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TECHNICAL SPECIFICATION

colour inside

Power quality management –
Part 3: User characteristics modelling

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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POWER QUALITY MANAGEMENT –

Part 3: User characteristics modelling

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IEC 63222-3 has been prepared by 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
8/1690/DTS	8/1702/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 http://www.iec.ch/standardsdev/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

- reconfirmed,
- withdrawn, or
- revised.

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POWER QUALITY MANAGEMENT –

Part 3: User characteristics modelling

1 Scope

This part of IEC 63222 is intended to provide provisions regarding recognized engineering practices applicable to assess the user's characteristics in power quality predicted assessment. It summarizes the best practice in non-linear, unbalanced, impact and fluctuating loads or generations modelling for power quality disturbance anticipation in public power systems at the planning stage.

This document focuses on frequency-domain modelling for AC power quality analysis in electric power networks, typically in the range up to the 50^{th} harmonic (2,5 kHz in 50 Hz systems or 3 kHz in 60 Hz systems). Unbalance is analyzed in three-phase systems and only negative sequence component is considered. The approach and modelling guidelines provided are valid on the representation of user installations connected to power systems acting as sources of disturbance. Modelling of the network elements is out of the scope of the document.

These guidelines will be valuable in the definition of power quality performance specifications for user equipment. They will also assist users when modelling their installation to assess or demonstrate compliance with the emission limits provided by the system owner/operator and to investigate and specify mitigation measures.

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, *Electromagnetic compatibility (EMC) – Part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems*

IEC TR 61000-3-7, *Electromagnetic compatibility (EMC) – Part 3-7: Limits – Assessment of emission limits for the connection of fluctuating installations to MV, HV and EHV power systems*

IEC TR 61000-3-13, *Electromagnetic compatibility (EMC) – Part 3-13: Limits – Assessment of emission limits for the connection of unbalanced installations to MV, HV and EHV power systems*

IEC 61000-4-30, *Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques – Power quality measurement methods*

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
power quality
characteristics of the electric current, voltage and frequency at a given point in an electric power system, evaluated against a set of reference technical parameters

[SOURCE: IEC 60050-614:2016, 614-01-01 − The note to entry has been deleted.]

3.2
point of common coupling
PCC
point in an electric power system, electrically nearest to a particular load, at which other loads are, or may be, connected

Note 1 to entry: These loads can be either devices, equipment or systems, or distinct network users' installations.

[SOURCE: IEC 60050-614:2016, 614-01-12]

3.3
point of connection
POC
reference point on the electric power system where the user's electrical facility is connected

[SOURCE: IEC 60050-617: 2009, 617-04-01]

3.4
system impedance
impedance of the electric power system as viewed from a designated point (e.g. point of common coupling or point of supply)

[SOURCE: IEC 60050-614:2016, 614-01-13]

3.5
short-circuit power
product of the current in the short circuit at a point of a system and a conventional voltage, generally the operating voltage

[SOURCE: IEC 60050-601:1985, 601-01-14]

3.6
RMS value
root-mean-square value
effective value
for a time-dependent quantity, positive square root of the mean value of the square of the quantity taken over a given time interval

[SOURCE: IEC 60050-103:2017, 103-02-03, modified – The notes to entry have been deleted.]

3.7
voltage deviation
difference between the supply voltage at a given instant and the declared supply voltage

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

3.8
voltage fluctuation
series of voltage changes or a continuous variation of the RMS or peak value of the voltage

Note 1 to entry: Whether the RMS or peak value is chosen depends upon the application, and which is used should be specified.

[SOURCE: IEC 60050-161:1990, 161-08-05]

3.9
flicker
impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time

[SOURCE: IEC 60050-614:2016, 614-01-28]

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

[SOURCE: IEC 60050-614:2016, 614-01-32]

3.11
unbalance factor
in a three-phase system, degree of unbalance expressed by the ratio (in per cent) of the RMS values of the negative sequence component (or the zero sequence component) to the positive sequence component of the fundamental component of the voltage or the electric current

[SOURCE: IEC 60050-614:2016, 614-01-33]

3.12
harmonic order
harmonic number
the integral number given by the ratio of the frequency of a harmonic to the fundamental frequency

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

3.13
harmonic content
the quantity obtained by subtracting the fundamental component from an alternating quantity

[SOURCE: IEC 60050-161:1990, 161-02-21]

3.14
nth harmonic ratio
ratio of the RMS value of the nth harmonic to that of the fundamental component

[SOURCE: IEC 60050-161:1990, 161-02-20]

3.15
total harmonic ratio
THD
total harmonic distortion
ratio of the RMS value of the harmonic content to the RMS value of the fundamental component or the reference fundamental component of an alternating quantity

Note 1 to entry: The total harmonic ratio depends on the choice of the fundamental component. If it is not clear from the context which one is used an indication should be given.

Note 2 to entry: The total harmonic ratio can be restricted to a certain harmonic order. This is to be stated.

[SOURCE: IEC 60050-551:2001, 551-20-13, modified – In the term, "factor" has been changed to "ratio", an equivalent term and an admitted term have been added; in the definition, "of an alternating quantity" has been replaced by "value of the fundamental component or the reference fundamental component of an alternating quantity" and note 2 to entry has been added.]

3.16
interharmonic frequency
frequency which is a non-integer multiple of the reference fundamental frequency

[SOURCE: IEC 60050-551:2001, 551-20-06]

3.17
voltage dip
sudden voltage reduction at a point in an electric power system, followed by voltage recovery after a short time interval, from a few periods of the sinusoidal wave of the voltage to a few seconds

[SOURCE: IEC 60050-614:2016, 614-01-08]

4 Model category and modelling methodology

4.1 Model category used for power quality assessment of distorting installations

Power quality predictive evaluation procedure follows three stages (IEC TR 61000-3-6, IEC TR 61000-3-7, IEC TR 61000-3-13). User characteristics modelling differs with three stages of power quality assessment. For stage 1, no power quality evaluation or modelling is necessary. For stage 2, the simplified calculation method is used to evaluate the impact of equipment. For stage 3, assessment is generally carried out by power system simulation software. Three types of modelling methods are involved in stage 3, including:

– frequency-domain modelling, with respect to simulations for analysis of harmonics, interharmonics and unbalance.
– electromechanical time-domain modelling, with respect to electromechanical transient simulations for analysis of voltage dip/surge, fast voltage variation and flicker.
– electromagnetic time-domain modelling of equipment such as power electronic converter, with respect to electromagnetic transient (EMT) simulations for analysis of harmonics and interharmonics.

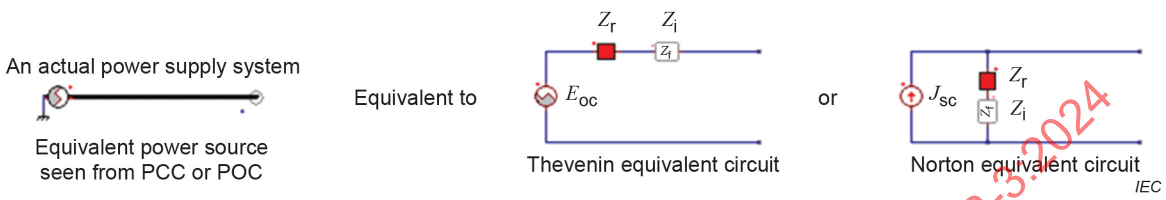
NOTE power quality simulations can be carried out based on load flow results in two ways:

– "fast RMS time domain modelling method" for analysis of voltage dip/swell, fluctuation, flicker, etc.
– "frequency domain modelling method" for analysis of harmonics, interharmonics and disturbances > 2 kHz, where all harmonic components are synchronized to fundamental voltages.

