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TECHNICAL SPECIFICATION

colour inside

Distributed energy resources connection with the grid –
Part 41: Requirements for frequency measurement used to control distributed energy resources (DER) and loads

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Distributed energy resources connection with the grid – Part 41: Requirements for frequency measurement used to control distributed energy resources (DER) and loads

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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IEC TS 62786-41 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
8/1649/DTS	8/1661/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.

It has been developed as part of measurement series together with IEC TS 62786-42 on voltage measurement.

A list of all parts in the IEC 62786 series, published under the general title *Distributed energy resources connection with the grid*, 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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DISTRIBUTED ENERGY RESOURCES CONNECTION WITH THE GRID –

Part 41: Requirements for frequency measurement used to control distributed energy resources (DER) and loads

1 Scope

This part of IEC 62786, which is a Technical Specification, defines minimum requirements for frequency and rate of change of frequency measurements used to control distributed energy resources (DER) and loads connected to electrical power networks.

This document specifies the characteristics of frequency and rate of change of frequency measurements to evaluate their performances. It describes the main use cases of frequency and rate of change of frequency measurements, with associated level of performances. It describes the principle of functional tests to evaluate the specified characteristics and defines the influencing factors that affect these performances, under steady state or dynamic conditions.

This document defines the functional requirements applicable to frequency and rate of change of frequency measurements which can be inside or outside the DER or loads. In the case of DER, this document provides requirements additional to those which are defined in the other parts of IEC 62786 or standards produced by the relevant IEC technical committees (e.g. TC 82 for photovoltaic systems, TC 88 for wind systems, TC 120 for electrical energy storage systems (EES)).

This document is applicable to DER and loads regardless of the voltage level of the point of connection to the grid.

This document does not specify hardware, software or a method for frequency or rate of change of frequency measurement. It does not specify tests linked to environmental conditions associated with hardware devices (climatic, electromagnetic disturbances above 3 kHz, mechanical stress, etc.).

Frequency and rate of change of frequency measurements associated with time stamping are not in the scope of this document. These measurements are already covered by IEC 60255-118-1 [1][1].

Frequency and rate of change of frequency measurements associated with protection functions or protection relays are not in the scope of this document. These requirements are already covered by IEC 60255-181 [2].

NOTE As defined in the first paragraph, this document is focused on frequency and rate of change of frequency measurements used to control DER and loads. But the technical requirements defined in this document, with the list of declared characteristics and their associated functional tests, can also be applicable for other uses where "fast" frequency and ROCOF measurement is required (small or large generators of power substations connected to transmission or distribution grids, power meter devices, power quality instruments, etc.).

2 Normative references

There are no normative references in this document.

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

3 Terms and definitions

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

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

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

3.1
instrument
<for frequency measurement> device or measurement function which performs frequency or ROCOF measurement

Note 1 to entry: As the frequency or ROCOF measuring functions can be performed inside different types of devices or systems (control system of distributed energy resources, power system loads, protection relays, metering devices, etc.), the generic term "instrument" is used in this document to designate frequency or ROCOF measuring function which must be characterized and tested.

3.2
rotating vector
representation of a sinusoidal function where a polar vector rotates at an angular velocity which can be a non-constant function of time and is expressed in radians per second

Note 1 to entry: The radius of the rotating vector can also be a non-constant function of time.

Note 2 to entry: Rotating vectors can represent periodic or non-periodic sinusoids.

Note 3 to entry: Power system signals can be represented by a combination of signals, each represented by one rotating vector, each with various angular velocities and various radii. Each of these rotating vectors represents one component of the power system signal (see Annex E).

Note 4 to entry: The noise component of a power system signal is not represented by a rotating vector. Noise is represented as a time series.

3.3
phase
angle of a rotating vector

Note 1 to entry: When the rotating vector is described in polar notation, the phase is the angle; when described in complex notation, the phase is the argument.

3.4
instantaneous phase
phase of a rotating vector at a specific moment of time

Note 1 to entry: Any point along a sinusoidal periodic function can be represented by a complex number. The instantaneous phase is the argument of that complex number.

3.5
frequency
rate of change of phase of a rotating vector

Note 1 to entry: If the period is a span of time, the unit of frequency is hertz (Hz) in cycles per second.

Note 2 to entry: Frequency can be a non-constant function of time.

3.6
power frequency
values of frequency used in the electricity supply systems

[SOURCE: IEC 60050-601:1985, 601-01-05, modified – In the definition, "conventionally" has been deleted.]

3.7
instantaneous frequency
rate of change of instantaneous phase

Note 1 to entry: Typical frequency reporting instruments report instantaneous frequency and can report the changing frequency within one period of the input energizing quantity.

3.8
measured frequency
estimated frequency provided by an instrument

3.9
fundamental component
rotating vector of interest for a waveform that is a sum of rotating vectors

Note 1 to entry: Generally, the fundamental component is the rotating vector with the greatest magnitude; sometimes it is the component with the lowest frequency (often called the first harmonic). However, neither is always the case, for example in AC current waveforms or in oscillating signals with sub-harmonics.

3.10
fundamental frequency
frequency of the fundamental component

Note 1 to entry: In AC electrical power systems, the fundamental frequency is to be maintained within relevant statutory deviation from the nominal frequency.

Note 2 to entry: In three-phase systems, measuring fundamental frequency for all three phases can yield slightly different measurements due to interference. Frequency can be obtained by a transformation of the individual phases such as by averaging the three frequency measurements or by calculating the rate change of instantaneous phase of the positive sequence since positive sequence cancels common-mode interference.

[SOURCE: IEC 60050-103:2009, 103-07-21, modified – In the definition, "of a periodic quantity" has been deleted. Notes 1 and 2 to entry have been added.]

3.11
nominal frequency
nominal value of power frequency

Note 1 to entry: In conventional power systems, nominal frequency is normally 50 Hz or 60 Hz.

3.12
rate of change of frequency
ROCOF
first time derivative of instantaneous frequency or second time derivative of instantaneous phase

3.13
harmonic component
rotating vector whose frequency is an integer multiple of the fundamental frequency for a signal that is the sum of rotating vectors

Note 1 to entry: The fundamental component is the first harmonic component.

3.14
interharmonic component
rotating vector whose frequency is not an integer multiple of the fundamental frequency for a signal that is a sum of rotating vectors

3.15
sub-harmonic component
interharmonic component having harmonic order lower than one

[SOURCE: IEC 60050-103:2009, 103-07-29]

3.16
settling time
for a step response the duration of the time interval between the instant of the step change of an input variable and the instant, when the difference between the step response and their steady-state value remains smaller than the transient value tolerance

SEE: Figure 3

[SOURCE: IEC 60050-351:2013, 351-45-37, modified – Figure 5 inside the terminology entry has been replaced by Figure 3.]

3.17
fast frequency response
FFR
fast active power response to frequency variations that uses a droop control

3.18
droop control
<for frequency measurement> control loop to control dispatchable generators or loads to ensure that the active power generation or consumption is a proportional function of the measured power frequency deviation

Note 1 to entry: The proportionality factor is an inverse of the frequency droop.

3.19
frequency droop
ratio of the per-unit changes in frequency $(\Delta f)/f_n$ to the per-unit change in power $(\Delta P)/P_n$

$\sigma = (\Delta f/f_n) / (\Delta P/P_n)$,

where f_n is the nominal frequency and P_n is the DER or load rated power

Note 1 to entry: The frequency droop is a $f(P)$ function, whereas often used characteristic curve is $P(f)$.

Note 2 to entry: The same principle can be applied for a voltage droop.

Note 3 to entry: The frequency gradient of a characteristic curve, which describes the power response to frequency, is the active power change per frequency change. In a 50 Hz system, a droop of σ % can be transformed into a gradient g % (in P_n/Hz) by the formula $g = 200/\sigma$; in a 60 Hz system $g = 166,7/\sigma$.

3.20
synthetic inertia
<in an electric power system> capability of a grid connected converter to emulate the effect of inertia of a synchronous generator to a prescribed level of performance

Note 1 to entry: A static converter can provide synthetic inertia as a controlled response.

3.21
inertia
<in an electric power system> property of a rotating rigid body according to which it maintains its angular velocity in an inertial frame in the absence of an external torque

[SOURCE: IEC 60050-113:2011, 113-03-02, modified – The entry has been adapted for the purpose of a rotating reference system.]

3.22
measuring range
range defined by two boundary values of the measurand, or quantity to be supplied, within which the limits of accuracy are specified

[SOURCE: IEC 60050-311:2001, 311-03-12, modified – In the definition, "boundary" has been added and "uncertainty of the measuring instrument" has been replaced by "accuracy".]

3.23
operating range
range defined by two boundary values of the measurand, or quantity to be supplied, within which the instrument performs its intended measurements without entering in any kind of saturation mode that requires a recovery time when the input returns into the measuring range.

3.24
effective resolution
practical lower limit of a measurement due to inherent noise and errors

3.25
distributed energy resources
DER
generators, including loads having a generating mode (such as electrical energy storage systems) connected to the low or medium voltage distribution network, with their auxiliaries, protection and connection equipment

[SOURCE: IEC TS 62786:2017, 3.3, modified – The term has been made plural.]

3.26
input energizing quantity
energizing quantity that by itself constitutes the characteristic quantity, or helps to constitute it

Note 1 to entry: For the frequency or ROCOF measurement, the input characteristic quantity could be voltage.

[SOURCE: IEC 60050-447:2020, 447-03-02, modified – The notes to entry have been replaced by a new Note 1 to entry.]

3.27
flicker
impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time

Note 1 to entry: Flicker phenomenon is due to voltage magnitude variation, which can be periodic or erratic, with a spectral decomposition between 0,5 Hz and 25 Hz.

[SOURCE: IEC 60050-161:1990, 161-08-13, modified – Note 1 to entry has been added.]

3.28
measurand
quantity intended to be measured

[SOURCE: ISO/IEC Guide 99:2007, 2.3]

3.29
total distortion factor
ratio of the RMS value of the total distortion content to the RMS value of an alternating quantity

Note 1 to entry: The total distortion factor 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.

[SOURCE: IEC 60050-551:2001, 551-20-16]

3.30
white noise
flat random noise
random noise which has a continuous spectrum and a constant power spectral density in the frequency band considered

[SOURCE: IEC 60050-702:1992, 702-08-39]

3.31
interfering signal
signal that impairs the reception of a wanted signal

[SOURCE: IEC 60050-161:2018, 161-01-04]

4 Performance description

4.1 General

Frequency and ROCOF measurement performances shall be described with characteristics presented in Clause 4 and listed in Table 1.

Table 1 – Performance characteristics presented in Clause 4

Items	Units
Input energizing quantities	V (voltage) and A (current)
Delay time	s (second)
Accuracy (declared via Maximum Absolute Error)	Hz (frequency) and Hz/s (ROCOF)
Resolution	Hz (frequency) and Hz/s (ROCOF)
Measuring range	Hz (frequency) and Hz/s (ROCOF)
Operating range	Hz (frequency) and Hz/s (ROCOF)
Settling time	s (seconds)
Reporting rate	1/s (1/second)

All these characteristics shall be declared by the manufacturer, verified by functional tests which are described in Clause 6.

These declared characteristics are impacted by different influencing factors. These factors are described in Clause 4, and the impact of these factors on declared characteristics is considered in Clause 6 and in Annex I.

4.2 Input energizing quantities

The input energizing quantities are the measuring signals of the frequency or ROCOF measurement function. The manufacturer shall state the type of input energizing quantities used by the measurement function. Examples are:

- single or multi phase-to-earth voltage measurement;
- single or multi phase-to-neutral voltage measurement;
- single or multi phase-to-phase voltage measurement;
- phase (line) currents.

The frequency or ROCOF measurement can be based on signal processing applied to these input energizing quantities or derived signals from phase quantities, for example, positive sequence voltage or calculated phase-to-phase voltages, etc.

4.3 Delay time

4.3.1 Description

The delay time is the time taken for an instrument to report the values (frequency and ROCOF) of the input energizing quantities. Instruments typically sample the input, process the input to determine the measurements, then output the value of the instrument reading at an output port. The time difference between the value given at the input port (see NOTE 3) and the instrument reading presented at the output port is the delay time. Delay times for frequency and ROCOF shall be declared by the manufacturer for frequency and ROCOF and published in accordance with the format shown in Table 2.

NOTE 1 The purpose of the delay time parameter is to inform the user of the instrument delay time in reporting a change in power system frequency and ROCOF. This delay includes instrument hardware and software signal processing delays.

NOTE 2 Delay time is essential to all of the validation methods described in Clause 6. For this reason, delay time is described first.

NOTE 3 Frequency and ROCOF values at the input port are based on test conditions described in 6.3. The injected instantaneous frequency or instantaneous ROCOF are controlled with synthetic signals, based on mathematical equations and definitions given in Clause 3.

4.3.2 Reporting of delay time declaration

The manufacturer shall publish the values in the format shown in Table 2. Depending on the frequency measuring technology, the delay time can differ from that given in Table 2, where the values are given as an example to indicate the format of the data.

Table 2 – Example of delay time

Quantity	Delay time
Frequency	0,089 5 s
ROCOF	0,086 1 s

The delay time of frequency and ROCOF measurements shall be verified according to functional test conditions defined in 6.3.

4.4 Effective resolution and accuracy

4.4.1 Description

The accuracy specification of the instrument measurement shall be declared by the manufacturer as the maximum allowable absolute value of frequency error and ROCOF error and published in accordance with the format shown in Table 3. Depending on the frequency measuring technology, the range can differ from that given in Table 3, where the values are given as an example to indicate the format of the data.

The effective resolution of frequency and ROCOF measurements shall be verified under steady state and dynamic conditions according to functional test conditions defined in 6.4. Accuracy is verified across the entire measuring range, which is described in 4.5 with verification procedures presented in 6.5.

4.4.2 Effective measurement resolution

The effective measurement resolution shall be declared by the manufacturer. Effective measurement resolution takes into account the internal noise of the instrument that causes variation in the measurement. The declared effective measurement resolution should be determined by validating the resolution of the stable part of the measurement result when the instrument inputs are connected to a low noise, frequency modulated sinewave voltage source.

Table 3 shows an example of effective measurement resolution from an actual instrument.

Table 3 – Example of measurement resolution and maximum absolute error for frequency and ROCOF measurements

Quantity	Effective measurement resolution	Steady state maximum absolute error	Dynamic maximum absolute error
Frequency	0,000 5 Hz	±0,005 Hz	±0,06 Hz
ROCOF	0,012 Hz/s	±0,04 Hz/s	±2,3 Hz/s

Effective measurement resolution shall be verified according to functional test conditions defined in 6.4.

4.4.3 Reporting of the frequency and ROCOF accuracy

The frequency and ROCOF accuracy are reported as a measurement error, as per the example shown in the maximum absolute error column of Table 3.

The manufacturer shall declare the maximum absolute error for frequency and ROCOF under steady state and dynamic operating conditions. This is the absolute value of the worst-case measurement error allowed by the instrument operating within its measuring range as described in 4.5. Frequency and ROCOF absolute error under steady state and dynamic conditions are verified during the verification of measuring range tests in 6.5.

4.5 Measuring range, operating range, and rejection of interfering signals

The measuring range of the instrument is that range of frequency or ROCOF for which the instrument maintains less than or equal to its maximum absolute frequency and ROCOF error specification.

The operating range of the instrument is extended beyond the measuring range, to ensure input frequency or ROCOF in the operating range does not cause the instrument to enter any form of saturation mode that requires a recovery time when the input returns into the measuring range.

Interfering signals are signal components of the input energizing quantities which are in addition to the fundamental component whose frequency is being measured by the instrument. Examples of interfering signals are sub-harmonics, interharmonics, and harmonics. The effect of interfering signals with frequencies within the operating range shall be included in the measurement; the effect of interfering signals with frequencies outside the operating range shall be rejected by the instrument and shall not cause the error of the measurement to be greater than the manufacturer's declared maximum absolute error of the instrument. The effect of interfering signals between the measuring range and operating range can cause the absolute value of the error of the instrument to be worse than the maximum absolute error.

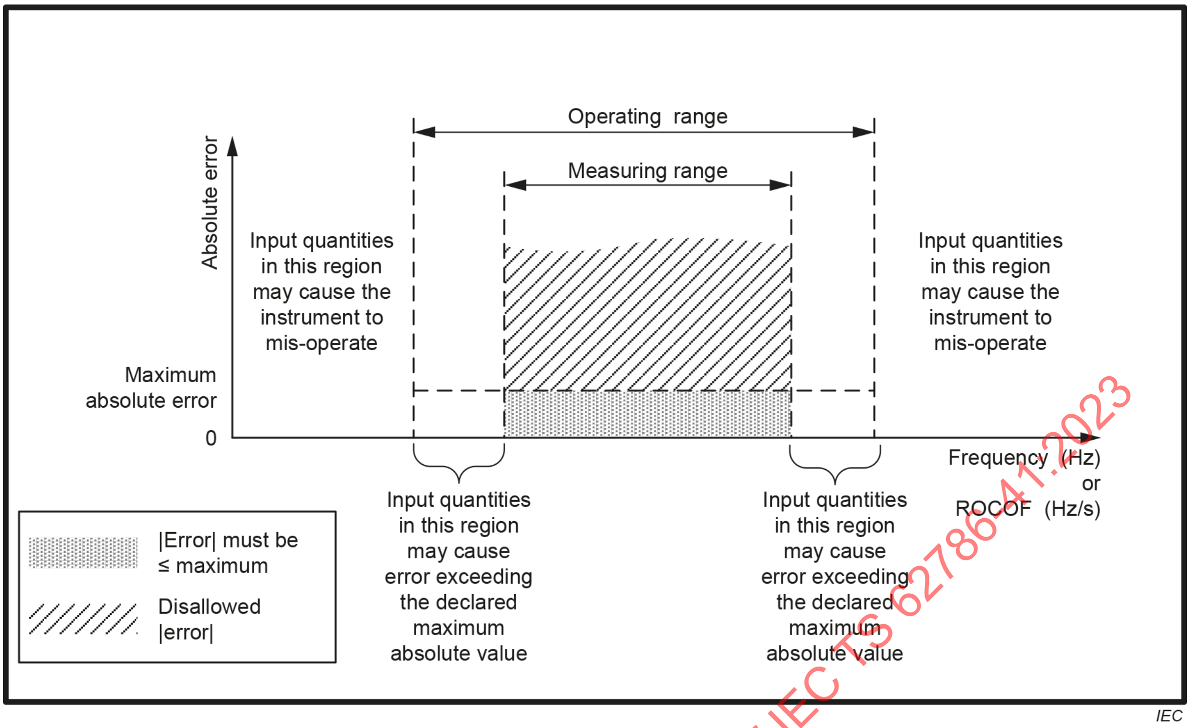


Figure 1 – Measuring range and operating range without interfering signals

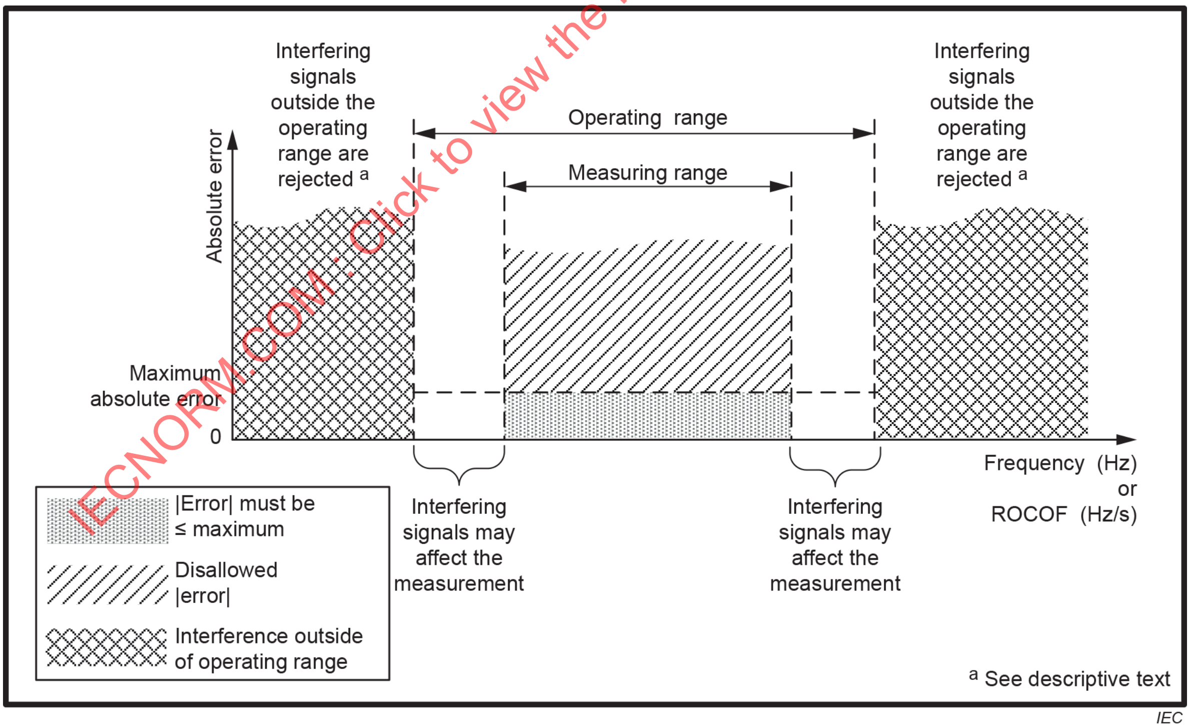


Figure 2 – Measuring range and operating range in the presence of interfering signals

Figure 1 details the measuring range and operating range when there are no interfering signals present. Within the measuring range, the absolute value of the error of the measurements shall be less than or equal to the manufacturer's declared maximum absolute error. Outside of the measuring range but within the operating range, the absolute value of the error of the measurements can be worse than the maximum absolute error. Frequency or ROCOF outside the operating range can cause saturation or other effects that lead the instrument to mis-operate and can require some time for the instrument to recover once the input energizing quantity returns to the operating range.

Figure 2 details the measuring range and operating range in the presence of interfering signals such as interharmonics or harmonics. Outside the operating range, interfering signals will be rejected and the absolute value of the error of measurements of frequencies within the measuring range will be less than or equal to the manufacturer's declared maximum absolute error.

The manufacturer shall declare the measuring and operating range of input energizing quantities of the measuring signals which are used to perform frequency and ROCOF measurements (for example, voltages). The instrument documentation shall also state the type of input energizing quantities used, as required in 4.2.

The measuring range and operating range of the instrument shall be declared by the manufacturer for frequency and ROCOF and published in accordance with the format shown in Table 4. Depending on the frequency measuring technology, the range can differ from that given in Table 4, where the values are given as an example to indicate the format of the data.

Measuring range and operating range under steady state conditions, dynamic conditions, and in the presence of interfering signals shall be verified according to functional test conditions defined in 6.5.

Table 4 shows an example taken from an actual instrument. In this example, the manufacturer of the instrument declares the measuring range to be the nominal frequency f_n ± 5 Hz (45 Hz to 55 Hz for 50 Hz nominal frequency and 55 Hz to 65 Hz for 60 Hz nominal frequency). The operating range is declared to be f_n ± f_n/2 (25 Hz to 75 Hz for 50 Hz nominal frequency and 30 Hz to 90 Hz for 60 Hz nominal frequency).

Table 4 – Example of measuring range and operating range for frequency and ROCOF measurements (taken from an actual instrument)

Quantity	Measuring range	Operating range
Power frequency [a]	45 Hz to 55 Hz for f_n = 50 Hz 55 Hz to 65 Hz for f_n = 60 Hz	25 Hz to 75 Hz for f_n = 50 Hz 30 Hz to 90 Hz for f_n = 60 Hz
ROCOF	−50 Hz/s to +50 Hz/s for f_n = 50 Hz −60 Hz/s to +60 Hz/s for f_n = 60 Hz	−800 Hz/s to +800 Hz/s [a]
Input energizing quantity (e.g. voltages)	20 V to 120 V	5 V to 150V
	20 V to 120 V	5 V to 150V

[a] ROCOF operating range is determined by the design of the instrument and can far exceed the needs of the power system measurement. Instruments can continue to function under test conditions with very high ROCOF without entering any form of saturation mode.

