

TECHNICAL SPECIFICATION

**Power quality management -
Part 4: Harmonic analysis on public electric power network**

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**Power quality management -
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The text of this Technical Specification is based on the following documents:

Draft	Report on voting
8/1747/DTS	8/1791/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.

A list of all parts in the IEC 63222 series, published under the general title *Power quality management*, can be found on the IEC website.

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

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1 Scope

This part of IEC 63222 is a Technical Specification. IEC TS 63222-4 specifies the requirements of the models, methods and procedures for harmonic analysis on the public electric power network. This document is applicable to harmonic analysis up to 40th harmonic at high, medium and low voltage of the public electric power network with nominal frequency of 50 Hz or 60 Hz.

NOTE 1 The boundaries between the various voltage levels can be different in different countries/regions. In this document, the following terms for system nominal voltage U_N are used:

- Low voltage (LV) refers to $U_N \leq 1$ kV;
- Medium voltage (MV) refers to 1 kV $< U_N \leq 35$ kV;
- High voltage (HV) refers to 35 kV $< U_N \leq 230$ kV.

NOTE 2 Because of existing network structures, the boundary between medium and high voltage can be different in some countries/regions.

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 TR 61000-3-6:2008, *Electromagnetic compatibility (EMC) - Part 3-6: Limits - Assessment of emission limits for the connection of distorting installations to MV, HV and EHV 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>

3.1 harmonic order

h

integral number given by the ratio of the frequency of a harmonic to the fundamental frequency

[SOURCE: IEC 60050-161:1990, 161-02-19]

3.2 harmonic frequency

f

frequency which is an integer multiple greater than one of the fundamental frequency or of the reference fundamental frequency

[SOURCE: IEC 60050-551-20:2001, 551-20-05]

3.3 total harmonic distortion THD

THD_Y

ratio of the RMS value of the sum of all the harmonic components ($Y_{H,h}$) up to a specified order (h_{\max}) to the RMS value of the fundamental component ($Y_{H,1}$):

$$THD_Y = \sqrt{\sum_{h=2}^{h_{\max}} \left(\frac{Y_{H,h}}{Y_{H,1}} \right)^2}$$

Note 1 to entry: The symbol Y is replaced, as required, by the symbol I for currents or by the symbol U for voltage.

Note 2 to entry: The value of h_{\min} is 2 and that of h_{\max} is 40 for the purpose of this document.

[SOURCE: IEC 61000-4-7:2009, 3.2.1]

3.4 fundamental component

component whose frequency is the fundamental frequency

[SOURCE: IEC 61000-4-30:2021, 3.7]

3.5 fundamental frequency

frequency in the spectrum obtained from a Fourier transform of a time function, to which all the frequencies of the spectrum are referred

Note 1 to entry: In case of any remaining risk of ambiguity, the fundamental frequency may be derived from the number of poles and speed of rotation of the synchronous generator (s) feeding the system.

[SOURCE: IEC 61000-4-30:2021, 3.8]

3.6 harmonic component

any of the components having a harmonic frequency

Note 1 to entry: Its value is normally expressed as an RMS value. For brevity, such component may be referred to simply as a harmonic.

[SOURCE: IEC 61000-2-2:2002, 3.2.4]

3.7 amplification index of harmonic voltage AHU

AHU_{fij}

ratio of the harmonic voltage $|\dot{U}_{fi}|$ of node i to the harmonic voltage $|\dot{U}_{fj}|$ of node j when the harmonic current in per unit or the harmonic voltage in per unit is injected into node j at frequency f :

$$AHU_{fij} = \frac{|\dot{U}_{fi}|}{|\dot{U}_{fj}|}$$

3.8 amplification index of harmonic current AHC

AHC_{fab}

ratio of the harmonic current on the branch between two nodes (node a, b) to the injected harmonic current of node j when the harmonic voltage or the harmonic current in per unit at frequency f is applied to node j:

$$AHC_{fab} = \frac{|i_{fab}|}{|i_j|}$$

3.9 participation factors PF

value calculated by modal analysis method to find the resonance centre

Note 1 to entry: The node with the largest value is the resonance centre, which means the node is with the largest harmonic voltage at the resonance frequency and the highest degree of participating the resonance.