4.2 Model structure

4.2.1 Power supply model

To analyze voltage deviation, voltage fluctuation, flicker, and voltage dip, an equivalent power source model is recommended, as in Figure 1. The parameters in the equivalent Thevenin or Norton source circuit is recommended in Table 1. This model can be used to represent background voltage disturbances at point of common coupling (PCC) or point of connection (POC).



Key

E_{oc} equivalent open-circuit voltage source (case Thevenin)

J_{sc} equivalent short-circuit current source (case Norton)

Z_r, Z_i source impedance in complex values

Figure 1 – Equivalent power source model

Table 1 – Example of representation/Template of the equivalent power source

Case Thevenin equivalent circuit:			
Phase	**Open circuit voltage E_{oc}** V	**Short-circuit impedance real part Z_r** Ω	**Short-circuit impedance image part Z_i** Ω
A			
B			
C			
Case Norton equivalent circuit:			
Phase	**Short-circuit current J_{sc}** A	**Source impedance real part Z_r** Ω	**Source impedance image part Z_i** Ω
A			
B			
C			

4.2.2 User model

For simulating harmonics and voltage variations caused by electric loads, a Thevenin/Norton equivalent circuit of electric load is recommended, see Figure 2. The Thevenin/Norton equivalent circuit is generally used and represented by means of an equivalent ideal current source and equivalent impedance for each frequency of interest. The parameters involved are shown in Table 2 and Table 3. In modelling of modern power electronic equipment such as voltage source converter (VSC) or local generation unit, harmonic emission can be a type of voltage source and should be modelled with Thevenin equivalent circuit. In both the two equivalent circuits, I_n and E_n are mutually converted at each frequency versus source impedance. Regardless of the model used, the equivalent source and impedance should be provided at the frequencies of interest for the intended application. Note that all three phases and other conductors such as neutrals of a distribution feeder shall be represented explicitly. For nonlinear load models, the source E_n and I_n are not zero.

NOTE For convergence issue of the actual power grid simulation, loads are often modelled with impedances calculated based on the P and Q at fundamental frequency (not with source E_n or I_n).

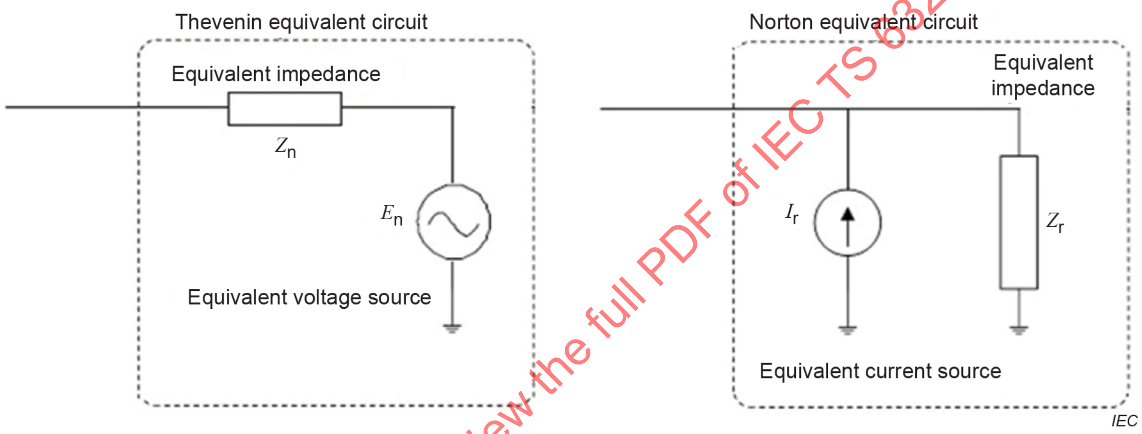


Figure 2 – Thevenin/Norton harmonic model including fundamental frequency

Table 2 – Example of representation/Template of the equivalent harmonic current source

Harmonic order	**Frequency**	**Current source I_n or voltage source E_n**	
	Hz	**Magnitude** A, V **or** **Ratio to fundamental** **%**	**Phase** °
1			
2			
3			
4			
…			

Table 3 – Example of representation/template of the equivalent frequency impedance

Harmonic order	Frequency	Impedance Z_n	
	Hz	Impedance real part R Ω	Impedance imaginary part X Ω
1			
2			
3			
4			
…			

4.3 Consideration on modelling

To describe time-varying characteristics of users (see Annex A for typical disturbing users), the proposed model structure allows for the implementation of representative time series or probabilistic distribution to represent the impact or fluctuating behaviour. The fundamental frequency current should be represented in the function of time or probability density function (typically Gaussian distribution). For one instant of time or a sample, the corresponding harmonic component can be obtained by Formula (1) and Formula (2).

Any power factor correction and harmonic filter capacitor banks associated with the device should be modelled or included in the equivalent harmonic impedance.

4.4 Input data requirement

The data required for modelling can be obtained from the frequency-dependent model built by the manufacturer of a device, or from measurement data provided by the operator. The manufacturer should be able to provide the operational impedances of the device and the injected current at each of the harmonic frequencies of interest at full load and at various operating conditions. Next, the background power quality data should be measured, preferably at various loading levels up to the full load so that the background power quality characteristics can be estimated and taken into account as the second input data for the system modelling requirement.

For the purpose of load modelling based on measurement data, class A measuring equipment defined in IEC 61000-4-30 is required. The measurement methods, time aggregation, accuracy and evaluation methods associated with the equipment are recommended in IEC 61000-4-30 to obtain reliable, repeatable and comparable results.

Measurements should be conducted as long as possible, ideally for not less than three months, including measurements of all three phases and power quality parameters concerned. 1 min aggregated value is recommended to record. In some cases, 3 s aggregated value or waveform record are necessary. Half cycle value of reactive and active power should be simulated in order to assess flicker level.

NOTE The aggregation method of phase angle can refer to IEC 61400-21-1 [7][1].

[1] Numbers in square brackets refer to the Bibliography.

4.5 Characterization of measured data

When considering characteristics of disturbance varied with time, one often finds that the disturbance contains a large number of irregularities which fail to conform to coherent patterns. The variations generally have random characteristics and the behaviour can be described in statistical terms which transform a large volume of data into compressed and interpretable forms.

Numerical descriptive measures are the simplest form of representing a set of measurements. These measures include minimum value, maximum value, average or root mean square value, 95th or 99th percentile value, and standard deviation. Mathematically, let a set of n measurements X_i, i = 1,…,n, with minimum value X_{min}, maximum value X_{max}.The average value X_{avg} and standard deviation σ_{X} are calculated by

$$X_{\text{avg}} = \frac{\sum_{i=1}^{n} X_i}{n} \quad (1)$$

$$\sigma_{\text{X}} = \sqrt{\frac{\sum_{i=1}^{n}\left(X_i - X_{\text{avg}}\right)^2}{n-1}} \quad (2)$$

Because it is often difficult to determine a priori the best distribution to describe a set of measurements, a more accurate method is a histogram which shows the portions of the total set of measurements that fall in various intervals.

5 Modelling for different power quality indices

5.1 Voltage deviation

5.1.1 Simplified calculation for voltage deviation analysis

For a simplified calculation, the user installation should be represented as an equivalent power model. The magnitude of the power source corresponds to the condition that the maximum reactive power is drawn by the user. Voltage deviation is estimated as follows:

$$\delta U = \frac{QX + PR}{U_{\text{N}}^2} \times 100\ \% \quad (3)$$

where

δU is the voltage deviation;

U_{N} is the nominal system voltage in kV;

Q is the maximum reactive power drawn by the user in MVar;

P is the corresponding real power in MW;

R is the resistance component of network equivalent impedance at the PCC in Ω;

X is the reactance component of system impedance at the PCC in Ω.