Using the maximum absolute error of 4.4, for 50 Hz nominal frequency, the instrument will measure frequencies from 45 Hz to 55 Hz with less than |±0,005 Hz| error under steady state conditions and |0,06 Hz| under dynamic conditions. Frequencies from 25 Hz to 75 Hz are allowed to have more error as long as the instrument does not enter into any kind of saturation mode which requires time to recover. Interfering signals such as interharmonics and harmonics lower than 25 Hz and greater than 75 Hz will not cause the absolute value of the error to be greater than |±0,005 Hz| under steady state conditions.

The manufacturer may flag the measurement results when the measurand is outside the measurement range or another exceptional condition has been detected.

4.6 Timing characteristics

4.6.1 Reporting rate

The reporting rate is defined as the number of readings per second that the instrument outputs. The instrument output can be based on digital or analogue signal. The reporting rate shall be declared by the manufacturer and published in accordance with the format shown in Table 5. If the reporting rate is dynamic, then it can be specified as a formula. The values shown are examples taken from an actual instrument and may be different for other instruments.

4.6.2 Settling time

Settling time shall be declared by the manufacturer for frequency and ROCOF and published in accordance with the format shown in Table 5. The values shown are examples taken from an actual instrument and may be different for other instruments.

In the case of frequency and ROCOF, the tolerance shall be 95 % and 105 % of the step size, defined by the initial value of the input signal (G_{init}) and the steady state value output measurement (G_{final}).

Table 5 – Example of reporting of settling time and reporting rate

Quantity	Reporting rate (1/s)	Settling time (s)
Frequency	50	0,158 0
ROCOF	50	0,088 0

The settling time of frequency and ROCOF measurements shall be verified according to functional test conditions defined in 6.6.

For frequency measurement, the initial value (G_{init}) shall be defined as the nominal power frequency (e.g. 50 Hz or 60 Hz) and the step size shall be 1,0 Hz. Both positive (+1,0 Hz) and negative (−1,0 Hz) steps shall be used. The manufacturer's declared frequency settling time shall be the greater of the settling times for the positive and negative steps.

For ROCOF measurement, the initial value shall be defined from a steady condition ($\mathrm{d}f/\mathrm{d}t = 0$, no frequency change) followed by a step change in ROCOF produced using constant frequency ramps of +1,0 Hz/s and −1,0 Hz/s beginning at the nominal power frequency. The manufacturer's declared ROCOF settling time shall be the greater of the settling times for the positive and negative steps.

NOTE 1 Steps sized are fixed for comparison between various instrument models.

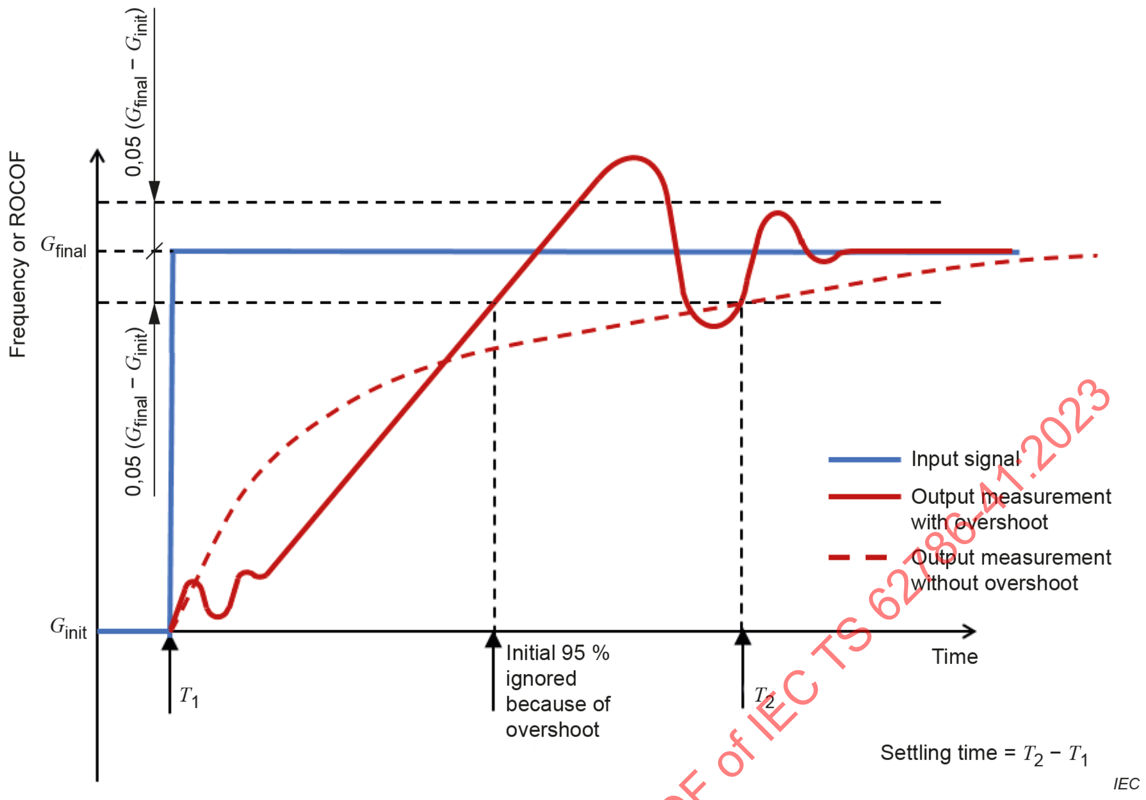


Figure 3 – Settling time description with input signal added

NOTE 2 The purpose of this parameter is to inform the user of the instrument time response following a step change in input signal phase.

5 Summary of typical performances associated with different use cases

Table 6 summarizes the list of "use cases" (see NOTE 1) considered for frequency and ROCOF measurement, with some main characteristics defined in Clause 4 (settling times, accuracies and measuring ranges). The requirements are applicable to frequency measurement and, for some use cases, ROCOF measurement. For use cases where there is a requirement for frequency measurement and another requirement for ROCOF, the requirements are given one under the other.

The term "use case" used in this document means a description of a possible application case of frequency or ROCOF measurements, which are in the scope of this document. This is not the same meaning as the description developed in the IEC 62559 series and used in several other IEC documents.

"Typical" accuracies, noted for each use case, are based on the maximum absolute error, as defined in 4.4. According to the declared settling time, such accuracy is based on a steady state maximum absolute error or on a dynamic maximum absolute error. For example, when the settling time is below 200 ms, it makes sense to refer to the dynamic maximum absolute error, because the measurement must be managed during frequency disturbances. When the settling time is above 500 ms (e.g. secondary reserve use case with a settling time of 1 s), it makes sense to refer to steady state maximum absolute error, because the measurement is more linked to steady state conditions (slow frequency change).

The detailed explanation of the different use cases is given in Annex B. Based on this use case list, measurement classes are proposed in Annex A.

Table 6 – List of use cases and associated requirements

Use case	Typical measuring range			Typical accuracy		Typical settling time	Class[a]
	Frequency (Hz)		ROCOF	Frequency	ROCOF		
	50 Hz system	60 Hz system					
PLL in PV power generating systems (Clause B.1)	44 Hz to 53 Hz	56 Hz to 63 Hz	−5 Hz/s to 5 Hz/s	±10 mHz	NA	Longer than the settling time of the voltage or current controller	C
Primary reserve (Clause B.2)			NA	±10 mHz	NA	200 ms to 1 000 ms	C
Secondary reserve – frequency measurement used for centralized control (Clause B.3)			NA	±1 mHz	NA	1 s	D
Fast frequency-active power proportional controller with dead band (Clause B.4)			NA	±50 mHz	NA	100 ms	B
Fast frequency response (Clause B.5)			NA	±50 mHz	NA	100 ms	B
Synthetic inertia (Clause B.6)			−15 Hz/s to +15 Hz/s	NA	±0,1 Hz/s	100 ms	1
Passive anti-islanding detection (Clause B.7)			NA	±100 mHz ±30 mHz	NA	60 ms 100 ms	A B
			−10 Hz/s to +10 Hz/s	NA	±0,05 Hz/s	250 ms	2
Active anti-islanding detection (Clause B.8)			NA	±10 mHz	NA	60 ms to 100 ms	C
ROCOF measurement used for centralized control (Clause B.9)			−0,03 Hz /s to +0,03 Hz /s	NA	±1 mHz/s	1 s	3
Load control with active power management (Clause B.10)			NA	±50 mHz	NA	100 ms	B
Self-dispatchable loads – Ultra fast current control – Very fast current control – Fast current control – Disconnectable loads – Primary control – Secondary control – Tertiary control (Clause B.11)			NA	 ±100 mHz ±30 mHz ±10 mHz ±1 mHz ±1 mHz ±1 mHz ±1 mHz	NA	 60 ms 100 ms 200 ms 1 s 1 s 1 s 1 s	 A B C D D D D
Under-frequency load shedding (Clause B.12)	43 Hz to 53 Hz	57 Hz to 63 Hz	NA	±30 mHz	NA	100 ms to 120 ms	B
			−4 Hz to 4 Hz/s	NA	±0,1 Hz/s	180 ms to 240 ms	2

NA not applicable

NOTE The values shown in Table 6 are examples of typical performances, associated with each use case. These values are not specific requirements applied to frequency or ROCOF measurements.

[a] Class level defined in Annex A that allows to fulfil the associated requirement for each use case.

Other potential use cases not dealt with in this document are listed below for information:

- load shedding schemes (based on frequency protection or frequency measurement);
- power sharing between grid-forming inverters in microgrids (primary regulation of inverter-based-generators);
- load management in microgrids based on frequency signal in a central device (experimental use case).

NOTE Application case of frequency protection is covered by the use case "Passive anti-islanding detection", based on over- or under-frequency and ROCOF functions. However, the frequency protection application, as a whole, is not in the scope of this document because protection relay types are numerous and a protection relay does not output a frequency measurement, only a logical start or operate signal. For the characterization of frequency protection performances, refer to IEC 60255-181.

6 Description of functional test principles

6.1 General

Clause 6 describes the functional tests to verify the manufacturer's declared characteristics. These functional tests can be sorted in two categories.

- Functional tests to verify or determine the following performances in specific conditions, which shall be declared by the manufacturer:
  - delay time for frequency and ROCOF measurement, in 6.3;
  - effective resolution for frequency and ROCOF measurement, in 6.4;
  - measurement and operating ranges common to frequency and ROCOF measurements, in 6.5;
  - settling time for frequency and ROCOF measurement, in 6.6.
- In Annex I: Functional tests to determine the impact of influencing factors. For each influencing factor defined in Clause I.1, specific tests are described to evaluate the impact on declared performances.

Manufacturer or testing laboratory shall produce a type test report. The structure of this report is defined in 6.7.

In Clause 6, the following terms are used:

- the "input signal" (or input energizing quantity) which are voltage and/or current test signal(s) applied to the input terminals of the instrument. The nature of the signal is defined for each test.
- the "instrument readings" which are outputted values of frequency and/or ROCOF. The manufacturer should specify which (if any) combination of ranges/settings have been tested. If different reporting rates are proposed, the manufacturer shall declare which reporting rate are used during the tests.
- the "instrument errors" – The errors of the instrument readings (i.e. frequency and/or ROCOF) determined by each test. The absolute value of instrument errors is used to verify some of the manufacturer's declared characteristics.

Clause 6 applies to single phase or three phase instruments. Three phase instruments should be tested with the input test signals as described in each subclause with the phase displaced by $2\pi/3$ radians, except if otherwise noted. For single phase test signal functions used in each subclause, the initial phase $\varphi_p = 0$. For three phase test signal functions used in each subclause, φ_p shall be set to 0, $-2\pi/3$ and $+2\pi/3$, respectively, for each phase.

Clause 6 is based on synthetic voltage or current signal waveforms. Mathematical equations of input signals are defined in each subclause. During transitions, the input signal shall be continuous, with no step change in its phase angle or magnitude except its frequency or ROCOF, unless otherwise specified in each functional test described in 6.3 to 6.6. The voltage level may be adjusted to keep within the withstand requirements of voltage inputs related to the rated volt/hertz level. If the frequency functions are based on phase (line) current, the same test methodology shall be followed, and the test conditions shall be fully described in the type test report.

A single phase of each of the test signal waveforms can be generated as an analogue signal, for example, by using a digital to analogue converter (DAC) such as an arbitrary waveform generator (AWG), personal computer DAC card or computer audio subsystem. The AWG or DAC can be loaded with a time series that represents a particular given test waveform. The sampled waveform reconstruction rate should be sufficiently high to meet the bandwidth requirements. A suitable "reconstruction" low pass filter can be used if the bandwidth is not sufficiently limited by other components in the test signal generation circuit.

The output of the AWG or DAC is likely to require amplification from its low voltage output to the working input signal level (voltage or current), which can be achieved using an amplifier of sufficient bandwidth. In the case of current signal generation, the output of the AWG or DAC may be converted to a current using a transconductance amplifier, which is defined as a voltage controlled current source (VCCS).

The −3 dB bandwidth of the whole input signal generation circuit should be at least 2 kHz (see Note).

In order to generate three phase test signals, three DAC or AWG channels with phase synchronized outputs can be used. Alternatively, three separate single-channel DAC or AWG can be used with a common sample clock and/or triggering such that the three output channels remain synchronized. The phase accuracy and stability of the $2\pi/3$ radians displacement between the phases should be checked prior to starting the tests.

When the functional test requires a sudden change in frequency, the applied signal shall be generated without discontinuity in voltage waveform, other than the required frequency change. This frequency change is illustrated in Annex F. Such test conditions are required to avoid adding the impact of voltage discontinuity on frequency or ROCOF measurement. Such impact is specifically tested in I.2.2.

NOTE Generation of input signal components below the nominal power frequency can be necessary to verify measuring range and operating range. Compensation can be made for any significant attenuation of low frequencies by the signal generation equipment by boosting the DAC output level at these frequencies.

When the measurement function is completely embedded inside the power conversion equipment of DER with no direct output of frequency or ROCOF measurement, the manufacturer shall describe the method used to perform these functional tests, specifically on frequency or ROCOF measurement functions. The manufacturer shall describe, in the type test report, the inputs and outputs which are used to perform these tests. For example, some functional tests can be based on DER outputs (e.g. active power, associated with the described relationship between the frequency or ROCOF measurement and the DER active power output).

If frequency or ROCOF measurement outputs are not accessible, functional tests can be performed with a digital simulation (digital twin) of the measuring chain, but the manufacturer shall describe how the digital simulation has been validated regarding the physical device (hardware and software parts).

When the input energizing quantities are used at the same time for measurement functions and the auxiliary power supply of the instrument, all the tests described in 6.3 to 6.6 shall be performed with same signals for measurement and power supply circuits.

As some functional tests described in Clause 6 and in Annex I are based on similar input signals, to facilitate tests and decrease testing time, the tests may be performed in a different order than presented in this document, except for the test to verify the delay time (6.3), which is required for some other tests.

6.2 Test reference conditions

Whilst it is possible to carry out functional tests on the software implementation of a measurement algorithm for development and diagnostic purposes, validation testing of the instrument shall be carried out in a laboratory using test equipment unless there is no direct output of the frequency or ROCOF measurement. The effect of the measurement chain including any transducers and signal conditioning circuits outside of the instrument should be compensated in the measured performance of the instrument.

When the tests are based on AWG or DAC with pure sinusoidal waveforms, the total distortion factor shall be below 2 % unless otherwise specified in the test.

Where possible, testing should be carried out in a temperature-controlled environment and the range of temperature variation that occurred during testing should be recorded.

6.3 Verification of delay time for frequency and ROCOF measurement

6.3.1 Test description

Delay time is presented first in Clause 4 and Clause 6 because the value of delay time is necessary to perform some of the verification test procedures which follow. Furthermore, the same data gathered during the delay time verification testing of 6.3 can also be used in the verification of effective measurement resolution test of 6.4.

Under steady state conditions, frequency and ROCOF are unchanging, so delay time cannot be verified with a steady state input. Using a linear ramp of frequency (also called linear chirp), the frequency delay can be verified but the ROCOF is unchanging so the ROCOF delay time cannot be verified. To validate both frequency and ROCOF delay times, a test with sinusoidal frequency modulation shall be conducted. The test has the added benefit that the data taken during this test will also be used to determine the effective measurement resolution. Since linear ramps of frequency occur in actual power systems, an optional test for frequency delay time during a linear frequency ramp is presented in Annex I.

The input signal used for validation of delay time for frequency and ROCOF measurement shall be a frequency modulated test signal generated using Formula (1). The values of K_{m} and f_{m} shall meet the manufacturer's specifications for measuring ranges of frequency and ROCOF. The input signal's frequency modulation shall cover the entire frequency measuring range. The input signal's peak ROCOF should be within the instrument's ROCOF measuring range but may extend beyond it into the ROCOF operating range. Equations for frequency and peak ROCOF are given by Formulas (2) and (3):

$$X_{\text{p}}(t) = X_{\text{c}} \times \sin\left(2 \times \pi \times f_0 \times t + \varphi_{\text{p}} + K_{\text{m}} \times \sin\left(2 \times \pi \times f_{\text{m}} \times t\right)\right) \quad (1)$$

where

$X_{\text{p}}(t)$ is the input energizing quantity at time t;

t is time;

X_{c} is the peak amplitude of the input signal;

f_0 is the nominal power frequency (50 Hz or 60 Hz);

φ_{p} is the initial phase of the signal, defined in 6.1 for single and three phase signals;

f_m is the modulation frequency in hertz;

K_m is the modulation index: $K_m = \frac{\Delta f}{f_m}$ where Δf (delta frequency) is the magnitude of the frequency oscillation around f_0. The fundamental frequency oscillated between $f_0 - \Delta f$ and $f_0 + \Delta f$. For example, if f_m = 2,0 Hz, then K_m = 2,5 will give Δf = ±5 Hz deviation from f_0; if f_0 = 50 Hz, then the modulation will range from 45 Hz to 55 Hz.

For the input signal defined by Formula (1), frequency ($f(t)$) and ROCOF functions of time are given by Formulas (2) and (3), respectively:

$$f(t) = f_0 + K_m \times f_m \times \cos(2 \times \pi \times f_m \times t) \quad (2)$$

$$\text{ROCOF}(t) = K_m \times 2 \times \pi \times {f_m}^2 \times \sin(2 \times \pi \times f_m \times t) \quad (3)$$

A test signal is applied with the test frequency set to the nominal power frequency. When the instrument has settled. Measurements are recorded for 10 modulation cycles. The duration of the recorded values will be $10/f_m$.

The delay time for frequency and ROCOF is determined by the time difference between the values of the input energizing signal and the time that those values appear at the instrument output. The value of the input energizing signal at the time of the instrument output is called the reference value. Since the recorded values are discrete (either discrete records of an instrument's continuous output or, more likely, values reported by an instrument at a discrete reporting interval), it is likely that the actual delay time will fall somewhere between discrete samples/instrument reports. For this reason, a correlation-based, sub-sample time delay estimation method is recommended to calculate the precise time delay.

If the sampling/reporting period is very high, the simplest method could be to find the peak of the cross-correlation between the reference and instrument values. However, the best resolution of this method will be one sampling/reporting period. However, it is possible to improve delay estimation resolution by interpolating the cross-correlation function between two samples/reports [3]. Because a frequency modulated test signal was applied and the frequency and ROCOF values are sinusoidal, a cosine-fit interpolation method will be suitable. This method is shown in the example in 6.3.2.

6.3.2 Example determination of delay time

Figure 4 shows an example from an actual instrument. In this test, modulation frequency was fixed at 1,0 Hz and modulation index was fixed at 5,0. The values of frequency and ROCOF of the input energizing signal (reference, shown in blue) are determined at the same time as the instrument frequency measurement output (shown in red).

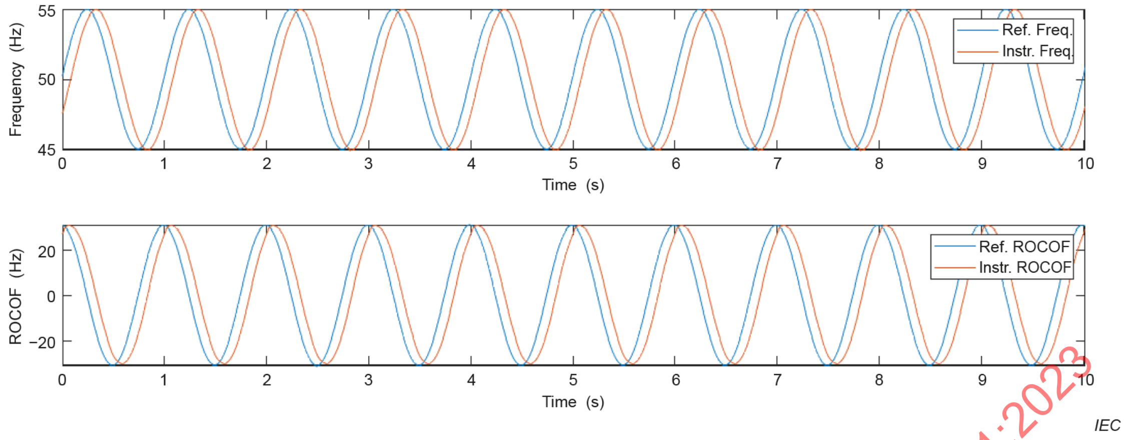


Figure 4 – Example of frequency delay time validation: measurement of delay time for a power frequency of 50 Hz

In order to calculate the cross-correlation for frequency, the frequency deviation around the nominal frequency shall first be normalized around 0 Hz. Subtract the nominal frequency from the input energizing and instrument frequencies then perform the cross correlation.

Figure 5 shows the cross-correlation of the normalized reference and instrument frequencies the x-axis is the lag. The red vertical line shows the lag of the maximum value of cross-correlation. This value, and the values on either side of it, will be used to estimate the subsample time delay. In this example, the reporting period of the instrument was 0,020 s.

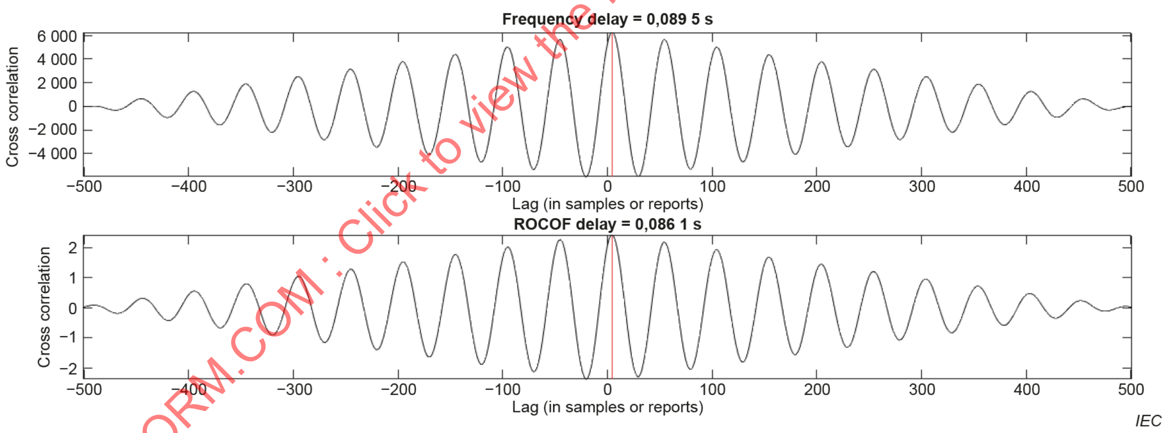


Figure 5 – Example of cross-correlations of the normalized frequencies and ROCOF

To estimate the sub-sample/sub-report delay value, a cosine fit is suitable for sinusoidal data. If k is the lag of the maximum cross-correlation value $xc(k)$, and the two neighbouring values are given as $xc(k-1)$ and $xc(k+1)$, then the interpolated peak can be calculated using Formulas (4), (5) and (6):

$$\omega = \left(\frac{xc(k-1) + xc(k+1)}{2xc(k)} \right) \quad (4)$$

$$\theta = \left(\frac{xc(k-1) - xc(k+1)}{2xc(k)\sin(\omega)} \right) \tag{5}$$

$$t_\text{d} = \left(\left(k - 1 - \text{floor}\left(\frac{m}{2} \right)_\text{r} \right) - \frac{\theta}{\omega} \right) \text{d}T \tag{6}$$

where

t_d is the delay time;

$\text{floor}\left(\frac{m}{2} \right)_\text{r}$ is half the number of samples (reports) rounded down;

$\text{d}T$ is the sampling or reporting period.