4 Harmonic models of public electric power network

4.1 General

The harmonic models of classical network elements, such as overhead lines, cables and power transformers, have been studied for years and a good summary can be found in CIGRE Technical Brochure C4/B4 [1]¹. This clause provides a recommendation on the model selection for different applications of harmonic studies.

4.2 Typical electric equipment models

4.2.1 Overhead lines

An overhead line comprises series parameters (resistance and reactance) and shunt parameters (conductance and susceptance), which are distributed over the entire length of the line and are affected by frequency. The model of the overhead line for harmonic studies considering long-line effect and skin effect are given in Clause A.1.

A simple representation of an overhead line is a lumped π model shown in Figure A.1. When the length of the line increases, the representation of long-line effects (i.e. distributed parameters) need to be improved by using hyperbolic functions, and the distributed π model is shown in Figure A.2. The following should be followed to determine whether the long-line effect needs to be considered.

- For the harmonic flow analysis: The selection of the lumped π model and the distributed π model depends on the length of the line. If the length of the overhead line is less than $12\,000/f$ km, the lumped π model can be used. Otherwise, the distributed π model should be adopted.
- For the harmonic resonance analysis: The lumped π model is only capable of representing the first resonant point, and the frequency of this resonance is always slightly below the first resonant frequency obtained with the accurate distributed π model. Therefore, the use of a distributed π model (including long line effects) is recommended as the default option in the resonance analysis.

¹ Numbers in square brackets refer to the Bibliography.

The model of an overhead line considering skin effect can be calculated by equations (A.7) and (A.8). Recommendations for whether to consider skin effect in the overhead line modeling are as follows:

- For the harmonic flow analysis: The conductor resistance is much smaller than the reactance, so the skin effect does not have an obvious impact on the flow of harmonics. This means that the skin effect may be ignored if a precise harmonic flow analysis is not required.
- For the harmonic resonance analysis: At (or near) resonance conditions, where the line impedance is dominated by the resistive component, changes in the resistive component of the line have a significant impact on the calculated resonance peak. Neglecting skin effect leads to underestimation of circuit damping at resonant frequencies, and the error introduced will increase with the frequency. In addition, skin effect would result in a slight upward shift of resonant frequencies caused by an effective reduction in the internal inductance of the phase conductors, and this effect is getting noticeable at high frequencies.

4.2.2 Underground cables

The underground cable model is essentially similar to the overhead line model shown in Clause A.1. The consideration of skin effect is consistent. In terms of long-line effect, the lumped π model shown in Figure A.1 can be used if the length of the underground cable is less than $3\,000/f$ km. Otherwise, the distributed π parameter model shown in Figure A.2 needs to be used [2]. Compared with overhead lines, cables are more likely to cause resonance at low frequencies.

4.2.3 Power transformers

Accurate representation of power transformer is paramount for performing meaningful harmonic studies in power systems. A transformer can be represented by a series combination of resistance and inductive reactance, and both components are frequency dependent. Clause A.3 gives six models to capture this feature. For Models 2 to 6, the demagnetization effect is considered to be weak and the reactance approximately increases linearly with frequency, which means that the selection of the transformer models does not affect the location of the resonant frequencies, but only changes the amplitude of the resonance peak. For Model 1, the reactance does not increase linearly with frequency. Model 1 takes into account the effect of demagnetization of induced eddy current in the wire on the decrease of leakage inductance with the increase of frequency. The reactance can be calculated by equation (A.14).

