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TECHNICAL SPECIFICATION

colour inside

Guidelines for the hosting capacity evaluation of distribution networks for distributed energy resources

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Guidelines for the hosting capacity evaluation of distribution networks for distributed energy resources

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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GUIDELINES FOR THE HOSTING CAPACITY EVALUATION OF DISTRIBUTION NETWORKS FOR DISTRIBUTED ENERGY RESOURCES

FOREWORD

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IEC TS 63276 has been prepared by Subcommittee 8B: Decentralized electrical energy systems, of IEC Technical Committee 8: System aspects of electrical energy supply. It is a Technical Specification.

The text of this Technical Specification is based on the following documents:

Draft	Report on voting
8B/212/DTS	8B/225/RVDTS

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
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GUIDELINES FOR THE HOSTING CAPACITY EVALUATION OF DISTRIBUTION NETWORKS FOR DISTRIBUTED ENERGY RESOURCES

1 Scope

This document specifies methods for the evaluation of the maximum export capacity of distributed energy resources (DER) that distribution networks can accommodate. It provides guidance on the technical constraints that should be considered in evaluating hosting capacity, information required to be collected to undertake a hosting capacity evaluation, and evaluation methods.

This document is applicable to AC distribution networks operating at a nominal frequency of 50 Hz or 60 Hz.

This document does not specify allowable values of system parameters that can be impacted by the addition of DER on a distribution network, such as maximum or minimum voltage, maximum current, etc. These values are to be determined by the user, from international or national standards, local regulations or the like, and used as an input to the evaluation methods described in this document.

Options for increasing the hosting capacity of distribution networks are not specifically considered, although the identification of constraints to the hosting capacity will assist users in developing methods for increasing the overall hosting capacity.

This document is mainly used by distribution system operators (DSO) and other organizations with corresponding qualifications and capabilities. The evaluation results can serve the DER investors, DSO, energy sector regulators and other stakeholders as a decision-making basis.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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.

IEC 60255 (all parts), *Measuring relays and protection equipment*

IEC 60364 (all parts), *Low-voltage electrical installations*

IEC 60834-1, *Teleprotection equipment of power systems – Performance and testing – Part 1: Command systems*

IEC 60909-0, *Short-circuit currents in three-phase a.c. systems – Part 0: Calculation of currents*

IEC 61000 (all parts), *Electromagnetic compatibility (EMC)*

IEC 61400-27-1, *Wind energy generation systems – Part 27-1: Electrical simulation models – Generic models*

IEC 61936-1, *Power installations exceeding 1 kV AC and 1,5 kV DC – Part 1: AC*

IEC TS 62749, *Assessment of power quality – Characteristics of electricity supplied by public networks*

IEC TS 62786-1, *Distributed energy resources connection with the grid – Part 1: General requirements*

IEEE 1547.4, *Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems*

3 Terms and definitions

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

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

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

3.1
distributed energy resources
DER
generators (with their auxiliaries, protection and connection equipment), including loads having a generating mode (such as electrical energy storage systems), connected to a low-voltage or a medium-voltage network

[SOURCE: IEC 60050-617:2017, 617-04-20, modified – "pl" was deleted from the term and abbreviated term.]

3.2
hosting capacity
maximum export capacity of DER that the distribution network can accommodate, under the condition that the distribution network operates safely and reliably

3.3
distribution network
electric power network for the distribution of electric power from and to network users for which a distribution system operator (DSO) is responsible

[SOURCE: IEC TS 62786:2017, 3.4]

3.4
distribution system operator
DSO
party operating a distribution network

[SOURCE: IEC 60050-617:2009, 617-02-10, modified – "distribution network operator" and "distributor" were deleted from the equivalent terms.]

3.5
reverse load rate
ratio of reverse active power through a transformer, line, cable, etc. to its actual maximum operating capacity

Note 1 to entry: Reverse direction of power flow is from downstream to upstream.

Note 2 to entry: The actual maximum operating capacity of a transformer, line, cable, etc. is affected by aging and climate.

3.6
thermal rating
ability of electrical equipment to bear the thermal effect of current in long-time operation

3.7
short-circuit current
electric current in a given short-circuit

[SOURCE: IEC 60050-614:2016, 614-02-03]

3.8
voltage deviation
difference between the supply voltage at a given instant and the declared supply voltage

[SOURCE: IEC 60050-614:2016, 614-01-04]

3.9
harmonic voltage
sinusoidal voltage with a frequency equal to an integer multiple of the fundamental frequency of the voltage

[SOURCE: IEC 60050-614:2016, 614-01-14]

3.10
voltage unbalance
in a polyphase system, a condition in which the RMS values of the phase voltages or the phase angles between consecutive phases are not all equal

[SOURCE: IEC 60050-161:1990, 161-08-09, modified – "voltage imbalance" was deleted for the equivalent terms.]

4 Basic requirements of the evaluation

4.1 Evaluation principle

The evaluation is to guide the development of DER to match the current situation and future development of distribution network. Therefore, the evaluation should be carried out to identify the hosting capacity of a distribution network while ensuring the safe and reliable operation of distribution network. The objective is to provide a reference for the planning, designing, reconstructing and operating of DER and distribution network.