In this example, k for both frequency and ROCOF is equal to 4, so, with a 50 reports per second reporting rate, without estimating the sub-sample value, the delays would have been calculated at 0,080 s. By using the cosine fit sub-sample delay estimation, the frequency delay is estimated at 0,089 5 s and the ROCOF delay at 0,086 1 s.

In the tests to follow in Clause 6, for the purpose of determining the frequency and ROCOF values of the input energizing signal at the time that the instrument determines its measurement, the instrument delay time shall be applied to determine the time at which to determine appropriate reference values of frequency and ROCOF of the input energizing signal. For this purpose, the delay time estimation technique presented in the above may be followed by a curve fitting technique which minimizes the difference between the instrument readings and the reference values. The estimated delay time determined above should be used as the initial estimate of this minimization process.

6.4 Verification of effective resolution for frequency and ROCOF measurement

6.4.1 Test description

The effective resolution of the frequency measurement function of the instrument is verified using the same data gathered during the verification of delay time in 6.3. No further data is required. From Formula (1), the values of K_m and f_m met the manufacturer's specifications for measuring ranges of frequency and ROCOF. The input signal's frequency modulation covered the entire frequency measuring range. The input signal's peak ROCOF should be within the instrument's ROCOF measuring range.

Measurements were recorded for 10 modulation cycles. The duration of the recorded values was $10/f_\text{m}$. For the rest of 6.4.1, the time series of frequency measurements is referred to as $F(t)$.

The effective frequency resolution in Hz, and ROCOF resolution in Hz/s, is determined by fitting a sinusoidal model of frequency values to the measured data and using the residual of the fit to determine the amount of measurement noise and distortion.

The sinusoidal model to be fitted is a model of sinusoidally modulated frequency values about a nominal centre frequency. The model parameters are based on the parameters used in Formula (1). The formula for the model is:

$$x[n] = A_0 \times \cos(2 \times \pi \times f_m \times t_n) + B_0 \times \sin(2 \times \pi \times f_m \times t_n) + f_0 \quad (7)$$

where t_n is the time associated with the nth data value. If the exact value of f_m is known, a three-parameter sine fit can be used; but if f_m is uncertain, a four-parameter sine fit can be used [4]. The four-parameter fit is recommended. f_0 will be the nominal frequency and is one of the parameters to be determined by the sine fitting function. The fitting function determines the parameters A_0, B_0, f_0, and (using a four-parameter fit) f_m.

Once the model parameters are determined using linear regression, the model amplitude will be the depth of modulation, M:

$$M = \sqrt{A_0^2 + B_0^2} \quad (8)$$

The model phase will be:

$$\phi = \text{arctan}(A, B) \quad (9)$$

The model fitted to the instrument measurements will be a series of sinusoidally modulated frequency values:

$$\overline{F(t)} = M\cos(2 \times \pi \times f_m \times t + \phi) + f_0 \quad (10)$$

The residual is the RMS value of the difference of frequency measured time series and the time series of the model. This RMS value of the residual is called the RMS Residual (R_rms).

$$\text{R}_\text{rms} = \left[\frac{1}{N}\sum_{n=1}^{N}\left(F[n] - \overline{F[n]}\right)^2\right]^{\frac{1}{2}} \quad (11)$$

where N is the number of measurements, $F[n]$ is the measurement at time t_n, $\overline{F[n]}$ is the value of $\overline{F(t_n)}$ at time t_n.

Effective resolution (E_res) is the ratio of the R_rms to the peak measurement of the modulation multiplied by the declared measuring range [5].

$$\text{E}_\text{res} = \frac{\text{R}_\text{rms}}{\text{P}_\text{meas}} \times \text{M}_\text{range} \quad (12)$$

where P_{meas} is the maximum instrument reading value recorded over the duration of the test and M_{range} is the difference between the maximum and minimum values of the declared measuring range.

6.4.2 Example determination of effective resolution

An example is shown for an actual instrument measuring nominal 50 Hz with a frequency measurement range of ±5 Hz and ROCOF over ±60 Hz/s. The input sinewave was sine modulated with K_m = 5,0 and f_m = 1,0 Hz. This provides 55 Hz peak frequency measurement and peak ROCOF measurement of 62,8 Hz/s. Figure 6 shows the measured frequency, the fitted sinewave, and the residual. The frequency effective resolution is 0,001 7 Hz. Figure 7 shows the ROCOF measured value, fitted signal and residual. The ROCOF effective resolution is 0,034 5 Hz/s.

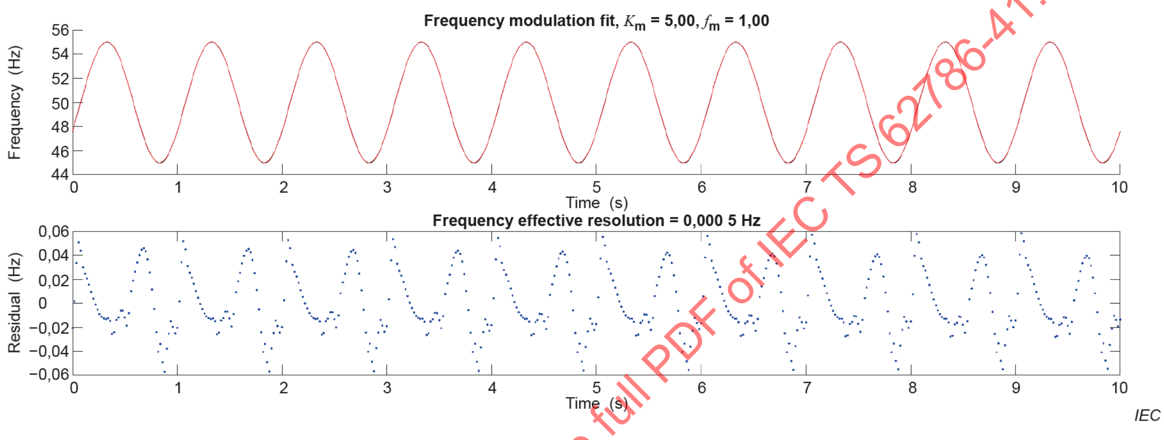


Figure 6 – Example of frequency modulation used to determine frequency effective resolution

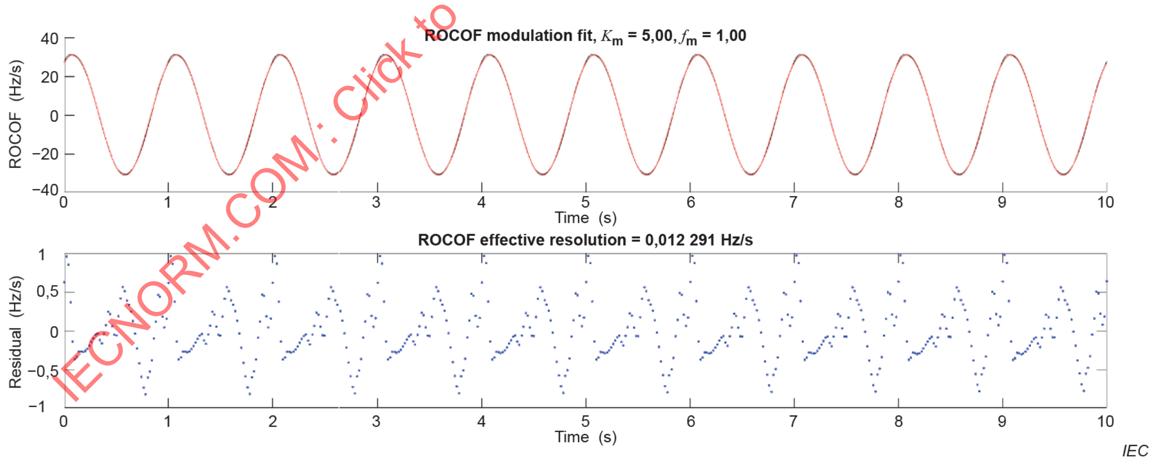


Figure 7 – Example of frequency modulation used to determine ROCOF effective resolution

6.5 Verification of measurement and operating ranges

6.5.1 Verification of measurement and operating ranges under steady state conditions

6.5.1.1 Test description

The measurement and operating ranges of the instrument under steady state conditions are determined using a test signal generated using Formula (13).

$$X_p(t) = X_c \times \sin(2 \times \pi \times f_a \times t + \varphi_p) \quad (13)$$

Where X_c is the peak amplitude of the input signal, f_a is the test frequency and φ_p is defined in 6.1 for single phase and three phase signals.

With reference to Figure 1 in 4.5, the test frequency f_a in Formula (13) is changed in increments of frequencies below and above the nominal power frequency. At each frequency, the instrument's frequency and ROCOF readings are observed as well as the input signal's frequency. Sufficient time should be allowed for the instrument to settle between frequency increments before measurements are observed (typically, more than five times the declared settling time). The duration at each frequency shall be the greater of 5 s or until 50 instrument reports have been collected.

The absolute value of the error of the measurements ($|f_{err}|$) is given by Formula (14).

$$|f_{err}| = \text{abs}(f_{meas} - f_{input}) \quad (14)$$

where

f_{meas} is the measured frequency by the instrument;

f_{input} is the frequency f_a of the input signal defined in Formula (13).

Frequencies should be tested across the entire operating range to verify that the instrument operates within this range.

6.5.1.2 Example of verification of measurement and operating range under steady state conditions

The instrument from the example given in 4.5 was tested to verify the manufacturer's declared measurement and operating ranges. The measurement range was declared by the manufacturer to be nominal frequency f_n ± 5 Hz (45 Hz to 55 Hz for 50 Hz nominal frequency). The operating range was declared at f_n ± $f_n/2$ (25 Hz to 75 Hz). The maximum absolute frequency error was given by the manufacturer to be |±0,005 Hz| and the maximum absolute ROCOF error was given by the manufacturer to be |±0,04 Hz/s|.

In this example, signals in accordance with Formula (13) were input to the instrument with frequencies ranging from 25 Hz to 45 Hz in 0,5 Hz increments, from 45 Hz to 55 Hz in 0,1 Hz increments and from 55 Hz to 75 Hz in 0,5 Hz increments. In other words, the increments within the measurement range are 0,1 Hz and the increments in the operating range but outside the measuring range were 0,5 Hz.

Figure 8 shows the highest recorded absolute frequency and ROCOF error for each frequency tested. The blue vertical dashed lines show the measuring range for frequency and ROCOF. The red vertical dashed lines show the operating range. Within the measuring range, the test validates that measurements output by the instrument were lower than the manufacturer's declared absolute error. Within the operating range but outside the measuring range, the test validates that measurements were output by the instrument; accuracy was not required to be lower than the manufacturer's declared maximum absolute error. This example validates that the instrument complies with the manufacturer's specification under steady state conditions.

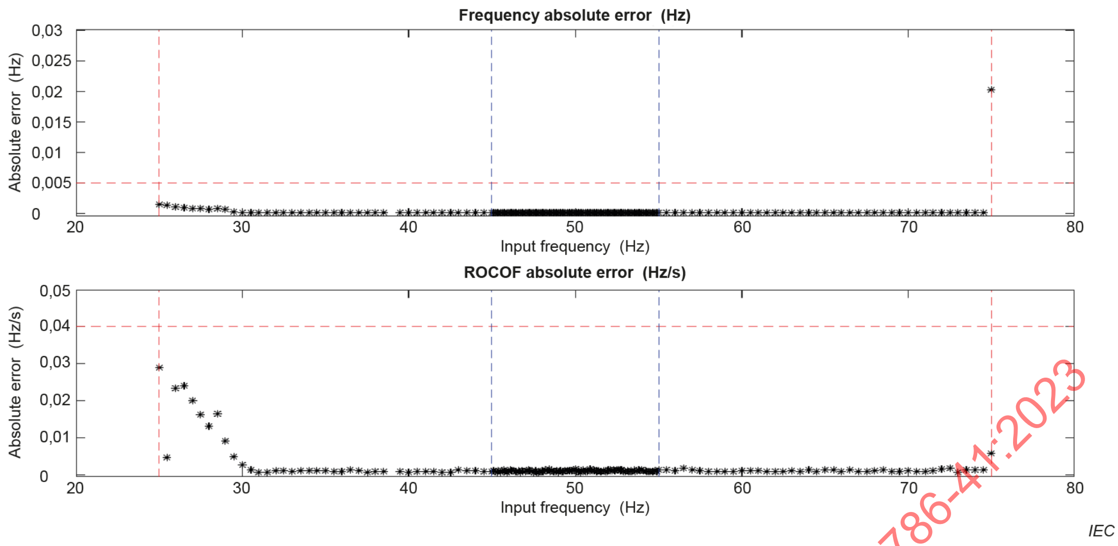


Figure 8 – Example of verification of measurement bandwidth under steady state conditions

6.5.2 Measuring and operating ranges under dynamic conditions

6.5.2.1 Test description

The measuring and operating ranges of the instrument under dynamic conditions are determined using a signal with a modulated frequency as given by Formula (1) in 6.3.1.

The base carrier function of the test signal is a sinusoidal waveform at the nominal power frequency f_0. The modulation function of the test signal is a sinusoidal waveform which causes a frequency variation in the declared measuring range of the instrument.

For the input signal defined by Formula (1), frequency and ROCOF functions of time are given by Formulas (2) and (3), respectively, in 6.3.1.

The values of K_m and f_m in Formula (1) determine the amount of frequency modulation that occurs on the test signal and the values of these parameters shall be adjusted in the test to declared measuring and operating ranges of the instrument under dynamic conditions.

Both K_m and f_m need to be varied to validate that the instrument is able to reach the measuring and operating ranges of both frequency and ROCOF. The modulation frequency f_m in Formula (1) is increased in steps such at least 10 measurements are made in the declared instrument operating range.

The value of K_m shall be adjusted to ensure that the frequency and ROCOF, given by Formulas (2) and (3), remain in the measuring or operating range declared by the manufacturer. The peak frequency (f_{peak}) and peak ROCOF ($ROCOF_{peak}$) reached by the input signal are functions of both K_m and f_m as shown in Formulas (15) and (16).

$$f_{peak} = f_0 + K_m \times f_m \tag{15}$$

$$\mathrm{ROCOF_{peak}} = K_\mathrm{m} \times 2 \times \pi \times f_\mathrm{m}^{\ 2} \tag{16}$$

where

K_m is the modulation index used in Formula (1);

f_m is the modulation frequency in hertz used in Formula (1).

The manufacturer shall declare in the type test report the K_m and f_m values which are used for this test. For symmetrical measuring or operating range around the nominal power frequency, the frequency f_0 can be defined to the nominal value. In case of unsymmetrical range, the f_0 value can be different from nominal value, to cover the full measuring and operating range with different K_m and f_m values.

6.5.2.2 Verification of measuring range under dynamic conditions

To verify the measuring range of frequency and ROCOF under dynamic conditions, a series of input tests, with, signals conforming to Formula (1), are used with the modulation frequency f_m fixed at the limit of the frequency measuring range and the modulation index K_m beginning at 0,1 and incrementing in 10 steps of 0,1 until K_m = 1 is reached. Each test will be conducted for at least 100 instrument reporting periods and the highest absolute value of error each test iteration will be used as the error for that iteration. The highest absolute value of error for all 10 test iterations should not exceed the manufacturer's declared maximum absolute error for measuring range under dynamic conditions.

6.5.2.3 Verification of operating range under dynamic conditions

To verify the operating range of frequency and ROCOF under dynamic conditions, a series of input tests, with signals conforming to Formula (1), are used with the modulation index K_m fixed equal to the limit of the measuring range and the modulation frequency beginning at 1,0 Hz and incrementing in steps of 0,5 Hz until the delta-frequency (the product of $K_\mathrm{m} \times f_\mathrm{m}$) has reached the limit of the frequency operating range. If the limit of the frequency operating range is not reached by an increment of 0,5 Hz, then one test at the operating range limit shall be performed. Each test will be conducted for at least 100 instrument reporting periods and the highest absolute value of error each test iteration will be used as the error for that iteration. It does not matter what the value of the absolute error of frequency and ROCOF are, as long as the instrument has not gone into a saturation mode where recovery time is required.

6.5.2.4 Example of verification of measuring range and operating range under dynamic conditions

The manufacturer of an actual instrument has declared the frequency measuring range to be the nominal frequency f_n ± 5 Hz with a maximum absolute frequency error under dynamic conditions to be 0,35 Hz and the ROCOF measuring range to be ±60 Hz/s with the maximum absolute ROCOF error under dynamic conditions to be 14 Hz/s. The manufacturer further declares the frequency operating range at 50 Hz nominal frequency to be f_n ± 25 Hz and the ROCOF operating range to be outside of ±800 Hz/s.

The tests to verify measuring range under dynamic conditions used the frequency modulated waveform specified in Formula (1) with a fixed modulation frequency f_m of 5 Hz and K_m from 0,1 to 1,0 in increments of 0,1. In Figure 9, the maximum absolute error inside the measuring range is plotted as blue asterisks. The measuring range limits are shown with blue vertical lines at ±5 Hz for frequency and ±60 Hz/s for ROCOF. The manufacturer's declared maximum error under dynamic conditions is shown by horizontal red dotted lines.

The tests to verify operating range under dynamic conditions used the frequency modulated waveform specified in Formula (1) with a fixed modulation index K_m of 5 and modulation frequencies f_m from 1 Hz to 5 Hz in increments of 0,5 Hz. The maximum absolute error outside the measuring range but inside the operating range is shown as red asterisks in Figure 9. The values of these errors beyond the measuring range do not matter as long as the instrument did not enter a saturation mode where time to recover was needed, which it did not during the test.

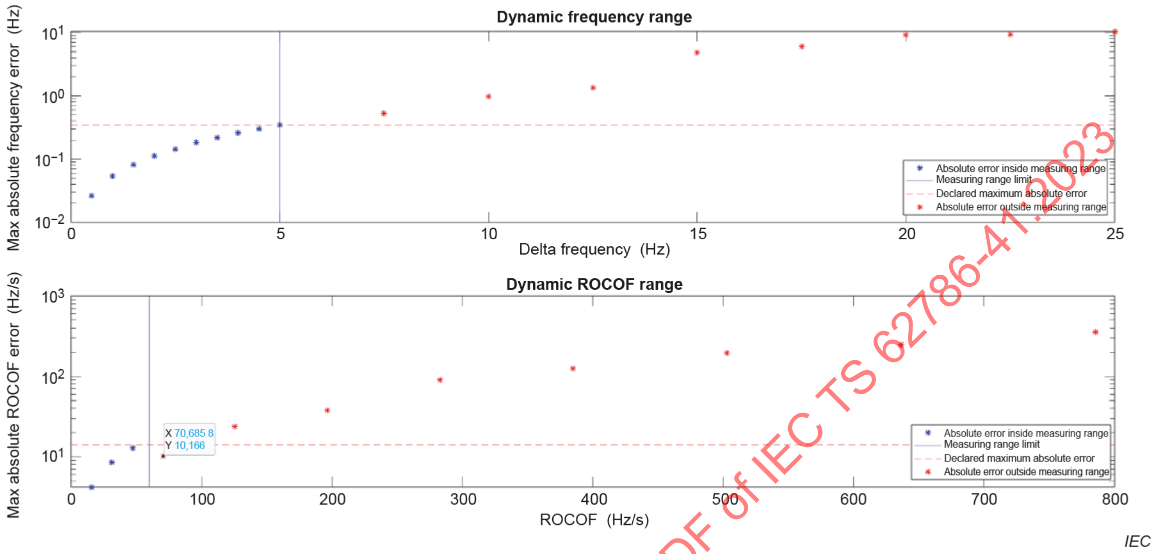


Figure 9 – Example of verification of measuring and operating ranges under dynamic conditions

6.5.3 Verification of rejection of interfering interharmonics

6.5.3.1 Test description

Interfering signals are signal components in addition to the fundamental component being measured by the instrument. As described in 4.5, interfering signals with frequencies outside the operating range shall not cause the error to be greater than the manufacturer's declared maximum absolute error. Interfering signals with frequencies between the measuring range and the operating range may cause the instrument error to be greater than the manufacturer's declared maximum absolute error.

The test to verify the rejection of interfering interharmonics shall combine a single sinusoidal interfering signal with a sinusoidal signal at the nominal power frequency. The equation for the test signal is:

$$X_p(t) = X_c \times \sin(2 \times \pi \times f_0 \times t + \varphi_p) + 0{,}04 \times X_c \times \sin(2 \times \pi \times f_i \times t + \varphi_p) \qquad (17)$$

where

$X_p(t)$ is the input energizing quantity at time;

t is time;

X_c is the peak amplitude of the fundamental component;

f_0 is the nominal frequency;

f_i is the frequency of the interfering signal;

φ_p is defined in 6.1 for single phase and three phase signals.

The duration for each test frequency shall be the greater of 5 s or until 50 instrument reports have been captured.

Multiple iterations of the test are run where the frequency of the interfering signal, f_i, is incremented. The f_i begins at 10 Hz and is incremented in steps of 0,5 Hz until the lower frequency of the measuring range is reached. The f_i is next set to the upper frequency of the measuring range and incremented by 0,5 Hz until the first harmonic of the nominal frequency is reached.

NOTE The magnitude of interfering signal is equal to 4 % of the fundamental component, based on Table 4 of IEC 61000-4-13:2002, applied to class 3.

Plots of the absolute value of error of frequency and ROCOF show the absolute error inside the operating range and is used to verify that the error outside the operating range is lower than the manufacturer's declared maximum absolute error.

6.5.3.2 Example of verification of rejection of interfering interharmonics

Figure 10 shows an example from an actual instrument of the verification of rejection of interfering interharmonics.

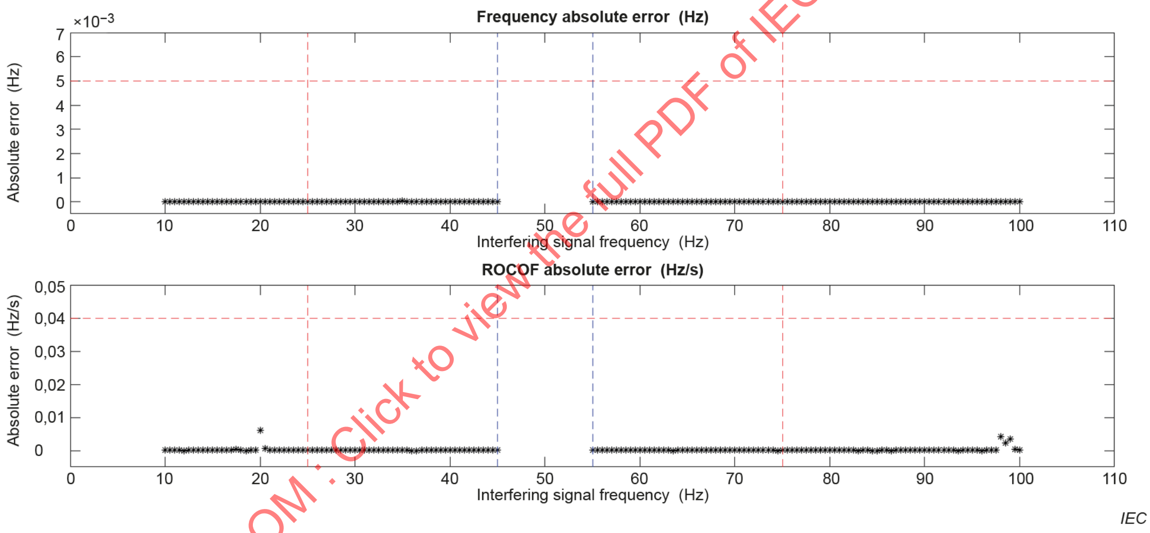


Figure 10 – Example of verification of rejection of interfering interharmonics

In Figure 10, the subplot at the top shows the frequency absolute error and the subplot below shows ROCOF absolute error. In the presence of a 1 p.u. sinewave at nominal frequency, interfering interharmonic signals were injected at frequencies from 10 Hz to the lower measuring range frequency of 45 Hz and from the upper measuring range frequency of 55 Hz up to and including the second harmonic of the nominal frequency. From each test period of 5 s, only the maximum absolute error is shown in Figure 10. Blue vertical dashed lines show the measuring range. Red vertical dashed lines show the operating range, and the red horizontal dashed lines show the manufacturer's declared maximum absolute error. Note that the instrument absolute error outside of the operating range is not required to fall below the manufacturer's declared maximum absolute error.

