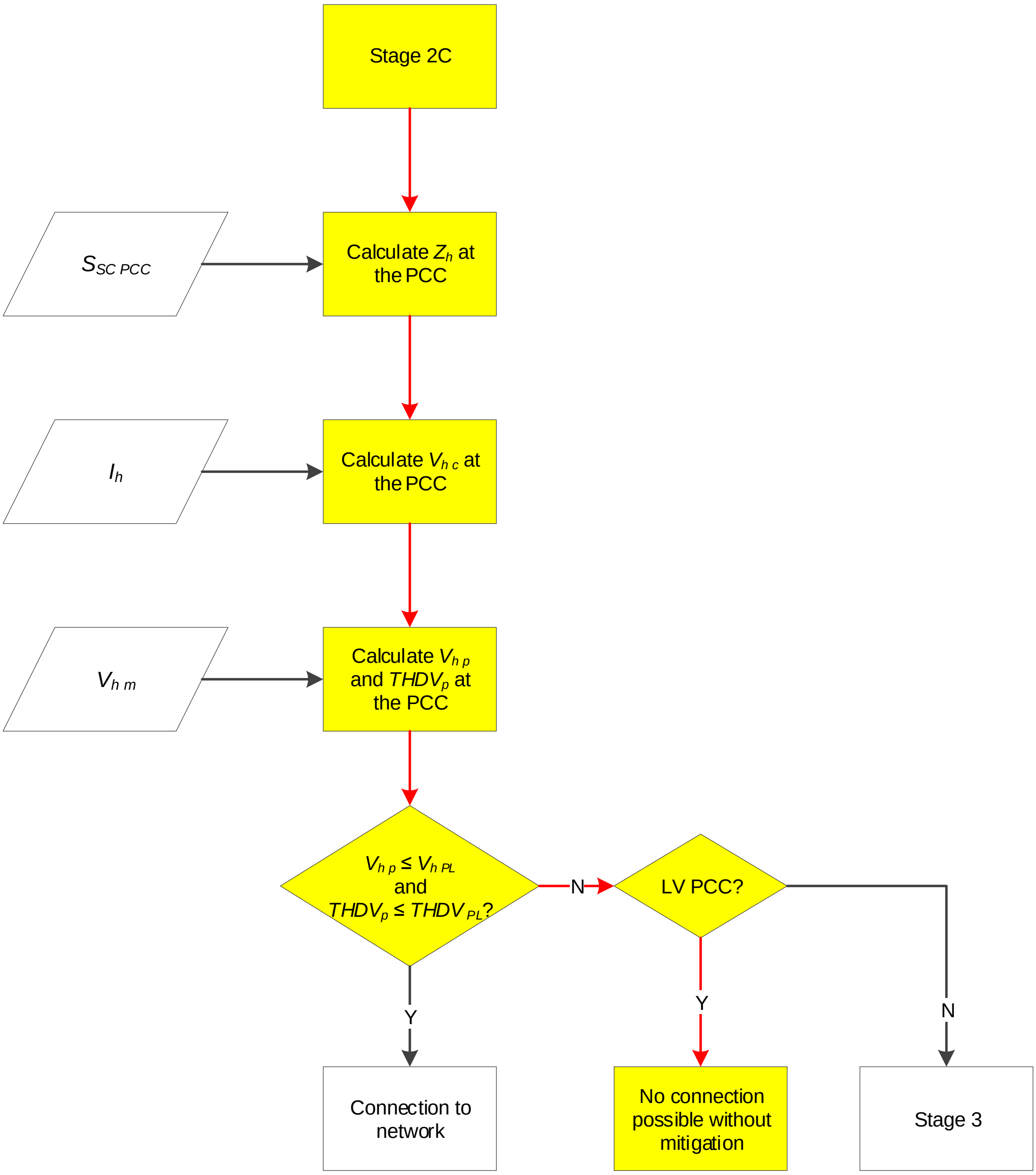

Figure E68 — Steps 5 to 10 for Worked Example 19

The three-phase short-circuit power at the PCC was given for this example as $S_{SC\ PCC}$ = 176.33 kVA.

21.6 Step 6

The connectee and DNO assemble the following harmonic current emission and background harmonic level data.

Table E30 — Harmonic current emission data at the PCC from the manufacturer for Worked Example 19

Harmonic order (*h*)	Manufacturer's stated harmonic current emission A
2	2.51
3	6.77
4	1.25
5	3.36
6	0.84
7	2.26
8	0.63
9	1.19
10	0.50
11	0.97
12	0.42
13	0.63
> 13	0.00

The DNO provided the following measured background harmonic levels:

Table E31 — Background harmonic levels at the PCC from the DNO for Worked Example 19

Harmonic order (h)	Harmonic voltage % h = 1		Harmonic order (h)	Harmonic voltage % h = 1
2	0.06		27	0.20
3	0.99		28	0.01
4	0.05		29	0.20
5	3.00		30	0.01
6	0.02		31	0.20
7	0.79		32	0.01
8	0.02		33	0.20
9	0.31		34	0.01
10	0.01		35	0.20
11	0.30		36	0.01
12	0.01		37	0.20
13	0.32		38	0.01
14	0.01		39	0.20
15	0.01		40	0.01
16	0.01		41	0.20
17	0.20		42	0.01
18	0.01		43	0.20
19	0.20		44	0.01
20	0.01		45	0.20
21	0.20		46	0.01
22	0.01		47	0.20
23	0.20		48	0.01
24	0.01		49	0.20
25	0.20		50	0.01
26	0.01		$THDV_m$	2.22

NOTE: The equipment to connect is single phase and so the measured values must also be single phase.