5.1.2 Advanced model for voltage deviation analysis

To conduct a simulation analysis, the user installation can be modelled as an equivalent circuit which comprises an equivalent power source and equivalent impedance at each frequency, as shown in Figure 2. Interaction between the user facility and grid can be assessed with an enhanced model (see 5.3.2). The power source and equivalent impedance in the model can be represented as a function of time to simulate the time-varying characteristic, which can be constructed based on 10 min aggregated values.

5.2 Voltage fluctuation and flicker

5.2.1 Simplified calculation for voltage fluctuation and flicker analysis

To analyse voltage fluctuation and flicker caused by impact or fluctuating loads (simplified to rectangular variation form), the user installation should be represented as variable powers P and Q model.

Steady state voltage change can be estimated as follows:

$$\Delta U_{\text{ss}} = \frac{R \times \Delta P + X \times \Delta Q}{U_{\text{N}}} \qquad (4)$$

where

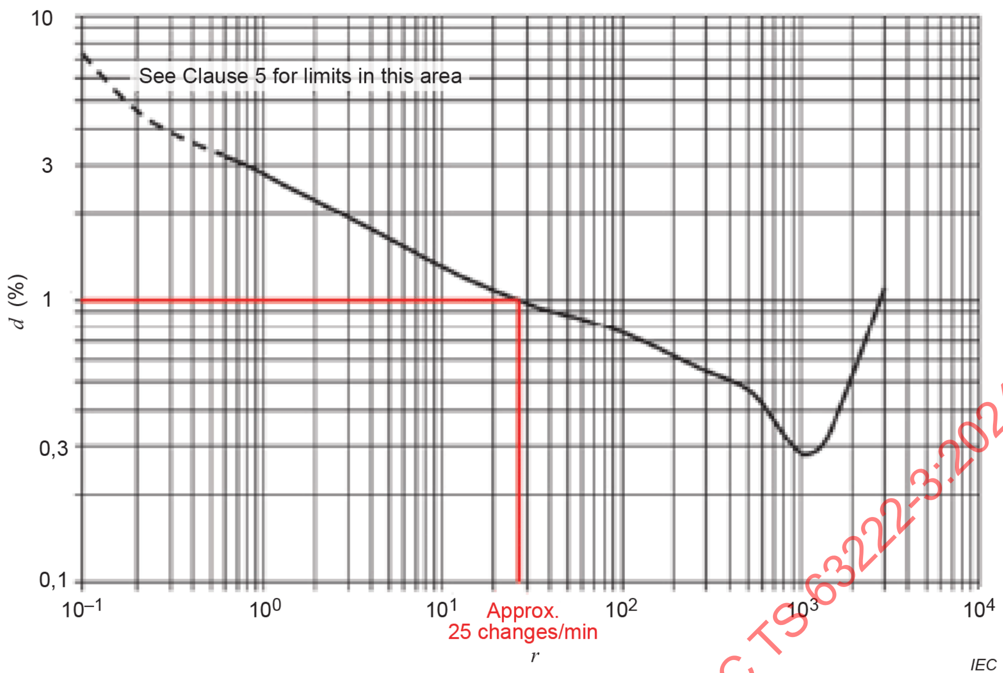
ΔU_{ss}	is the steady state voltage change in kV;
ΔP and ΔQ	is the change of active power in MW and reactive power in MVar, respectively;
U_{N}	is the nominal system voltage in kV;
R	is the resistance component of network equivalent impedance at the PCC in Ω;
X	is the reactance component of system impedance at the PCC in Ω.

For a periodic and equally spaced rectangular wave (or step wave) load, the resultant flicker can be estimated by relative voltage change d and voltage change frequency per minute r. d is given by the following formula:

$$d = \Delta U_{\text{ss}} / U_{\text{N}} \qquad (5)$$

When d and r are known, the relative voltage changes d_{lim} corresponding to short term flicker limit can be found from r using the P_{st} = 1 curve in Figure 3, and the short-term flicker value can be calculated as follows:

$$P_{\text{st}} = \frac{d}{d_{\text{lim}}} \qquad (6)$$



Source: IEC 61000-3-3, 2013, Figure 2 [8].

Figure 3 – P_{st} = 1 curve

For non-periodic loads, the flicker can be estimated by the flicker coefficient according to the load characteristics. For example, the flicker caused by the electric arc furnace can be calculated according to Formula (7), and the maximum voltage change d_{max} caused by the electric arc furnace at the PCC can be obtained by Formula (5).

$$P_{st} = K_{lt} \times d_{max} \tag{7}$$

where

K_{lt} is device dependent. For AC electric arc furnace $K_{lt} = 0,48$, for Consteel electric arc furnace $K_{lt} = 0,25$, for DC electric arc furnace $K_{lt} = 0,30$, for refining electric arc furnace $K_{lt} = 0,20$.

5.2.2 Advanced model for voltage fluctuation and flicker analysis

For simulation analysis, user should be modelled as an equivalent power model of P and Q. The time interval used in the equivalent voltage fluctuation and flicker modelling should be as short as possible, at least one cycle of fundamental frequency. The main difference between voltage fluctuation and voltage deviation lies in the time interval considered in voltage variations. Representative load model time series can be identified from monitoring data covering all process states of the user's installation and should be capable of reflecting the impact and fluctuating characteristics of the user. With the recent grid monitoring system, it is possible to record RMS values every half cycle (equivalent 100 Hz in 50 Hz system), see Electric Arc Furnaces (EAF) application case in B.2.2.

It is possible to consider flicker attenuation phenomenon from higher voltage level to lower voltage level through analytical, laboratory, and field measurement. Aggregated flicker model is proposed for a number of distribution loads in order to assess flicker propagation effect, see clause 4.3 in reference [9]. For a flicker source in the HV grid that produces some measurable P_{st} value, the corresponding flicker level measured in a local MV area will likely be less than that present in the HV supply. This attenuation is largely due to the load response to the voltage fluctuations. It is certain that the load power is not constant under the conditions of fluctuating voltages, but the manner in which the load changes dynamically remains the subject of research. Variable P&Q load models with voltage sensitivity, variable load impedances, and complete time domain simulations can all be used to capture the attenuation phenomenon (refer to Annex B for application examples).

5.3 Harmonics/interharmonics

5.3.1 Simplified calculation for harmonics/interharmonics analysis

Non-linear users should be represented as an ideal current source for each frequency of interest. The nth harmonic ratio of the resultant voltage U_n % at the PCC to which a nonlinear user is connected can be estimated as follows:

$$U_n\% = \frac{\sqrt{3} Z_n I_n}{10 U_N} \quad (8)$$

where

Z_n is the system harmonic impedance in Ω;

I_n is the RMS value of harmonic current injected by the user in A;

U_N is the nominal voltage at the PCC in kV.

Note that the background harmonic voltage is neglected in Formula (8).

As to the aggregation of harmonic sources which are assumed to be time independent, if the phase angles are known, the resultant harmonic current can be calculated by Formula (9); if the phase angles are unknown, the resultant harmonic current can be calculated by Formula (10):

$$I_n = \sqrt{I_{n1}^2 + I_{n2}^2 + 2 I_{n1} I_{n2} \cos\theta_n} \quad (9)$$

where

I_n is the current magnitude at harmonic order n;

I_{n1} is current magnitude of harmonic source 1 at harmonic order n;

I_{n2} is current magnitude of harmonic source 2 at harmonic order n;

θ_n is the phase difference between harmonic source 1 and 2 at harmonic order n.

$$I_n = \sqrt[\alpha]{\sum_i I_{ni}^{\alpha}} \tag{10}$$

where

I_{ni} is the magnitude of the various emission levels at order n to be combined;

α is an exponent which mainly depends on the degree to which individual harmonic currents vary randomly in terms of magnitude and phase.

5.3.2 Advanced model for harmonics/interharmonics analysis

As to thyristor or IGBT based loads, both harmonic emissions and harmonic impedance of the device should be taken into consideration. The Thevenin/Norton equivalent circuit model should be used to reflect the interactions between the harmonic sources and networks.