6.5.4 Verification of rejection of harmonics

6.5.4.1 Test description

This test assesses the errors of the instrument to signals containing harmonics.

The instrument errors in the presence of steady-state harmonics shall be determined using the input signal given by Formula (18).

$$X_\text{p}(t) = X_1 \sin\left(2 \times \pi \times f_0 \times t + \varphi_\text{p}\right) + \sum_{h=2}^{13} X_h \times \sin\left(h \times (2 \times \pi \times f_0 \times t + \varphi_\text{p}) + \varphi_k\right) \quad (18)$$

where

X_1 is the peak amplitude of the input signal with no harmonic distortion;

X_h is the peak amplitude of the input signal of the harmonic distortion of the hth harmonic;

f_0 is the nominal power frequency;

φ_p is defined in 6.1 for single phase and three phase signals;

φ_k is the phase shift of the harmonic component with respect to the fundamental;

h is the number of the harmonic, which is an integer value.

Table 7 gives the magnitudes (see Note 1) of the harmonic components, X_h given as a percentage of X_1, and the waveform is shown in Figure 11 (in Figure 12 for three-phase signals).

NOTE 1 The harmonic magnitudes are based on the compatibility levels given in IEC 61000-2-2 [6], applicable to public low-voltage power supply systems.

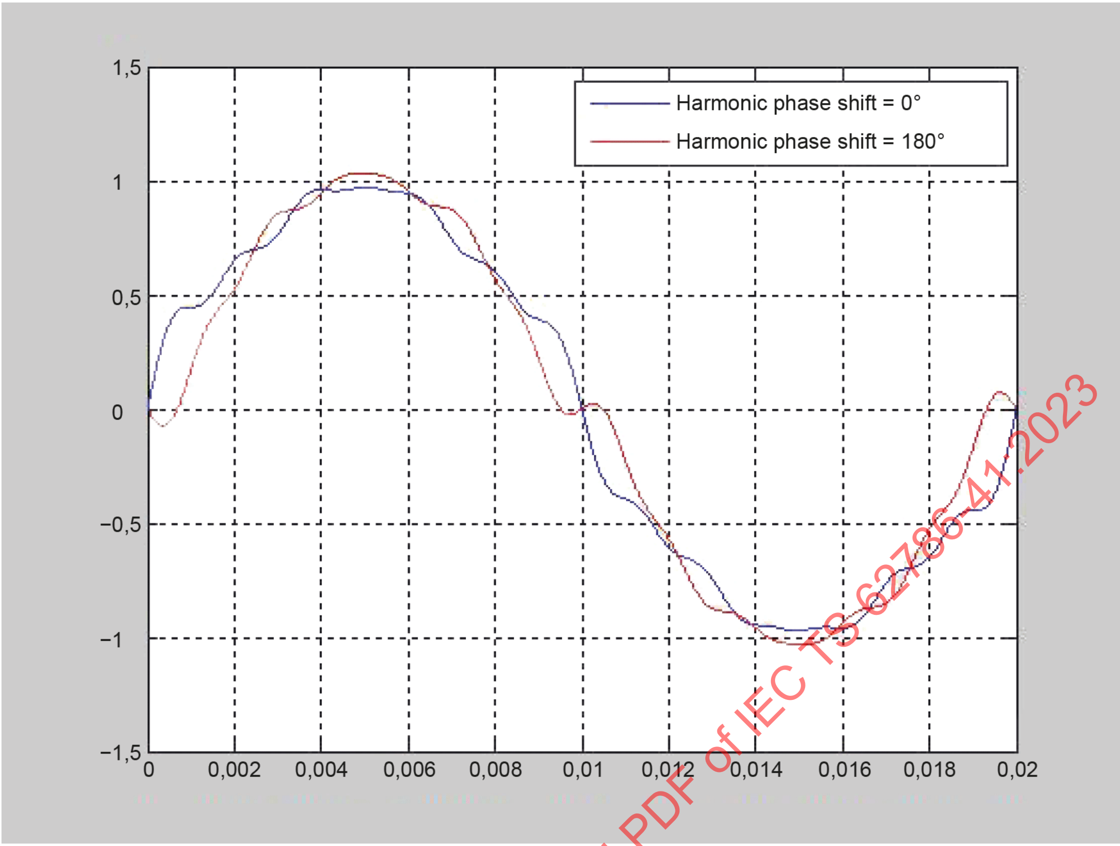
Table 7 – Input signal harmonic magnitudes

Harmonic number, h	2	3	4	5	6	7	8	9	10	11	12	13	THD
Magnitude, X_h (% of X_1)	2,0	5,0	1,0	6,0	0,5	5,0	0,5	1,5	0,5	3,5	0,5	3,0	10,7

The test shall be repeated for φ_k set to 0° and 180° (see Note 2).

NOTE 2 Phase φ_k equal to 180° generates additional zero crossings in the signal, which is used to check that the frequency measurement is not sensitive to additional zero crossing due to harmonics. Such harmonic content and phase shift are already proposed in IEC 60255-181 [2].

The amplifier and other test equipment used to generate the input signal should have sufficient bandwidth to generate the harmonics given in Table 7 to within 5 % of the value.



Blue signal has φ_k = 0°, red signal has φ_k = 180°.

Figure 11 – Waveforms with superimposed harmonics

The test shall be repeated for f_0 set to nominal and to ±2 Hz either side of the nominal power frequency.

The duration of the test shall be the greater of 5 s or the period required to collect 50 reports from the instrument.

When the input energizing quantities are based on three-phase injection, the test signals shall be performed in accordance with Formula (19):

$$\begin{aligned} X_{pa}(t) &= X_1 \times \sin(2 \times \pi \times f \times t) + \ldots \\ &+ X_k \times \sin(k \times 2 \times \pi \times f \times t + \varphi_k) + \ldots \\ &+ X_{13} \times \sin(13 \times 2 \times \pi \times f \times t + \varphi_k). \\ X_{pb}(t) &= X_1 \times \sin(2 \times \pi \times f \times t - 2 \times \pi / 3) + \ldots \\ &+ X_k \times \sin(k \times (2 \times \pi \times f \times t - 2 \times \pi / 3) + \varphi_k) + \ldots \\ &+ X_{13} \times \sin(13 \times (2 \times \pi \times f \times t - 2 \times \pi / 3) + \varphi_k). \\ X_{pc}(t) &= X_1 \times \sin(2 \times \pi \times f \times t + 2 \times \pi / 3) + \ldots \\ &+ X_k \times \sin(k \times (2 \times \pi \times f \times t + 2 \times \pi / 3) + \varphi_k) + \ldots \\ &+ X_{13} \times \sin(13 \times (2 \times \pi \times f \times t + 2 \times \pi / 3) + \varphi_k). \end{aligned} \tag{19}$$

where

t is the time;

f is the tested power frequency;

X_1 is the peak magnitude of the fundamental component (X_1 = 100 %);

X_k is the peak amplitude level of the k^{th} harmonic (according to Table 7);

φ_k is the phase shift of the harmonic component (expressed in radians).

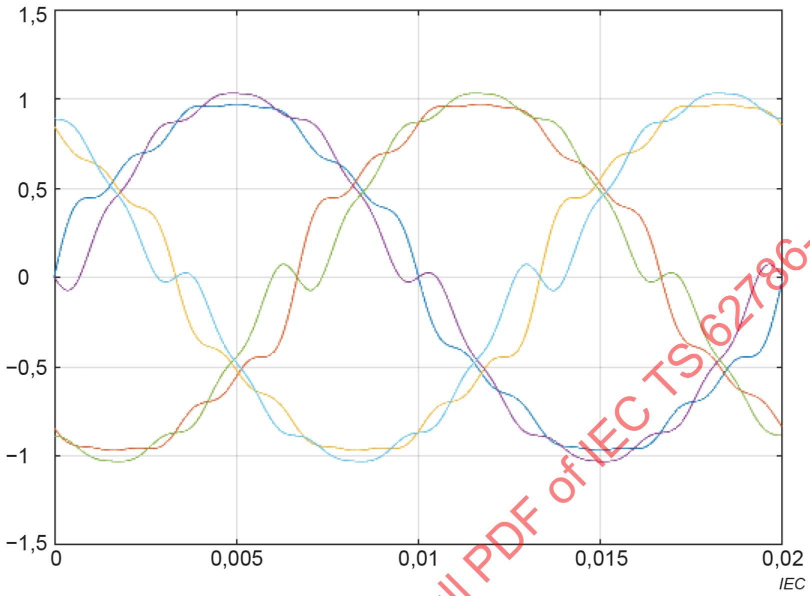
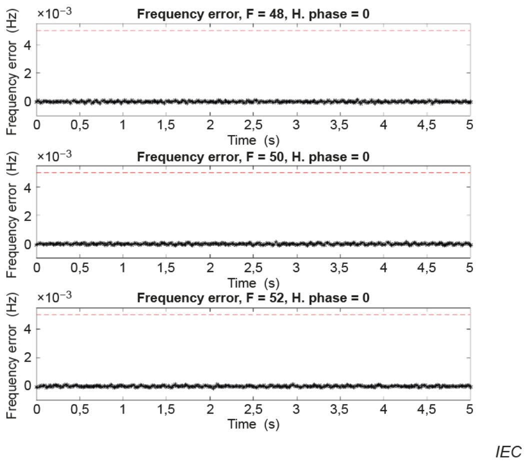


Figure 12 – Three-phase harmonic test signals, 0° and 180° harmonic phases

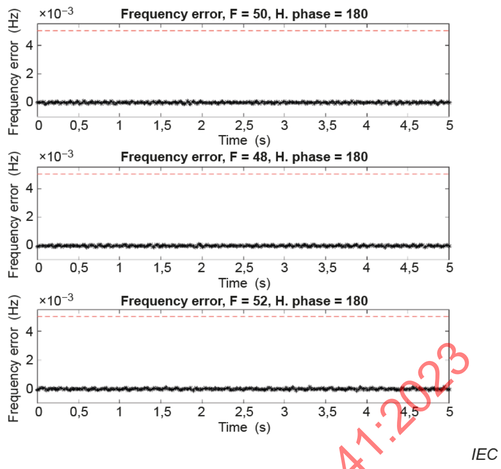
6.5.4.2 Example of verification of rejection of interfering harmonics

Figure 13 shows an example from an actual instrument of the rejection of harmonic interference. Each subfigure shows fundamental frequency and harmonics of 48 Hz, 50 Hz and 52 Hz. Subplots for harmonic phase equal to 0° and 180° are shown. Pairs of subplots for frequency error and ROCOF error are shown. Red dashed lines show the manufacturer's declared maximum absolute errors for frequency and ROCOF.

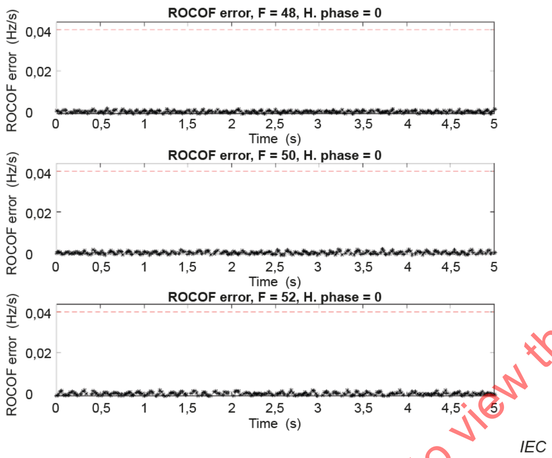
As shown in Figure 13, this actual instrument has no errors above the manufacturer's declared absolute error over the test duration of 5 s.



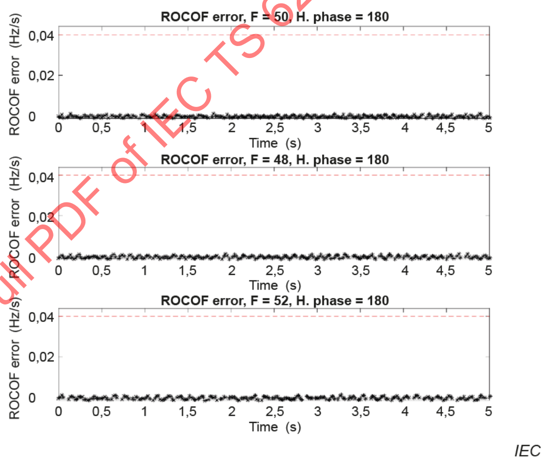
a) **Frequency error, 0° harmonic phase**



b) **Frequency error, 180° harmonic phase**



c) **ROCOF error, 0° harmonic phase**



d) **ROCOF error, 180° harmonic phase**

Figure 13 – Example of verification of rejection of harmonics

6.6 Verification of settling time

6.6.1 Test description

The settling time, defined in 3.16, is determined from the instrument readings with reference to Figure 3. In the case of frequency, the tolerance shall be 95 % and 105 % of the step size. It is possible that the instrument readings could be affected by the phase of start point of the frequency step relative to the zero crossing of the input signal. The start point phase used in the input signal should be varied and the test repeated to determine the worst-case settling time.

When the functional test requires a sudden change in frequency, the applied signal shall be generated without discontinuity (i.e. phase step) in the input energizing quantity. This frequency change is illustrated in Annex F.

It is likely that the instrument readings will be affected by the finite reporting time of the instrument, in particular, when the reporting rate is long compared to the settling time. Because a frequency step can occur at any point in the reporting interval (the frequency could change at the start of the reporting time, or in the middle, etc.), the settling of the instrument as determined by the subsequent instrument reading(s) will be variable. This variation can be produced systematically using an "equivalent time sampling" technique, where a series of step changes are each separated by an arranged interval. This interval is calculated such that successive steps occur at increasing fractions of the instrument reporting rate. Typically, 10 equivalent time steps per reporting period provide sufficient resolution to determine settling time. Details of this approach are given in Annex G.

6.6.2 Verification of settling time for frequency measurement

The settling time of the frequency measurement function of the instrument is determined using a test signal that contains a step change in frequency as given by Formula (20).

$$X_{\rm p}(t) = X_{\rm c} \times \sin\left(2 \times \pi \times f_0 \times t + \varphi_{\rm p} + h1(t) \times 2 \times \pi \times k_{\rm f} \times t\right) \qquad (20)$$

where

$X_{\rm c}$ is the peak amplitude of the input signal;

f_0 is the nominal power frequency;

$h1(t)$ is a unit step function;

$k_{\rm f}$ is the frequency step size;

$\varphi_{\rm p}$ is defined in 6.1 for single phase and three phase signals.

The step size should be 1,0 Hz for a consistent test of all instrument models.

6.6.3 Example of verification of frequency settling time

Ten individual test runs are performed where the time of the step change in frequency is incremented by the instrument reporting rate divided by 10. The resulting data is recorded and later interlaced to form an equivalent time series. The input reference values are compared to the step response and the settling time is calculated at the period from the step of input frequency until the instrument reading reaches and remains within 95 % to 105 % of the step size around the final input value.

Figure 14 and Figure 15 show the results of the equivalent time sampled step response (black) and the input frequency (green). Time t = 0 is set to the time of the step of input frequency. The blue vertical line shows the settling time where the instrument readings have reached and remain within 95 % to 105 % of the step.

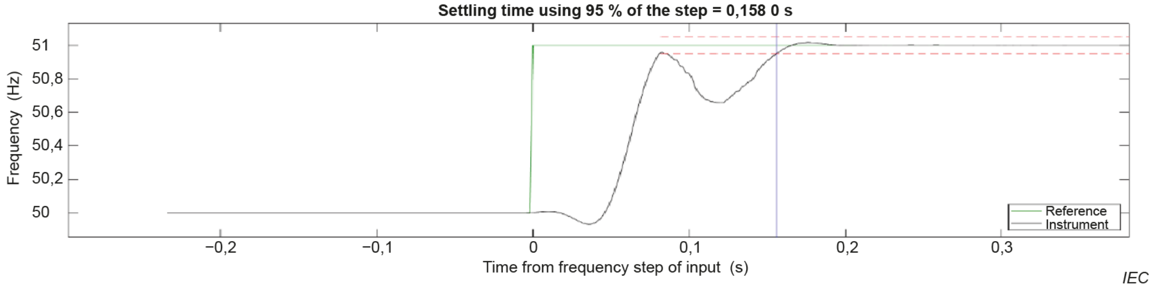


Figure 14 – Example of verification of frequency settling time using positive 1 Hz step in frequency

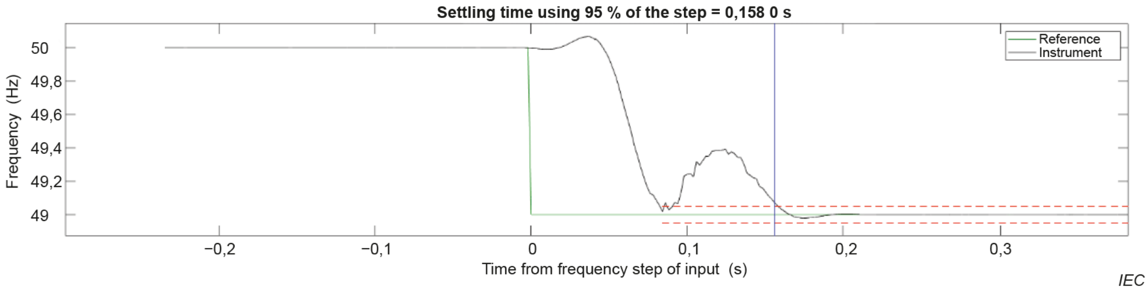


Figure 15 – Example of verification of frequency settling time using negative 1 Hz step in input frequency

6.6.4 Verification of settling time for ROCOF measurement

The settling time of the frequency measurement function of the instrument is determined using a test signal that contains a step change in ROCOF as given by Formula (21).

$$X_p(t) = X_c \times \sin\left(2 \times \pi \times f_0 \times t + \varphi_p + h1(t) \times \pi \times r_f \times t^2\right) \quad (21)$$

where

X_c is the peak amplitude of the input signal;

f_0 is the nominal power frequency;

$h1(t)$ is a unit step function;

r_f the ROCOF step size;

φ_p is defined in 6.1 for single phase and three phase signals.

The step size should be 1,0 Hz/s for a consistent test of all instrument models. The test can end one second following the step unless the settling time is longer than one second, in which case the test should end at least one-half second after the ROCOF has settled.

6.6.5 Example of verification of ROCOF settling time

Ten individual test runs are performed where the time of the step change in ROCOF is incremented by instrument reporting rate divided by 10. The resulting data are recorded and later interlaced to form an equivalent time series. The input reference values are compared to the step response and the settling time is calculated at the period from the step of ROCOF until the instrument reading reaches and remains within 95 % to 105 % of the step size around the final value.

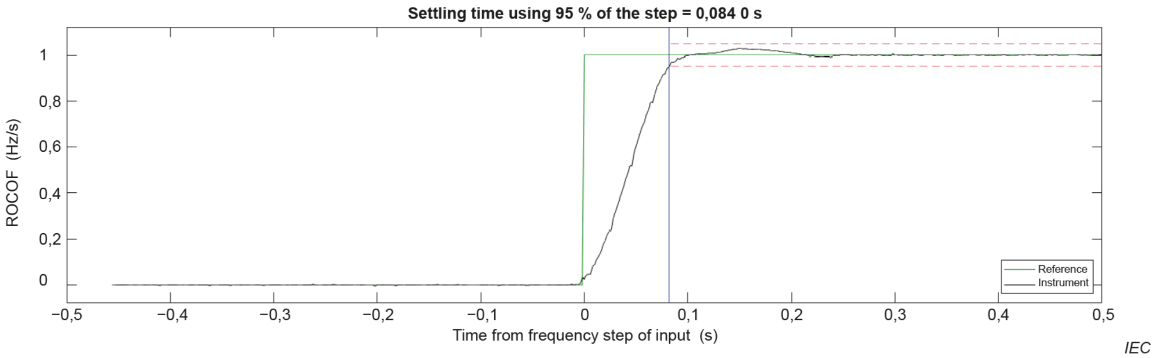


Figure 16 – Example of verification of ROCOF settling time using positive 1 Hz/s step in ROCOF

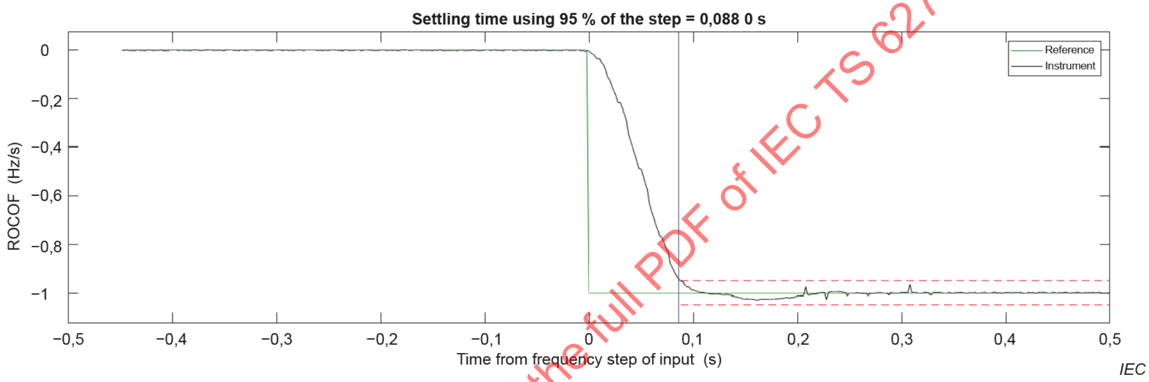


Figure 17 – Example of verification of ROCOF settling time using negative 1 Hz/s step in ROCOF

Figure 16 and Figure 17 show the results of the equivalent time sampled step response (black) and the input ROCOF (green). Time t = 0 is set to the time of the step of input frequency. The blue vertical line shows the settling time where the instrument readings have reached and remain within 95 % to 105 % of the step.

6.7 Type test report

The manufacturer or testing laboratory shall produce a type test report for the functional elements described in this document.

As a minimum, the following aspects shall be recorded.

- Instrument under test references: this includes description of instrument/function under test, as well as specific details such as model number and firmware version.
- Test equipment: equipment name, model number, calibration information.
- Instrument interfaces: inputs and outputs of the instrument, used to perform the tests, shall be described.
- Test results: a heading for each of the tests in 6.3 to 6.6. The results of testing shall be given under each heading together with the method used, the instrument settings, and any other pertinent information.

If it was not possible to perform a particular test or if the test was not applicable, the heading should still be included and an explanation for the absence of the test results according to the methods described in 6.3 to 6.6 should be given. In that case, the manufacturer can declare an alternative test method used to perform the test, if that is the case.

Annex A
(informative)

Measurement classes

Requirements regarding the settling time and the accuracy – as the most relevant characteristics of frequency and ROCOF measurement – are grouped in Table A.1 and Table A.2 on measurement classes. They have been derived from the compilation of use cases in Table 6. Classification serves the purpose of providing standardized products (e.g. class A1 or C2), which can serve different use cases.

Table A.1 – Measurement classes for frequency measurements

Characteristic	Measurement class requirement			
	A	**B**	**C**	**D**
Settling time	60 ms	100 ms	200 ms	1 000 ms
Accuracy: maximum absolute error under steady state or dynamic conditions	100 mHz (steady state and dynamic)	30 mHz (steady state and dynamic)	10 mHz (steady state and dynamic)	1 mHz (steady state)

Table A.2 – Measurement classes for ROCOF measurements

Characteristic	Measurement class requirement		
	1	**2**	**3**
Settling time	100 ms	250 ms	1 000 ms
Accuracy: maximum absolute error under steady state or dynamic conditions	0,1 Hz/s (steady state and dynamic)	0,05 Hz/s (steady state and dynamic)	0,001 Hz/s (steady state)

An instrument can provide user settings to cover several classes. In this case, the manufacturer provides the relationship between setting(s) and class level.