The hosting capacity of a certain voltage level should not exceed that of the corresponding upper level. Therefore, the evaluation should be based on the principle of "hierarchical evaluation zone by zone", i.e. it should be carried out from the whole to the segment and from higher-voltage level to lower-voltage level according to the power supply area and voltage level.

The evaluation should be carried out periodically in synchronization with the analysis of distribution network operation mode and distribution network planning. The evaluation period should be appropriately adjusted according to the changes of distribution network structure, electrical load and power generation, which can be shortened in the distribution network of low hosting capacity.

4.2 Evaluation scope and objects

The evaluation scope could be the whole distribution network or a part of it, for example, a control area of DSO or a supply zone of a transformer, etc.

The evaluation objects should include corresponding electrical equipment, including transformers, lines, cables, switching equipment, corresponding relay protection equipment, etc.

4.3 Impact factors

4.3.1 Structure of distribution network

The hosting capacity is directly related to the structure and equipment capacity of the distribution network. If the structure of distribution network is strong and the equipment capacity of distribution network is large, the corresponding hosting capacity of distribution network is relatively large.

4.3.2 Composition of existing power generation

The equipment capacity in a distribution network is generally fixed. Other power generation transmitted through the same channel as DER in the distribution network can cause congestion in certain parts or sections of infrastructures of determined areas. Therefore, it is necessary to consider the composition of the existing power generation when planning additional DER installations.

4.3.3 DER under construction or approved

Different nodes in a distribution network have different thermal rating margins, voltage deviations, and short-circuit capacities. As a result, different nodes can support different capacities of DER. The additional DER should consider the DER under construction and approved at the specific connection node.

4.3.4 Load characteristics

Consumption including local consumption and delivery of DER should be analysed with the load distribution and its operation curve. The higher the load density of the distribution network or the more similar the shape of the load curve to the DER output curve is, the higher the hosting capacity is.

5 Evaluation contents

5.1 Thermal rating

The evaluation objects should include transformers, lines, cables, etc. within the evaluation scope. The reverse load rate λ should be used as the evaluation index for thermal rating evaluation.

The reverse load rate λ should be calculated according to factors such as the distribution network operation mode, transformers, lines and cables limits, load characteristics, and output characteristics of DER and other power generations.

The reverse load rate λ should be calculated according to Formula (1).

$$\lambda(t) = \frac{P_G(t) - P_L(t)}{S_e(t)} \qquad (1)$$

where

$P_G(t)$ is the output of DER and other power sources in the evaluation scope at time t;

$P_L(t)$ is the electrical load at time t;

$S_e(t)$ is the actual maximum operating capacity of transformers, lines, cables etc. at time t.

The maximum additional export capacity of DER should be calculated according to Formula (2).

$$P_m = (k_r - \lambda_{max}) \times S_e \qquad (2)$$

where

P_m is the maximum additional export capacity of DER that can be connected to the evaluated line, cable or transformer;

k_r is the allowable reverse load rate;

NOTE k_r can be determined by DSO or equipment operators based on grid operation and equipment conditions.

λ_{max} is the historical maximum value of reverse load rate;

S_e is the actual maximum operating capacity of transformers, lines, cables, etc. corresponding to λ_{max}.

5.2 Short-circuit current

The short-circuit current of distribution network can be affected by the connection of DER. If the existing short-circuit current of distribution network is large, or the interrupting capacity margin of switchgear is small, the additional DER capacity able to be installed can be limited.

The short-circuit current should be checked based on the principle that the short-circuit current of each bus of the distribution network does not exceed the corresponding circuit breaker breaking current limit after the additional DER are connected. The short-circuit current of the system should be calculated according to IEC 60909-0 based on the normal/typical operation mode of distribution network, and the capacity of additional DER within the evaluation scope.

Short-circuit current should be checked according to Formula (3).

$$I_{sc} < I_{minb} \qquad (3)$$

where

I_{sc} is the short-circuit current of the bus;

I_{minb} is the minimum value of the breaking current limit of all equipment (including circuit breakers) connected with the bus.

5.3 Voltage deviation

During the high output period of DER, the downstream power flow of the distribution network can become lighter or even reversed, which can cause the voltage to exceed the limit. Under any normal operating conditions, the connection of DER should not cause the voltage of distribution network to exceed the limit.

The voltage deviation should be checked based on the principle that the voltage does not exceed the limit after the additional DER are connected. The voltage deviation should meet the relevant requirements of IEC TS 62749 and IEC TS 62786-1. The voltage of each bus within the evaluation scope should be checked.

The maximum positive voltage deviation δU_{H} and the maximum negative voltage deviation δU_{L} should be calculated and checked based on the capacity of additional DER.

The voltage deviation should be checked according to Formula (4) and Formula (5).

$$\delta U_{\mathrm{H}} < \Delta U_{\mathrm{H}} \tag{4}$$

$$\delta U_{\mathrm{L}} < \Delta U_{\mathrm{L}} \tag{5}$$

where

δU_{H} is the maximum positive voltage deviation;

δU_{L} is the maximum negative voltage deviation;

ΔU_{H} is the maximum allowable value of positive voltage deviation;

ΔU_{L} is the maximum allowable value of negative voltage deviation.