For non-linear time-varying installation, statistical techniques for harmonic analysis are more suitable. A harmonic current phasor can be described by its magnitude and phase $I\angle\theta$. Typically, it can be assumed that its magnitude varies randomly with a uniform distribution between a_1 and a_2, while its phase varies randomly with a uniform distribution between θ_1 and θ_2.The joint probability density function of the sum of independent phasors can be obtained by applying convolution of bivariate functions. Such integrations are complicated and one often resorts to Monte Carlo simulation. If a relatively large number of phasors are to be added and none of the phasors is dominant, then the central limit theorem can be applied.

With recent power electronic based loads, the disturbance behaviours are not always as current source type (thyristor-based), i.e., the load current harmonic emission depends considerably on grid impedance and grid background harmonics (magnitude and phase angle).

Five disturbance modelling approaches are studied in [10], in which at least 4 methods can be used to make harmonic modelling. These approaches give different degrees of accuracy in disturbance modelling.

1) Simplified constant passive model (for all frequencies);
2) RMS parameters variation for analysing interharmonics (f < 50/60 Hz);
3) Equivalent frequency domain source model (see 4.2.1, 4.2.2);
4) Local time domain model of nonlinear load (or other dynamic models such as frequency-coupling matrix and artificial intelligence models) within hybrid simulation platform (see B.1.4);
5) Model with built-in statistical functions.

Among above modelling methods, the local time domain model of the nonlinear load concerns the simplified time domain model of a disturbance source, or the dynamic model (the rest of the simulated grid is modelled in frequency domain or time-variable RMS model) which can take into account the interactions between the grid (impedance and background disturbances) and the load. Consequently, a time domain solver or EMT simulation tool is needed to simulate the local time domain model and get steady state current spectra as output results. If many dynamic models are used in the same network, iteration or hybrid simulations should be carried out in order to guarantee the convergence.

NOTE Full time domain modelling and simulation can give precise results if all models are available. However, it is not very easy in practice to get precise models of all power electronic structures and control algorithms.

5.4 Unbalance

5.4.1 Simplified calculation for unbalance analysis

To analyse the impact of unbalance loads, the load should be represented as a negative sequence current source. Assuming the positive sequence impedance at PCC is equal to the negative sequence impedance, the negative sequence voltage unbalance factor can be calculated as follows:

$$\varepsilon_{U2} = \frac{\sqrt{3} I_2 U_L}{S_{SC}} \tag{11}$$

where

I_2 is the negative sequence current;

U_L is the phase-to-phase voltage;

S_{SC} is the short-circuit power at PCC.

Considering the background voltage unbalance, the resultant unbalance factor can be estimated as follows:

$$\varepsilon_{UT} = \sqrt[\alpha]{\varepsilon_{UL}^{\alpha} + \varepsilon_{UB}^{\alpha}} \tag{12}$$

where

ε_{UT} is the total negative sequence voltage unbalance factor;

ε_{UL} is the negative sequence voltage unbalance factor induced by the load;

ε_{UB} is the background voltage unbalance;

α is the summation exponent whose value range is typically within [1, 2].

For worst-case study, α shall be taken as 2, except for worse-case study.

The magnitude of the negative sequence current can be obtained by statistical analysis of monitoring data considering different operating conditions of load.

5.4.2 Advanced model for unbalance analysis

For simulation study, full phase representation of a network and multiphase analysis is required. Single-phase users connected in different phases of a system can only interact with each other through the system. Each single-phase user should be modelled separately. A three-phase user should be modelled as a multiphase model. To study the characteristics of variation, the model should be represented in the function of time.

Unbalance behaviour of induction motors should be studied with a dedicated model. In fact, in an industrial network, an induction motor has a special behaviour to unbalanced voltage. The correct way is to model an induction motor with positive sequence impedance and negative sequence impedance, see Figure 4. For a general induction motor, negative sequence impedance is smaller compared to the positive one, while this is the key parameter to be considered to access the overall grid unbalance.

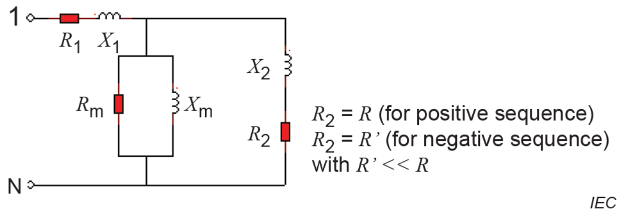
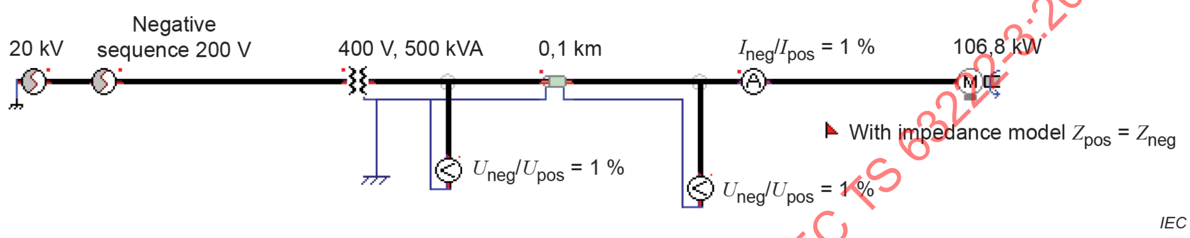
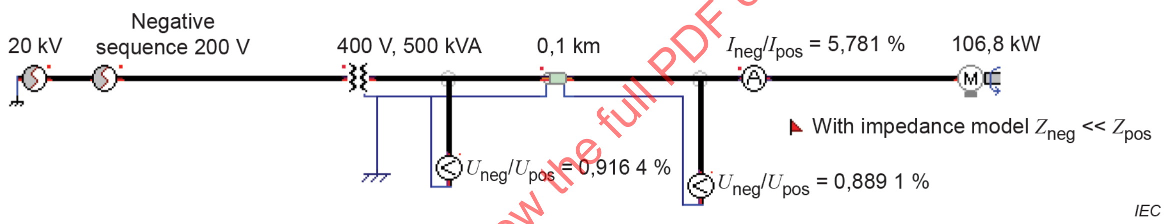


Figure 4 – Equivalent phasor model of induction motor

Figure 5 shows the effect of negative sequence impedance of general induction motors under 1 % of voltage unbalance: the current unbalance is 5,7 % (the assessment result linked with motor models is very important).



a) R_2=R



b) R_2=R'

Figure 5 – Unbalance modelling of induction motor based on negative impedance

5.5 Voltage dip

5.5.1 Simplified calculation for voltage dip analysis

During start-up, an induction motor takes a larger current than normal, typically five to six times as large. This current remains high until the motor reaches its nominal speed, typically in several seconds to one minute. Inrush current due to the starting of induction motors could result in voltage dip at the PCC. To analyse the voltage dip, the load should be represented as an impedance, as shown in Figure 6.

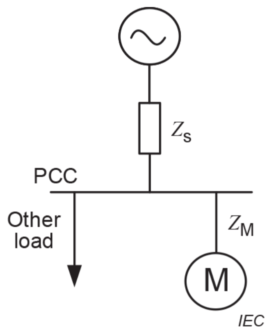


Figure 6 – Equivalent circuit for voltage dip due to induction motor starting

The voltage dip experienced by a load fed from the same bus as the motor can be derived from the voltage formula:

$$U_{\mathrm{sag}} = \frac{Z_{\mathrm{M}}}{Z_{\mathrm{S}} + Z_{\mathrm{M}}} \tag{13}$$

where

Z_{S} is the source impedance;

Z_{M} the motor impedance during run-up. The motor impedance during starting can be obtained as follows:

$$Z_{\mathrm{M}} = \frac{U_{\mathrm{rated}}^{2}}{\beta S_{\mathrm{motor}}} \tag{14}$$

where

U_{rated} is the rated voltage of the motor;

S_{motor} is the capacity of the motor;

β is the ratio between the starting current and the nominal current.