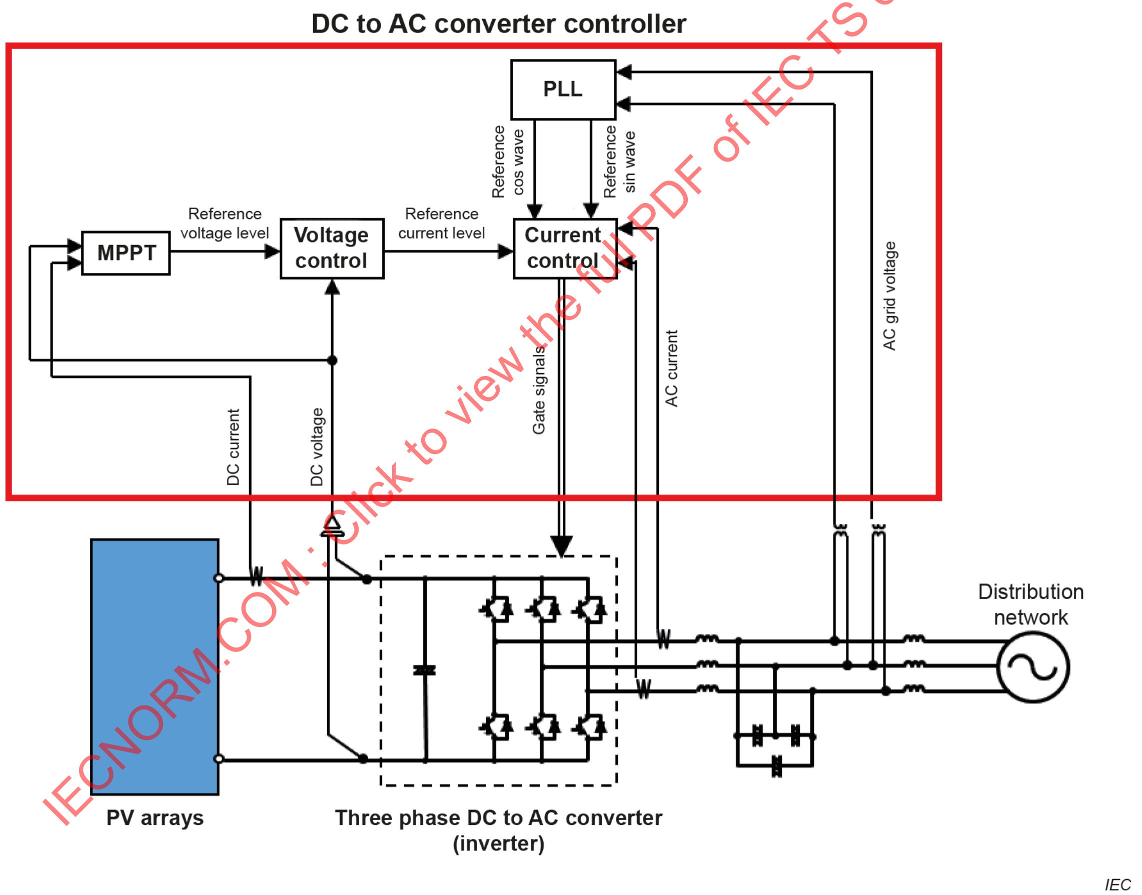
Annex B
(informative)

Description of frequency or ROCOF measurement use cases

B.1 Use case "PLL in photovoltaic power generating systems"

B.1.1 Technical background of the use case

Photovoltaic power generating systems (PV systems) convert DC power, which is generated by solar photovoltaic arrays, into AC power and feed the AC power into the AC grid. Figure B.1 shows an example of a system diagram of a PV system. In distribution networks, the phase locked loop (PLL) is used to synchronize AC output current of the PV system to AC grid voltage, so that the PV system can control active and reactive power which are fed into the AC grid. In this control mode, the DC to AC converter controller in the PV system consists of current control with PLL.



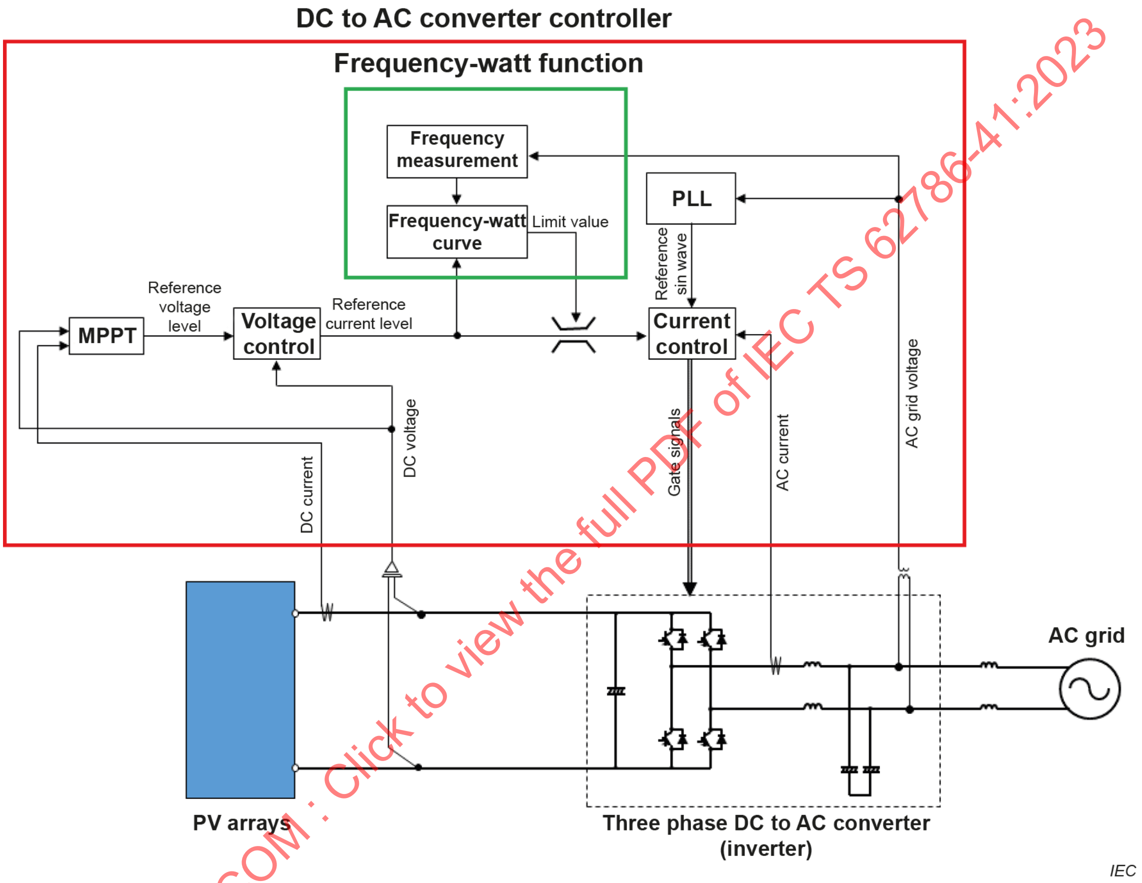
Key

MPPT maximum point power tracking

PLL phase locked loop

Figure B.1 – Example of a system diagram of a PV system with a three-phase DC to AC converter

As an alternative to current control shown above, the PLL can use voltage control to connect the PV system to the AC grid. PLL is used to synchronize inverter voltage of the PV system to AC grid voltage so that the PV system can connect with the AC grid. Figure B.2 shows an example of a system diagram of the PV system. In this control mode, the DC to AC converter controller in the PV system consists of voltage control with PLL. The voltage control and PLL operate to minimize differences of phase angle, frequency and voltage amplitude across a circuit breaker. When the differences of phase angle, frequency and voltage amplitude across a circuit breaker are kept within specified tolerances, the circuit breaker is closed, and the PV system is connected with the AC grid. Then, the PV system starts to control active and reactive power in current control mode.



Key

PLL phase locked loop

Figure B.2 – Example of system diagram of a three-phase PV system for voltage control

B.1.2 Resulting requirements for measurement

PV systems have two modes such as current control and voltage control to synchronize with the AC grid. In both modes, frequency measurement of PLL in PV systems should feature the characteristics given in Table B.1.

Table B.1 – Typical requirements for frequency measurement of PLL in PV systems

Measuring range (Hz) [b]	Typical accuracy (mHz)	Typical settling time (ms)
44 / 53 [c] 56 / 63 [d]	±10	Longer than settling time of voltage or current controller [a]

[a] Typically, 2 or 3 cycles of fundamental frequency may be required to ensure PLL synchronization in case of frequency step change.

[b] For ROCOF measurement, PLL has capability to follow 5 Hz/s in a power system of sufficient size (e.g. interconnected system) where power generators can provide sufficient inertia. In small power systems, e.g. small islands where power generators do not have sufficient inertia, up to 15 Hz/s may be required.

[c] Possible frequency range on a 50 Hz network.

[d] Possible frequency range on a 60 Hz network.

B.2 Use case "Primary reserve"

B.2.1 Technical background of the use case

Primary control is aimed at rapidly re-establishing the balance between active power produced and active power consumed immediately after an event on the power system that results in an active power unbalance (e.g. loss of a power plant). Supply of primary reserve may be required from some of the power plants connected to the transmission and the distribution networks. When it is required, frequency measurements are necessary on each of the relevant power plants to dispatch and control the reserve. They should measure frequency relatively fast and with a good accuracy to allow a rapid and accurate response of the primary regulation, especially in future power systems that may feature less inertia than today's power systems.

To illustrate this use case, an example or real application of power proportional controller is described in B.2.3.

B.2.2 Resulting requirements for measurement

The frequency measurements should feature the characteristics given in Table B.2.

Table B.2 – Typical requirements for frequency measurement – use case "Primary reserve"

Measuring range (Hz)	Typical accuracy (mHz)	Typical settling time (ms)
44 / 53 [a] 56 / 63 [b]	±10 [c]	200 [c] to 1 000 [d]

[a] Possible frequency range on a 50 Hz network.

[b] Possible frequency range on a 60 Hz network.

[c] ENTSOE requirement in view of a power system with less inertia, in particular small systems and microgrids. See § 4.4 in reference [7].

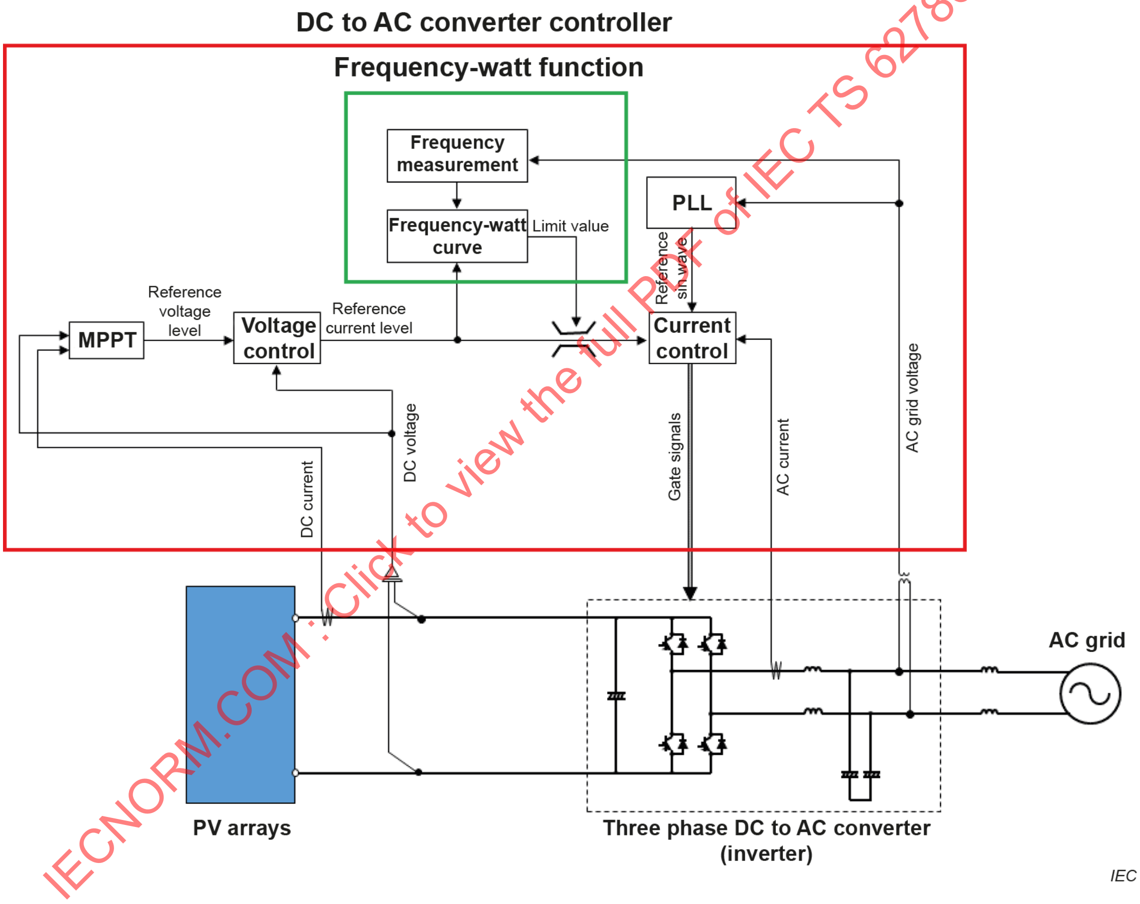
[d] Wider range for settling time, typically for frequency control of DER connected to larger power systems.

B.2.3 Example of "frequency-watt" function in photovoltaic power generating systems

B.2.3.1 Technical background of this example

Some national grid codes require the reduction of active power generated from PV systems when the frequency of AC grid rises. Figure B.3 shows an example of a system diagram of the PV system which has active power control function responding to frequency deviation. The frequency-watt function controls a reference level of output active power, responding to the level of frequency of AC grids. The PV system has frequency measurement of AC grid in a frequency-watt function, or the frequency-watt function receives measured values of frequency from PLL.

Figure B.4 shows an application example of the frequency-watt function in PV systems which control active power in a way that maximum active power output is limited when the AC grid frequency rises and exceeds certain levels.



Key

MPPT maximum point power tracking

PLL phase locked loop

Figure B.3 – Example of system diagram of PV system with frequency-watt function

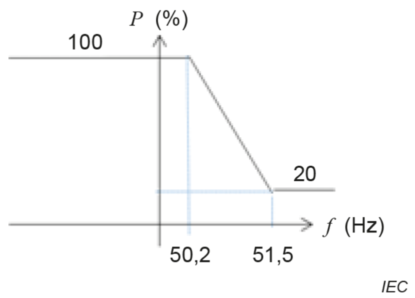


Figure B.4 – Application example of frequency-watt function for PV systems

B.2.3.2 Example of resulting requirements for measurement

Frequency measurement for the frequency-watt function of PV systems should feature characteristics given in Table B.3.

Table B.3 – Example of requirements of frequency-Watt function of PV systems

Measuring range (Hz)	Typical accuracy (mHz) [a]	Typical settling time (s) [b]
Within frequency protection	±10	1

[a] Accuracy of frequency measurement for the frequency-watt function depends on accuracy of PLL when the frequency-watt function receives measured values of frequency from PLL.

[b] Settling time of frequency measurement for the frequency-watt function is longer than that for PLL.

B.3 Use case "Secondary reserve – frequency measurement used for centralized control"

B.3.1 Technical background of the use case

Secondary control aims to bring frequency back to its setpoint value (nominal frequency 50 Hz or 60 Hz) after a transient on the power system while rebalancing trans-border power flows. Currently, the control of the secondary reserve is based on active power set points transmitted to power plants from a centralized control centre, usually managed by the transmission system operator (TSO) at the country level. In this configuration, the supply of secondary reserve does not require frequency nor ROCOF measurements at the power plant level.

However, in the future, the secondary reserve might be decentralized on each power plant or some of the power plants connected to the transmission or the distribution network. In a decentralized system, frequency measurements would be necessary on each of the relevant power plants. These frequency measurements would not have to be fast but should be very precise.

B.3.2 Resulting requirements for measurement

The frequency measurements should feature the characteristics given in Table B.4.

Table B.4 – Typical requirements for use case "Secondary reserve – frequency measurement used for centralized control"

Measuring range (Hz)		Typical accuracy (mHz)	Typical settling time (ms)
44 / 53 [b]	56 / 63 [c]	1 [a]	1 000 [a]

[a] Sufficient performance expected for secondary regulation. A 500 ms settling time would be possible to reach a 1 mHz accuracy and is also required by the § 4.4 of reference [7].

[b] Possible frequency range on a 50 Hz network.

[c] Possible frequency range on a 60 Hz network.

B.4 Use case "Fast frequency-active power proportional controller with dead band"

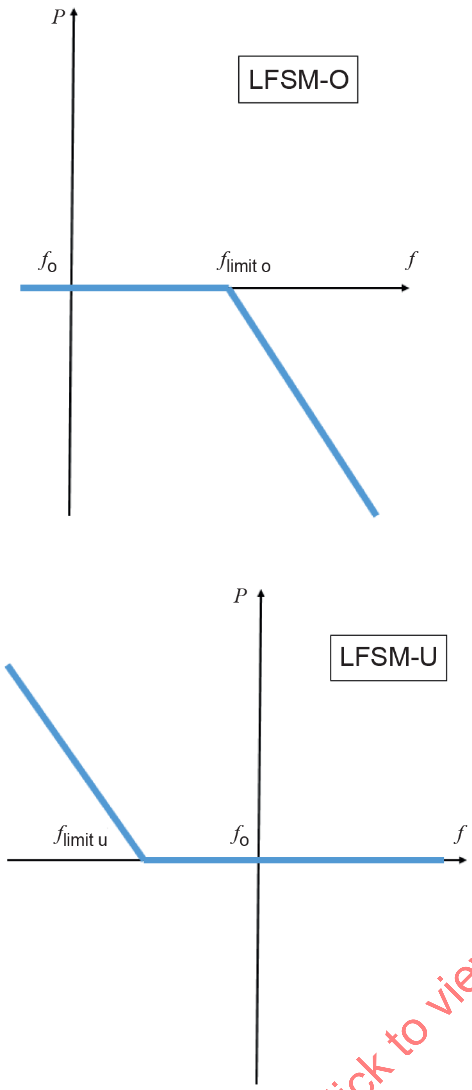
B.4.1 Technical background of the use case

A fast proportional controller with a dead band is aimed at preventing frequency overshoots and undershoots on the power system in case of very large unbalances between active power generated and consumed (e.g. sudden loss of interconnection lines between a massively exporting country and a massively importing country also known as system split).

It works by applying a droop-response of active power produced as a function of frequency and operating when the frequency deviates from nominal frequency value beyond a given limit (in case of over-frequency on a 50 Hz power system, for instance, 50,2 Hz). This controller uses a proportional controller with regard to frequency variations.

The supply of this ancillary service may be required from power plants connected to transmission and distribution networks. When it is required, frequency measurements are necessary at each of the relevant power plants or storage systems. They should measure frequency as fast as possible and with an acceptable accuracy to allow a rapid response of this $P(f)$-function. Compared to primary reserve (Clause B.2), frequency is subject to a faster variation and therefore requires a shorter frequency measurement time. A lesser accuracy of the frequency measurement may be acceptable compared to the primary reserve use case.

An application example is the Limited Frequency Sensitive Mode – Overfrequency (LFSM-O) or Underfrequency (LFSM-U) as defined in the European Grid Code (RfG – Requirement for Generators) and shown in Figure B.5.



if $f > f_{limit\ o}$ then $\frac{P - P_M}{P_{ref}} = -\frac{1}{D_p}\frac{f - f_{limit\ o}}{f_o}$

P : active power generated
f : frequency measured by the generator
P_M : active power generated when f crosses $f_{limit\ o}$
P_{ref} : can be for instance the rated power for a synchronous machine or P_M for an inverter
f_o : reference frequency (50 Hz or 60 Hz)
$f_{limit\ o}$: frequency above which the LFSM-O is activated
droop: droop of the LFSM-O (in p.u.)

if $f > f_{limit\ u}$ then $\frac{P - P_M}{P_{ref}} = -\frac{1}{D_p}\frac{f - f_{limit\ u}}{f_o}$

P : active power generated
f : frequency measured by the generator
P_M : active power generated when f crosses $f_{limit\ u}$
P_{ref} : can be for instance the rated power for a synchronous machine or P_M for an inverter
f_o : reference frequency (50 Hz or 60 Hz)
$f_{limit\ u}$: frequency below which the LFSM-U is activated
droop: droop of the LFSM-U (in p.u.)

IEC

Figure B.5 – Example of fast frequency-active power proportional controller with dead band (LFSM-O and LFSM-U characteristics from European Grid Code)

NOTE 1 These droop characteristics are inside the frequency operating range, with no operation of over- or under-frequency protection relays. The characteristics of this $P(f)$-function must be coordinated with both over- and under-frequency protection relays settings.

NOTE 2 The droop is typically 2 % to 12 % in Europe.

B.4.2 Resulting requirements for measurement

The frequency measurements should feature the characteristics given in Table B.5.

Table B.5 – Typical requirements for frequency measurement – use case "Fast frequency-active power proportional controller with dead band"

Measuring range (Hz)		Typical accuracy (mHz)	Typical settling time (ms)
44 / 53 [b]	56 / 63 [c]	±50 [a]	100 [a]

[a] Same as ENTSOE requirement in view of a power system with less inertia, in particular small systems and microgrids, and requirement for an as fast as possible response of active power in case of abnormal over-/under-frequency. See case "LFSM" of § 4.4 of reference [7].

[b] Possible frequency range on a 50 Hz network.

[c] Possible frequency range on a 60 Hz network.

B.5 Use case "Fast frequency response"

B.5.1 Technical background of the use case

Fast response to frequency variation is used in order to limit the overshoot or nadir of the frequency development after a major power imbalance by acting rapidly before the action of the primary reserve of conventional generation is fully deployed. On a weak power system with low inertia, e.g. typically on a geographical island, the loss of a power plant that represents a significant share of the generating power will result in a major frequency dip before the steady state is reached. Fast frequency response is typically implemented on battery energy storage systems (BESS). The relevant electrical energy storage systems and generating plants should measure frequency and ROCOF as fast as possible and with an acceptable accuracy to allow a very rapid response.

The fast frequency response uses a proportional controller.

B.5.2 Resulting requirements for measurement

The frequency measurement should feature the characteristics given in Table B.6.

Table B.6 – Typical requirements for frequency measurement – use case "Fast frequency response"

Measuring range (Hz)		Typical accuracy (mHz)	Typical settling time (ms)
44 / 53 [b]	56 / 63 [c]	±50 [a]	100 [a]

[a] Same as ENTSOE requirement in view of a power system with less inertia, in particular small systems and microgrids, and requirement for response of active power to be as fast as possible, in case of rapid change of frequency. See case "LFSM" of § 4.4 of reference [7].

[b] Possible frequency range on a 50 Hz network.

[c] Possible frequency range on a 60 Hz network.

B.6 Use case "Synthetic inertia"

B.6.1 Technical background of the use case

Synthetic inertia provides a fast proportional response of the active power to the rate of change of power frequency (ROCOF), which is used in order to limit the ROCOF after a major power imbalance by acting rapidly as a differential transfer function. On a weak power system with low inertia, e.g. as typical on a geographical island, the loss of a power plant that represents a significant share of the generating power will result in a sharp $\mathrm{d}f/\mathrm{d}t$ gradient of a fast frequency decline.

Frequency and ROCOF should be measured as fast as possible and with an acceptable accuracy to allow a very rapid response.

Synthetic inertia is typically implemented on battery energy storage systems (BESS).

B.6.2 Resulting requirements for measurement

The ROCOF measurement should feature the characteristics given in Table B.7.

Table B.7 – Typcial requirements for ROCOF measurement – use case "Synthetic inertia"

Measuring range (Hz/s)	Typical accuracy (Hz/s)	Typical settling time (ms)
−15 / +15 [b]	±0,1 [a]	100 [c]

[a] Requirement on accuracy is defined on the basis of functional requirement (accuracy of at least 0,1 Hz/s is recommended) as well as on state-of-the-art knowledge issued from relay manufacturers: 0,1 Hz/s accuracy seems feasible with 0,1 s settling time.

