Guideline

P13162

Recommended practice for assessing the connection of small generators based on renewable energy sources to low-voltage and medium-voltage municipal grids

prepared for

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1 Introduction

This guideline is aimed at assisting engineers at municipalities in assessing whether any network changes are required to enable the connection of generators. It applies to connections of generation at low voltage, as well as generation at medium voltage. It applies to small-scale embedded generators (ratings up to 100kW) as well as larger generator (ratings in the range >100kW to 5MVA).

In the case of connections to an LV network, this guideline can be used whenever the guideline NRS 097-2-3 requires detailed studies to be performed. It can also be used as an alternative to that guideline since it also covers a simplified decision-making process.

In addition, this document provides guidelines for studying the impact of connecting generators to the MV grid.

Examples of some connection assessments and associated studies are included in the Annex.

2 Definitions

Shared LV network	LV network supplying more than one customer. The network includes the MV/LV transformer as well as all electrical equipment up to the POCs. The network may contain shared feeders as well as dedicated feeders.
Dedicated LV network	LV network that supplies only one customer. The network includes the MV/LV transformer as well as all electrical equipment up to the POC.
Shared feeder	LV feeder supplying more than one customer. It starts at the main LV terminal (at the MV/LV transformer) and extends up to all three-phase metering kiosks (ABC-N).
Dedicated feeder	LV feeder supplying one customer. It starts at the main LV terminal (at the MV/LV transformer) and extends up to the three-phase metering kiosk (ABC-N).
Service connection feeder	LV feeder from metering kiosk up to the customer’s POC. It is often a single-phase connection.

3 Requirements

The outcome of the detailed studies must be evaluated against the specifications of NRS 048. The applicable specifications from these two sources are summarised below:

From NRS 048-2:

a) The magnitude of supply voltage shall be within ±10% for voltage levels <500 V and ±5% for voltage levels >500 V.

b) The compatibility level for voltage unbalance on LV, MV and HV three-phase networks is 2%. On LV networks, a compatibility level of 3% may be applied.

The NRS 097-2-3 states the following as technical limits that constrain embedded generation:

c) The thermal ratings of the installed equipment such as feeder cables may not be exceeded.

d) The maximum change in LV voltage caused by embedded generation may not exceed 3%.

e) The fault level at the customer point of supply should be greater than 210 A, or the minimum fault level at which the generator is rated.

From NRS 048-4:

f) The indicative planning level for the rapid voltage change as percentage of the nominal voltage $\Delta U/U_n$ is 3-6% at MV level depending on the repetition rate of changes in a period (see Table A.5 in [1]).

The above documents do not specify a limit for rapid voltage change (due to switching on embedded generators) at LV level. It is recommended to use a limit of 3% in practice as per VDE AR-N-4105.

It is noted that numerous other requirements apply to small embedded generators. The South African Grid Code for Renewable Power Plants Version 2.9, for example, requires that:

g) For generators connected to three-phase supplies, the difference in capacity between phases shall be at most 4.6kVA. Note that this does not prevent generators >4.6kVA to be connected to single-phase supplies.

h) Generators up to 100kVA are operated at unity power factor (unless otherwise specified).

i) Generators in the range 100-1000kVA must have a power factor capability of 0.95 leading to 0.95 lagging.

j) Harmonic current emission shall be in accordance with IEC61727 and flicker in accordance with SANS61000-3. Total harmonic distortion shall be less than 5%. No further assessments are required.

4 Design rules

4.1 Voltage limits

4.1.1 LV networks

4.1.1.1 Legal limits

NRS 048 requires the voltages in the LV networks (typically 400V three-phase, 230V single-phase) to be within 90-110%. These limits are also specified in IEC 50160.

4.1.1.2 Design limits

It is recommended to adhere to the following limits at the customer interface points (POC) in the design:

- A lower limit of ≥92% is recommended under no generation, maximum load, minimum MV supply voltage. Therefore, it is recommended to maintain at least a 2% design margin for the lower limit.
- An upper limit of 110% is recommended under maximum generation, minimum simultaneous loading conditions.

It is further recommended to constrain the voltage rise in LV networks, under maximum generation and minimum simultaneous loading conditions, as follows:

- 3% in the case of shared LV networks
- Either 2% or 3% in dedicated LV networks, which include transformers

The limit applies from the MV terminals of the MV/LV transformer up to the customer POCs. Therefore, it includes the transformer and cable impedances.

<u>Shared LV networks</u>

The combination of the 3% limit and the maximum voltage in the LV system of 110% limits the allowable MV supply voltage at the interface to the LV network.

The 3% voltage rise limit is also used to define design criteria within the LV network. It is proposed to allocate the 3% as shown in Figure 1, namely:

a) 1% voltage rise allocated to the transformer

b) 1% voltage rise allocated to the feeder up to the last metering kiosk (three-phase cabling)

c) 1% allocated to the service connection feeder up to the POC (often single-phase)

The above limits apply to shared feeders as well as dedicated feeders within the shared LV network.

Based on the above, the following absolute voltage limits can be derived:

1) The voltages at the ends of the feeders (at the last metering kiosks) are limited to 109%.
2) The voltage on the LV side of the MV/LV distribution transformer should be limited to 108%.

In general, it is recommended that:

3) The voltages at all ABC-N terminals (metering kiosks) is limited to 109%. This applies to all phase-to-neutral as well as all phase-to-phase voltages.

Since the presence of load counteracts the voltage rise due to generation, it can and should be considered when assessing the voltages in LV networks. It is recommended to use the minimum load, known with 95% confidence, which can occur simultaneously with maximum generation (day-time load in the case of PV). Generally, the certainty increases with an increase in the number of customers. A single customer's minimum load may be zero, but a group of 100 customers with similar life styles may have a minimum load, with 95% confidence, of e.g. 30kW.

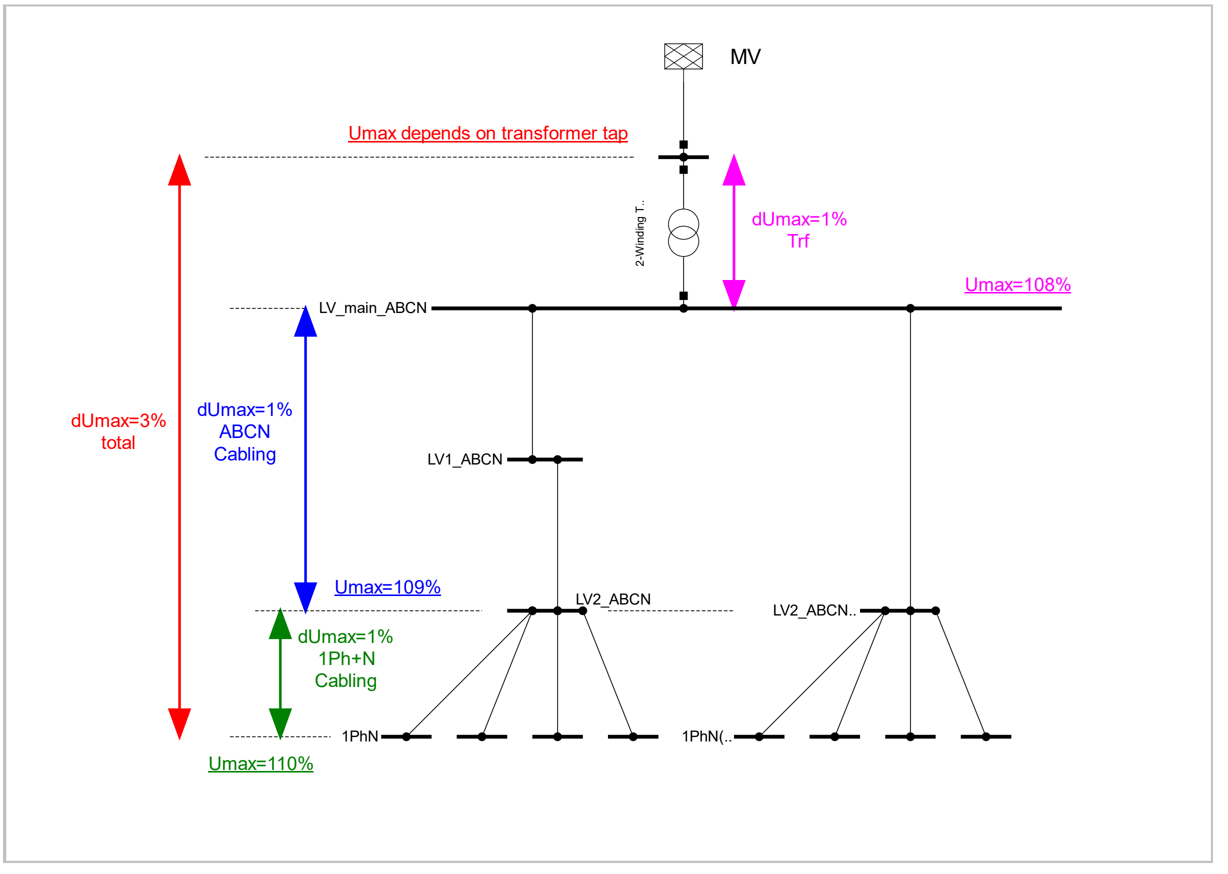

Figure 1: Proposed voltage change limits and corresponding voltage limits in shared LV network

The voltage rise allocation partly defines the maximum hosting capacity, i.e. the maximum allowable generation connected in the LV network. The 1% voltage rise in the transformer, for example, limits the current and therefore also the power through the transformer. The same applies to the maximum power in each feeder and service connection feeder.