5.5.2 Advanced model for voltage dip analysis

For simulation analysis, an impact load should be represented as an ideal current source or impedance in a function of time. The time interval should be as short as possible, at least half cycle (IEC 61000-4-30). Representative load current time series can be identified from monitoring data of RMS currents or waveforms during the starting of the load, see example in Clause B.3 (Figure B.12).

Annex A
(informative)

Typical disturbing users and power quality parameters to be concerned

Table A.1 gives the types of installation.

Table A.1 – Type of installation

Installation type included	Power quality parameters to be concerned
Wind farm	Flicker, harmonics (Interharmonics)
PV station	Harmonics, disturbances > 2 kHz
AC electrified railway	Unbalance, harmonics, voltage dip, flicker
DC electrified railway	Harmonics
AC electric arc furnace	Harmonics (Interharmonics), flicker, unbalance
DC electric arc furnace	Harmonics, flicker
Induction heating furnace	Harmonics (Interharmonics), flicker
Polysilicon ingot furnace, monocrystal oven, crucible oven	Harmonics
AC/DC rolling mill	Harmonics (Interharmonics), flicker
Electric welding machine	Harmonics, flicker, unbalance
Electrolysis	Harmonics
Electric shovel, cargo lifter and gantry crane	Harmonics (Interharmonics), flicker
ASD	Harmonics
Switched mode power supply	Harmonics
EV charger	Harmonics
Energy-efficient lighting	Harmonics
Induction motor (starting mode)	Voltage dip

Annex B
(informative)

Model example applications

B.1 New type of installations with power electronic interface

B.1.1 Device with rectifier and inductive DC bus

A controlled (thyristor) or uncontrolled (diode) rectifier with inductive DC bus is one of the most traditional power electronic structures used in electrolysis, DC motor control, high power speed drive, etc. This convertor is found in LV and MV industrial applications, from fractional kW to a few thousand kW. There is a relatively large DC link inductance to stabilize the DC current.

For harmonic penetration studies in the frequency domain, the common model for this kind of rectifier is the ideal harmonic current source model, at the characteristic (and non-characteristic, if applicable) harmonic frequencies.

For simplified approaches, harmonic currents could be given by Formula (B.1) and Formula (B.2) as follows (n is the harmonic order, k is an integer, and p the pulse number such as 6-pulse, 12-pulse, etc.). The potential worst case in terms of amperes (highest magnitude of any harmonic component) is expected to correspond to the maximum load.

$$\frac{I_n}{I_1} = \frac{1}{n} \tag{B.1}$$

$$n = k \times p \pm 1, k = 1, 2, 3\ldots \tag{B.2}$$

B.1.2 Device with rectifier and capacitive DC bus

An uncontrolled (diode) front-end rectifier is one of the most common configurations used in EV charger, computers, variable frequency drives, etc. This convertor is found in LV and low power commercial and light industrial applications, from fractional kW to a few thousand kW. There is a relatively large DC link capacitor to stabilize the DC current, which is controlled to be constant.

For harmonic penetration studies in the frequency domain, the common model for diode front end voltage source converter (VSC) is the ideal harmonic current source model, at the characteristic (and non-characteristic, if applicable) harmonic frequencies. In addition to this model, any power factor correction and harmonic filter capacitor banks should also be represented separately.

In reality, the AC input inductance, which is mainly caused by the feeding network and supply transformers as well as the converter transformer winding and the load current will have a significant effect on the AC input current waveform. The percent distortion currents for an actual diode rectifier can be significantly different compared to the theoretical values. For more realistic adjustments of harmonic current magnitudes, a look-up table approach is recommended, thus different load conditions, different AC grid inductance or DC link inductance values and the effect of unbalance in the supply voltage can be considered.

For harmonic assessments in the frequency domain, if equivalent model for "diode rectifier + DC capacitor" is used, Formula (B.2) is always correct, but the harmonic magnitudes and phase angles can't be estimated with Formula (B.1) because the DC current can be in discontinuous mode. Some simplified formulas can be extracted from a given rectifier structure, but it is difficult to build general models. In practice, the equivalent spectral model can be built by means of:

– electromagnetic transient (EMT) simulation,
– local time domain model of nonlinear load within hybrid simulation platform (see 5.3.2, B.1.4),
– on-site measurements,
– machine learning model built from tests and measurements.

For more accurate spectral assessment, simplified time domain model should be used on typical converter working points. In the case of a controlled rectifier and if the control algorithm is unknown, the following simplified models (see Figure B.1) together with input EMC filters can be used under time domain simulation for building disturbance spectra (see Clause B.3 for waveform and spectral examples).

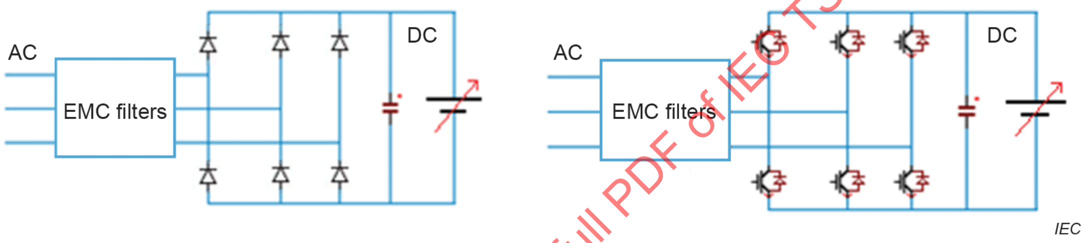


Figure B.1 – Simplified harmonic models by small size simplified time domain equivalent model

Based on laboratory tests, it is also possible to build an accurate harmonic model by machine learning on testing results, i.e. the above time domain simulation circuit can be replaced by a frequency-coupling matrix or machine learning model.

In practice, if the above equivalent time domain model can't be totally put into force, at minimum, it is recommended to take into account the input EMC filter together with an equivalent current source method mentioned before. In fact, EMC filters have a significant impact on overall grid impedance, resonance frequencies and harmonic levels, especially on high order ones.

B.1.3 Device with PWM rectifier

An effective and often cost-effective alternative to diode rectification is the switch-mode PWM rectifier. The active rectifier offers the features of reduced low-order input current harmonics for smaller filter requirements and near unity power factor operation.

It should be noted that the presence of the rectifier's PWM carrier frequency (typically from 3 kHz to 15 kHz for medium and high power installation, 20 kHz to 140 kHz for small power electric appliances) and the associated harmonics will be seen in the input current but are usually above the frequencies of interest for this document. However, in medium voltage high power devices, to reduce switching losses, the carrier frequency can be lower, normally below 1 500 Hz. In that case, the harmonics cannot be neglected.

The harmonic emissions from the rectifier into the external system are sensitive to background harmonics due to interaction with the PWM controls. It is hereby recommended to use a model structure represented as Thevenin/Norton equivalent circuits at each harmonic frequency of interest.