All models provide increasing damping with frequency. Larger differences in performance are observed when the main resonances appear at the higher frequency range. Each model has different accuracy in different working conditions. If high accuracy is needed in the harmonic studies, it is recommended to obtain frequency dependent characteristics for R and X from the transformer manufacturer. In the absence of measurements to validate models, the analysis in [1] suggests the use of Model 5 with default parameters or Model 1 with 50/60 Hz datasheet X/R value as options with reasonable results.

Note the influence of the transformer models on the harmonic studies is related to the distance between the node and the transformer. Therefore, the choice of transformer model is of key importance for nodes where the harmonic impedance is dominated or influenced by power transformers. For nodes that are electrically distant from power transformers, the selection of a transformer model does not have material impact on the calculation results.

4.2.4 Shunt capacitors/reactors

The parameters of shunt capacitors and reactors in power systems are independent of harmonics. Their harmonic models are specified in Clause A.4.

4.2.5 Synchronous generators

Two harmonic impedance models are commonly used to represent synchronous generators, as shown in Clause A.5.

The reactance of both models is assumed to increase linearly with frequency and can be calculated based on the negative sequence reactance X_{neg} at the fundamental frequency. For Model 1, the change of resistance with frequency is represented by h^α ; thus, the value of α should be appropriately selected (α is in the range of 0,5 to 1,5. $\alpha = 0,5$ is theoretically correct, and $\alpha = 1,0$ was verified through limited tests). For Model 2, the change of resistance with frequency is represented by \sqrt{h} . Therefore, the model selection does not affect the frequency of the resonance, but there is a difference in the damping provided at the resonant point. In general, Model 1 with $\alpha = 1,5$ provides the highest level of damping, while Model 2 provides the lowest damping.

Note the influence of synchronous generator model on the harmonic studies is related to the distance between the node and the generator. For a transmission node near large synchronous generators, the selected model affects the amplitude of the harmonic resonance. Therefore, the use of frequency-dependent data from manufacturers is recommended. For a transmission node where the synchronous generator is far away, the selection of a synchronous generator model has no material effect on the harmonic impedance at that point.

4.2.6 Loads

Loads have a considerable influence on the harmonic characteristics of the network in terms of location of resonances and level of damping, and their appropriate modelling is a very important consideration.

The load models for harmonic analysis of power systems are shown in Clause A.6 [3], where the fraction (or participation) K of the induction motors into the total load demand P is defined as the ratio P_M/P , and P_M is the induction motor demand. For the application of the load models, this standard recommends:

- $K < 0,1$: If K is relatively small, the aggregate linear load behaves as constant impedance load. In this case, Models 1, 2, and 3 provide a good approximation of the load harmonic impedance, with Models 2 and 3 resulting in higher damping. Model 3, in addition, provides frequency dependent parameters (i.e. skin effect).
- $0,1 < K < 0,3$: Model 4 and 5 can be adopted. The harmonic impedance of the motor load in Models 4 and 5 is jhX_{IM1} . Note that this approximation is not accurate for harmonic orders below 5. These models neglect the harmonic attenuation and therefore are to be used if the participation of the induction motors is moderate.
- $K > 0,3$: If the load consists predominately of motors, a more accurate representation results by including a resistor in series with X_{IM1} . The harmonic impedance of the motor load becomes $R_1 + jhX_{IM1}$. The value of R_{IM1} is found directly from the resistance of the rotor circuit. Thus, if the locked rotor circuit has a quality factor $Q = X_{IM1}/R_{IM1} = K_0$, then $R_{IM1} = X_{IM1}/K_0$. K_0 assumes values of approximately 8.

Depending on where the models are connected and which models are used, different load models will have a significant impact on the harmonic characteristics. For a highly accurate assessment of the damping effect of loads, detailed time-domain modelling might occasionally be preferable. Neglecting loads may result in a pessimistic evaluation of harmonic distortion.

4.3 System equivalence requirements

In order to analyse the harmonic transfer characteristic through the network accurately, it is important to have a good representation of all network elements. For many studies, however, the extent of the network model may be limited for a number of practical reasons. In such cases, the rest of the network for which the system elements (lines, cables, transformers, loads, etc.) are not represented in detail, can be represented by an equivalent network. The equivalents are generally provided as either Thévenin or Norton circuit, which are effectively identical in their performance and can be converted from one to another.