5.4 Harmonic voltage

Harmonic voltage should be checked based on the principle that the harmonic voltage limits of the distribution network should not be exceeded. The harmonic voltage should meet the relevant requirements of IEC TS 62749. All nodes affected by harmonic voltage provided by DER should be checked.

Harmonic voltage should be checked in accordance with Formula (6).

$$U_{\mathrm{hv,h}} < U_{\mathrm{h}} \tag{6}$$

where

$U_{\mathrm{hv,h}}$ is the h-th harmonic voltage;

U_{h} is the allowable value of the h-th harmonic voltage.

5.5 Voltage unbalance

The voltage unbalance check should be performed for single-and-three-phase connections of DER complying with the principle to ensure the unbalance factor of the three-phase voltage in the distribution network does not exceed the limits. The voltage unbalance should meet the relevant requirements of IEC 62749 and IEC TS 62786-1. The voltage of each bus within the evaluation scope should be checked.

Voltage unbalance should be checked according to Formula (7).

$$\varepsilon_{u_2} < \overline{\varepsilon}_{u_2} \tag{7}$$

where

ε_{u_2} is the unbalance factor of negative sequence voltage;

$\overline{\varepsilon}_{u_2}$ is the allowable value of unbalance factor of negative sequence voltage.

5.6 Protection configuration

The goal of protection configuration is to ensure that the distribution network is safe, secure and reliable after the connection of additional DER. The protection configuration should be in accordance with normal operation mode of DER which is decided by the operator of DER and DSO.

The content of the protection configuration check is whether the protection system can effectively respond when a fault or abnormal condition occurs when additional DER is connected and operating. The protection configuration check should be carried out on the basis of typical operation modes of the distribution network. The configuration of teleprotection equipment of the distribution network should meet the relevant requirements of IEC 60834-1; the electromagnetic compatibility configuration should meet the relevant requirements of the IEC 61000 series; the relay protection configuration should meet the relevant requirements of the IEC 60255 series; the device configuration should meet the relevant requirements of the IEC 60364 series and IEC 61936-1; the impact of DER on the network's fault levels, protection coordination, and fault ride-through capability should meet the relevant requirements of IEC 60909-0, IEC TS 62786-1, IEC 61400-27-1, and IEEE 1547.4.

NOTE Typical operation modes refer to heavy load operation mode, light load operation mode, etc.

6 Data preparation

6.1 Data preparation

6.1.1 Distribution network

Distribution network data includes distribution network topology, equivalent impedance, and the short-circuit capacity of buses.

6.1.2 Equipment parameter

a) Equipment parameter data of distribution network includes existing (under construction and approved) transformer parameters, line parameters, breaking capacity of switchgear, etc.

b) Equipment parameter data of power generators includes existing (under construction and approved) number and type (synchronous generator, asynchronous generator or converter), rated power and apparent power, installed capacity, theoretical power output, power factor adjustment range, etc.

c) Equipment parameter data of energy storage includes the charging/discharging power range and rate, etc.

d) Settings and configuration of protection.

6.1.3 Operating state

a) Operating state refers to normal operation mode, as well as the operation modes at light load and heavy load.

b) The operating data of distribution network includes historical data of power generation, load, charging/discharging power of energy storage, line power flow, bus voltage and harmonic voltage, etc.

6.1.4 Operating limit

Operating limit data includes thermal rating limit, short-circuit current limit, bus voltage deviation limit, harmonic voltage allowable value, and voltage unbalance allowable value of the distribution network.

6.2 Data processing

In order to facilitate the evaluation of hosting capacity, the data of distribution network performance, equipment parameter, operating state and operating limit collected in the data preparation will be classified, sorted and calculated.

Power generation units of the same zone, type, and attribute will be classified, sorted and calculated equivalently according to the actual situation of power generation installation in the distribution network.

Annex A gives detailed sources and uses of data that is needed for hosting capacity evaluation.

7 Evaluation method and process

The evaluation should be carried out in the order of data preparation, calculation and analysis, grade classification, and suggestions.

a) Clarify the scope of the distribution network to be evaluated and draw the single-line diagram.

b) Carry out the evaluation hierarchically from higher-voltage level to lower-voltage level. The data needed for evaluation should be collected.

c) Carry out the thermal rating analysis and check according to the calculation of the reverse load rate in normal operation mode of the distribution network.

d) If the reverse load rate of the transformers, lines, cables, etc. calculated according to step c) exceeds the allowable reverse load rate, additional DER cannot be connected. Otherwise, calculate the capacity of additional DER according to Formula (2).

   NOTE Relevant measures and economic and technical analysis are necessary to deal with the reverse load rate exceeding the limit that can be caused by the connection of additional DER.

e) Re-check short-circuit current, voltage deviation, harmonic voltage, voltage unbalance and protection configuration.

f) In case of failure to pass the check in step e), gradually reduce the capacity of additional DER that can be connected and repeat step e) until the check is passed. The last value obtained is the capacity of additional DER.

g) After step f), carry out the evaluation hierarchically to the lower voltage level according to steps c) to f). Check the calculation results of each voltage level with each other. The check principle is that the capacity of additional DER of the lower-voltage level should not be higher than the capacity of additional DER of the corresponding higher-voltage level, so as to ensure that the calculation results match each other.

h) Hosting capacity equals the capacity of additional DER obtained in step g) plus the capacity of DER already connected.