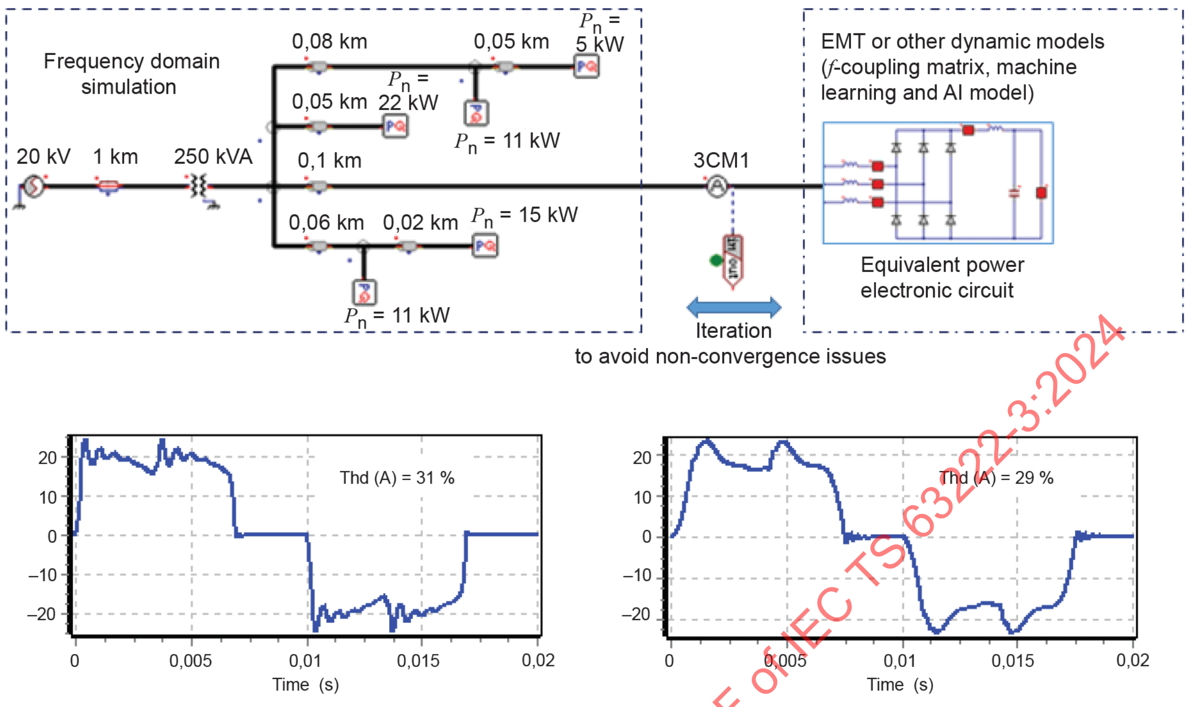
The steady state operation of a PWM rectifier can be characterized by a Thevenin/Norton equivalent representation based on equivalent ideal current sources and equivalent operational impedance at each harmonic frequency of interest. The equivalent sources and impedances will be dependent on the converter control frequency response (due to the interaction between the PWM controls and the background harmonics) at a particular frequency. The equivalent current sources in the model represent the disturbance caused by (non-ideal) PWM switching. Any harmonic filter/PFC (Power Factor Correction) capacitor banks associated with the device should be explicitly modelled or included in the equivalent impedance.

If passive filters are used to mitigate the effects of the sidebands of the PWM carrier frequency, they should be included with the Thevenin/Norton equivalent circuits.

In the recommended equivalent Thevenin/Norton model, both the source and the impedance at each harmonic frequency are dependent on the rectifier control strategies and control interaction to background harmonics at each harmonic frequency. Ideally, the equivalent sources and the operational impedance at each harmonic frequency of interest should be available from the device manufacturer over a range of loading levels for the particular device. If not, then the harmonic behaviour of the device can be investigated based on time-domain simulations with a manufacturer's model (if it is available). The time domain steady-state response should be reflected in the frequency/harmonic domain. If not available, measurements could be made at the input to the actual device. Measurements should consider the device both in and out of service so that the natural background harmonics can be estimated and taken into account.

B.1.4 Example of hybrid power quality simulation

As mentioned in the above sections, a dynamic harmonic model can be integrated in a frequency domain simulation to get correct interaction between grid back ground disturbance and a nonlinear load. Figure B.2 shows an EMT model of EV charger integrated in a frequency domain simulation loop. The harmonic current spectra obtained by hybrid simulation are near that from whole time domain EMT simulation, but with less computation burden and are interesting for power quality assessment in large scale power grid.



a) Current (A) simulated with EMT simulation

b) Current (A) simulated with hybrid simulation

Xavier YANG has kindly provided the above figure.

Figure B.2 – Harmonic assessment results based on frequency domain and time domain hybrid simulation

B.2 Traditional disturbing installations

B.2.1 Large drive systems

Phase-controlled cycloconverters are in use for many industrial applications such as cement and ball mill drives, mine winders, rolling mill drives, drives for hydro-electric pumped storage, etc. One disadvantage of cycloconverter is that it generates a wide band of interharmonics in addition to the characteristic harmonics.

The cycloconverter is expected to have a model structure represented as a Norton equivalent circuit at each harmonic frequency of interest. For the particular cycloconverter of interest, being a special-purpose application-dependent power converter and a significant source of a wide range of harmonics, the specialist manufacturer should be able to supply the spectrum and the operational impedance at each harmonic. If the cycloconverter uses dedicated harmonic filtering/PFC capacitor banks, the design details of these should also be provided by the specialist manufacturer and captured in the model.

The input currents of the cycloconverter are expected to have complex harmonic patterns. The input current harmonics are at frequencies:

$$(n \times p \pm 1)\, f_{\text{i}} \pm m \times f_{\text{o}} \qquad \text{(B.3)}$$

where

f_i is the input frequency to the rectifier;

f_o is the output frequency;

m is constrained by the following requirement:

$$\left(n \times p \pm 1\right) \pm m = \text{odd integer} \tag{B.4}$$

where

p is the pulse number;

m is the integer;

n = 1,2,3....

B.2.2 Electric arc furnace (EAF)

Almost always connected to the transmission grid, EAF usually have large power requirements compared to the short circuit capacity at their connection point. They are known to be some of the most disturbing applications from the perspective of power quality. Their non-linear operation produces an input current that is fluctuating, unbalanced and very rich in harmonics.

There are several distinct process states during the cycle of operation of the EAF: initial arc striking, start of melting, melting, refining, etc. The start of melting is a chaotic state and generally results in the worst case for power fluctuation and harmonic generation while the melting process is more stable and having generally lower levels of harmonic current injections, but this state persists for longer periods of time than for initial melting. The disturbing behaviour strongly depends on the process state, which changes the operating point of the furnace. Each state can be characterized by a harmonic current spectrum. Thus, decisions shall be made as to which process states of the furnace cycle should be considered; perhaps a single "worst case" is sufficient for some needs.

There are two kinds of EAF: AC arc furnaces and DC furnaces. An AC EAF has three graphite electrodes, electrode arms, a high current system with currents up to 80 kA and a three-phase furnace transformer. A DC EAF usually has one or two graphite top electrode(s) (cathode) and is usually supplied by a 12-pulse or 24-pulse thyristor rectifier. Both kinds produce odd and even harmonics and a continuous spectrum in the harmonic range. Additional equipment, such as harmonic filters, SVCs or STATCOMs, are frequently installed at EAF plants to keep power quality (normally flicker, unbalance and harmonics) within specified limits.

For harmonic assessment, it is recommended that the EAF is represented by its transformer with a Norton (or Thevenin) equivalent having a harmonic current (or voltage) source at each frequency along with its internal harmonic impedance, see Figure B.3.

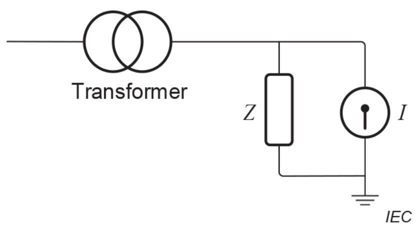


Figure B.3 – Norton equivalent model

In some cases, multiple models can be required in order to capture different process states. This can be implemented by means of look-up tables. It should be noted that the harmonic components generated by AC EAF are not, in general, independent from one another and this should also be reflected in the harmonic source model.