To get the equivalent impedance of the Thévenin circuit, a rough estimation can be achieved by using power frequency network equivalents (short circuit impedance or other variations). However, such an equivalent is only adequate when the external network does not exhibit any resonances within the frequency range of interest or when the external network is electrically so far from the area of study that does not have significant impact on the harmonic impedance at the buses of interest. Therefore, it is recommended to obtain the equivalent impedance of the Thévenin circuit using the frequency dependent network equivalent from a detailed network model. However, in most cases, the detailed network model is not available in a simulation tool. Then the network can be modelled in detail up to a certain distance from the point of interest and with power frequency network equivalent, like Thévenin voltage source, beyond this distance. In terms of minimum number of nodes or distance to be accurately represented, a sensitivity study progressively extending the network model until the results from two consecutive iterations converge is suggested [4].

The extent of the network represented in detail must be sufficient to incorporate all contingencies and operation conditions that need to be studied. The following should be considered in the study:

- In the case of a planning study, it is recommended to consider at least the year of connection as well as that corresponding to some years later or the last year of the planning horizon; In the case of an operational study, it is important to replicate as much as possible the conditions that can be the cause of trouble or investigation.
- To reduce the number of cases, the contingencies up to the third node away from the point of interest are recommended, unless there is evidence that other contingencies beyond that boundary could result in more onerous conditions within the range of harmonic frequencies.
- At least two or three system demand levels: minimum, intermediate and maximum should be considered. The objective is to capture the changes in system resonances and damping associated with the various levels and composition of the load as well as the status of reactive compensation equipment.
- Only realistic operating conditions should be considered in order to limit the computational burden and, more importantly, to avoid overly-pessimistic results.

The calculated harmonic impedances under different contingencies, demand levels and operating conditions can be presented as envelopes in an R-X plane encompassing all possible values. The harmonic impedance data can then be displayed graphically in a single envelope including all frequencies of interest or as a family of envelopes each comprising one or more harmonic frequencies. To derive the harmonic impedance envelopes, the following should be considered.

- A suitable frequency step resolution needs to be selected in order to capture all resonances in the frequency scan calculations. In general, a frequency step no larger than 5 Hz should be adopted for a 50 Hz system.
- Since low harmonic orders do not tend to exhibit large resonances, the impedance can be adequately defined with individual harmonic order envelopes or with narrow frequency bands. At higher frequencies, it is necessary to widen the size of the frequency bands to confidently capture possible resonance shifts and/or modelling uncertainties.
- The introduction of some overlapping between subsequent envelopes is recommended as a safety margin to account for uncertainties.

- The shape of the envelopes, e.g., circles, sectors and polygons, should be selected to minimize "empty" areas without realistic impedance points. Polygons are recommended as they can provide a very close fit to a set of calculated impedance points.

The background harmonic voltages in the Thévenin circuit should be measured for a "representative measuring period" to derive a representative signature of the background distortion at that location. The minimum duration requirement is system dependent, but in general it can be stated that measuring should be conducted for as long as possible, ideally for not less than three months, including measurements of all three phases. As it is often the case, some nodes cannot be monitored (or have not been built yet), therefore background harmonic estimation is needed, which can be done by harmonic state estimation approach or "Constant Voltage behind Thévenin Equivalent" approach [5].

5 Methods for analysis of harmonic transfer characteristics

5.1 General

The harmonic currents caused by non-linear equipment will spread in the power system. Harmonic currents lead to increased losses and heating in numerous electrical devices/installations. High levels of harmonic voltage and current distortion may occur in the resonant condition, which will endanger the safety of the system and equipment.