Annex B gives the evaluation flowchart.

8 Evaluation results

Based on the calculation results, this clause will present the hosting capacity, as well as the corresponding evaluation grade.

The evaluation grade of the hosting capacity should be determined hierarchically zone by zone. The evaluation grade is defined in Annex C.

The evaluation grade should be determined according to corresponding λ_{max}, short-circuit current, voltage deviation, harmonic voltage, voltage unbalance and protection configuration, while considering the coordination between different voltage levels. The evaluation grade of the lower-voltage level should be lower than that of the higher-voltage level, otherwise, it should be degraded to the grade of the corresponding higher-voltage level.

The evaluation results of hosting capacity of distribution network for DER should include at least the hosting capacity, evaluation grade, and the result graph.

Annex C gives a recommendation of evaluation grade classification.

Annex D gives an example of evaluation chart.

Annex A
(informative)

Sources and uses of data needed for hosting capacity evaluation

Table A.1 shows the detailed sources and uses of data that are needed for hosting capacity evaluation.

Table A.1 – Data needed for hosting capacity evaluation

No.	Data	Type	Uses	Source
1	Distribution network topology	Distribution network performance	Determine the scope of evaluation	DSO
2	Equivalent impedance of distribution network	Distribution network performance	Short-circuit current and the voltage deviation check	DSO
3	Short-circuit capacity of bus	Distribution network performance	Short-circuit current check	DSO
4	Transformer impedance	Equipment parameter	Short-circuit current and voltage deviation check	Manufacturer
5	Actual maximum operating capacity of transformer	Equipment parameter	Thermal rating evaluation	DSO
6	Line current limit	Equipment parameter	Thermal rating evaluation	DSO
7	Line impedance	Equipment parameter	Short-circuit current and voltage deviation check	Manufacturer
8	Breaking capacity of the switchgear	Equipment parameter	Short-circuit current check	Manufacturer
9	Information of already connected power generation	Equipment parameter	Thermal rating evaluation, short-circuit current, voltage deviation and voltage unbalance check	DSO
10	The charging/discharging power range and rate of energy storage	Equipment parameter	Thermal rating evaluation, short-circuit current, voltage deviation and voltage unbalance check	Manufacturer
11	Settings and configuration of protection	Equipment parameter	Protection configuration check	DSO
12	Operation mode	Operating state	Thermal rating evaluation, short-circuit current, voltage deviation and voltage unbalance check	DSO
13	Power generation	Operating state	Thermal rating evaluation, voltage deviation and voltage unbalance check	DSO
14	Load	Operating state	Thermal rating evaluation, short-circuit current, voltage deviation and voltage unbalance check	DSO
15	Charging/discharging power of energy storage	Operating state	Thermal rating evaluation, voltage deviation and voltage unbalance check	DSO
16	Line power flow	Operating state	Thermal rating evaluation, voltage deviation and voltage unbalance check	DSO
17	Bus voltage	Operating state	Voltage deviation check	DSO
18	Harmonic voltage	Operating state	Harmonic voltage check	DSO
19	Voltage unbalance factor	Operating state	Voltage unbalance check	DSO

No.	Data	Type	Uses	Source
20	Short-circuit current limit	Operating limit	Short-circuit current check	Standard or local regulations
21	Voltage deviation limit	Operating limit	Voltage deviation check	Standard or local regulations
22	Harmonic voltage allowable value	Operating limit	Harmonic voltage check	Standard or local regulations
23	Voltage unbalance factor allowable value	Operating limit	Voltage unbalance check	Standard or local regulations
24	Reverse load rate allowable value	Operating limit	Thermal rating evaluation	DSO or equipment operators

Annex B
(normative)

Evaluation process

Figure B.1 shows the flowchart of the evaluation process.