In the case of an existing LV network, the voltage rise allocation proposed above inherently apportions the hosting capacity to the individual customers. Feeders with a high number of customers generally have higher cross-sections (lower resistances), so that the 1% voltage rise occurs at a higher power level compared to a feeder with lower cross-section. Therefore, the voltage rise allocation provides some degree of fairness. Further constraints could be added to increase the fairness between customers, if required.

Dedicated LV networks

The voltage rise in the LV network, from the MV terminal up to the POC, is set at 2% in the case of three-phase POCs, and 3% in the case of single-phase POCs. An example is shown in Figure 2.

The allocation of voltage rises is the same as in the case of shared LV networks.

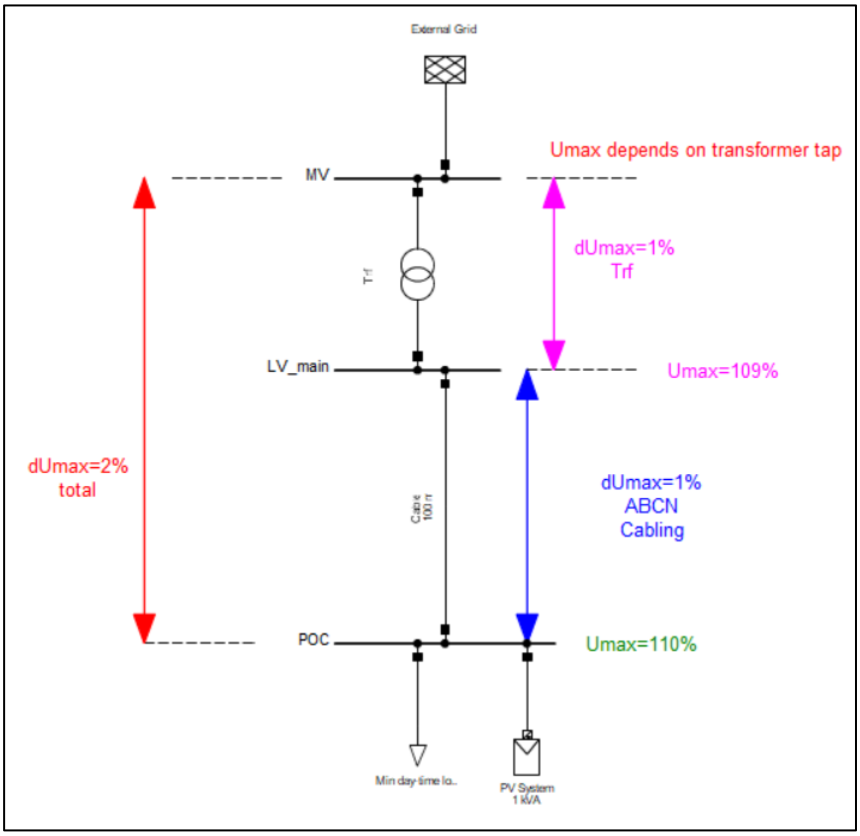

Figure 2: Typical voltage rise limits in dedicated LV networks, three-phase POC

Improving voltage profiles in shared and dedicated networks

A very high level of generation in LV networks could cause one of the above criteria no to be met. The voltages can be improved by:

i. Balancing single-phase generators as evenly as possible across the three-phase and connecting new generators to two or three phases,
ii. Using three-phase connections instead of single-phase connections,
iii. Selecting an appropriate transformer tap position, or
iv. Strengthening the network (e.g. exchanging transformer or replacing some cables).

4.1.2 MV networks

4.1.2.1 Legal limits

NRS 048 requires that, unless otherwise agreed in supply contracts, the compatibility levels of voltages in MV networks shall be within 95-105% of the declared voltage (a fixed voltage as agreed to between the customer and the licensee, which may be in the range of 95-105% of the nominal voltage).

4.1.2.2 Design limits

The upper voltage limit may need to be constrained further to ensure that the voltages in downstream LV networks do not exceed 110%, even with embedded generation in those networks. The additional constraint depends on the voltage rise allocated to LV networks and the voltage ratios of the MV/LV distribution transformers (which also depend on their tap settings). An example, of how an upper limit could be derived, follows:

Example (urban area):

> An MV network in an urban area supplies numerous MV/LV transformers in a residential area. It is expected that numerous PV plants will be connected at LV level in the future. Suppose that the declared MV voltage is 11.5kV (104.5%), and that the MV/LV distribution transformers have ratios of 11kV/400V, i.e. 100%/100%, or 0% boosting. The LV voltages must be limited to 110%. If the voltage rise in the LV network is limited to 3% (including the voltage rise in the transformer), then MV voltage must be limited to 110% - 3% - 0%=107% of nominal, or 11.77kV. This limit applies on the MV side of the MV/LV transformers.
>
> As another example, consider a network in which the MV/LV transformers have voltage ratings of 11kV/410V, i.e. effectively 100%/102.5%. Allowing 3% voltage rise in the LV network, the MV voltage at the MV/LV transformers should be limited to 110% - 3% - 2.5% = 104.5%.

Example (rural area):

> An MV network in a rural area supplies some individual customers at MV level and some individual customers at LV level. Suppose that the declared voltage is 100% of nominal. According to NRS 048, the upper limit should then be 105%. On the other hand, if embedded generation is to be connected on the LV side of an 11kV/415V transformer (3.75% boosting) and if a voltage rise of 2% had been allocated to the LV system, then the LV network would constrain the MV voltage to at most 110% - 2% - 3.75% = 104.3%. Therefore, the lower of the above two limits applies, i.e. 104%.

It is noted that the voltage limit also applies in the case of single contingencies. In the case of urban MV rings, this typically means that the operation with the ring being supplied only from one side must be considered.

The maximum allowable voltages in an MV network can often be increased by changing the taps of MV/LV supply transformers. In this case, it must be verified that the LV network voltage profile will be satisfactory under peak load, no generation conditions. This may, however, have been considered already in the design.

In general, the voltage profiles in MV networks may be improved using:

i. appropriate selection of the HV/MV transformer voltage regulation settings,

ii. the use of line drop/rise compensation in such voltage regulation,

iii. the use of reactive power sources such as shunts and under-excited generators,

iv. the use of line voltage regulating transformers or, if required,

v. network strengthening such as cable replacement.

4.2 Thermal loading

Often, maximum load exceeds maximum generation. In addition, the application of the 1% voltage rise limit inherently limits the loading of the equipment. Therefore, the maximum thermal loading is often not affected by the integration of small-scale generation. If the generation exceeds the load in any part of the network, the thermal loading capability of the equipment must be checked.

Despite the above, it is recommended to verify the adequacy of the thermal ratings of all equipment whenever the topology is changed, or a new generator is connected. It must also be checked if the tap setting of a transformer is changed. The thermal ratings are obtained from datasheets. In the case of cables, the method of installation must be considered, since ducts and parallel cables reduce the current carrying capability.

4.3 Fault currents

It needs to be ensured that the short-circuit capability of all equipment is not exceeded. The maximum three-phase short-circuit currents and the maximum single-phase to ground (/neutral) short-circuit currents in the MV networks and at the LV terminals of the MV/LV distribution transformers should be calculated according to IEC60909:2016. The contribution of embedded generators should be considered. This may be obtained from data sheets. Typical values are specified in NRS 097-2-3.

The maximum short-circuit currents within the LV network can be assessed by considering the current-limiting properties of circuit breakers, if applicable.

4.4 Voltage unbalance

Most of the unbalance occurs in LV networks, where many customers have single-phase connections.

Customers with single-phase connections are not, of course, affected by voltage unbalances, but customers with multi-phase connections are affected. By limiting the voltage rises in each individual phase, the voltage unbalance is also limited.

A good voltage balance is achieved by spreading single-phase connections between phases. Therefore, care should be taken to spread single-phase generation amongst the three phases and to keep track of which generator is connected to which phase.

The voltage unbalance is calculated in the LV network in which the new generator is to be connected It is calculated from the positive-sequence voltage U_1 and the negative sequence voltage U_2 as follows:

$$Unbalance = \frac{U_2}{U_1}$$

Slightly lower limits should be used in the design of LV networks than specified in the NRS standard so that there is some margin to cater for the limited accuracy in the calculations (especially simplifications about simultaneity in LV networks). The following limits are proposed:

Design voltage unbalance limit, LV: 1.0%

Design voltage unbalance limit, MV: 1.0%

The impact on MV networks is reduced through the use of Dyn transformers. In cases of doubt, the unbalance can be calculated and compared against the limit of 1.8% (NRS 048).

The unbalance in MV networks should be assessed, from time to time, using measurements.

4.5 Harmonics

The generators must comply with NRS 048-2 and the South African Grid Code for Renewable Power Plants. Version 2.9 of the grid code does not require further analyses.

It is noted that the grid code contains more extensive requirements for plants with ratings >5MVA. The applicant is required to demonstrate compliance by means of simulation and measurements. For this purpose, the applicant needs the harmonic limits as well as the network’s harmonic impedance as a function of frequency. This information must come from the utility.