This document aims for harmonic analysis oriented to engineering situations of public electric power network balanced, where frequency-domain methods based on the impedance/admittance matrixes are employed, including frequency scanning, modal analysis and harmonic flow calculation, to analyse harmonic transfer and resonance characteristics, node voltage distortion and branch harmonic current flows, etc.

5.2 Methods of harmonic resonance analysis

5.2.1 General

The method of harmonic resonance analysis is not only to obtain the resonant frequencies, quantify the severity of harmonic resonance amplification but also to investigate the participation degrees of nodes for the resonances. Two kinds of methods are often used for the harmonic resonance analysis.

- Frequency scanning method, is to obtain all the resonant frequencies and calculate the resonant amplification indices, which can represent the resonant influence degree.
- Modal analysis method is to obtain all the parallel resonant frequencies and participation factors of resonance buses and sensitivity of influencing components on the resonances.

5.2.2 Frequency scanning

5.2.2.1 Magnitude-frequency curves of harmonic self-impedance

The resonant frequency can be obtained from magnitude-frequency curves of harmonic self-impedances. The steps of frequency scanning method are as follows:

- Based on harmonic models in chapter 4, the model in a single-line diagram of public electric power network with n nodes is established and the node admittance matrix $Y_{fn \times n}$ is obtained in per unit. Obtain the nodal impedance matrix $Z_{fn \times n}$ at frequency f calculated by the inverse of $Y_{fn \times n}$;
- Take the appropriate frequency resolution as the change step in the frequency band to scan the self-impedance at node j for frequency f in $Z_{fn \times n}$;

NOTE The change step can be selected based on actual engineering requirements. The range from 1 Hz to 10 Hz is recommended;

- c) Calculate $|Z_{fji}|$ ($j=1,2,\dots,n$) and plot the magnitude-frequency curve of self-impedance of each node in the frequency band scanned.

The frequencies corresponding to the peak values of the magnitude-frequency curves of self-impedance are the parallel resonance frequencies and the frequencies corresponding to the valley values of the magnitude-frequency curves of self-impedance are the series resonance frequencies in the analyzed public electric power network.

5.2.2.2 Calculation of harmonic amplification index

AHU can be calculated based on $Z_{fn \times n}$, as shown in equation (1).

$$AHU_{fij} = \frac{|\dot{U}_{fi}|}{|\dot{U}_{fj}|} = \frac{|Z_{fij}|}{|Z_{fji}|} \quad (1)$$

where

Z_{fij} is the transfer impedance between nodes i ($i=1,2,\dots,n$, and $i \neq j$) and j for frequency f , p.u., which shows the mutual impedance between two different nodes;

Z_{fji} is the self-impedance at node j for frequency f , p.u..

The harmonic voltage at node i is greater than that at node j where the harmonic current injected and a non-local resonance has occurred if $AHU_{fij} > 1$. The severity of harmonic resonance and influence area of resonance can be confirmed according to the harmonic voltage amplification indices.

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AHC can be calculated based on $Z_{fn \times n}$, as shown in equation (2).

$$AHC_{fab} = \frac{|\dot{I}_{fab}|}{|\dot{I}_{fj}|} = \left| \frac{Z_{faj} - Z_{fbj}}{Z_{fab}} \right| \quad \begin{array}{l} a \in \{1, \dots, n\} \\ b \in \{0, 1, \dots, n\} \text{ and } b \neq j \end{array} \quad (2)$$

where

\dot{I}_{fj} is the harmonic current phasor at node j for frequency f , p.u.;

Z_{fab} is the impedance of the branch between node a ($a \in \{1, \dots, n\}$) and node b ($b \in \{0, 1, \dots, n\}$ and $b \neq j$ where 0 means reference node), p.u.;

\dot{I}_{fab} is the harmonic current phasor on the branch between node a and node b at frequency f .

The harmonic current on the branch between node a and node b is greater than that at the node j injected by the harmonic voltage, which the harmonic current is amplified if $AHC_{fab} > 1$. The influence area and the corresponding severity of the harmonic resonance can be confirmed according to the amplification index of harmonic current.