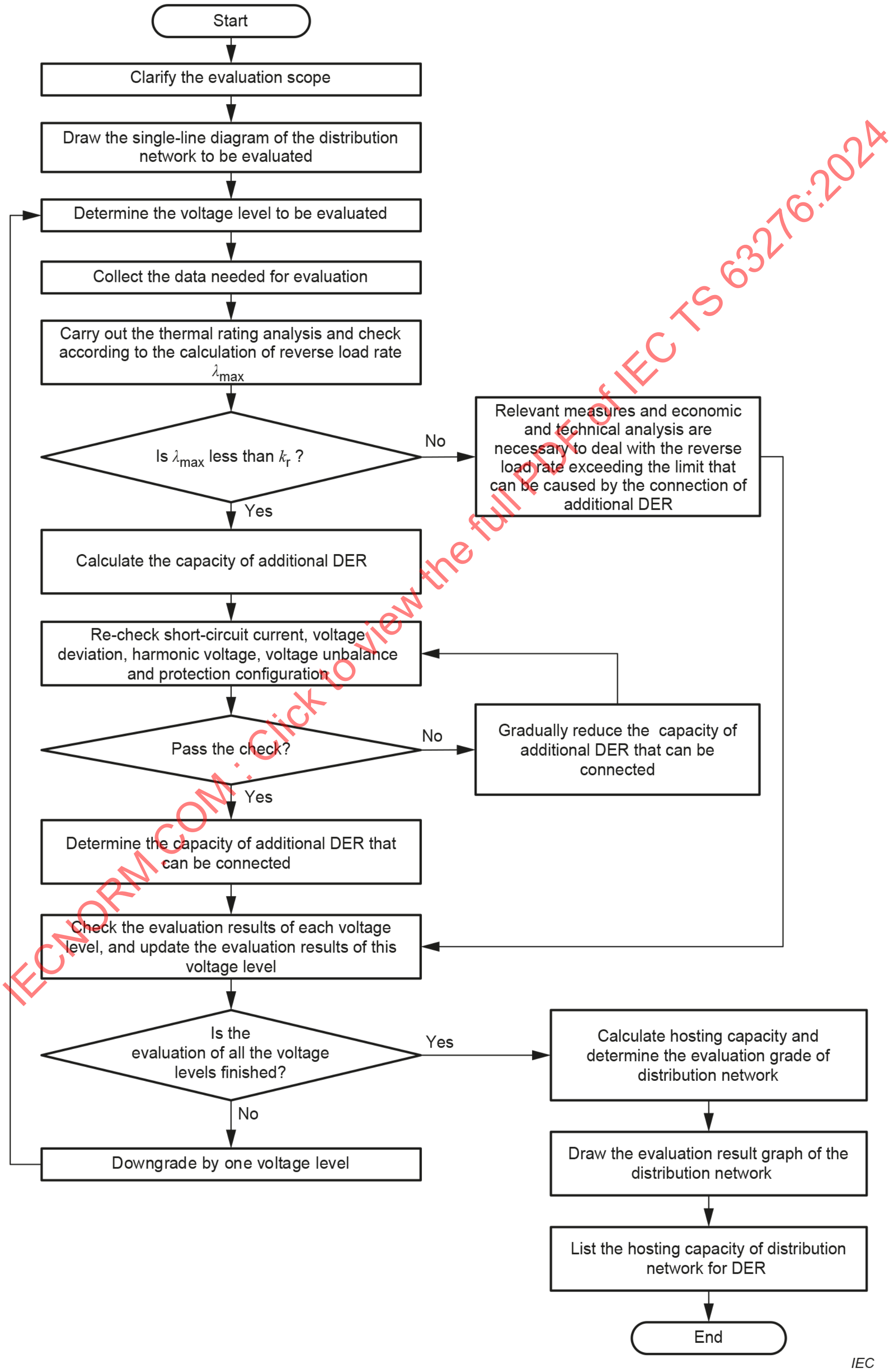

Figure B.1 – Evaluation process

Annex C
(normative)

Evaluation grade

The evaluation grade can be divided into five grades: green, blue, yellow, orange and red, from high to low, according to the degree of impact of DER on the distribution network. The evaluation grade can be divided according to the provisions of Table C.1.

Table C.1 – Evaluation grade

Evaluation grade	Basis	Meaning	Suggestions
Green	$-100\ \% \leq \lambda_{max} < -50\ \%$; The short-circuit current, voltage deviation, harmonic voltage, voltage unbalance and protection configuration are all qualified.	The DER penetration is low, and the DER are fully consumed locally. The hosting capacity is abundant.	The evaluation procedures of DER connection can be simplified, and DER connection is recommended.
Blue	$-50\ \% \leq \lambda_{max} < 0$; The short-circuit current, voltage deviation, harmonic voltage, voltage unbalance and protection configuration are all qualified.	The DER penetration is low, and these DER are fully consumed locally. The hosting capacity is good.	The evaluation procedures of DER connection should be in accordance with Clause 7.
Yellow	$0 \leq \lambda_{max} < 0{,}5\ k_r$; The short-circuit current, voltage deviation, harmonic voltage, voltage unbalance and protection configuration are all qualified.	The reverse power flow of the distribution network does not exceed $0{,}5\ k_r$ of the equipment, and the distribution network has a certain amount of hosting capacity.	Additional DER can be connected. The evaluation procedures of DER connection should be in accordance with Clause 7. And the operation mode of the distribution network should be optimized.
Orange	$0{,}5\ k_r \leq \lambda_{max} < k_r$; The short-circuit current, voltage deviation, harmonic voltage, voltage unbalance and protection configuration are all qualified.	The reverse power flow of the distribution network is more than $0{,}5\ k_r$ but less than k_r of the equipment, and the distribution network hosting capacity is in shortage.	Additional DER connection should be temporarily suspended, and besides checking in accordance with Clause 7, special analysis should be made of those projects that do need to connect to the grid.
Red	$\lambda_{max} \geq k_r$; Or any indexes of short-circuit current, voltage deviation, harmonic voltage, voltage unbalance, or protection configuration exceeds the limit.	The reverse power flow of the distribution network is more than k_r of the equipment, there are risks with the distribution network operation safety.	Additional DER connection should be suspended until the distribution network hosting capacity is effectively improved.
NOTE $-100\ \% \leq \lambda_{max} < 0$ means normal direction of power flow is from upstream to downstream, $0 \leq \lambda_{max} < 100\ \%$ means reverse direction of power flow is from downstream to upstream at the moment.			