The requirements with respect to harmonics are presently being reviewed. It is possible that recommendations will be developed, which municipalities need to follow to ensure that harmonic limits are complied with.

4.6 Long-term flicker

The South African Grid Code for Renewable Power Plants version 2.9 specifies the emission requirements for power plants up to 5MVA. Inverters shall conform to the voltage fluctuation and flicker limits as per SANS61000-3-3 for equipment rated less than or equal to 16 A per phase and SANS61000-3-5 for equipment rated greater than 16 A per phase. Compliance shall be determined by type testing.

As in the case of harmonics, further analyses are required for plants >5MVA.

4.7 Rapid voltage change

Rapid voltage changes can occur during the sudden energisation or de-energisation of network components (e.g. transformers), or the sudden drop in active power (e.g. due to a drop in wind in the case of wind turbines, or a cloud in the case of PV generation).

As long as the voltage rise in LV networks is limited 3%, as recommended in section 4.1, then the sudden drop in generation (e.g. a cloud affecting all PV generators in an LV network), will not result in a voltage change bigger than 3%. Therefore, there is no need to analyse the voltage change in LV networks designed according to the 3% criteria.

In general, PV inverters do not have significant inrush currents, which could lead to rapid voltage changes. Therefore, no calculations are required.

5 Evaluating LV connections

5.1 Applicability

The process described below applies to LV-connected generators. It includes simplified procedures, which are based on look-up tables and, in some cases, simple hand calculations. These, in turn, ignore the effects of reactances and reactive power.

In the case of exceptionally large generators, or if the LV generators will be operated at non-unity power factor (unusual at LV-level), the evaluation process should consider reactances and reactive power. The easiest way to do this is by means of computer simulation. Guidance for such simulation is given in the Annex.

5.2 Overview

Figure 3 shows a flow diagram, which summarises the process of evaluating LV generator connections. The terms SFHC, NHC and FHC are explained graphically in Figure 3.

The steps S1 to S5 are explained below. Determining the hosting capacities in steps S2, S3 and S4 is done using tables and / or hand-calculations. In some cases, S4 may need to be repeated using more refined calculation methods.

5.3 Step S1: Data collection

The data to be collected includes:

1. Data of the PV inverter to be connected
2. Transformer main parameters (power rating, rated voltages, tap setting, preferably datasheet)
3. Lengths and cross-sections of affected cables (preferably also datasheets)
4. Records of existing generators connected to LV system

5.3.1 Generator data

The following data is required for the generator to be connected:

1. Address and Erf number, where generator is to be installed
2. Maximum active power at grid connection point in kW
3. Rated voltage, current, power factor
4. Number of phases
5. Confirmation that harmonics are in accordance with IEC 61000-3-2 or 6100-3-12
6. Manufacturer and type

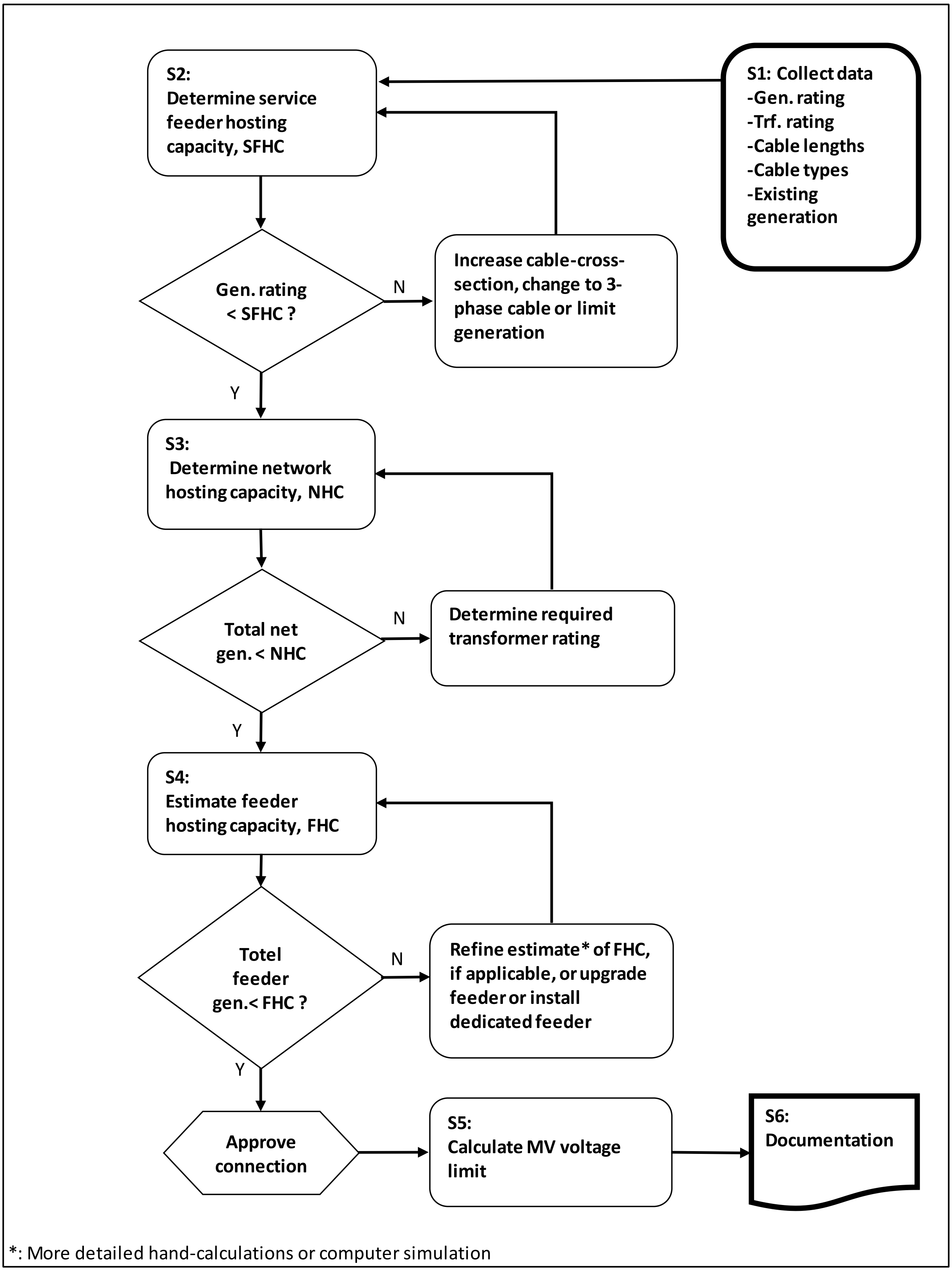

Figure 3: Flow diagram for evaluating LV generator applications

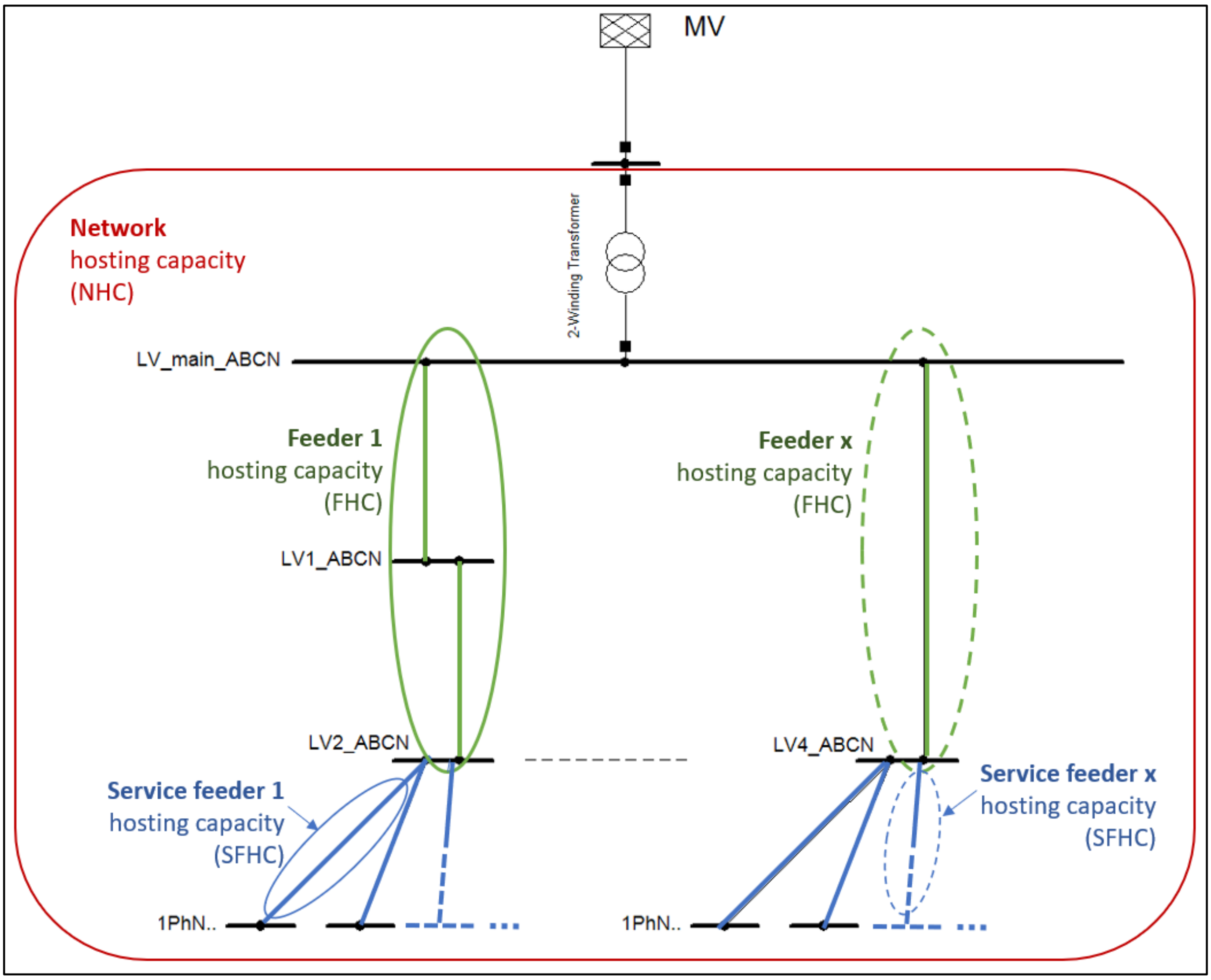

Figure 4: Graphical explanation of the terms NHC, FHV and SFHC

5.3.2 Network data

The following equipment data should be collected:

1. Single lines diagrams or street maps showing cable routes. If necessary, cable routes and lengths may be estimated using data from satellite photos or site visits.
2. Cable parameters, i.e. length, cross-section, insulation type, conductor material, number of cores.
3. MV/LV transformer parameters, i.e. rating, parent substation, short-circuit impedances u_k, nominal voltages and tap changer details (number of taps, percentage voltage change per tap, direction of voltage change) from the transformer datasheets or from their nameplates.
4. LV cable impedances from manufacturer cable datasheets.
5. The ratings of all existing generators in the LV network.

Ideally, a single-line diagram of the LV network will be available. If necessary, it should be developed either manually or by transferring data from geographical information systems electronically. The latter method, however, is not recommended unless the source data is available electronically and is of a very high quality. It should include the transformer, the affected feeder and all other feeders that contain embedded generation. Other feeders need not be shown in detail.

The following operational data is required:

1. Actual tap positions of all MV/LV distribution transformers.
2. Operational voltage range on MV side of HV/MV transformers, e.g. 99-101% or 100-103%. Details of voltage regulation method, e.g. normal voltage control or line drop compensation.

5.4 Step S2: Determine hosting capacity of service connection feeder

5.4.1 Estimation

Typical SFHCs can be estimated from Table 1 to Table 4, which are based on typical low-voltage cable parameters and for an installation in a duct.

Table 1: Typical hosting capacities of single-phase service connection feeders, copper

Single-phase	**Cross-section (mm^2), conductor and insulation material**		
	50 Cu PVC	**25 Cu PVC**	**16 Cu PVC**
Distance (metres)	**SFHC (kW)**		
5	>20	>20	17
10	>20	>20	17
15	>20	>20	13
20	>20	15	10
25	>20	12	7.7
30	19	10	6.4
35	16	8.7	5.5
40	14	7.6	4.8
45	13	6.8	4.3
50	11	6.1	3.8

Table 2: Typical hosting capacities of single-phase service connection feeders, aluminium

Single-phase	**Cross-section (mm^2), conductor and insulation material**		
	70 Al PVC	**50 Al PVC**	**25 Al PVC**
Distance (metres)	**SFHC (kW)**		
5	>20	>20	17
10	>20	>20	17
15	>20	>20	11
20	>20	17	8.6
25	20	14	6.9
30	17	11	5.7
35	14	10	4.9
40	12	8.6	4.3
45	11	7.6	3.8
50	10	6.9	3.4

Table 3: Typical hosting capacities of three-phase feeders, copper

Three-phase	Cross-section (mm^2), conductor and insulation material							
	300 Cu PVC	240 Cu PVC	185 Cu PVC	150 Cu PVC	120 Cu PVC	95 Cu PVC	70 Cu PVC	50 Cu PVC
Distance (metres)	SFHC (kW)							
10	266	237	206	181	161	141	118	95
15	266	237	206	181	161	141	118	95
20	266	237	206	181	161	141	118	95
25	266	237	206	181	161	141	118	95
30	266	237	206	181	161	141	118	95
35	266	237	206	181	161	141	118	95
40	266	237	206	181	161	141	118	85
50	266	237	206	181	161	137	99	68
75	266	226	175	140	114	91	66	45
100	209	169	131	105	86	68	49	34
200	105	85	66	53	43	34	25	17
300	70	56	44	35	29	23	16	11

Table 4: Typical hosting capacities of three-phase feeders, aluminium

Three-phase	Cross-section (mm^2), conductor and insulation material							
	300 Al PVC	240 Al PVC	185 Al PVC	150 Al PVC	120 Al PVC	95 Al PVC	70 Al PVC	50 Al PVC
Distance (metres)	SFHC (kW)							
10	204	185	158	139	124	108	90	72
15	204	185	158	139	124	108	90	72
20	204	185	158	139	124	108	90	72
25	204	185	158	139	124	108	90	72
30	204	185	158	139	124	108	90	69
35	204	185	158	139	124	108	85	59
40	204	185	158	139	124	103	75	52
50	204	185	158	128	104	83	60	41
75	173	140	107	85	70	55	40	28
100	130	105	80	64	52	41	30	21
200	65	52	40	32	26	21	15	10
300	43	35	27	21	17	14	10	7

5.4.2 Calculation

If a datasheet can be obtained for the installed cable, then it is recommended to calculate the SFHC according to the method described below.

The voltage drop across the cabling from the three-phase LV terminal up to the actual point of connection is calculated, and it is ensured that this does not exceed **1%**.

The easiest method is a hand calculation, noting the following:

In the case of a single-phase connection, the voltage drop in Volt is given by:

$$\Delta U = \left|\{(R_{ph} + R_n) + j(X_{ph} + X_n)\} \cdot \{Icos(\varphi) + jIsin(\varphi)\}\right|$$

where R is the sum of the cables' resistances in Ohm, X is the sum of the cables' reactances in Ohm, I is the rated current of the generator in A, φ is the operating power factor angle, ph refers to the phase conductor and N to the neutral conductor.

The resistances and reactances are obtained by multiplying the corresponding parameters from the datasheets (Ohm per m) by the cable length(s).

Generally, small single-phase generators are operated at unity power factor, and connected to cables with a low cross-section, e.g. 16mm², having the same type of phase and neutral conductors. In such cases, the cable reactances can be neglected and the voltage drop calculated using:

$$\Delta U = I \cdot 2R$$

All the cables from the terminal in the model up to the generator connection point must be considered. As an example, Figure 5 shows a service feeder with 55m of 16mm² cabling between the terminal in the model and the generator connection point. A typical 16mm² single-phase cable would have a voltage drop of 2 x 1.38 = 2.76 mΩ/m.

As an example, if a 4.6kW single-phase generator were connected at both “House_1” and “House_2”, but to two different phases, then the voltage rises would be as follows:

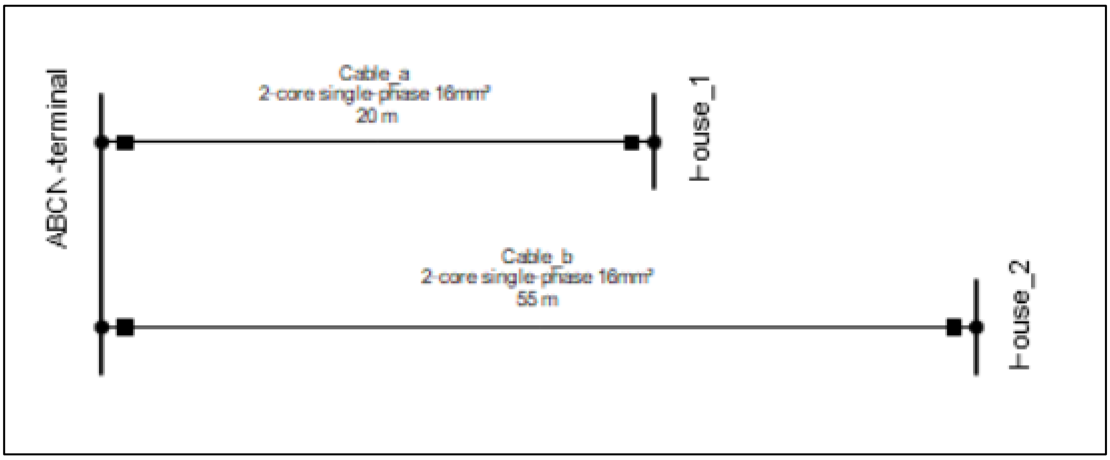

Figure 5: Example of cables to consider in hand calculation

Rated current per generator = 4600W/ 230V = 20A

Voltage rise from ABCN-terminal in Figure 5 up to House_1 and 2:

Δu_1 = 2.76/1000Ω/m * 20m * 20 A = 1.1 V, or 0.5%

Δu_2 = 2.76/1000Ω/m * 55m * 20 A = 3.0 V, or 1.3%

In this case, the voltage rise in the connection to house 2 is too high. The problem could be solved by replacing the cable with one having a higher cross-section.