The generation of harmonic currents by DC furnaces strongly depends on the rectifier type. Assuming ideal commutation and smoothing conditions, the harmonics are generated at orders $n = k \times p \pm 1$ (p is the pulse number and k is an integer) and can be estimated using the well-known formula based on the ideal square wave or stepped square wave input current:

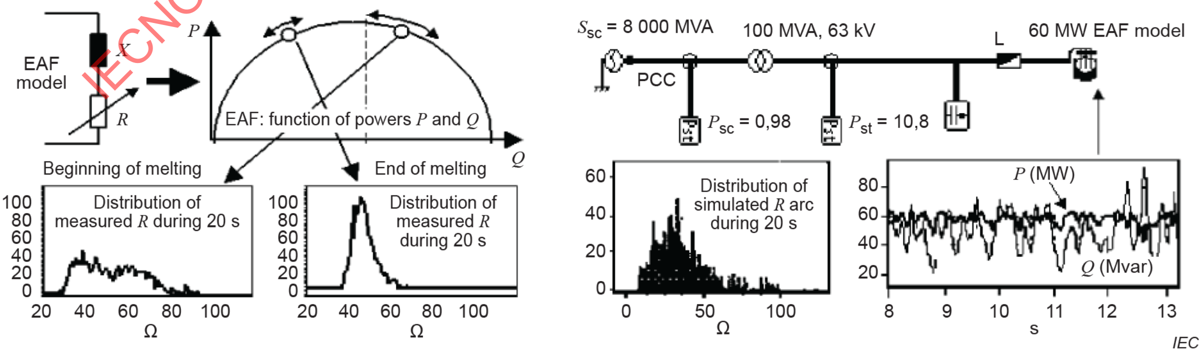
$$I_n = \frac{I_1}{n} \tag{B.5}$$

One equivalent impedance per harmonic frequency for each stage of the process (or each relevant operating point of the furnace) is also needed. This impedance represents the passive behaviour of the furnace components (including any power factor correction device, harmonic filters, etc.) and accounts for the influence of the furnace on the network harmonic impedance. In addition to all passive assets, the influence of the controller (if applicable) shall be covered in the harmonic impedance.

When frequency domain models are not sufficient to capture the complex behaviour of the EAF, time domain simulations with detailed models of the installation can be needed. For the case of submerged arc furnaces, it means a detailed representation of the converter components (thyristors) and their control laws. These time-domain models can also be used to develop or validate simplified models for frequency-domain analysis according to the structure shown in Figure B.3.

For flicker assessment, it is recommended that the EAF is represented by variable impedances R (active power) and X (reactive power). Fast RMS computation together with RMS-based IEC 61000-4-15 [11] flicker meter is one of the easier ways to evaluate fast voltage fluctuation and flicker.

Power variations of an electric arc furnace are very irregular. One proposed method [11] concerns a simplified dynamic EAF model by setting a chaotic variation on equivalent arc resistance. The principle of this method is based on the theoretical P and Q locus of EAF (Figure B.4 for a 60 MW EAF). Here is the simulation scheme and results with 10 ms RMS values.



Xavier YANG has kindly provided the above figure.

Figure B.4 – EAF modelling by two chaotic functions per phase and simulated flicker levels

The above modelling method can be also used for flicker assessment of a welding machine, see [12] for detail simulation parameters.

B.2.3 AC electrified railway

B.2.3.1 Traction power system

An AC electrified railway is a typical non-linear, unbalanced, impact and fluctuating load. Harmonics and negative sequence are the focus of power quality assessment. For the purposes of power quality assessment, the railway electrification system consists of three principal parts, the transmission/distribution network, the traction power system and the interface between these two systems, which can consist of traction transformers, compensation equipment, filters, etc. (see Figure B.5).

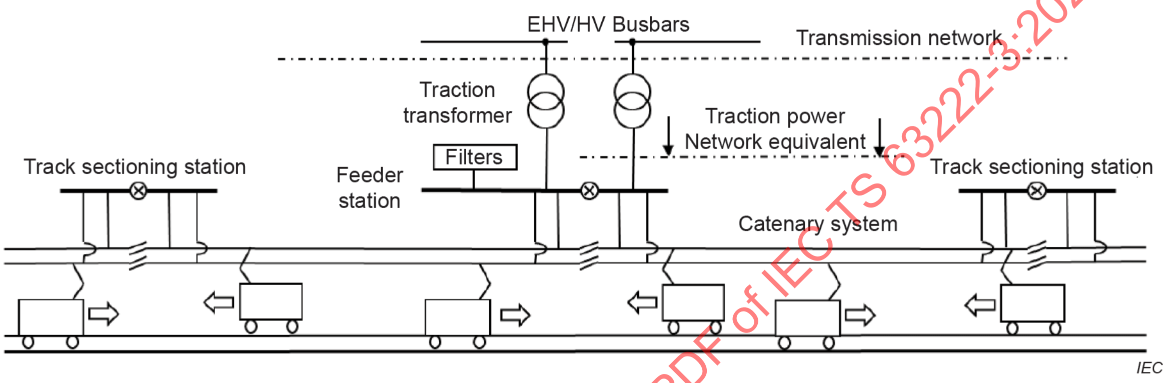


Figure B.5 – Principal arrangement of traction system

One of the main challenges when assessing the power quality impact of electric railways is the distribution of the rolling stock along the railway route in both time and space. Electric railways can be very long and as such supplied from the transmission/distribution network at many points which to some degree need to be assessed as one system, not as individual independent connections. One way of achieving this is to represent the traction power system by a number of equivalents which together represent the entire railway effect on the transmission/distribution system.

The representation of the railway system should consider all trains operating on a given schedule or timetable. It is recommended to utilise network equivalents of each feeder station or traction supply point which accounts for the effects of the ac traction system impedance on the harmonic propagation through the system and the aggregated traction load.

B.2.3.2 Traction load equivalent

Each train acts as a harmonic current source or voltage source with series/parallel impedances, with the fundamental and harmonic currents propagating through the catenary system, traction transformer and into the EHV/HV system, as illustrated in Figure B.4. The fundamental and harmonic current distribution will depend on the catenary system parameters, train parameters and train location.

The network equivalent should adequately represent the system at each traction power supply point in order to account for all parameters. The equivalent should account for several trains (potentially of different types) running to a given timetable. Different equivalents can be required for different railway sections, modes of train operation, timetables, train types, etc. Some averaging methods can be employed to simplify the process. The feeder currents in traction substation can be represented by statistical characteristic quantity over a period of time e.g., one week, such as maximum, average, RMS, 95 % percentile value and variance, etc.

For a new railway, the statistical characteristics of the feeder currents can be estimated by traction calculation simulation or in-situ measurement data analysis from similar situations.

1) In traction system simulation, all trains moving along the railway route in line with the timetable need to be taken into account. Different operation modes of trains, e.g. accelerating, coasting, braking and stopping at stations, also need to be considered.
2) In the statistical analysis of traction load, the probability distribution can be estimated by a parametric method or nonparametric method. Parametric method is recommended and the probability density of feeder current can be assumed to conform to beta distribution. The parameters of the traction load probability density are affected by the number of trains, traffic density, line conditions, etc. Based on the measurement data of existing railway traction substation, the effective and feasible method is to divide the measured data into several categories according to certain rules.

B.2.3.3 Aggregation of harmonics

For harmonic study, typically, an ideal harmonic current source should be used for easiness to represent harmonics spectrum under different modes of train operation. The harmonic currents generated by all trains operating on the railway should be aggregated using a suitable aggregation rule. Power electronic converters typically used in trains can require different summation law. For non-synchronized sources, linear summation is recommended for harmonics less than order 6^{th}, RMS summation for harmonics above order 6^{th}. For synchronized sources, linear summation is recommended.