[b] Possible ROCOF range on weak power systems (with low inertia).

[c] Requirement on settling time is defined to ensure a rapid response of the function. 0,1 s is necessary for certain power systems like small islands where the overall power response must be given within 300 ms.

B.7 Use case "Passive anti-islanding detection"

B.7.1 Technical background of the use case

Areas of a power network will occasionally become isolated from the wider network either deliberately for maintenance or accidently due to a fault. If the isolated "islanding" area contains embedded generation, any personnel working to restore power will be at serious risk from intermittent unexpected voltages. Anti-islanding protection relays are therefore required to disconnect embedded generation when the wider network is not present.

This is done by assuming that the wider synchronized network has a more stable frequency than an isolated small sub-network. It follows that frequency or the rate of change of frequency can be used in protection relays to detect islanding and trip off the embedded generation to ensure protection of engineering personnel. When frequency or ROCOF exceed a given value, it is considered that these variations cannot happen on an interconnected system and that the system is islanded. These measurements should be as fast as possible with an acceptable accuracy.

A protection should trip within an acceptable operate time and with an acceptable accuracy while taking into account the following.

- The frequency and ROCOF measurements used by the protection should follow accurately frequency variations.
- The protection should not operate if the fault lasts less than a given duration in order to avoid false tripping during short perturbations or short-circuits inside upstream power system which must be cleared by the protection system.

As in this use case the protection operates by using the frequency or the ROCOF measured by a frequency measurement or a ROCOF measurement, respectively, the previously mentioned requirements need to consider and be consistent with the settling time of the measurement. For instance, the settling time of a PLL in an inverter in case of frequency step is usually considered to be about 2 to 3 periods. So, the frequency measured by a PLL may not be taken into account by the protection in a reliable way before about 2 to 3 periods. Reciprocally there should be a maximal settling time admissible for frequency or ROCOF measurement to ensure the right behaviour in dynamic conditions with more or less fast frequency variations.

Also, frequency protections must be stabilized with a delay time and/or an undervoltage blocking element in order to avoid false tripping and to meet fault ride through requirements defined by the grid codes.

Therefore, the minimal operate time for the protection should be set at a value of the greater of the settling time of the frequency or ROCOF measurement and a delay time defined by the system operator. The maximal operate time for the protection should be set at a value of the greater of the maximal time admissible for frequency or ROCOF protection operation and the intentional delay time defined by the system operator.

NOTE The performances of frequency and ROCOF protections are characterized in IEC 60255-181.

B.7.2 Resulting requirements for measurement

The frequency and ROCOF measurements should feature the characteristics given in Table B.8 and Table B.9, respectively. These characteristics regard only the frequency and ROCOF measurement and not the delay time to be defined by the system operator for the operation of the protection.

Table B.8 – Set of typical requirements for frequency measurement – use case "Passive anti-islanding detection"

Measuring range (Hz)		Typical accuracy (mHz)	Typical settling time (ms)
44 / 53 [d]	56 / 63 [e]	±100 [b]	40 to 60 [a]
44 / 53 [d]	56 / 63 [e]	30 [c]	90 to 120 [c]

[a] Typical settling time of a PLL in case of frequency step. This settling time provides a lower value for the minimal time of response for the protection (called "start time" in IEC 60255-181).

[b] Typical accuracy required for a frequency measurement with a settling time of 40 ms to 60 ms.

[c] Requirement for the maximal response time and the associated accuracy of a frequency-based protection without taking into account the intentional delay time defined by the system operator to get the required protection operate time. This time is called "start time" in IEC 60255-181. See the case "Protection" of § 4.4 of reference [7]. This requirement corresponds to the start time of the protection, without the associated intentional delay time, defined by the system operator. The accuracy required for the frequency start value (threshold) is also defined.

[d] Possible frequency range on a 50 Hz network.

[e] Possible frequency range on a 60 Hz network.

Table B.9 – Typical requirements for ROCOF measurement – use case "Passive anti-islanding detection"

Measuring range (Hz/s)	Typical accuracy (Hz/s)	Typical settling time (ms)
−10 / +10 [b]	±0,05 [a]	180 to 240 [a]

[a] ENTSOE requirement for the time of response and the associated accuracy of a ROCOF based protection without taking into account the intentional delay time defined by the system operator to get the required protection operate time. This time is called "start time" in IEC 60255-181. See the case "RoCoF protection" of § 4.4 of reference [7]. This requirement corresponds to the start time of the protection, without the associated intentional delay time, defined by the system operator. The accuracy required for the ROCOF start value (threshold) is also defined.

[b] Possible setting range of ROCOF function used to detect anti-islanding detection.

To improve the sensitivity and the stability of anti-islanding detection, the criteria could be a combination of frequency and ROCOF measurement.

B.8 Use case "Active anti-islanding detection"

B.8.1 Technical background of the use case

In case of large penetration of DER, in particular inverter-based generators, the risk of unwanted islanding situations is higher such that they cannot be correctly protected by conventional anti-islanding protection, based on "passive" detection principles.

To ensure this anti-islanding detection, many active methods have been developed such as impedance measurement, active power or reactive power fluctuation method, etc. One of them, used in Japan, is a temporary reactive power injection method. It is based on power frequency measurement and a positive feed-back function of measured frequency to reactive power injection into the grid. If the monitored power sub-system remains connected to the main grid, the reactive power injection is absorbed by the main grid and has no impact on the frequency of the sub-system. Power frequency is kept by the main grid without deviations and fluctuations. Whereas if the monitored sub-system is operated in un-intentional islanding situation, frequency is no longer maintained at or close to its nominal value by the main power system. The injected reactive power is fed into the monitored sub-system. Voltage on the monitored sub-system is defined by the amount of loads and the reactive power, and the phase of voltage leads in the case that the injected reactive power is inductive or lags in the case that the injected reactive power is capacitive. Because the injected reactive power is controlled on the basis of the voltage phase of the monitored sub-system, the phase of voltage continues to lead or lag. Consequently, frequency of voltage of the monitored sub-system becomes rapidly faster or slower. The temporary reactive power injection method detects this rapid change of frequency and assumes that the monitored sub-system is in islanding condition.

When such a scheme is implemented, detection of frequency perturbations and injection of reactive power are designed to avoid unwanted operation. These designs are based on appropriate filters and dead-band characteristics. If the injection of reactive power is not managed correctly, it could lead to worse power quality, with nuisance voltage flicker according to grid impedances. Therefore, the performance of the temporary reactive power injection method depends on the accuracy of frequency and ROCOF measurements.

B.8.2 Resulting requirements for measurement

The frequency measurements should feature the characteristics given in Table B.10.

Table B.10 – Typical requirements for frequency measurement – use case "Active anti-islanding detection"

Measuring range (Hz)		Typical accuracy (mHz)	Typical settling time (ms)
44 / 53 [c]	56 / 63 [d]	±10 [a]	60 to 100 [b]

[a] Requirement proposed based on the experience in Japan.

[b] Operate time: maximum time to detect islanding.

[c] Possible frequency range on a 50 Hz network.

[d] Possible frequency range on a 60 Hz network.

NOTE The detection of an islanding situation is not based on the crossing of frequency or ROCOF thresholds. So, there are no frequency nor ROCOF thresholds defined. This active detection is made by observing the way the frequency behaves when reactive power is injected/absorbed. On an islanded network, the injection of reactive power into the network usually causes its frequency to decrease whereas the absorption of reactive power from that network usually causes its frequency to increase. This is due to the behaviour of usual loads as well as of cables with regard to reactive power, more precisely the consumption of reactive and active power by loads and the generation of reactive power by cables as functions of frequency and voltage. So, on an islanded system, frequency usually decreases or increases depending on total residual system loads' reactive power consumption including cables, and of leading or lagging reactive power that is injected from the power converter equipment of DERs by their active anti-islanding functions. The frequency shift that occurs in the islanded system is detected by DERs. When they detect this frequency shift, they stop the injection of power to the grid to complete the islanding prevention function.

B.9 Use case "ROCOF measurement used for centralized control"

B.9.1 Technical background of the use case

ROCOF may have to be measured at the synchronous area level for control purposes of transmission system operators (TSOs), for instance for assessment of the level of inter synchronous-area oscillations. The accuracy of 1 mHz/s and the settling time of 1 s are necessary as these frequency oscillations usually produce frequency change of a few mHz to a few tens of mHz, with a periodicity of 1 s or more. As 500 ms are usually enough to measure frequency with a 1 mHz accuracy, a measurement time of 1 s is enough to measure a ROCOF of 1 mHz/s. However, a settling time of 1 s will not allow the detection of a periodicity of about 1 s or less.

B.9.2 Resulting requirements for measurement

The ROCOF measurement should feature the characteristics given in Table B.11.

Table B.11 – Typical requirements for ROCOF measurement – use case "ROCOF measurement used for centralized control"

Measuring range (mHz/s)	Typical accuracy (mHz/s)	Typical settling time (ms)
−30 / +30 [b]	±1 [a]	1 000 [a]

[a] ENTSOE requirement for the time of response and the associated accuracy of a ROCOF measurement used for centralized control. See the case "RoCoF evaluation on synchronous area level" of § 4.4 of reference [7].

[b] Possible ROCOF range for frequency oscillations on a 50 Hz or 60 Hz network. Measured on the European power system during frequency oscillation incidents.

B.10 Use case "Load control with active power management"

B.10.1 Technical background of the use case

Demand units may use frequency measurement to ensure demand response frequency control function. Such a function is similar to the power droop power function described in Clause B.4 for generators but applied to a load or a group of loads. This load control is aimed at participating to the balance between active power generated and consumed. It works by applying a droop-response of active power consumed as a function of frequency and operating when the frequency deviates from nominal beyond a given limit. This function is generally specified with a dead band around the nominal system frequency (50 Hz or 60 Hz) to avoid too much interaction with generator active power control.

B.10.2 Resulting requirements for measurement

The frequency measurements should feature the characteristics given in Table B.12.

Table B.12 – Typical requirements for frequency measurement – use case "Load control with active power management"

Measuring range (Hz)	Typical accuracy (mHz)	Typical settling time (ms)
44 / 53 [b] 56 / 63 [c]	±50 [a]	100

[a] Requirement consistent with droop functions associated with generators, described in Clause B.4.

[b] Possible frequency range on a 50 Hz network.

[c] Possible frequency range on a 60 Hz network.

B.11 Use case "Self-dispatchable loads" (microgrid applications)

B.11.1 Technical background of the use case

Self-regulation of loads (SRL) is a well-known phenomenon. This effect emerged from the dynamic behaviour of electric motors that were used to power directly mechanical drivetrains, e.g. for pumps or air blowers. The higher the rotational speed of that drive, the more power was needed and vice versa. This effect automatically contributes to frequency stabilization without a supervisory control.

The SRL concept is to emulate the above explained beneficial behaviour with dispatchable loads. Dispatchable loads are able to change their active power consumption to support grid needs including regulating frequency. Typically, the internal control of that device would react to frequency deviations depending on the user settings and system state (e.g. temperature or state of charge). Depending on the capabilities of individual dispatchable loads, aggregate pools of dispatchable loads are able to respond to frequency with response times from microseconds to several seconds. Since these loads only require a local measurement of frequency, neither digital communication channels nor distributed control systems are needed to use small loads in the task of keeping the electric system stable.

SRL may allow to provide a wide range of services as described in Table B.13.

B.11.2 Resulting requirements for measurement

As different loads may have different dynamic characteristics the use case has different accuracies, which need to be declared by the manufacturer.

Table B.13 – Typical requirements for frequency measurement – use case "Self-dispatchable loads"

Measuring range (Hz)		Typical accuracy (mHz)	Typical settling time	Use case
44 / 53 [c]	56 / 63 [d]	±100	60 ms	Ultra fast power control
44 / 53 [c]	56 / 63 [d]	±30 [a b]	100 ms [a]	Very fast current control
44 / 53 [c]	56 / 63 [d]	±10 [a b]	200 ms [a]	Fast current control
44 / 53 [c]	56 / 63 [d]	±1 [a b]	1 s [a]	Disconnectable loads
44 / 53 [c]	56 / 63 [d]	±1 [a b]	1 s [a]	Primary control
44 / 53 [c]	56 / 63 [d]	±1 [a b]	1 s [a]	Secondary control
44 / 53 [c]	56 / 63 [d]	±1 [a b]	1 s [a]	Tertiary control

[a] Requirement based on requirements in IEC TS 62898-3-3:2023 [8], Table 1 and Table 3.

[b] It is up to the manufacturer to declare the accuracy.

[c] Possible frequency range on a 50 Hz network.

[d] Possible frequency range on a 60 Hz network.

B.12 Use case "Under-frequency load shedding" (UFLS)

B.12.1 Technical background of the use case

Under-frequency load shedding (UFLS) is an emergency measure to avoid a total blackout of the electrical system due to generation/load unbalance, the load being greater than the injected production. This production/consumption difference implies a drop in the frequency of the electrical system which must then draw on the kinetic energy of the machines connected to the electrical system. In case of major unbalances (from a few percent to several tens of percent), under-frequency load shedding shall be applied in order to arrest further deterioration of the frequency, automatically disconnecting parts of the consumption. It is important to note that the stored kinetic energy, indirectly called inertia within the framework of the electrical system, is not sufficient to compensate the imbalance over long periods as the frequency drops quickly over a few seconds to tens of seconds. This under-frequency is accompanied with significant system dynamics and several devices are likely to disconnect automatically to avoid damaging the equipment or because the electrical system to which they are connected does not itself appear stable. The scheme for the automatic low frequency demand disconnection (load shedding) can also use ROCOF.

To ensure frequency selectivity, mainly during major generation losses, it is imperative to have good control of the voltage during load shedding operations. In fact, excessive voltage variation during load shedding operations leads to load variation that alters the generation/real load imbalance due to load-voltage relationship. On a voltage-sensitive system, the simultaneous tripping of shunt capacitors of the distribution systems and the active load is required to ensure adequate control of overvoltages. To be effective, the under-frequency load shedding plan must be very fast; it therefore uses a combination of frequency thresholds and ROCOF with no time delays. For example, Hydro Quebec uses a total of six thresholds ranging from 58,5 Hz to 56,0 Hz in 0,5 Hz steps and four frequency gradients (ROCOF) ranging from −0,4 Hz/s to −1,2 Hz/s.

B.12.2 Resulting requirements for measurement

The frequency measurements should feature the characteristics given in Table B.14 and Table B.15.

Table B.14 – Typical requirements for frequency measurement – use case "Under-frequency load shedding"

Measuring range (Hz)	Typical accuracy (mHz)	Typical settling time (ms)
47 / 53 [a] 53 / 63 [a]	±30	100 to 120

[a] Other possible frequency measuring range could be between 0,9 p.u. and 1,1 p.u., in particular for microgrids operated in islanded mode.

Table B.15 – Typical requirements for ROCOF measurement – use case "Under-frequency load shedding"

Measuring range (Hz/s)	Typical accuracy (Hz/s)	Typical settling time (ms)
−4 / +4	±0,10	180 to 240

Annex C
(informative)

Summary of requirements expressed in standards and grid codes related to frequency and ROCOF measurements

Standards related to power systems and grid codes define requirements with a direct or indirect link to frequency and ROCOF measurements. These requirements, extracted from these documents, are summarized in Table C.1. This table is used to feed the use cases and their associated characteristics defined in Clause 5.

The requirements in power system standards or grid codes are generally not directly expressed with the characteristics defined in Clause 4. However, these requirements may have an indirect impact on frequency and ROCOF measurements and must be considered to define typical performances defined in Clause 5.

For each characteristic, the reference of the subdivision within the concerned standard or grid code is added in parenthesis.

Table C.1 – Requirements expressed in standards and grid codes related to frequency and ROCOF measurements

Title	Frequency operating range	Frequency time characteristics	Frequency measuring accuracy	ROCOF operating range	ROCOF time characteristics	ROCOF measuring accuracy	Comments
IEC TS 62786:2017 [9]: Distributed energy resources connection with the grid.	Continuous operating range: 47 Hz to 52 Hz at 50 Hz 57 Hz to 61,8 Hz at 60 Hz Limited operating range: 45 Hz to 57 Hz at 50 Hz 57 Hz to 61,8 Hz at 60 Hz (Annex A)	No request	No request (see comment)	No mandatory request but 2,5 Hz/s value is required in some countries regarding generating unit withstand capability	No request	No request	No request about the performances related to droop function to perform active response to frequency deviation. Only reference to local system requirements is expressed.

Title	Frequency operating range	Frequency time characteristics	Frequency measuring accuracy	ROCOF operating range	ROCOF time characteristics	ROCOF measuring accuracy	Comments
CLC/EN 50549-1 (02/2019): Requirements for generating plants to be connected in parallel with distribution networks – Part 1: Connection to a LV distribution – Generating plants up to and including Type B [10].	47 Hz to 52 Hz at 50 Hz related to droop function for active response to frequency deviation. (4.4.2)	No request (4.4.3)	No requirement on frequency accuracy but a frequency resolution is defined, equal to or below ±10 mHz, see comment (4.6.1)	No request but at least 2 Hz/s is requested for asynchronous machines and 1 Hz/s for synchronous machine to define generating unit withstand capability (4.5.2)	No request but a sliding window of 500 ms is defined, associated with 1 Hz/s or 2 Hz/s ROCOF immunity, to define generating unit withstand capability (see comment). For control action based on frequency measurement shorter measurement periods are expected to be necessary (4.5.2)	No request	• Frequency resolution of ±10 mHz is based on droop function required to perform active power response to frequency deviation. Accuracy of ±10 % or the nominal power is defined for the active power at the output of the droop function. • Frequency operating range is based on the range where generating plant should be capable of operating until the interface protection trips. • Frequency measurement time is defined as the time required to establish the power frequency. • The ROCOF operating range is based on the generating unit withstand capability without disconnection from the main grid. For non-synchronous generating technology, the ROCOF immunity is defined with at least 2 Hz/s value. For synchronous generating technology, the ROCOF immunity is defined with at least 1 Hz/s value. The ROCOF value is defined with a sliding window of 500 ms. This characteristic is not related to ROCOF measurement. • Immunity to PQ and EMC compatible with EN 61000 series (4.8). • Voltage operating range: at least 50 % to 120 % of rated voltage (4.10.2, 4.10.3). • Requirements on frequency protection are also defined (4.9.2) but not in the scope of this table.
CLC/EN 50549-2 (02/2019): Requirements for generating plants to be connected in parallel with distribution networks – Part 2: Connection to a MV distribution network – Generating plants up to and including Type B [11].	See above part 1	See above part 1	See above part 1	See above part 1	See above part 1	See above part 1	Same performances are required in part 1 (LV connections) and part 2 (MV connections)

Title	Frequency operating range	Frequency time characteristics	Frequency measuring accuracy	ROCOF operating range	ROCOF time characteristics	ROCOF measuring accuracy	Comments
IEEE Std 1547 (04/2018): IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces [12].	Measurement accuracy requirements (4.4, Table 3), for steady state measurements						IEEE Std 1547 establishes criteria and requirements for interconnection of distributed energy resources with electric power systems (EPS) and associated interfaces. It provides requirements relevant to the interconnection and interoperability performance, operation and testing. Pertaining to the interconnection and interoperability of DER, frequency measurements are needed to determine: • If the DER, or collection of DER can be connected (enter service) to the area EPS or must be disconnected (trip) either to operate independently (as an island) or to be de-energized. • If and when the DER can be re-connected to the area EPS. • "Ride-through" operation of the DER. "Ride-through" is the ability of the DER to withstand voltage and frequency disturbances inside defined limits and continue operating as specified. • Reclosing coordination between DER and area EPS • Frequency-droop response of DER ROCOF measurements are used to determine ride-through operation of the DER.
	Nominal frequency minus 10 Hz to nominal frequency plus 10 % of nominal frequency (40 Hz to 55 Hz or 50 Hz to 66 Hz)	Frequency measurement window: 1,0 s	minimum 10 mHz		According to ROCOF ride-through requirements, the averaging window is at least 0,1 s (4.3)	No performance requirements for ROCOF were given but the near steady-state ROCOF ride-through on clause 6.5.2.5 Table 21 specifies 0,5 Hz/s which implies a measurement accuracy of at least ¼ of that number or 0,125 Hz/s under near steady-state conditions	
	Measurement accuracy requirements (4.4, Table 3), for transient measurements						
	Same as above	Frequency measurement window: 0,1 s	Minimum 100 mHz			Under transient conditions a ride through of 3,0 Hz/s implies a transient performance requirement of 0,75 Hz/s	

Title	Frequency operating range	Frequency time characteristics	Frequency measuring accuracy	ROCOF operating range	ROCOF time characteristics	ROCOF measuring accuracy	Comments
European Union: Network code on requirements for grid connection of generators (RfG – Requirements for Generators – 04/2016) [13].	47 Hz to 52 Hz	No request	No request, see comment	No request ROCOF protection for anti-islanding detection is quoted (Article 14) ROCOF immunity of generating unit withstand capability is quoted (values defined by TSO), unless disconnection by Loss-Of-Main (Article 13.1b). Use of ROCOF protection for Loss-of-Main function is quoted (Article 14.3 b-iii)	No request	No request	• A frequency response insensitivity is defined between 10 mHz to 30 mHz for the action of the droop function (Article 15). • ROCOF is quoted to define generating unit withstand capability or as Loss-of-Main protection principle, but without any values, which will be defined by the relevant TSO.
European Union: Network code on Demand Connection (DCC – Demand Connection Code – 08/2016) [14].	47 Hz to 52 Hz To manage droop function for active power demand	No request, but the following request is expressed: "Measurements shall be updated at least every 0,2 seconds" (Article 29 item f);	No request, but the following request is expressed: "be able to detect a change in system frequency of 0,01 Hz." (Article 29 item g)	No request	ROCOF calculated over a 500 ms time frame (Article 28 item k). Response time for fast active power control shall be no longer than 2 seconds (Article 30 item 2b).	No request	The European grid code (DCC) introduces the use of ROCOF to manage specific and faster demand response. The technical requirements must be defined by the system operator but few requirements on ROCOF measurements are defined, as noted in the table.

Title	Frequency operating range	Frequency time characteristics	Frequency measuring accuracy	ROCOF operating range	ROCOF time characteristics	ROCOF measuring accuracy	Comments
EN 50160 (02/2011) Voltage characteristics of electricity supplied by public electricity networks, 4.2.1 Power frequency [15]	a) for systems with synchro–nous connection to an interconnected system: i) 50 Hz ± 1 % (i.e. 49,5 Hz... 50,5 Hz) during 99,5 % of a year; ii) 50 Hz + 4 % / − 6 % (i.e. 47 Hz to 52 Hz) during 100 % of the time; b) for systems with no synchronous connection to an interconnected system (e.g. supply systems on certain islands) i) 50 Hz ± 2 % (i.e. 49 Hz to 51 Hz) during 95 % of a week; ii) 50 Hz ± 15 % (i.e. 42,5 Hz to 57,5 Hz) during 100 % of the time.	10 seconds	10 mHz for class A and 50 mHz for class S (according to IEC 61000-4-30)	No request	No request	No request	Measurement methods are specified in IEC 61000-4-30:2015 [16] and IEC 62586-2:2017 [17].

Title	Frequency operating range	Frequency time characteristics	Frequency measuring accuracy	ROCOF operating range	ROCOF time characteristics	ROCOF measuring accuracy	Comments
JEAC 9701-2019: Grid-interconnection Code (From the Japan Electric Association) [18]	Standard setting value region for frequency protection of DER Over-frequency protections: 50,5 Hz to 51,5 Hz (50 Hz area), 60,6 Hz to 61,8 Hz (60 Hz area) Under-frequency protections 48,5(47,5*) Hz to 49,5 Hz (50 Hz area), 58,2(57,0*) Hz to 59,4 Hz (60 Hz area) *: for the generation system to which fault ride through function is applied	Operate time: typical: 1 s Operate time range for trip: 0,5 s to 2,0 s	No request	±2 Hz/s	No trip until OFR/UFR level detection	No request	

Annex D
(informative)

Maximum ROCOF to be considered on power systems in case of incidents

D.1 General

This Annex D provides a few examples of extreme ROCOFs that may be encountered on power systems in the future. It is to be noted that the value of ROCOFs mentioned may depend on the way they are calculated so may reflect slightly different transient situations from one country to another.