If the generator rating exceeds the service feeder capacity, then the service feeder needs to be upgraded the evaluation re-started.

5.5 Step S3: Determine overall hosting capacity of LV network

5.5.1 Estimation

If hosting capacities of LV networks, as limited by the transformer sizes and minimum loads, may be estimated using Table 5. This table is based on typical transformer voltage ratings and impedances.

If the minimum load, which may occur simultaneously with maximum generation, is not known, then it may be estimated based on a conservative qualitative assessment. Such assessment should consider the type and number of customers (see also subsequent section). It is recommended to start gathering information, which will enable municipalities to improve their estimates.

Table 5: Typical network hosting capacities

	Transformer rating (kVA)			
Min. certain load (%)	**200**	**315**	**500**	**600**
0	164	259	446	502
5	174	275	471	532
10	184	291	496	562
15	194	307	521	592
20	204	322	546	622
25	214	338	571	652
30	224	354	596	682
35	234	370	621	712
40	244	385	646	742
50	264	417	696	802

5.5.2 Calculation

The overall hosting capacity is determined by the transformer's characteristics. The current at which the voltage rise across the transformer changes by 1% is calculated. From that, the power is calculated. Finally, the minimum load, which can occur simultaneously with maximum generation, is added. In the case of shared feeders, this minimum is typically only considered at this stage of the analyses, since the confidence in the value increases with an increase in the number of customers.

For relatively small transformers, the R/X ratio is quite high. Since the generators operate at unity power factor, a very good estimate of the maximum power can be obtained by ignoring reactance, reactive power, magnetising current and no-load losses. When in doubt, the hand calculations can be extended to include reactance and reactive power, or the maximum power can be calculated using a simple simulation model.

For example, the maximum power of a 315kVA transformer with a nominal voltage ratio of 11kV/420V, a short-circuit impedance of 3.8% and an X/R ratio of 3.3 is calculated as follows:

$$Z = 3.8\% * \left[\frac{420}{400}\right]^2 = 4.2\%$$

$$Z = \sqrt{R^2 + X^2} = \sqrt{R^2 + (3.3 * R)^2} = R\sqrt{12}$$

$$R = 1.2\%$$

$$I_{max} = \frac{\Delta U_{ph}}{R} = \frac{1\%}{1.2\%} = 83\%$$

$$P_{max} = I_{max} * U = 83\% * 100\% = 83\%\ or\ 0.83 * 315kW = 261kW$$

If the result for P_{max} had been bigger than the transformer rating, it would be limited to the transformer rating before continuing.

If the minimum day-time load of the network is 10% (31.5kW), then the hosting capacity for PV generation is: 261kW+31kW = 292kW

The rated power of the generator to be installed is added to the existing total installed power of all embedded generators in the network. If the total power exceeds the hosting capacity, then the network must be strengthened.

5.6 Step S4: Determine hosting capacity of affected feeder

5.6.1 Hosting capacity of a dedicated feeder

In the case of a dedicated feeder, the feeder's hosting capacity can be estimated using Table 3 and Table 4.

For more accuracy, the cable's resistance can be obtained from its datasheet, and the following formulae applied to calculate the hosting capacity:

$$\boxed{I_{max} = \frac{\Delta U_{ph}}{R}} \qquad \boxed{P_{feeder} = \sqrt{3}.U_l.I_{max}}$$

In the case of a dedicated feeder, the minimum load, which may occur simultaneously with maximum generation, may be known. It may then be considered in the calculation.

Example for a dedicated feeder:

A 95mm² PVC three-phase copper cable could have a resistance of 0.195 Ω/km. A 100m long cable has a resistance of:

R = 0.195 Ω/km x 100m = 0.0195 Ω

Ignoring reactive power, the maximum current and maximum power are:

$$I_{max} = \frac{\Delta U_{ph}}{R} = \frac{230V * 1\%}{0.0195\Omega} = 118A$$

$$P_{max} = \sqrt{3}.U_l.I_{max} = \sqrt{3} * 400V * 118A = 81kW$$

5.6.2 Hosting capacity of a shared feeder

5.6.2.1 First estimate of hosting capacity of shared feeder

A conservative estimate of the feeder's hosting capacity is obtained by assuming that all generation in the shared feeder is connected at the end of the feeder, and the entire feeder has the cross-section equal to the smallest cross-section of all sections.

The estimated hosting capacity is then obtained using Table 3 and Table 4, as in the case of a dedicated feeder.

In the case of Figure 6, the cross-section of the cable between Ty and Tz is used, and the length taken as Lx+Ly+Lz.

If, in the case of a shared feeder, the hosting capacity suffices, there is no need to calculate the feeder's hosting capacity more accurately.

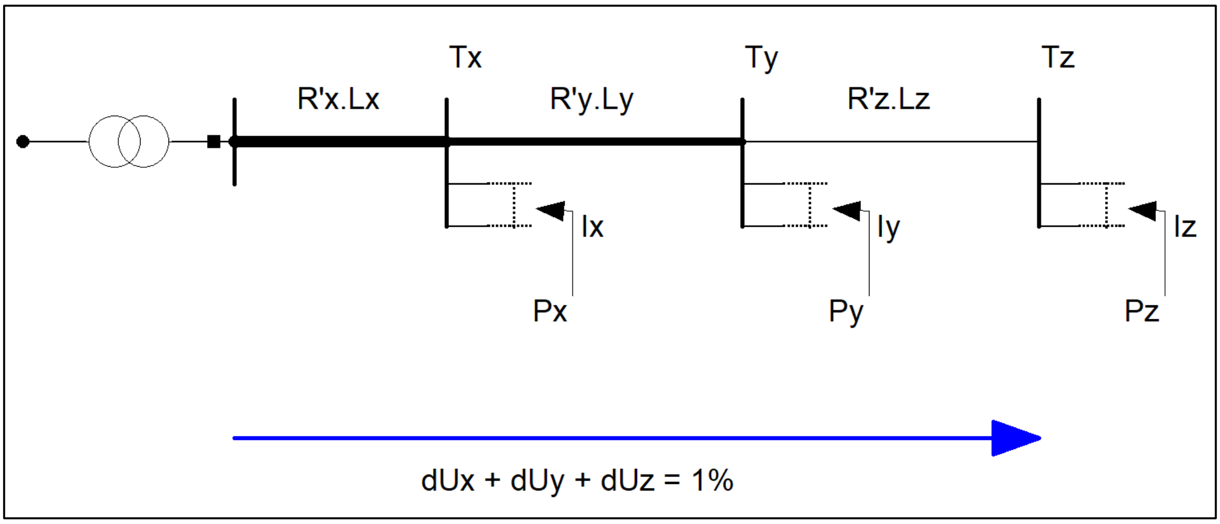

Figure 6: Schematic diagram of a tapered shared feeder

Example of a shared feeder

In Figure 6, the cable lengths and cross-sections are as follows:

$L_x + L_y + L_z = 264$m, all copper conductor
Minimum cross-section: 50mm^2

Using Table 3, the SFHC is estimated at (17+11)/2 = 14kW.

5.6.2.2 *Improved estimate of hosting capacity of shared feeder*

For a shared feeder, the calculation can be improved by calculating the resistance from the lengths and characteristics of the individual cable sections. Ohm’s law is applied to find the current, which leads to a 1% voltage rise. Following that, the power is calculated.

Example of a shared feeder

If the feeder consists of sections of different cross-sections, the total resistance must be calculated as the sum of the resistances of the individual sections.

If there are three sections, as in Figure 6, then the total resistance is:

$$\boxed{R_{tot} = R'_x.L_x + R'_y.L_y + R'_z.L_z}$$

where

R'_i is resistance per unit length per phase of section i

L_i is the length of section i

The maximum current, and hence the maximum power (estimated hosting capacity) is then calculated as in the example of the dedicated feeder. The result is conservative, since it is unlikely that all generation is applied at the end of the feeder.

Example of a shared feeder

In Figure 6, the cable lengths and cross-sections are as follows:

L_x = 83m	L_y = 93m	L_z = 88m
95mm^2	95mm^2	50mm^2

From *Table 6*, typical values for the resistances per unit length can be taken:

R'_x = 0.233 Ω/km	R'_y = 0.233 Ω/km	R'_z = 0.468 Ω/km

Hence, all variables are available which are required to calculate R_{tot}:

$R_{tot} = R'_x.L_x + R'_y.L_y + R'_z.L_z$

$= 0.233\ \Omega/km \cdot 0.083\ m + 0.233\ \Omega/km \cdot 0.093\ m + 0.468\ \Omega/km \cdot 0.088\ m = 0.082\ \Omega$

$$I_{max} = \frac{\Delta U_{ph}}{R} = \frac{230V * 1\%}{0.082\Omega} = 28.0\ A$$

$$P_{feeder} = \sqrt{3}.U_l.I_{max} = \sqrt{3} * 400V * 28.0\ A = 19.4\ kW$$

If the hosting capacity is not exceeded using the above estimate, there is no need to calculate the hosting capacity more accurately. Otherwise, either the apportionment method or the simulation method is applied, as discussed below.