21.7 Step 7

We are given the X/R ratio and so we do not need to explicitly calculate the harmonic impedance and can instead use the X/R ratio directly with Equation 39 – the single-phase version of Equation 35 – that is reproduced and solved below for the example of the 12th harmonic.

$$V_{h\,c} = \frac{100\; I_h V_{phase} \sqrt{h + k^2 h^2 \left(\frac{X_1}{R_1}\right)^2}}{S_{SC\;1ph} \sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}} \tag{29}$$

From Table 22:

- k = 0.5 for h = 12 for 400 V phase–phase connection, which corresponds to 230 V phase–neutral.

$$V_{12\,c} = \frac{100\;(0.42\text{ A})\,(230\text{ V})\sqrt{12 + (0.5^2)\,(12^2)\,(1.1^2)}}{176.33\text{ kVA}\sqrt{1 + (1.1^2)}}$$

$V_{12\,C}$ = 72.0043 kVA / 262.1334 kVA = 0.2747%.

21.8 Step 8

We know that the measured 12th harmonic level is 0.01%, so we must now aggregate the measured 12th harmonic voltage with the incremental – using the appropriate aggregation exponent (α) from Table 16 – to find the predicted harmonic voltage distortion ($V_{h\,p}$).

From Table 16 for h = 12:

- α = 2.

Using Equation 7 in Section 6.3.3 of EREC G5:

$V_{h\,p} = \sqrt[\propto]{V_{h\,c}^{\;\propto} + V_{h\,m}^{\;\propto}} = \sqrt[2]{0.2747^2 + 0.01^2} = \sqrt[2]{0.07545 + 0.0001}$ = 0.2749%.

21.9 Step 9

A spreadsheet is used to solve for all individual harmonic orders ($V_{h\,p}$) and for the total harmonic voltage distortion ($THDV_p$).

Table E32 — Harmonic compliance assessment table for Worked Example 19

Harmonic order (h)	I_h at 400 V, A	k	$V_{h\,c}$ at PCC, % $h = 1$	$V_{h\,m}$ at PCC, % $h = 1$	α	$V_{h\,p}$ at PCC, % $h = 1$	$V_{h\,PL}$ at PCC, % $h = 1$	Pass/ Fail
2	2.51	1	0.576	0.060	1	0.636	1.600	Pass
3	6.77	1	2.215	0.990	1	3.205	4.000	Pass
4	1.25	1	0.532	0.050	1	0.582	1.000	Pass
5	3.36	1	1.748	3.000	1.4	3.949	4.000	Pass
6	0.84	1	0.516	0.020	1.4	0.520	0.500	Fail
7	2.26	1	1.613	0.790	1.4	2.018	4.000	Pass
8	0.63	0.5	0.288	0.020	1.4	0.293	0.400	Pass
9	1.19	0.5	0.605	0.310	1.4	0.766	1.200	Pass
10	0.50	0.5	0.279	0.010	1.4	0.281	0.400	Pass
11	0.97	0.5	0.588	0.300	2	0.660	3.000	Pass
12	0.42	0.5	0.275	0.010	2	0.274	0.200	Fail
13	0.63	0.5	0.441	0.320	2	0.545	2.500	Pass
14	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
15	0.00	0.5	0.000	0.010	2	0.010	0.500	Pass
16	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
17	0.00	0.5	0.000	0.200	2	0.200	1.600	Pass
18	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
19	0.00	0.5	0.000	0.200	2	0.200	1.500	Pass
20	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
21	0.00	0.5	0.000	0.200	2	0.200	0.200	Pass
22	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
23	0.00	0.5	0.000	0.200	2	0.200	1.200	Pass
24	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
25	0.00	0.5	0.000	0.200	2	0.200	1.000	Pass
26	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
27	0.00	0.5	0.000	0.200	2	0.200	0.200	Pass
28	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
29	0.00	0.5	0.000	0.200	2	0.200	0.862	Pass
30	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
31	0.00	0.5	0.000	0.200	2	0.200	0.806	Pass

32	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
33	0.00	0.5	0.000	0.200	2	0.200	0.200	Pass
34	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
35	0.00	0.5	0.000	0.200	2	0.200	0.714	Pass
36	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
37	0.00	0.5	0.000	0.200	2	0.200	0.676	Pass
38	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
39	0.00	0.5	0.000	0.200	2	0.200	0.200	Pass
40	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
41	0.00	0.5	0.000	0.200	2	0.200	0.610	Pass
42	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
43	0.00	0.5	0.000	0.200	2	0.200	0.581	Pass
44	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
45	0.00	0.5	0.000	0.200	2	0.200	0.200	Pass
46	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
47	0.00	0.5	0.000	0.200	2	0.200	0.532	Pass
48	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
49	0.00	0.5	0.000	0.200	2	0.200	0.510	Pass
50	0.00	0.5	0.000	0.010	2	0.010	0.200	Pass
THD				$THDV_m$ = 2.22		$THDV_p$ = 5.761	$THDV_{PL}$ = 5	Fail

21.10 Step 10

Two individual harmonic orders, $V_{6\,p}$ = 0.520% and $V_{12\,p}$ = 0.275%, are predicted to reach non-compliant levels (levels greater than the relevant planning levels of 0.5% and 0.2% respectively) following connection of the proposed equipment.

In addition, the predicted $THDV_p$ level is 5.761%, which is also above the planning level for THD, $THDV_{PL}$, of 5%.

Note that the measured values of $V_{h\,m}$ and $THDV_m$ are below the planning levels, $V_{h\,PL}$ and $THDV_{PL}$, so there is not a pre-existing problem.

Since the PCC is LV, this analysis indicates that no connection is possible without mitigation. Reinforcement of the network may also be considered.