D.2 UK

The OFGEM document "Changes to the Distribution Code and Engineering Recommendation G59: Frequency Changes during Large Disturbances and their Impact on the Total System" of 23 July 2014 requires ROCOF interface protection settings for generators of 0,5 Hz/s for synchronous generators commissioned before 1 July 2016 and 1 Hz/s for other generators (the measured ROCOF should remain continuously for 500 ms above the threshold for the protection to be triggered). This latter requirement (threshold at 1 Hz/s and delay time of 500 ms) is confirmed by the new ENA Engineering recommendation G99. So the ROCOF on the UK power system may reach in the future up to 1 Hz/s.

D.3 European continent

Today, the theoretical ROCOF seen on the continent in the design case (loss of 3 GW at minimum demand level without split of the European power system) is less than 0,1 Hz/s. As far as the future is concerned, the ENTSOE document "Frequency Stability Evaluation Criteria for the Synchronous Zone of Continental Europe" of March 2016 mentions the possibility of ROCOFs up to 3 Hz/s (in case of a split power system and very large unbalances similar to the ones observed during the November 2006 incident).

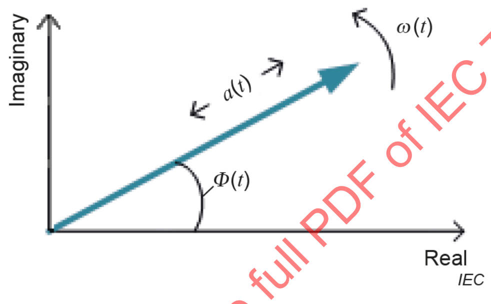
D.4 Islands

ROCOFs on small islands (e.g. French islands La Martinique, Guadeloupe) may reach a few Hz/s (2 Hz/s to 4 Hz/s and potentially more in extreme cases).

Annex E
(informative)

Frequency and rotating vectors

Frequency is defined in 3.5 in terms of rotating vectors, which is familiar to most power system engineers. Some power system engineers think of the signals in terms of phasors as described in Figure E.1, which is synonymous to rotating vectors. If the signal on an actual power system is represented as a single rotating phasor, the amplitude and the angular velocity of the vector will be continually changing (including within a single period). The angular velocity, of course, is the frequency multiplied by 2π radians. A signal can be decomposed into a sum of rotating vectors with each vector representing one of the components of the signal, each component has an angular velocity which can be changing even within a single period of rotation. The signal can be filtered until the angular velocity approximates a constant, but the filtering is imperfect and leads only to an approximation of the angular velocity. If the angular velocity changes over the course of a single period, the reciprocal of the period is only an average of the frequency over the single period.



Amplitude (a), angle (Φ) and angular velocity (ω) are all functions of time and may change within a single period.

Figure E.1 – Phasor representation of a power system signal, which has amplitude (a), angle (Φ) and angular velocity (ω)

Other power system engineers think of the signal components as the values from the bins from the discrete Fourier transform (which are imperfect approximations [19]). Continuous-time Fourier analysis would completely and precisely describe the signals at a given moment of time, but a complete and precise (ideal) description would require an infinite amount of information about the signal. Discrete Fourier Transform (DFT) uses finite information and yields approximations of the epicycles at a given moment of time. Additionally, Fourier transforms completely describe stationary signals. Power system signals are not stationary, so the Fourier transform is also an approximation of the power system signal.

In general, the term used to describe a quantity to be measured is a "measurand" [20]. A good measurand is not based upon any methodology of measurement but is defined with sufficient completeness such that measurements of any accuracy can be compared with an "ideal" value [21]. Theoretically, it is impossible to make any ideal measurement, but measurement accuracy can be specified based upon the requirements of the application (how we intend to use the measurements).

To extend the definition of frequency to all fields of study and provide a valid description of the physical quantity of "frequency", the more generalized signal decomposition which works for both stationary and non-stationary signals is empirical mode decomposition (EMD). Like Fourier transform, EMD decomposes a signal into a series of rotating vectors; but unlike Fourier, each rotating vector can have changing (non-stationary) amplitude and angular velocity. Using EMD, a signal is decomposed into one or a series of intrinsic mode functions (IMFs). In the power system, one of the IMFs will be the power system fundamental signal. The fundamental signal frequency is generally constrained by grid code to be within a small deviation from the nominal frequency of 50 Hz or 60 Hz.

Other IMFs may also be present and may come and go from the power system signal; they may include some harmonic IMFs, some interharmonics induced by loads, power electronics and the like, and some noise. Noise is generally a relatively small amplitude IMF with random phase.

The signals found in electrical power systems are constantly changing. Ideally, they would consist of single, unchanging, pure sine waves at one continuous frequency (the nominal frequency). In reality, the signals consist of sums of many components which are continually changing in frequency and amplitude. Power system engineers may be interested only in one intrinsic mode function (rotating vector) which would be the "fundamental component", or a few intrinsic mode functions (rotating vectors), for example the fundamental and some harmonics, or the fundamental and a few closely related interharmonics (side-bands) which combine to create amplitude and/or frequency modulations of the fundamental [22]. To make a measurement, the IMFs which exist but are not of interest must be removed, usually by filtering the signal, which cannot be performed perfectly in finite time.

Each IMF in the series has an amplitude, and that amplitude may be changing over time. Each IMF has an instantaneous frequency – it's instantaneous rate of change (the derivative) of phase, which also may be changing over time. Each IMF, at any instant, has a relative phase to all other IMFs (which can be determined at the starting point of an observation). To most power engineers, the most well-known application of empirical mode decomposition is the less-generalized form, Fourier analysis, where each IMF has a constant amplitude and frequency in time.

When measurements are being made in an attempt to determine the frequency (or frequencies) at a given moment of time, a "snapshot" of the signal is made at an instant of time, the frequencies of the IMFs would all be the instantaneous rates of change of the phases of the IMFs at that moment of time. The instantaneous rate of change is called a "derivative". Heisenberg [23] proved that we cannot know both the position and the location of a quantity, so to know both the phase and rate of change of the phase, we need to look at more than one moment of time and estimate the phase and derivative of phase with respect to time at the moment we are interested in. While we might try to define frequency this way, that definition is not ideal and depends on the method of measuring rather than the quantity itself.

This document uses the concept of rotating vectors to distinguish between the various signal components that make up a power system signal such as a time series of voltage, current, or derived signals such as power. The fundamental component is defined as the rotating vector of interest and almost always is the vector near to 50 Hz or 60 Hz in frequency (the power system's nominal frequency). Harmonics are rotating vectors which have frequencies at integer multiples of the fundamental frequency, and interharmonic components are all other components that are not fundamental or harmonic. Usually, a group of small amplitude interharmonics will be considered "noise," but, as proven by Fourier, consists of a sum of rotating vectors which are usually of low amplitude and change rapidly.

Annex F
(informative)

Synthetizing input signals with sudden frequency change without discontinuity in voltage waveform

When functional tests are based on sudden frequency change, the applied voltage signal shall be managed without discontinuity in the voltage waveform, except its frequency change. Annex F illustrates how to manage a three phase voltage injection with a continuous signal. The same approach can be applied with a single phase injection.

In the equations below, the sudden frequency change occurred at the time t_o.

- The initial frequency is f_1.
- The final frequency is f_2.
- Before the time t_o, the applied signal is based on following equations:
  - $V_{L1}(t)$ = amp × sin(2 × π × f_1 × t);
  - $V_{L2}(t)$ = amp × sin(2 × π × f_1 × t − 2 × π/3);
  - $V_{L3}(t)$ = amp × sin(2 × π × f_1 × t + 2 × π/3).
- After the time t_o (sudden frequency change), the applied signal is based on following equations:
  - $V_{L1}(t)$ = amp × sin(2 × π × f_2 × t + φ) + …;
  - $V_{L2}(t)$ = amp × sin(2 × π×f_2 × t − 2 × π/3 + φ) + …;
  - $V_{L3}(t)$ = amp × sin(2 × π × f_2 × t + 2 × π/3 + φ) + …;

  where φ is computed to ensure no discontinuity in the voltage waveform. This condition is ensured with φ = 2 × π × t_o × (f_1 − f_2).

Such applied signal is illustrated in Figure F.1.

The first graph displays the three phase voltages with a sudden frequency change from 50 Hz to 55 Hz at t_o = 0,02 s. The other graphs display each phase voltage with the two power frequencies (50 Hz with solid line curve and 55 Hz with dotted line curve).

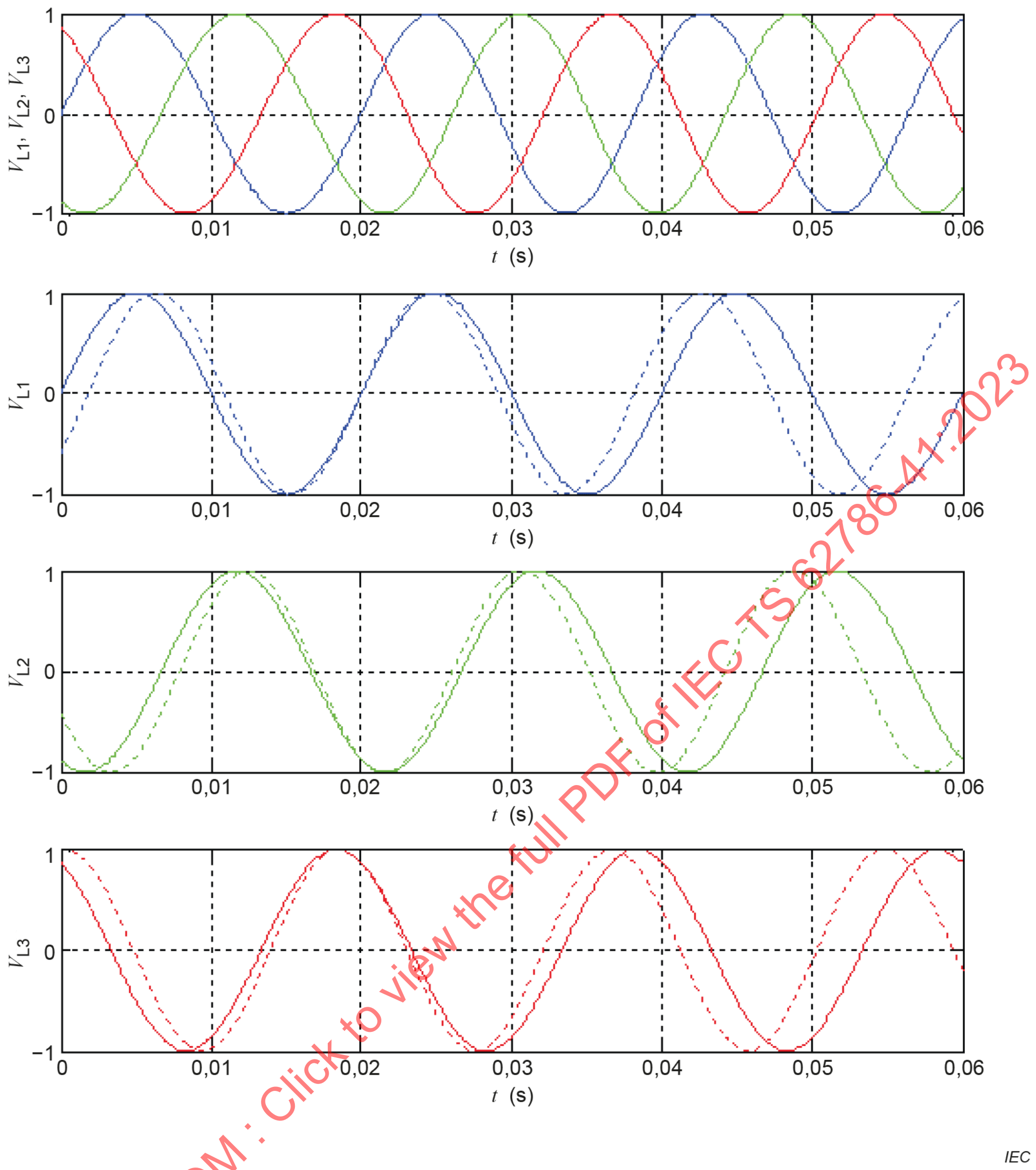


Figure F.1 – Example of voltage waveform without discontinuity at t_o = 0,02 s

The same example is illustrated in Figure F.2, where the sudden frequency change at t_o = 0,02 s is managed with a discontinuity in voltage waveform. In this figure, the signal with frequency f_2 (55 Hz) is computed with an angle φ = 0.

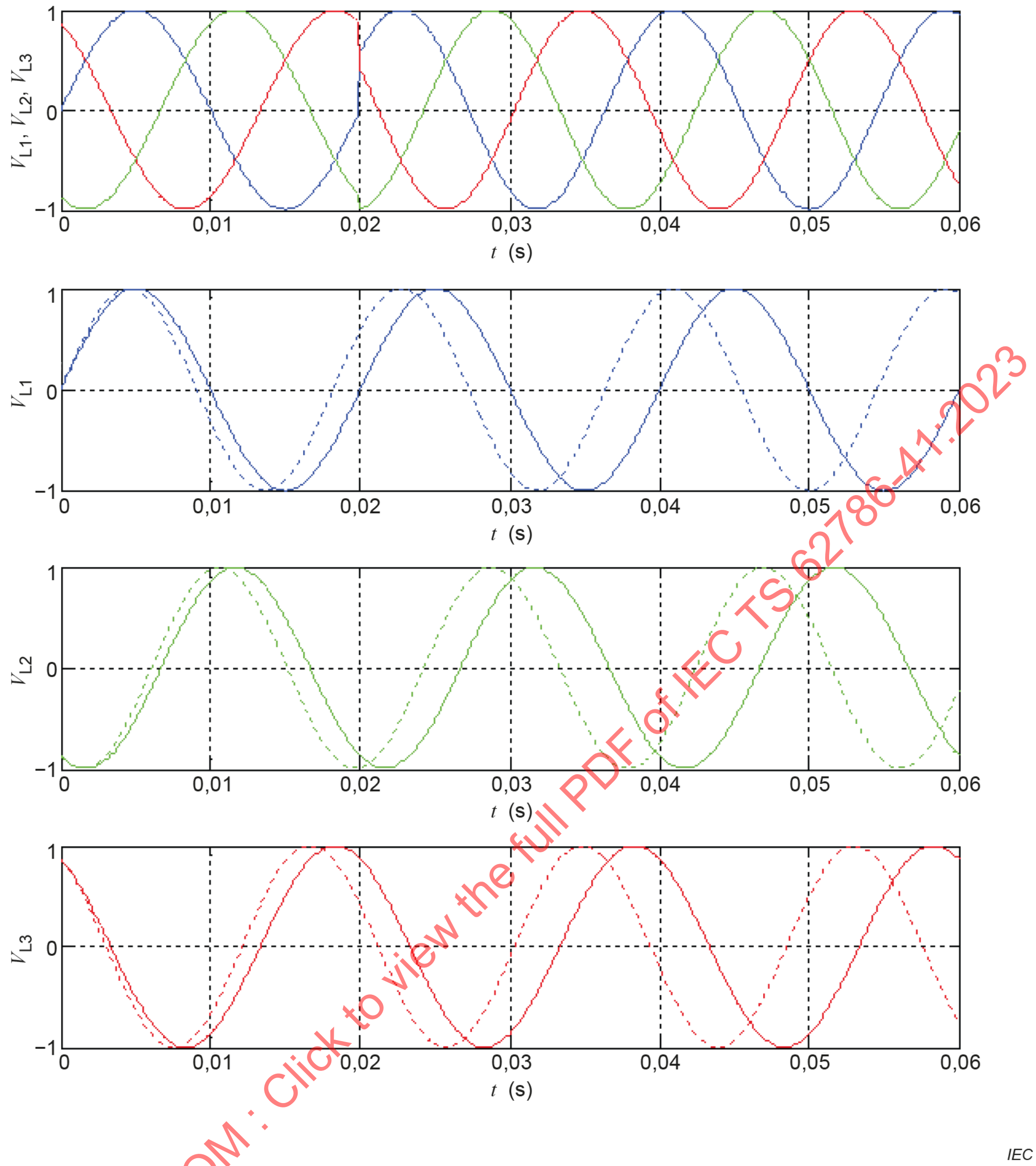


Figure F.2 – Example of voltage waveform with discontinuity at t_o = 0,02 s

Annex G
(informative)

Step test equivalent time sampling technique

G.1 Overview

In Clause 6 and Annex I, the descriptions of functional test principles list step changes in phase, magnitude, and phase and magnitude combined as influencing factors. Settling time, defined in 3.16, is measured with a transition between two steady-state measurements before and after a step change in frequency or ROCOF is applied to the input of the instrument. Figure 3 shows graphically how to determine the settling time from a step in the input signals phase and amplitude. Figure 3 illustrates a continuous-time output from the instrument; however, most modern instruments report their measurements discretely, so only discrete points along the output measurement curve will be reported by the instrument depending on the reporting rate of the instrument, the time of occurrence of the step relative to the time of the reports, and the phase of the input signal at the time the step occurred.

Figure G.1 illustrates plots from the step response of an actual frequency and ROCOF measuring instrument which reports measurements once each nominal power system cycle (50 or 60 reports per second). These plots show different responses to steps occurring at different relative times in the reporting cycle and at different phases in the input signal:

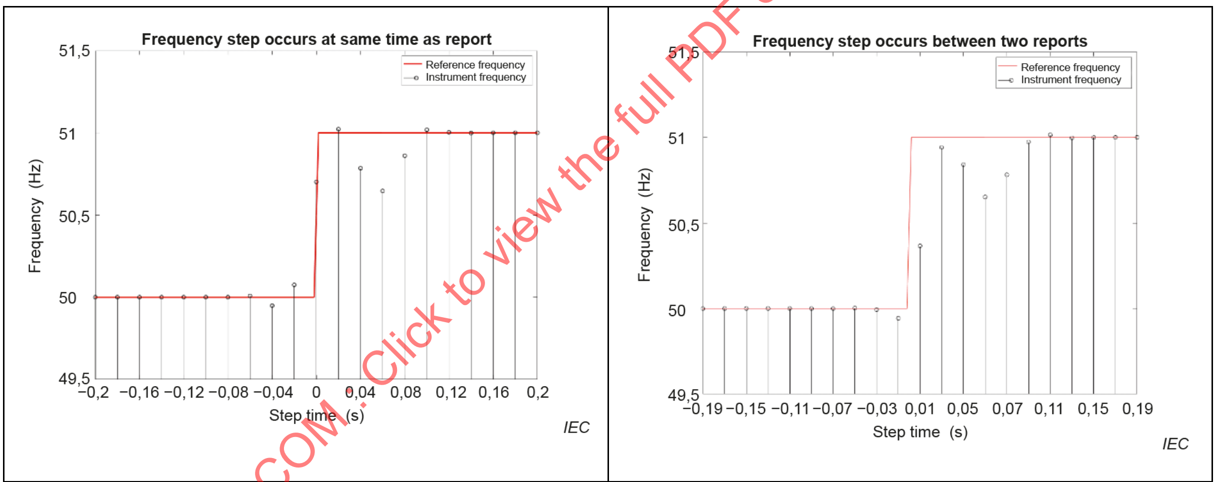


Figure G.1 – Example of reports during step response

If we interlace equivalent time sampled (ETS) instrument responses relative to one reference frequency step at time t = 0, we can get higher resolution images of the instrument step response as shown in Figure G.2:

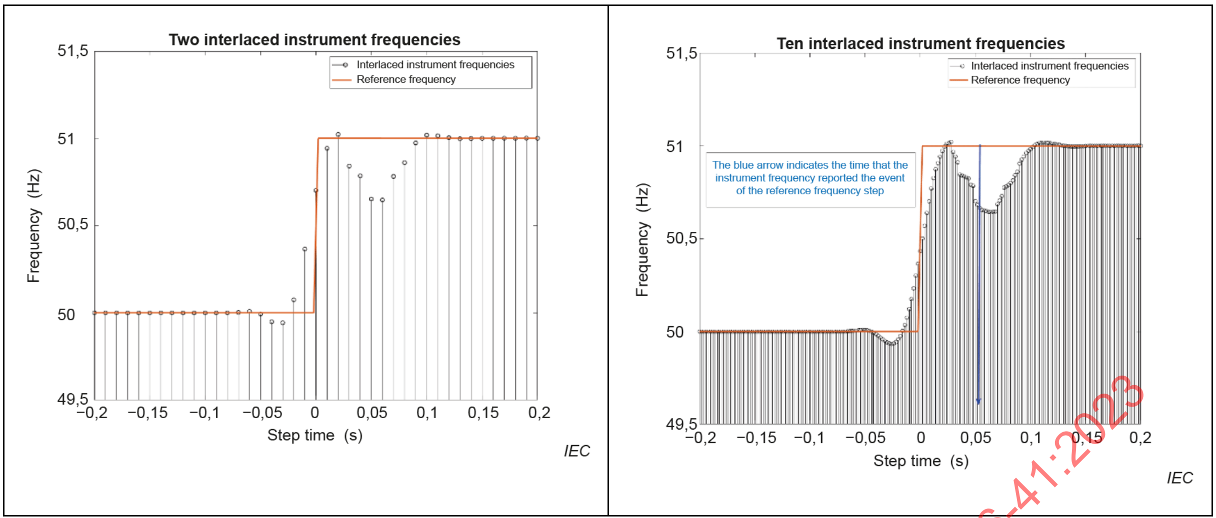


Figure G.2 – Example of reports during step response with higher resolution

The instrument frequency will be reported some time after the reference frequency. The blue arrow in Figure G.2 shows the time relative to the reference frequency step that the measured frequency at that time was reported by the instrument.[2] This explains why it appears that the response to the step is occurring before the step itself occurred. The instrument cannot foresee the future, it simply reports its response later than the occurrence.

G.2 Equivalent time sampling

The technique of capturing samples of periodic functions at different times then interlacing the captured time series is called "equivalent time sampling" (ETS). This technique is used in digital sampling oscilloscopes to increase the "effective" sampling rate. If the signal being captured is periodic, then samples of repeating cycles, taken at slightly different times, can be interlaced and presented to appear as if a higher sampling rate was used. There are other methods of implementing ETS, such as using multiple samplers with offset sample times or repeating an event at slightly different periods.

It is the latter technique that applies to determining with high resolution an instrument's response to an event such as a step. If repeating steps occur at slightly different relative periods, then the instrument's response to those events can be interlaced to present a high-resolution view of the instrument response.

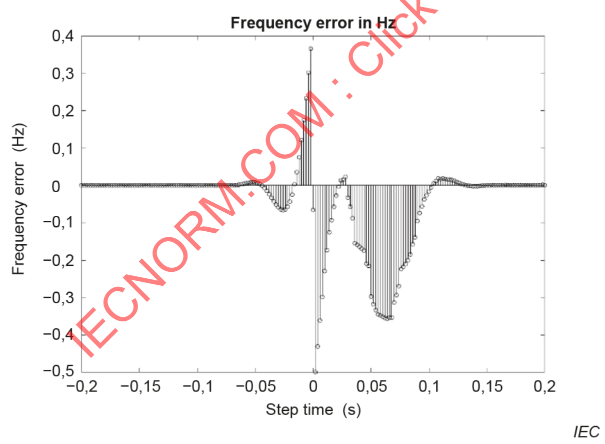
2 In this case, the reported instrument reached 50 % of the step but this may not be the case for all instruments.