5.6.3 Apportionment method

This method provides a more accurate estimation of the feeder's hosting capacity, since it is not based on a calculation in which all generation is at the end of the feeder. An additional constraint is introduced, namely that the feeder's total hosting capacity is split between the intermediate sections according to fixed ratios, for example, according to number of households supplied by that section or the corresponding sum of nominal maximum demands. Therefore, this method does not only calculate the feeder's hosting capacity, but also apportions this hosting capacity to the terminals within the feeder.

The method is explained using Figure 6 as an example.

The total voltage rise along the feeder must be limited to 1%:

$$R_z \cdot I_z + R_y \cdot (I_z + I_y) + R_x \cdot (I_x + I_y + I_z) = 1\% * 230V = 2.3V$$

Where R_x, R_y and R_z are the resistances of the individual cable sections, as calculated in section 5.6.2.

Suppose that the sums of the nominal maximum demands at each of the terminals are N_x. N_y. and N_z. Then the feeder's hosting capacity is apportioned to the three terminals as follows:

$$I_x = I_{tot}\frac{N_x}{N_x + N_y + N_z}, \quad I_y = I_{tot}\frac{N_y}{N_x + N_y + N_z} \quad and \quad I_z = I_{tot}\frac{N_z}{N_x + N_y + N_z}$$

where $I_x, I_y\ and\ I_z$ represent the maximum currents.

$$I_{tot} = I_x + I_y + I_z$$

From this:

$$I_x = I_{tot}\frac{N_x}{N_x + N_y + N_z}, \quad I_y = I_x \cdot \frac{N_y}{N_x} \quad and \quad I_z = I_x \cdot \frac{N_z}{N_x}$$

Substituting:

$$R_z \cdot I_x \cdot \frac{N_z}{N_x} + R_y \cdot I_x \cdot \left(\frac{N_z}{N_x} + \frac{N_y}{N_x}\right) + R_x \cdot I_x \cdot \left(1 + \frac{N_z}{N_x} + \frac{N_y}{N_x}\right) = 2.3V$$

Or,

$$\boxed{I_x = \frac{N_x \cdot 2.3V}{R_z \cdot N_z + R_y \cdot \left(N_y + N_z\right) + R_x \cdot (N_x + N_y + N_z)}} \quad \boxed{I_y = I_x \cdot \frac{N_y}{N_x}} \quad \boxed{I_z = I_x \cdot \frac{N_z}{N_x}}$$

$$I_x = \frac{N_x \cdot 2.3V}{R_z \cdot N_z + R_y \cdot \left(N_y + N_z\right) + R_x \cdot (N_x + N_y + N_z)}$$

The hosting capacities may also be limited by the cables' thermal ratings. Therefore, I_x, I_y and I_z must be limited to the thermal ratings of the cables.

If no datasheets are available, then typical values of resistance and current ratings may be obtained from *Table 6*.

The hosting capacities are then:

$$\boxed{P_{feeder} = P_x + P_y + P_z = \left(I_x + I_y + I_z\right) \cdot 230\ V \cdot 3}$$

$$\boxed{P_x = I_x \cdot 230 \cdot 3} \quad \boxed{P_y = I_y \cdot 230 \cdot 3} \quad \boxed{P_z = I_z \cdot 230\ V \cdot 3}$$

$$P_{feeder} = P_x + P_y + P_z = \left(I_x + I_y + I_z\right) \cdot 230\ V \cdot 3$$

$$P_x = I_x \cdot 230 \cdot \sqrt{3}, \quad P_y = I_y \cdot 230 \cdot \sqrt{3} \quad and \quad P_z = I_z \cdot 230\ V \cdot 3$$

If the total generation (including the new generator) connected at each of the terminals Tx, Ty and Tz is less than the apportioned maximum generation, then there is no need to study the feeder hosting capacity any further.

The current rating depends on the ambient temperature and method of laying. Typical values for the current rating with a cable laying in duct are provided in *Table 6*.

Table 6: Typical values for current rating and resistance of low-voltage PVC-isolated cables

Cable Type	**Cable Size in mm^2**	**Current Rating in Duct in A**	**R_{AC} at 20° in Ω/km**	**R_{AC} at max. operating temp. in Ω/km**
Cu	16	75	1.153	1.380
	25	96	0.727	0.870
	35	116	0.524	0.627
	50	138	0.391	0.468
	70	171	0.270	0.323
	95	205	0.195	0.233
	120	234	0.156	0.186
	150	263	0.126	0.151
	185	298	0.101	0.121
	240	344	0.079	0.094
	300	385	0.064	0.076
Al	25	73	1.283	1.540
	35	87	0.866	1.039
	50	104	0.642	0.770
	70	130	0.444	0.533
	95	157	0.321	0.385
	120	179	0.254	0.305
	150	201	0.208	0.249
	185	229	0.166	0.199
	240	268	0.127	0.152
	300	296	0.103	0.123

Example of a shared feeder

In Figure 6, the cable lengths and cross-sections are as follows:

L_x = 83m 95mm^2	L_y = 93m 95mm^2	L_z = 88 m 50mm^2

From *Table 6*, typical values for the resistances per unit length can be taken:

R'_x = 0.233 Ω/km	R'_y = 0.233 Ω/km	R'_z = 0.468 Ω/km

This leads to the following resistances:

R_x = 0.019 Ω	R_y = 0.022 Ω	R_z = 0.041 Ω

The apportionment shall be done based on the number of households, which is as follows:

Nx = 7	Ny= 10	Nz=8

$$I_x = \frac{7 \cdot 2.3V}{0.041\,\Omega \cdot 8 + 0.022\,\Omega \cdot (10 + 8) + 0.019 \cdot (7 + 10 + 8)}$$

$$= 13.4\ A$$

$$I_y = I_x \cdot \frac{N_y}{N_x} = 13.4\,A \cdot \frac{10}{7} = 19.2\,A$$

$$I_z = I_x \cdot \frac{N_z}{N_x} = 13.4\,A \cdot \frac{8}{7} = 15.4\,A$$

$$P_{feeder} = P_x + P_y + P_z = \left(I_x + I_y + I_z\right) \cdot 230 \cdot 3 = (13.4\,A + 19.2\,A + 15.4\,A) \cdot 230\ \cdot 3 = 33.1\,kW$$

$$P_x = I_x \cdot 230\,V \cdot 3 = 13.4\,A \cdot 230\,V \cdot 3 = 9.3\,kW$$

$$P_y = I_y \cdot 230\,V \cdot 3 = 19.2\,A \cdot 230\,V \cdot 3 = 13.2\,kW$$

$$P_z = I_z \cdot 230\,V \cdot 3 = 15.4\,A \cdot 230\,V \cdot 3 = 10.6\,kW$$

5.6.4 Simulation method

The voltage rise in a feeder following the connection of a new generator can be checked by means of a simulation model. This is especially useful if the municipality decided not to follow the apportionment method (previous section) or if significant unbalances are expected.

The voltage rise in each phase must be limited to 1%.

Further information about the simulation of LV networks is presented in the Annex.

Example

Figure 7 below is a simulation result, which is based on the example in section 5.6.3. It confirms that the generation levels Px, Py and Pz lead to a 1% voltage rise in the feeder.

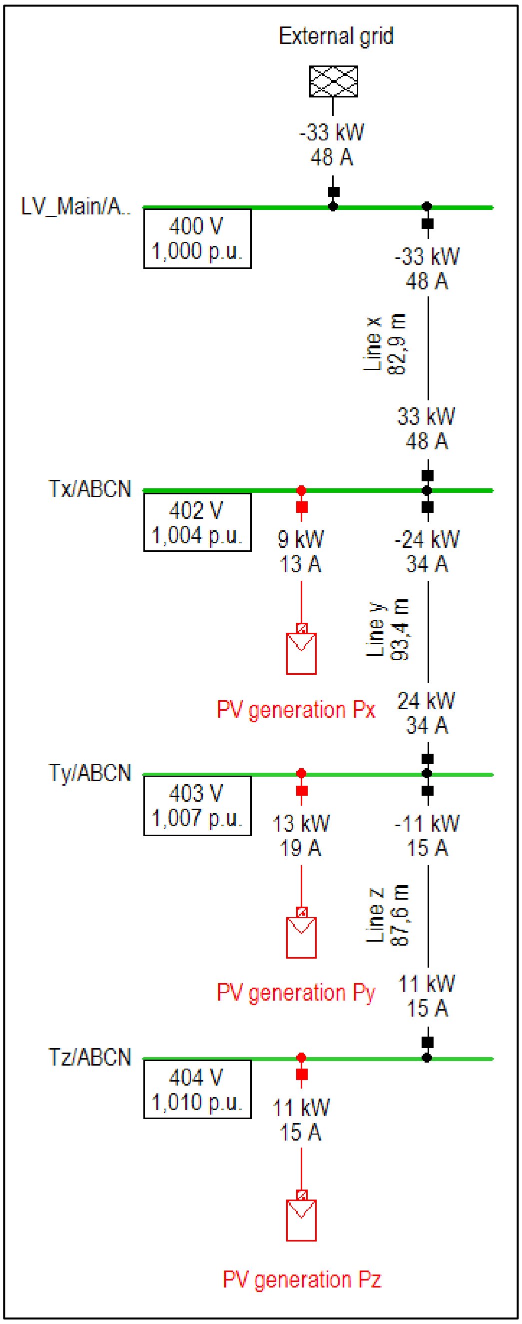

Figure 7: Simulation results, shared feeder

5.7 Step S5: Determine maximum allowable MV voltage

The maximum allowable voltage at the MV terminal of the LV network is determined from the allocated voltage rise in the network, the transformer nominal voltage ratio and the transformer tap setting.