For the linear summation rule, the total current i_{lin} obtained as the sum of moduli is

$$i_{\text{lin}} = \sum_n I_n \tag{B.6}$$

For the RMS summation rule, the total current i_{RMS} obtained as the square root of the sum of squared moduli is

$$i_{\text{RMS}} = \sqrt{\sum_n I_n^2} \tag{B.7}$$

B.2.3.4 Case study of power quality modelling of a high-speed train traction system

B.2.3.4.1 General

The case study [12] introduces power quality mitigation application of high-speed train in France. In this case, voltage unbalance and harmonic compensations have been committed in a HV substation which supplies high speed train traction systems. This application is a general case where single-phase loads are connected to a HV grid whose short-circuit power was not high enough to absorb neither unbalance currents nor harmonic currents generated by traction loads at this substation.

Facing this problem, French railway companies, TSO and R&D of Electricité de France (EDF[2]) have built a partnership that resulted in a real experimentation of a voltage sourced converter (VSC) based imbalance compensator rating 20 MVA, which was connected to a 90 kV railway substation. Based on the feedback on the commissioning of this installation with a particular emphasis on the results of unbalance and harmonic field measurements, simplified modelling and simulation have been carried out (see Figure B.6). The following sections give the main figures of the performance simulation of the power quality mitigation dedicated to the train traction system.

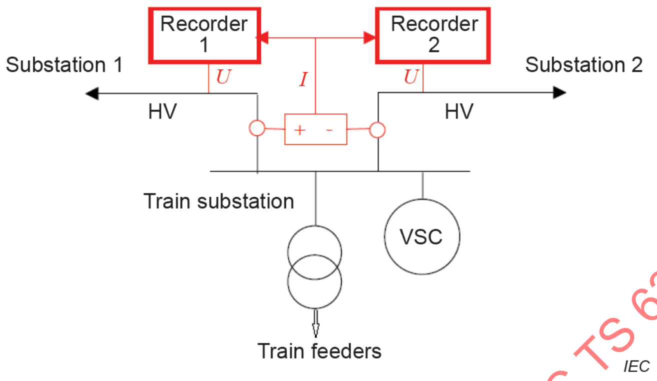
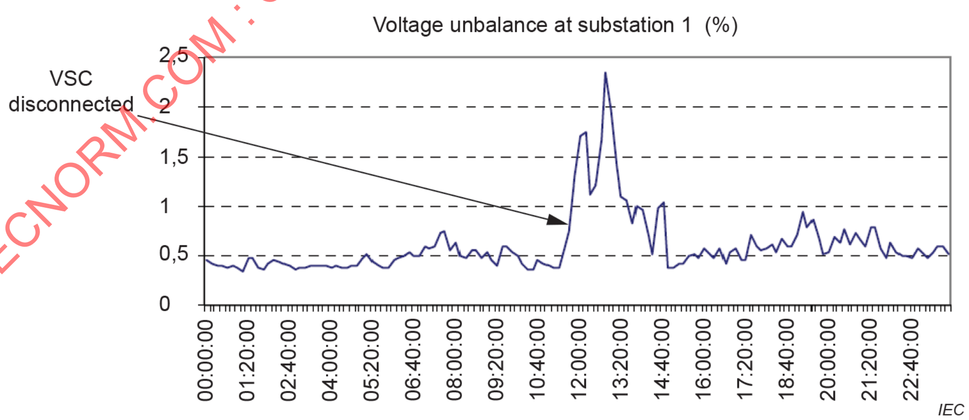


Figure B.6 – High speed train traction system with *PQ* recorders and VSC compensator

B.2.3.4.2 Unbalance compensation and modelling

Since high-speed trains are single-phase loads, and each train is connected to phase-phase voltages, one important power quality issue in traction system is voltage unbalance. According to French TSO power quality contract and European power quality standard EU 50160 [13], voltage unbalance should be less than 2 %.

The following figure illustrates the on-site measurements during commitment the tests of the VSC. In the absence of VSC compensation, substation voltage unbalance exceeds 2 %. As a result of VSC compensation, voltage unbalance in substations has been limited to less than 1 % (Figure B.7).

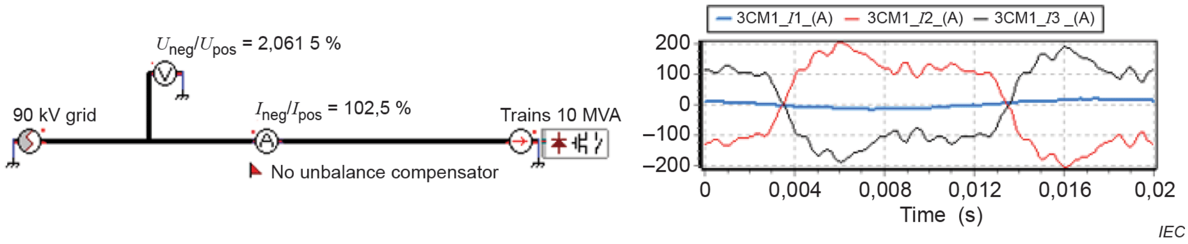


Xavier YANG has kindly provided the above figure.

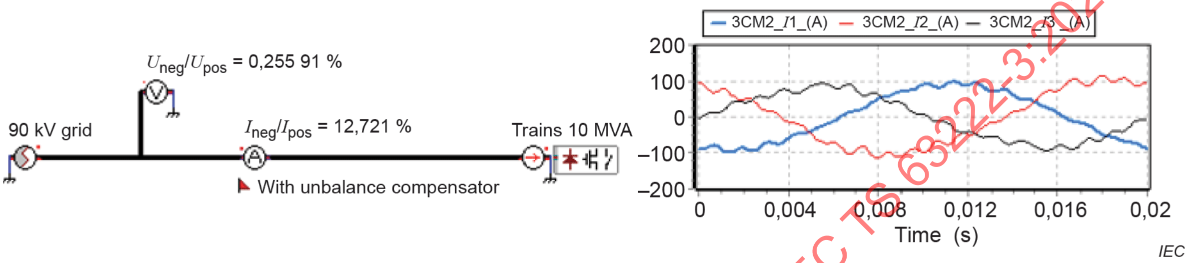
Figure B.7 – Recordings of voltage unbalances with and without VSC compensator

2 This trade name is provided for reasons of public interest or public safety. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC.

The site recordings have been used to compute detail power quality indices and to build simulation models (Figure B.8).



a) **Unbalance and phase currents (case without VSC compensation)**



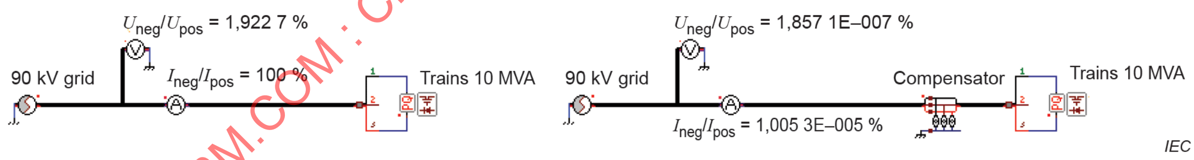
b) **Unbalance and phase currents (case with VSC compensation)**

Xavier YANG has kindly provided the above figure.

Figure B.8 – On-site measurements with and without VSC compensator

B.2.3.4.3 Unbalance modelling with on-site measurements

Train load between phase 1 and phase 3 is modelled with on-site recordings, i.e., phase currents of train at 10 MVA power level (Figure B.9). Theoretical VSC injection currents are deduced from frequency domain simulation. Unbalance voltage and current are computed at 90 kV busbar only for fundamental frequency according to unbalance definition in IEC 61000-4-30.



Xavier YANG has kindly provided the above figure.

Figure B.9 – Simulation of unbalances and with VSC compensation

B.2.3.4.4 Shunt active harmonic compensation: measurements and modelling

Furthermore, harmonic issues can be also important in the traction system in presence of power electronic converters. The above-mentioned VSC compensator has another built-in function: active harmonic filter by shunt current injection.