Annex D
(informative)

Example of evaluation

D.1 Basic information of the example

Taking the distribution network of a city in China as an example, a local 220 kV distribution network was selected as an evaluation example to calculate the hosting capacity of the distribution network for DER under a historical typical day. This area is located in the eastern inland of China, with good solar energy resources and poor other renewable energy resources such as wind power. Therefore, distributed photovoltaic is mainly considered in this example. Considering the actual situation of the country where the calculation example is located, the value of k_r is 80 %.

The single-line diagram of the distribution network is shown in Figure D.1. The evaluation scope includes one 220/110/35 kV, one 110/10 kV, two 110/35 kV, and two 35/10 kV transformers.

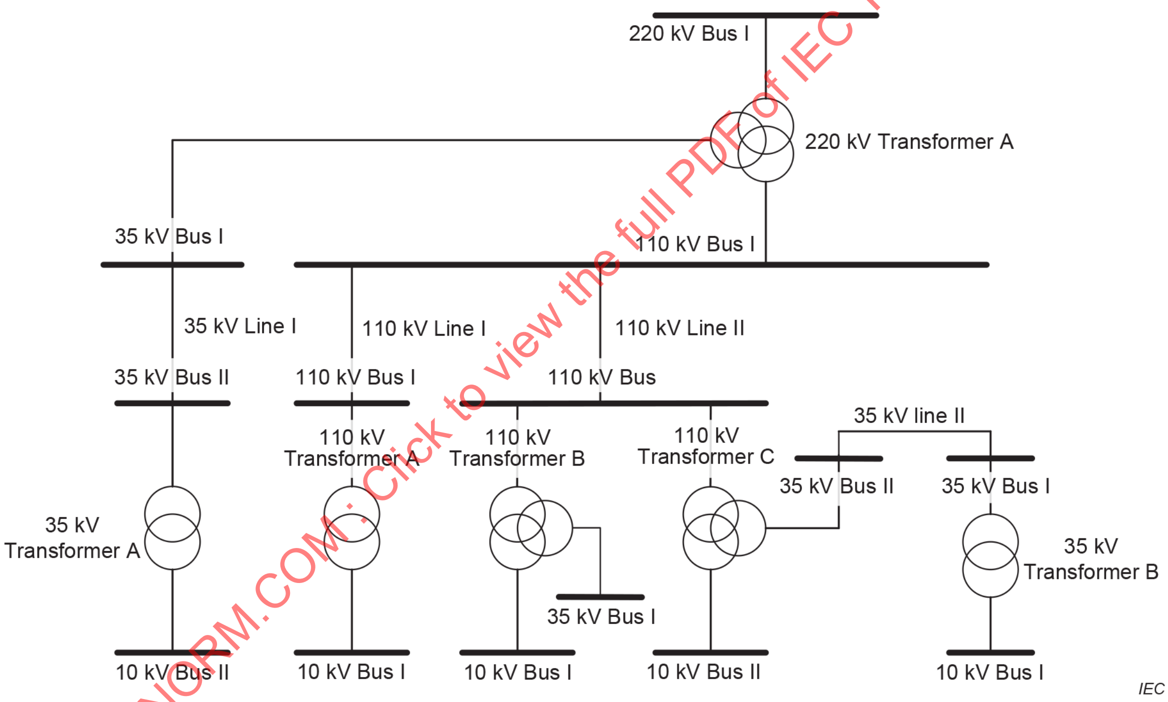

Figure D.1 – Single-line diagram of the example

The historical typical daily load curve on the high-voltage side of the 220 kV transformer in Figure D.1 is shown in Figure D.2. It can be seen that the minimum load occurred at 13:30, which is 27,34 MW.

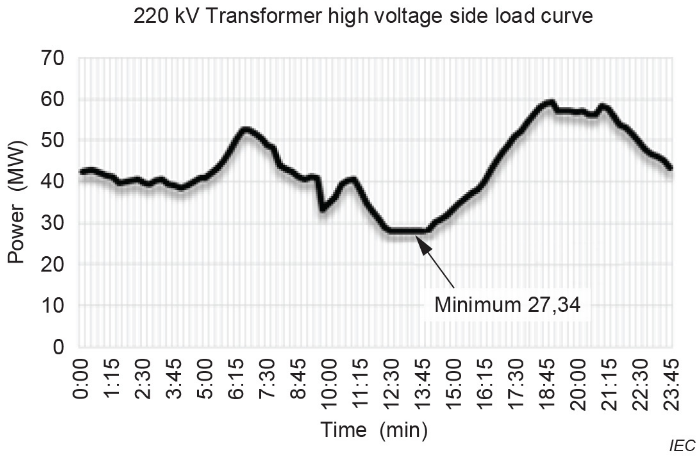

Figure D.2 – Operation data of typical day

D.2 Calculation of hosting capacity for DER

According to the principle of hierarchical evaluation from higher voltage level to lower voltage level, the hosting capacity of each bus of 220 kV, 110 kV, 35 kV and 10 kV for DER is evaluated in turn according to the process shown in Figure B.1. The results are shown in Table D.1.