Since the maximum voltage of all POCs in the LV network is 110% and since 3% voltage rise was allocated, the maximum voltage is calculated as:

110% - 3% - Voltage boosting through transformer

In some cases, the result may be quite restrictive. Before making changes to either the design or the method of operating the MV network, one could determine the degree to which the hosting capacities of the LV networks are exploited. If less than half of LV networks' individual hosting capacities are used, then the MV voltage could be limited to:

110% - 1.5% - Voltage boosting through transformer

Example 1

The nominal voltage in the MV network is 11kV, and if the transformer has a nominal voltage rating of 11kV +/- 2 x 2.5% / 420V and is tapped at +1, the effective voltage ratio is

102.5% : 105%, or 100% : 105%/1.025, or 100% : 102.4%

i.e., the boosting is 2.4%

Therefore, the maximum MV voltage is:

110% - 3% - 2.4% = 104.6%

Example 2

The transformer in example 1 is operated at the principal tap. The effective voltage ratio is:

100% : 105%, i.e. the boosting is 5%.

The maximum MV voltage is 110% - 3% - 5% = 102%.

If less than half of the hosting capacities of all LV networks (connected to the same MV network) are used, then it suffices to limit the MV network voltage to:

110% - 1.5% - 5% = 103.5%.

5.8 Step S7: Documentation

A short report should be written on each grid study performed.

Records of the calculations and data sources should be stored together with the above report.

6 Evaluating MV connections

6.1 Applicability

Detailed studies of the MV network are required to:

- calculate the hosting capacity of embedded LV generation,
- verify the feasibility of a new generator connection at MV level, and
- further develop the MV network to increase the hosting capacity.

It is possible to calculate the hosting capacity of embedded LV networks in advance, and to use this to make decisions about LV generator connections.

6.2 Step M1: Model construction

A model of the MV network model is prepared, including the following:

- HV/MV substation including the transformers with their automatic on-load tap changers
- MV cabling.
- Equivalent loads and generators at the terminals where the MV/LV transformers are located and, if applicable, to the MV terminals. The generators represent the net generation in the LV networks, after considering the simultaneous minimum loads. All equivalent loads and generators should be three-phase balanced devices[1].
- A Thevenin equivalent source is connected to the main HV terminal (typically 66kV or 132kV) to represent the upstream network.

6.3 Step M2: Voltage profile analysis

In this step, the voltage profile in the MV network is calculated using a balanced load flow calculation.

The voltage profile is calculated for worst case scenarios. These may include maximum generation, minimum simultaneous load, maximum supply voltage and (n-1)-contingency conditions (see also Figure 8). Maximum supply voltage means that the voltage is at the upper end of the transformer's voltage regulating relay's dead-band, at the point where the voltage is being regulated.

It is verified that all voltages at the load points do not exceed the limits specified in NRS 048 and that they do not exceed the calculated limits for the LV networks (see section 4.1.2.2).

Note that the maximum voltage at the MV terminals was calculated assuming that the full hosting capacity of the LV networks was used. As a result, the maximum voltages could be very restrictive, especially if the MV/LV transformers increase the voltage substantially, e.g. by 5%. Before modifying the MV network or the way in which its voltage is controlled, the level of penetration in each of the underlying LV networks is re-assessed. If half of the corresponding hosting capacities is not exceeded in any such network, the maximum voltage limits at the MV terminals may be increased by 0.5%.

Section 4.1.2.2 explains how voltage exceedances above the voltage limits can be resolved.

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[1] *Based on the assumption, that generation is spread fairly evenly between the three phases.*

If required, the effectiveness of any proposed network changes is verified.

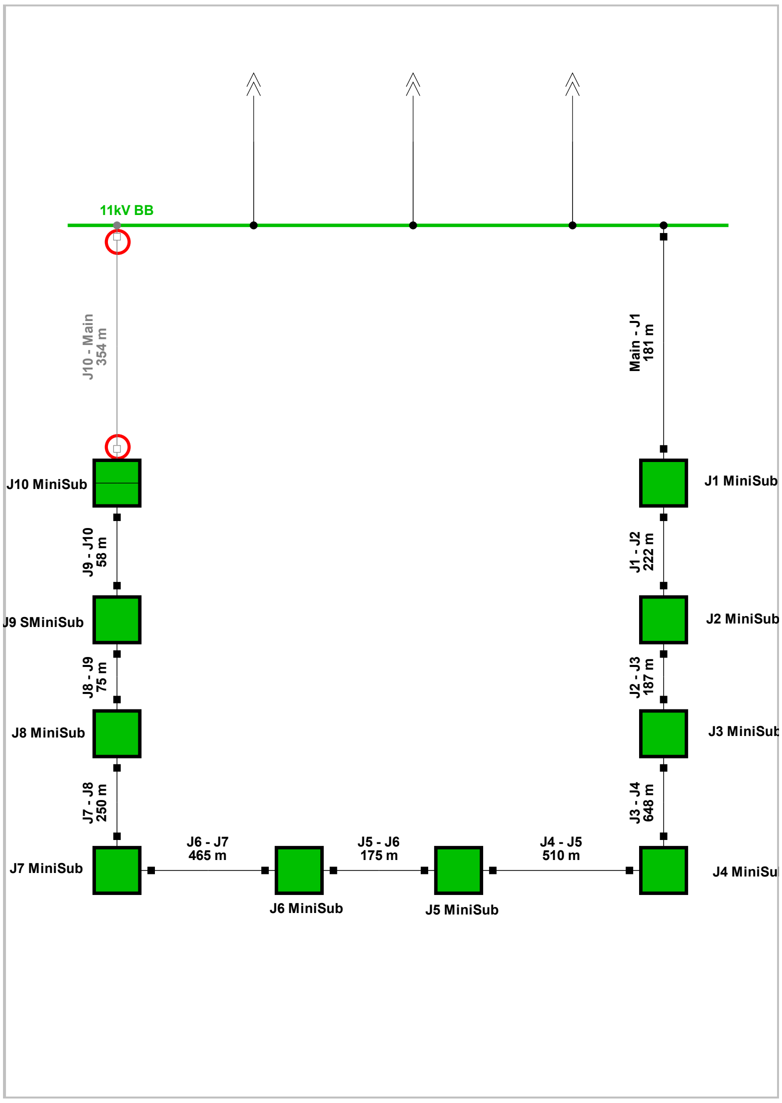

Figure 8: Example of MV network model under (n-1) operating conditions (open breakers marked red)

6.4 Step M3: Thermal loading analysis

It is verified that the thermal ratings of all components are not exceeded under worst-case operating conditions (which may include contingencies).

6.5 Step M4: Short-circuit analysis

Maximum three-phase and single-phase short-circuit currents (i_p, I_{th}, I_k'') are calculated in accordance with IEC60909 (2016). It is ensured that the contribution of embedded generators is considered. It is verified that the short-circuit ratings of equipment are not exceeded.

Many LV generators will not contribute to the short-circuit currents at MV level during faults in the MV network. Generators >100kW and especially generators connected at MV level will have a more significant contribution. The contribution depends on the type of generator.

The fault current contribution of generators should be checked for plausibility by comparison with the following typical values:

a) synchronous generators: eight times the rated current;

b) asynchronous generators: six times the rated current;

c) inverter based generators: rated current.

6.6 Step M5: Rapid voltage change (due to generator trip)

It is verified that the tripping of any single generator does not lead to a voltage change in the MV network higher than 3%.

The analysis is performed by ‘freezing’ the automatic tap changers of transformers, calculating the voltages at the new generator’s POC with the generator connected and disconnected, and calculating the change in voltage.

The utility may deviate from the 3% value in exceptional cases (see section 4.7).

See section 4.5 regarding harmonics.

6.7 Step M6: Decision-making

In the case of an LV connection, if the conditions in the preceding analyses (simplified and, where applicable, detailed) have been met and the hosting capacity of the MV network is not exceeded, the connection can be approved. Otherwise, if the hosting capacity of the MV network is exceeded, the MV network could be modified - see 4.1.2.

In the case of an MV connection, if any design criterium is not met, the network could be modified (see 4.1.2) or an alternative point of connection located, at which the requirements are met.

6.8 Step M7: Documentation incl. final decision

A short report should be written on each grid study performed.

Records of the calculations, the model and the data sources should be stored together with the above report.

ANNEX

A Simulation studies of LV networks

A.1 Applicability

Simulation studies of the LV network are required when:

- The feeder hosting capacity needs to be studied with high accuracy and the municipality has chosen not to apply the apportionment method (see sections 5.6.3 and 5.6.4),
- One or more generator is to be operated at non-unity power factor (unusual in LV networks),
- MV/LV transformer rating more than 600kVA,
- High degree of unbalance anticipated, or
- Voltage problems reported by customer.

A.2 Step L1: Model construction

Two types of models could be constructed:

- A model of the affected feeder, including a voltage source to represent the main LV terminal and all embedded generators connected to the feeder.
- A model of the entire three-phase LV network, including a voltage source to represent the MV network and all embedded generators.

Often only the feeder hosting capacity needs to be studied (section 5.6.4), so that only the affected feeder needs to be modelled. For more extensive studies, the entire LV network can be modelled.

Some important characteristics of LV network models are listed below:

a. All terminals must be of the ABC-N type.
b. All cable models must include neutral conductors. Typically, the same parameters can be assumed as for the positive sequence parameters.
c. A practical way to model embedded generators may be negative loads connected to the three-phase terminal. The rated powers of the connected generators are added for each phase, and entered into the load model.
d. Generators with power ratings >100kVA are modelled separately using the static generator model. Initially, it is assumed that they operate at unity power factor.
e. In the simple model listed above, the voltage source must have its neutral connected to the terminal. In the more detailed model, the transformer's neutral must be connected to the terminal.
f. In the simple model, the voltage source must be set to represent the maximum voltage of the main LV terminal, i.e. 108%. In the detailed model, the MV voltage must be set to represent the calculated maximum MV voltage, e.g. 104.6%.
g. It must be ensured that the MV/LV transformer model has the correct nominal power, nominal voltages, tap position, and short-circuit impedance (both in the positive sequence and in the zero sequence). The impedance is defined by two components, e.g. impedance and X/R ratio.
h. A load model is connected to the main LV terminal to represent the total minimum load (which can occur simultaneously with maximum generation) of all shared feeders. The corresponding

minimum load of dedicated feeders may be known and thus modelled as directly connected to these feeders.

The models can be prepared completely manually, by transferring data from single-line diagrams, geographical information systems, spreadsheets and field data into the analysis software. Alternatively, the modelling data can be imported, followed by the manual completion of the model. The method using DGS is not recommended if the information from the GIS system does not have a very high quality, since this would lead to extensive manual work before and after the importing process.

An example of a detailed LV network model is shown below.

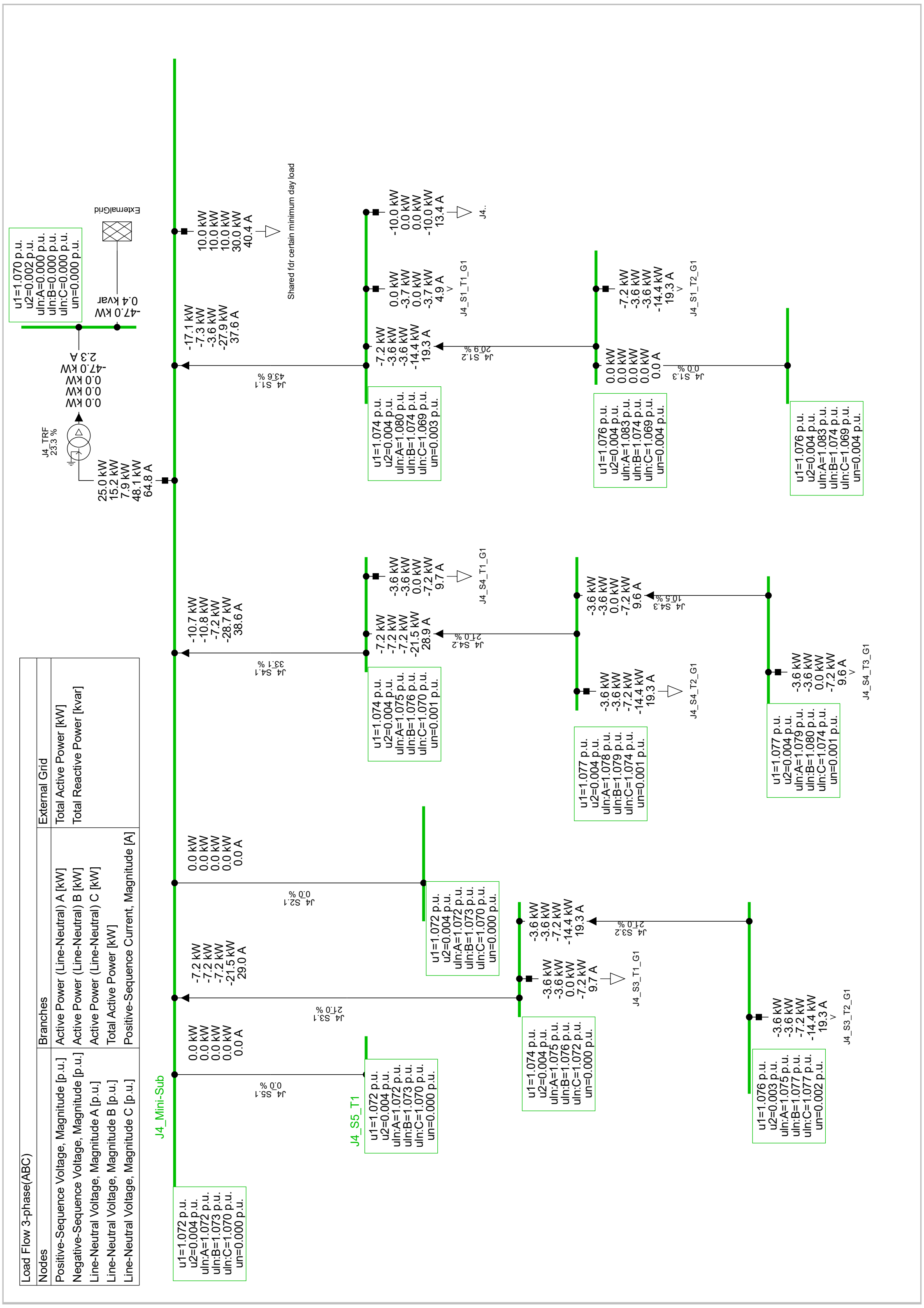

Figure 9: Example of LV network model

A.3 Step L2: Voltage profile analysis

The voltage profile is calculated under maximum generation, minimum simultaneous load conditions and maximum MV voltage at the supply terminal to the LV network. An unbalanced load flow is executed, and an appropriate solution accuracy is selected considering the sizes of the generators (typically **0.1kVA**).

It is verified that all voltage rise limits and absolute voltage limits specified in section 4.1.1 are met. The voltage rise in each phase of the affected feeder may not exceed 1%. It is also verified that the conditions are met for all other feeders.

Voltage violations can be addressed by one or more of the following:

a. connecting to a different phase,
b. converting from a single-phase to a three-phase connection,
c. network strengthening, e.g. using higher cable cross-sections,
d. operating the large generators at a constant under-excited power factor.

According to the grid code version 2.9, generators larger than 100kVA are required to be capable of absorbing reactive power. Therefore, the voltage rise may be limited, for example by operating the inverter at a fixed under-excited power factor. This is typically only a practical solution in the case of relatively high power levels, where the X/R ratios become appreciable. The voltage is typically fairly insensitive to changes in reactive power and the flow of reactive power may increase losses significantly. It is more common to use reactive power absorption in MV networks than in LV networks. However, considering the grid code requirements, a generator connection >100kVA could be granted subject to under-excited operation.

A.4 Step L3: Thermal loading analysis

It is verified that the thermal ratings of cables and the transformer are not exceeded.

A.5 Step L4: Short-circuit analysis

The maximum one-phase-to-neutral and three-phase short-circuit currents are calculates according to IEC 60909. It is ensured that equipment ratings are not exceeded.

Fault level problems are not anticipated for inverter based generators <100kW as the fault current contribution is typically approximately equal to the converter current rating.

The fault current contribution of generators should be checked for plausibility by comparison with the following typical values:

a) synchronous generators: eight times the rated current;

b) asynchronous generators: six times the rated current;

c) inverter based generators: rated current.

A.6 Step L5: Unbalance, harmonic and flicker analyses

The unbalance is calculated from the load flow results and it is verified that it lies within the limit stated in section 4.4.

It is verified that the generator complies with IEC61727 in terms of harmonic current emission, and with IEC61000-3 / -11 in terms of flicker. If this is the case, no further calculations are required.

A.7 Step L6: Decision-making

See Figure 3.

A.8 Step L7: Documentation

A short report should be written on each grid study performed.

Records of the calculations, the model and data sources should be stored together with the above report.

7 References

[1] NERSA: Grid Connection Code for Renewable Power Plants (RPPs) Connected to the Electricity Transmission System (TS) or the Distribution System (DS) in South Africa, Version 2.9

[2] IEC61400-21: Wind turbines –Measurement and assessment of power quality characteristics of grid connected wind turbines, Edition 2, 2008-08

[3] IEC61000-3-6: Electromagnetic Compatibility (EMC) – Part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems, Edition 2.0, 2008-02

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[6] FGW e.V.: Technische Richtlinien für Erzeugungseinheiten – Teil 4: Anforderungen an Modellierung und Validierung von Simulationsmodellen der elektrischen Eigenschaften von Erzeugungseinheiten und –anlagen, Revision 5, 23.03.2010

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[8] IEC60034-4: Rotating electrical machines; Part 4: Methods for determining synchronous machine quantities from tests

[9] IEEE Guide 115: Guide for Test Procedures for Synchronous Machines; Part I —Performance and acceptance testing and Part II—Test Procedures and Parameter Determination for Dynamic Analysis

[10] IEEE Standard 421.5: Recommended Practice for Excitation System Models for Power System Stability Studies

[11] IEEE Standard 421.2: IEEE Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control Systems