Table D.1 – Sheet of thermal rating evaluation

Evaluated bus (line)	Maximum value of P_G-P_L (MW)	Operating limit of transformers or lines S_e (MW)	λ_{max}	P_m (MW)	Remarks
220 kV bus I of 220 kV transformer A	−27,34	180	−0,15	171,34	
110 kV bus I of 220 kV transformer A	−24,44	178,80	−0,14	167,48	
35 kV bus I of 220 kV transformer A	−2,64	89,40	−0,03	74,16	
110 kV bus of 110 kV transformer B	−9,25	87,64	−0,11	79,36	
35 k V bus I of 110 kV transformer B	−3,85	31,50	−0,12	29,05	
10 kV bus I of 110 kV transformer B	−1,65	31,50	−0,05	26,85	
35 kV bus II of 110 kV transformer C	−4,19	50	−0,08	44,19	
10 kV bus II of 110 kV transformer C	−1,53	50	−0,03	41,53	
35 kV bus I of 35 kV transformer B	−4,01	31,22	−0,13	28,99	
10 kV bus I of 35 kV transformer B	−3,07	20	−0,15	19,07	
110 kV bus I of 110 kV transformer A	−7,16	87,64	−0,08	77,27	
10 kV bus I of 110 kV transformer A	−3,15	31,5	−0,10	28,35	
35 kV bus II of 35 kV transformer A	−1,05	26,98	−0,04	22,63	
10 kV bus II of 35 kV transformer A	2,09	10	0,21	5,91	

Check short-circuit current, voltage deviation, harmonic voltage, voltage unbalance and protection configuration. Check results are shown in Table D.2 to Table D.4.

Table D.2 – Sheet of short-circuit current check

Evaluated bus (line)	**The allowable short-circuit current value** I_m (kA)	**The short-circuit current value of bus** I_{xz} (kA)	**Short-circuit current check (pass/fail)**	P_m (MW)	**Remarks**
220 kV bus I of 220 kV transformer A	-	21,18	Pass	171,34	
110 kV bus I of 220 kV transformer A	40	9,07	Pass	167,48	
35 kV bus I of 220 kV transformer A	31,5	10,51	Pass	74,16	
110 kV bus of 110 kV transformer B	40	6,42	Pass	79,36	
35 kV bus I of 110 kV transformer B	31,5	5,76	Pass	29,05	
10 kV bus I of 110 kV transformer B	20	14,59	Pass	26,85	
35 kV bus II of 110 kV transformer C	31,5	6,13	Pass	44,19	
10 kV bus II of 110 kV transformer C	20	15,86	Pass	41,53	
35 kV bus I of 35 kV transformer B	31,5	2,88	Pass	28,99	
10 kV bus I of 35 kV transformer B	20	6,73	Pass	19,07	
110 kV bus I of 110 kV transformer A	40	6,08	Pass	77,27	
10 kV bus I of 110 kV transformer A	20	17,08	Pass	28,35	
35 kV bus II of 35 kV transformer A	31,5	3,43	Pass	22,63	
10 kV bus II of 35 kV transformer A	20	5,60	Pass	5,91	

Table D.3 – Sheet of voltage deviation check

Evaluated bus (line)	Maximum allowable positive voltage deviation ΔU_H	Maximum allowable negative voltage deviation ΔU_L	Maximum reactive power provided by DER Q_{max}(MVar)	Maximum positive voltage deviation after additional DER connected δU_H	Maximum negative voltage deviation after additional DER connected δU_L	Voltage deviation check (pass/fail)	P_m (MW)
220 kV bus I of 220 kV transformer A	10 %	−10 %	34,79	1,3 %	−1,3 %	Pass	171,34
110 kV bus I of 220 kV transformer A	10 %	−10 %	34,01	3,3 %	−3,3 %	Pass	167,48
35 kV bus I of 220 kV transformer A	10 %	−10 %	15,06	3,2 %	−3,2 %	Pass	74,16
110 kV bus of 110 kV transformer B	10 %	−10 %	16,12	2,1 %	−2,1 %	Pass	79,13
35 kV bus I of 110 kV transformer B	10 %	−10 %	5,90	2,6 %	−2,6 %	Pass	29,05
10 kV bus I of 110 kV transformer B	7,0 %	−7,0 %	5,45	3,5 %	−3,5 %	Pass	26,85
35 kV bus II of 110 kV transformer C	10 %	−10 %	8,97	4,0 %	−4,0 %	Pass	44,19
10 kV bus II of 110 kV transformer C	7,0 %	−7,0 %	8,43	5,5 %	−5,5 %	Pass	41,53
35 kV bus I of 35 kV transformer B	10 %	−10 %	5,89	5,7 %	−5,7 %	Pass	28,99
10 kV bus I of 35 kV transformer B	7,0 %	−7,0 %	3,87	8,1 %	−8,1 %	Failed	19,07
110 kV bus I of 110 kV transformer A	10 %	−10 %	15,69	2,3 %	−2,3 %	Pass	77,27
10 kV bus I of 110 kV transformer A	7,0 %	−7,0 %	5,76	2,6 %	−2,6 %	Pass	28,35
35 kV bus II of 35 kV transformer A	10 %	−10 %	4,60	3,2 %	−3,2 %	Pass	22,63
10 kV bus II of 35 kV transformer A	7 %	−7 %	1,20	1,7 %	−1,7 %	Pass	5,91

Table D.4 – Sheet of harmonic voltage check

Evaluated bus (line)	Harmonic voltage check (pass/fail)	Remarks
220 kV bus I of 220 kV transformer A	Pass	
110 kV bus I of 220 kV transformer A	Pass	
35 kV bus I of 220 kV transformer A	Pass	
110 kV bus of 110 kV transformer B	Pass	
35 kV bus I of 110 kV transformer B	Pass	
10 kV bus I of 110 kV transformer B	Pass	
35 kV bus II of 110 kV transformer C	Pass	
10 kV bus II of 110 kV transformer C	Pass	
35 kV bus I of 35 kV transformer B	Pass	
10 kV bus I of 35 kV transformer B	Pass	
110 kV bus I of 110 kV transformer A	Pass	
10 kV bus I of 110 kV transformer A	Pass	
35 kV bus II of 35 kV transformer A	Pass	
10 kV bus II of 35 kV transformer A	Pass	

According to the calculation results, the voltage deviation of the 10 kV bus at the low voltage side of the 35 kV transformer B exceeds the limit, and the P_m on this bus shall be adjusted. After backtracking calculation, the P_m of the 10 kV bus at the low voltage side of the 35 kV transformer B is adjusted to 16,50 kW. After adjustment, the re-check results are shown in Table D.5.

Table D.5 – Sheet of thermal rating evaluation (after adjustment)

Evaluated bus (line)	Maximum value of $P_G - P_L$ (MW)	Actual maximum operating capacity of transformers or lines S_e (MW)	λ_{max}	P_m (MW)	Remarks
220 kV bus I of 220 kV transformer A	−27,34	180	−0,15	171,34	
110 kV bus I of 220 kV transformer A	−24,44	178,80	−0,14	167,48	
35 kV bus I of 220 kV transformer A	−2,64	89,40	−0,03	74,16	
110 kV bus of 110 kV transformer B	−9,25	87,64	−0,11	79,36	
35 kV bus I of 110 kV transformer B	−3,85	31,50	−0,12	29,05	
10 kV bus I of 110 kV transformer B	−1,65	31,50	−0,05	26,85	
35 kV bus II of 110 kV transformer C	−4,19	50	−0,08	44,19	
10 kV bus II of 110 kV transformer C	−1,53	50	−0,03	41,53	
35 kV bus I of 35 kV transformer B	−4,01	31,22	−0,13	28,99	
10 kV bus I of 35 kV transformer B	−3,07	20	**−0,03**	**16,50**	
110 kV bus I of 110 kV transformer A	−7,16	87,64	−0,08	77,27	
10 kV bus I of 110 kV transformer A	−3,15	31,5	−0,10	28,35	
35 kV bus II of 35 kV transformer A	−1,05	26,98	−0,04	22,63	
10 kV bus II of 35 kV transformer A	2,09	10	0,21	5,91	

NOTE The row of the adjusted P_m is shown in bold.

According to the obtained λ_{max} and P_m to check short-circuit current, voltage deviation, harmonic voltage, voltage unbalance and protection configuration. Check results are shown in Table D.6 to Table D.8.

Table D.6 – Sheet of short-circuit current check (after adjustment)

Evaluated bus (line)	Allowable short-circuit current I_m (kA)	Short-circuit current of bus I_{sc} (kA)	Short-circuit current check (pass/fail)	P_m (MW)	Remarks
220 kV bus I of 220 kV transformer A	-	21,18	Pass	171,34	
110 kV bus I of 220 kV transformer A	40	9,07	Pass	167,48	
35 kV bus I of 220 kV transformer A	31,5	10,51	Pass	74,16	
110 kV bus of 110 kV transformer B	40	6,42	Pass	79,36	
35 kV bus I of 110 kV transformer B	31,5	5,76	Pass	29,05	
10 kV bus I of 110 kV transformer B	20	14,59	Pass	26,85	
35 kV bus II of 110 kV transformer C	31,5	6,13	Pass	44,19	
10 kV bus II of 110 kV transformer C	20	15,86	Pass	41,53	
35 kV bus I of 35 kV transformer B	31,5	2,88	Pass	28,99	
10 kV bus I of 35 kV transformer B	20	**6,51**	**Pass**	**16,50**	
110 kV bus I of 110 kV transformer A	40	6,08	Pass	77,27	
10 kV bus I of 110 kV transformer A	20	17,08	Pass	28,35	
35 kV bus II of 35 kV transformer A	31,5	3,43	Pass	22,63	
10 kV bus II of 35 kV transformer A	20	5,60	Pass	5,91	