The instrument reports measurements at a fixed period, so repeating step occurrences by the reporting interval, plus or minus a fraction of the reporting interval, gives reports at different points on the measurement response curve. These measurements are combined by translating the step and response measurement points back to the reference point (the time of one of the steps) to give a step response result with a time resolution less than the reporting interval. This technique controls the relation between the step time t in the unit step function H(t) and one of the reporting times.[3] The unit step function time is adjusted to fall on a reporting time for one step test. Successive step tests are performed with the unit step function times falling at increasing fractions of a reporting interval after a reporting time. Thus, if t_r is a reporting time, T is the reporting interval, and n is the number of tests to be performed, one test is performed with a H(t_r). The next test is performed with a H(t_r + T/n), and the next with a H(t_r + 2T/n), and so on until the nth test is performed with a H(t_r + (n − 1)T/n). The resulting measurement points are combined by interleaving all the steps and combining the measurements with their corresponding offsets from the step. This gives an equivalent measurement step response with a time resolution of T/n. In general, an accurate measurement of the instrument response time, the delay time, and the overshoot percentage can be made with n = 10 (however for low reporting rates where the test result may be indeterminate, higher numbers for interleaving – such as n = 20 – should be used). To determine the boundaries more precisely, linear interpolation can be used between two ETS measurements. Overshoot and undershoot are measured on either side of a waveform transition.

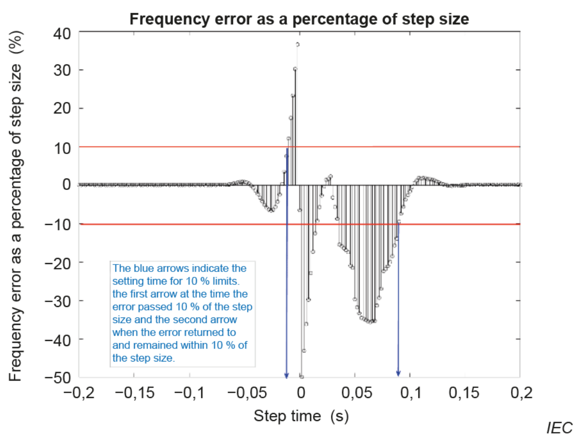
G.3 Determination of settling time using instrument errors

The settling time can be determined from a plot of the step response as shown in 4.6.2 and verified in 6.6. Another method which yields the same results uses the error of reported frequency relative to the reference frequency rather than the step response itself.

The two graphs in Figure G.3 show n = 10 step responses alongside their error plots. Figure G.3 a) shows the frequency error in hertz: FE(Hz) = $f_{instrument}$ − $f_{reference}$. Figure G.3 b) shows frequency error as a percentage of step size: FE(%$_{step}$) = 100 × ($f_{instrument}$ − $f_{reference}$) / (Δt_{size})



a) **Frequency error in hertz**



b) **Frequency error as percentage of step size**

Figure G.3 – Example of reports during step response with higher resolution

[3] H(t) is used to represent a step function which is also called the “Heaviside” function

Figure G.3 illustrates how the settling time could be defined relative to an absolute error from the beginning and end frequencies of the step or as a percentage of the step. In the example above, since the step size was 1 Hz, the absolute error of 0,1 Hz corresponds to 10 % of the step size. If this were the requirement for determining settling time, the settling would start at approximately −0,01 s relative to the step and end at approximately 0,09 s relative to the step for a settling time of 0,10 s. It is also interesting to note that the total response begins at approximately −0,07 s and ends at 0,13 s, for a total response time of 0,2 s or 10 cycles at 50 Hz. This is the instrument's internal analysis window size.

Annex H
(informative)

Voltage and phase angle changes during transmission line faults related to the type of transformer connection

H.1 Overview

This Annex H shows voltage and phase angle changes that can occur during line-to-line short circuit faults on transmission or distribution lines and their dependence on the connection types of substation transformer. Its aim is to explain the requirements of influencing factors for frequency measurement tests with combined magnitude and phase step change in Annex I.

The examples show some of the conditions which the frequency measurement capabilities of DER systems may encounter during fault conditions.

Specific regulations for these types of fault and the performance of the frequency measurement systems are specified in some countries. Discussion presented in this document for phase-to-phase fault is based on requirements of Japanese grid code: JEAG9701-2019, Grid-interconnection Code. Grid codes, in different countries, require that DER stay connected during a transient event for line-to-line or three phase faults on transmission or distribution lines.

When the interconnected transformer connection types are Δ-Δ, or Y-Y, phase angle change is the same between the voltage on primary and secondary sides of a power transformer. However, when the interconnected transformer connection type is Δ-Y or Y-Δ, the voltage phase angle change is different between the primary and secondary sides of the transformer, for the duration of the unbalanced short circuit fault until it is cleared.

In case of two-line short circuit fault, phase angle change is larger on the un-faulted side than on the faulted side, when the transformer connection type is Δ-Y or Y-Δ.

This Annex H describes the nature of the voltage magnitude and phase angle step change during a line fault.

H.2 Power line short circuit fault and protection

A power system configuration which includes synchronous generators, substation transformers and DER during a power transmission line fault and protection operation is shown in Figure H.1. Figure H.1 shows a lightning strike on the transmission line, which induces a short circuit on the transmission line. The lightning strike on the line causes the insulation to fail, resulting in voltage sag and voltage phase angle change.

An associated transient speed acceleration of the synchronous generators in power plant occurs, because the line voltage is shorted and the synchronous generators are not able to deliver power and then it accumulates rotational energy. When the short circuit fault is cleared by opening the circuit breakers on both ends of the transmission line, the phase voltage comes back towards the original point, and the rotational speed returns to the nominal speed.

Figure H.2 shows an example of the sequence of the transmission protection for a short circuit fault. During the short circuit, a voltage sag and a frequency change with phase step change are observed. At the point of coupling of DER on medium voltage distribution line, the voltage sag magnitude and phase change step are limited by the finite line impedance between the fault point and DER connection point.

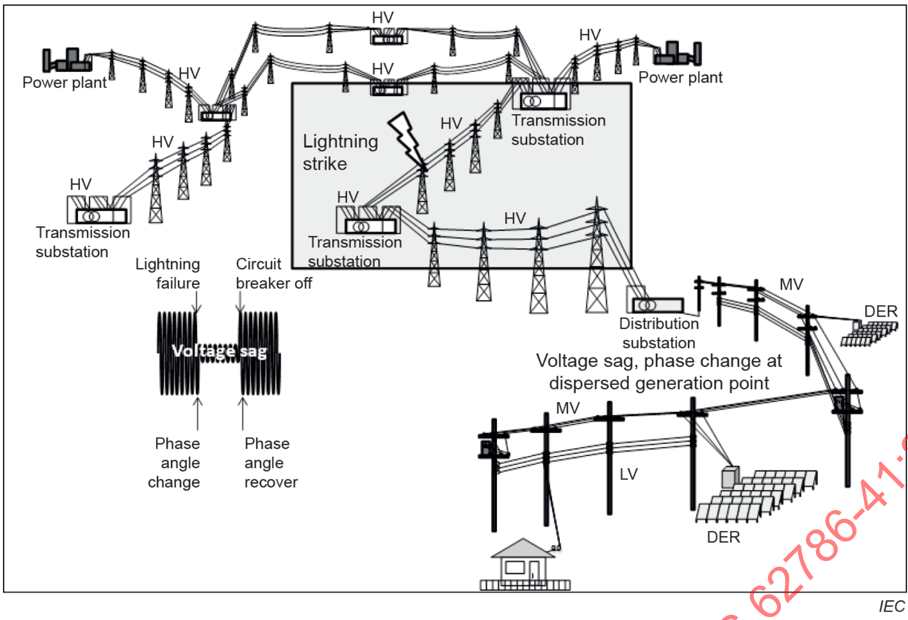


Figure H.1 – Voltage phase change by transmission line short circuit fault

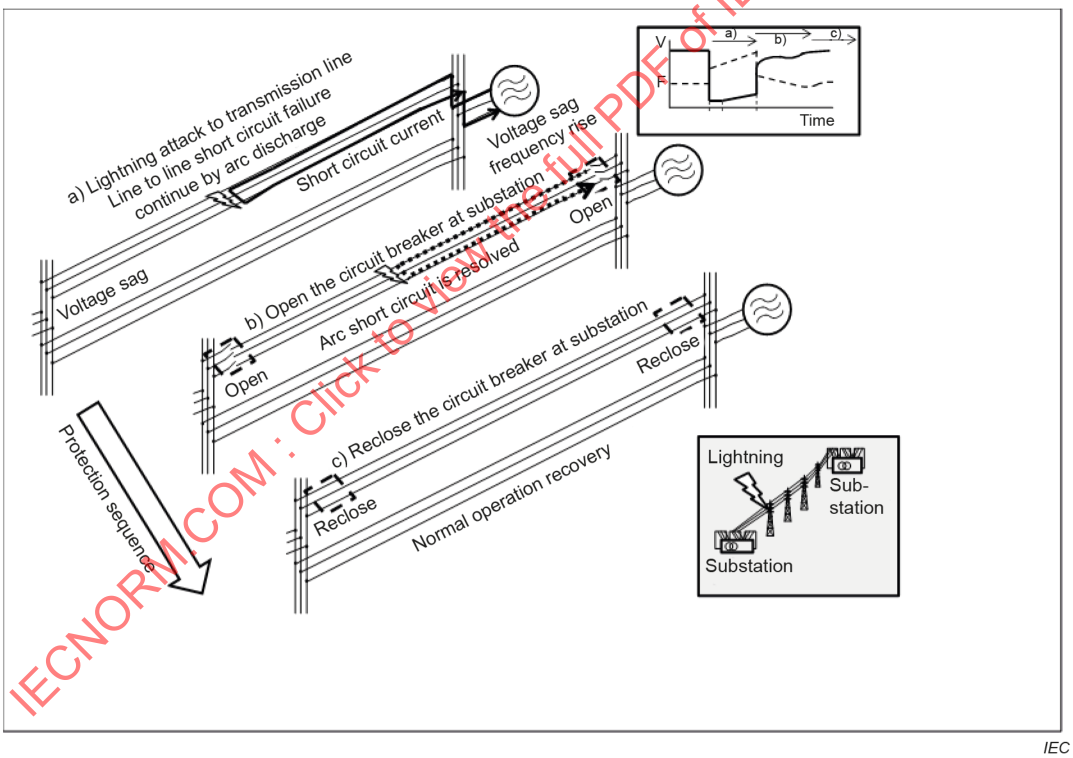


Figure H.2 – Transmission line protection sequence and line voltage, frequency change

As the reduction of rotational inertia energy is an issue for power system frequency stability when the power electronic converter-based DER become dominant, a synthetic inertia function reacting to the quick frequency change is required. For this function, appropriate and quick detection of power system frequency, without frequency measurement errors caused by voltage phase change, is essential.

H.3 Voltage magnitude and phase angle change at line fault

H.3.1 General

Voltage magnitude and phase angle change at line fault are observed, depending on short circuit fault type and substation transformer windings' connection types.

The change in voltage magnitude ratio and phase angle changes with transformer windings' connection type are described in H.3.2 and H.3.3.

H.3.2 Balanced-three-phase short circuit fault

The three-phase short circuit fault case has the most significant effect on voltage magnitude on un-faulted side. Figure H.3 shows the voltage and phase angle change example at the event of three-phase short circuit fault on Y-connection side with remaining voltage of 20 %. In this case, phase angle change is not observed in the Δ-connection side line to line voltage of transformer output.

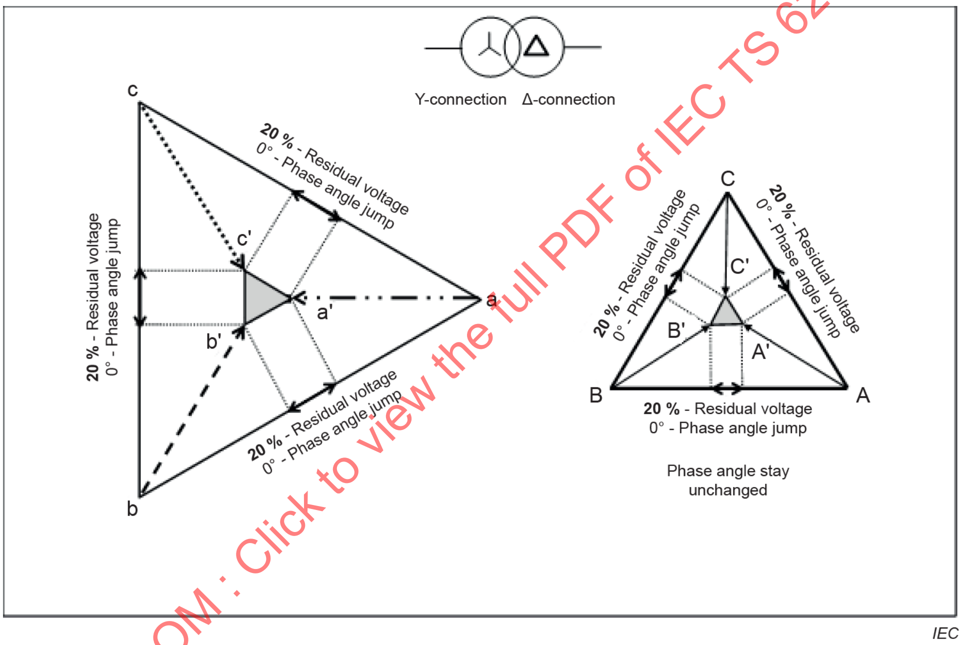


Figure H.3 – Voltage and phase angle change at three-phase short circuit

H.3.3 Line-to-line short circuit fault

For line-to-line short circuit fault, remaining voltage and phase angle change depend on the type of transformer windings' connection. Figure H.4 shows the relation of voltage phase angle between Y-connection and Δ-connection. In a transformer, the concentric windings, on an iron core leg for each phase, have the same voltage direction of vectors because of the common magnetic flux.

Voltages whose vector direction are the same, are:

- Y side voltage at port (a-n) is in parallel with Δ-connection side voltage at port (A-B);
- Y side voltage at port (b-n) is in parallel with Δ-connection side voltage at port (B-C);
- Y side voltage at port (c-n) is in parallel with Δ-connection side voltage at port (C-A).

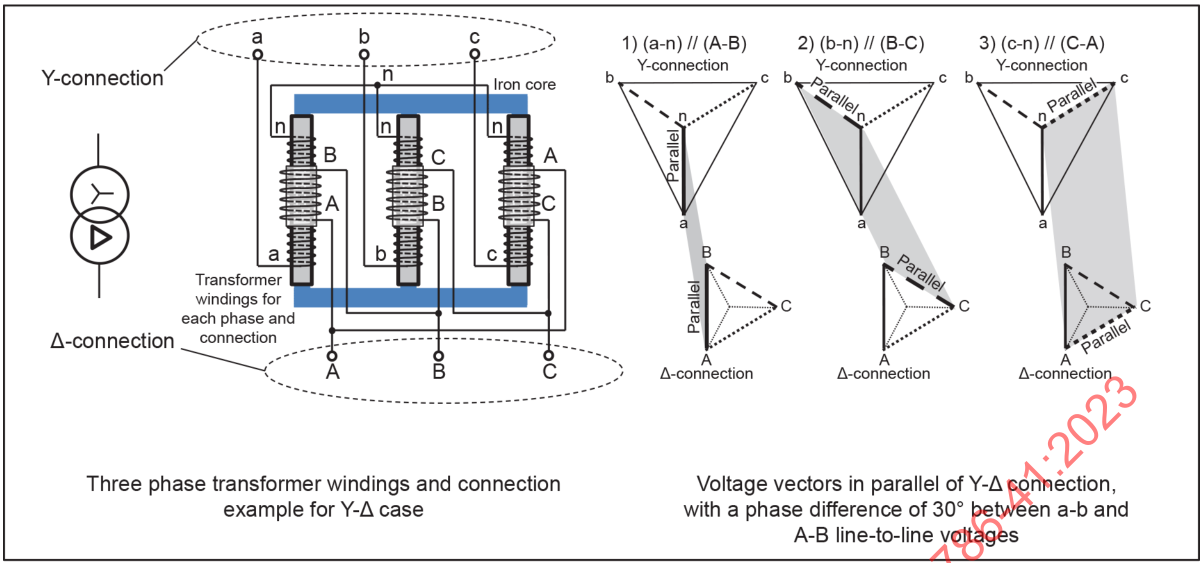


Figure H.4 – Relationship of voltage phase angle between Y-connection side and Δ-connection side

Figure H.5 shows the voltage and phase angle change during a line-to-line short circuit fault on the Y-connection side. Figure H.5 shows an example with voltage in Y-connection side reduced to 20 % due to line to line short between phase b and phase c. Keeping the paralleling relationship of voltage between Y-connection side phases and Δ-connection side line to line, the resulting voltage and phase angle change are different. The phase angle change is observed as a step change. For frequency measurement at DER, phase step changes should be appropriately filtered for stable operation.

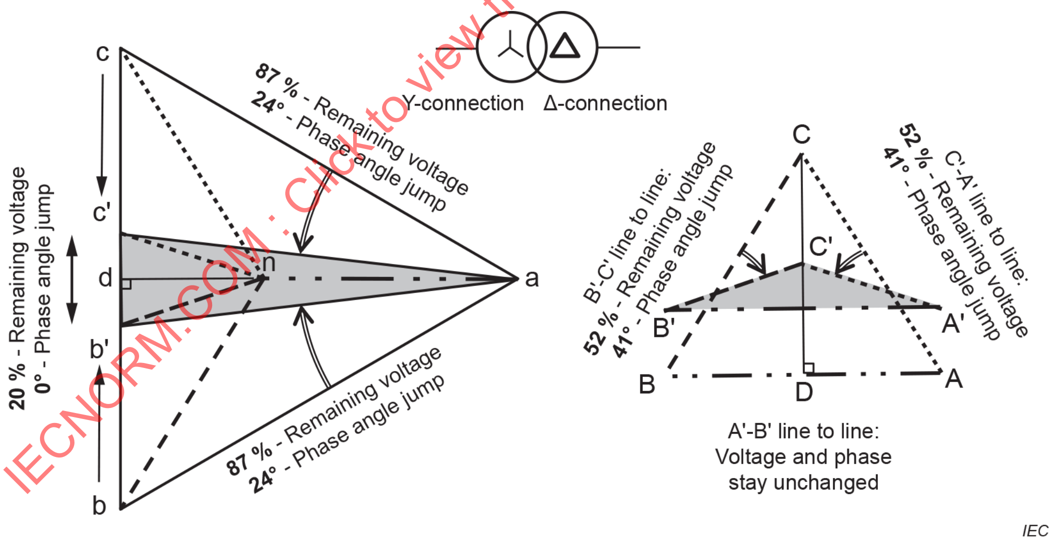


Figure H.5 – Voltage magnitude and phase angle change at two-phase short circuit fault

As an example, voltage and phase change at short circuit fault is calculated as below.

For b-c line to line fault case with remaining voltage of 20 % on Y-connection side of the transformer.

- Y-connection side:

$$(\text{a-c'}) = \sqrt{(0{,}1)^2 + \left(\sqrt{3}/2\right)^2} \approx 0{,}87$$

$$\angle(\text{c'-a-d}) = \text{atan}\left(\frac{(\text{c'-b'})/2}{\sqrt{3}/2}\right) = 6{,}6°;$$

Phase angle change = 30° − 6.6°≈ 24°.

- Δ-connection side:

(c'-d) = 0,5 × (c'-b') = 0,1

$$(\text{d-n}) = (\text{a-d}) - (\text{a-n}) = \left(0{,}5 \times \sqrt{3}\right) - \left(0{,}5 \times \frac{2}{\sqrt{3}}\right) \approx 0{,}29$$

$$\angle(\text{C'-A'-D'}) = \angle(\text{c'-n-d}) = \text{atan}\left(\frac{0{,}1}{\text{d-n}}\right) = \text{atan}\left(\frac{0{,}1}{\left(0{,}5 \times \sqrt{3}\right) - \left(0{,}5 \times \frac{2}{\sqrt{3}}\right)}\right) = 19{,}1°$$

Phase angle change = 60° − 19,1° ≈ 41°

(A'-C') = 0,5/cos 19,1°≈ 0,52

It can be seen that the phase angle change on the Y-connection side is 24° and on the Δ-connection side is approximately 41°.

H.4 Conclusion

For frequency measurement at the point of coupling of DER, care should be taken of voltage and phase angle step changes that are observed when short circuit fault on transmission lines occurs. The step change voltage ratio and phase angle depend on the type of fault and substation transformer winding configuration.

Voltage and phase angle step changes are categorized and referred to IEC TS 62910:2020 [24].

Annex I
(informative)

Influencing factors and functional tests

I.1 Influencing factors

This Annex I describes influencing factors which may affect the characteristics of frequency and ROCOF measurements defined in Clause 4. Annex I describes functional tests to validate the instrument's performance in the presence of these influencing factors. At this time the impact of these influencing factors on declared characteristics is informative. After some experience with instruments and the functional testing described in Annex I, the impact may become normative in a future revision of this document. Until such time, the impact need not be declared by the manufacturer.

The functional tests in Annex I are informative and are not required, but manufacturers can perform these tests to gain a better understanding of the characteristics of the measurements and in preparation for a future revision where these functional tests may become required.

Table I.1 summarizes the influencing factors addressed in Annex I.

Table I.1 – Influencing factors of frequency and ROCOF measurements

Influencing factor	Impacted characteristics and comment
Phase step change	error, step response time, see I.2.2
Magnitude step change	error, step response time, see I.2.3
Combined magnitude and phase step change	error, step response time, see I.2.4
Voltage magnitude drop and restoration	error, step response time, see I.2.5
Noise	absolute error, see I.2.6
Unbalanced magnitude of energizing input quantities	Additional absolute error, see I.2.7. When the frequency and ROCOF measurement is based on three phase input signals (e.g. three phase-to-ground voltages), the influence of unbalance signal shall be tested.
Linear ramp of frequency	error, see I.2.8

I.2 Functional tests

I.2.1 General

The following tests describe the methods to assess the effect on the characteristics of frequency or ROCOF measurement in the presence of various influencing factors on the voltage signals.

Frequency and ROCOF measurements shall be evaluated as the difference between the measured values provided by the algorithm/device (measured) and the input signal values (reference values (ref)) under test conditions.

I.2.2 Phase step change

I.2.2.1 Test description

For single phase instruments, performance during step-change in input signal phase can be determined by applying the input signal represented in Formula (I.1):

$$X_p(t) = X_c \times \sin\left(2 \times \pi \times f_0 \times t + \varphi_p + k_p \times h1(t)\right) \quad (I.1)$$

where X_c is the peak amplitude of the input signal, f_0 is the nominal power frequency, $h1(t)$ is a unit step function and k_p is the phase step size.

The variable φ_p is defined in 6.1 for single phase and three phase signals. For three phase instruments, performance during step changes in phase can be determined by applying balanced three phase step changes to balanced three-phase input signals.

A phase step size k_p = +0,3 radian and −0,3 radian should apply.

NOTE 0,3 radian is based on field measurements of signals during grid fault conditions. Examples of phase step inside power systems are described in Annex H.

To determine the instrument errors, the instrument should be in a steady state condition prior to the phase step and the instrument readings should be determined. Following the step change, the instrument errors are given by the maximum deviation instrument readings from the instrument readings that occurred following the phase step.

During this test, the response time of the instrument readings will be determined. The response time is the period from when the instrument absolute error first becomes greater than the manufacturer's declared maximum absolute error until the time that the error returns to and remains below the manufacturer's declared maximum absolute error.

It is likely that the instrument readings will be affected by the finite reporting time of the instrument, in particular, when the reporting rate is long compared to the settling time. Because a phase step can occur at any point in the reporting interval (the phase could change at the start of the reporting time, or in the middle, etc.), the error response of the instrument as determined by the subsequent instrument reading(s) will be variable. This variation can be produced systematically using an "equivalent time sampling" technique, where a series of step changes are each separated by an arranged interval. This interval is calculated such that successive steps occur at increasing fractions of the instrument reporting rate. Typically, 10 equivalent time steps per reporting period provide sufficient resolution to determine settling time. Details of this approach are given in Annex G.

For consistency, the input phase in successive test iterations should not change, only the time that the phase step occurs. In this manner, the step will occur at different signal phases between each test iteration.

I.2.2.2 Example of phase step change test

An actual instrument was tested with phase step change in accordance with I.2.2 and using the equivalent time sampling techniques described in Clause G.2. Results are shown below.

Figure I.1 shows an example from an actual instrument of frequency errors due to positive and negative phase steps. For each test, a set of 10 step iterations were performed where the input phase was the same for each iteration but the time the step occurred was shifted by one tenth of the instrument's reporting period. Later, the results from the individual iterations were interleaved to form a single equivalent time samples set of instrument error values shown in Figure I.1.

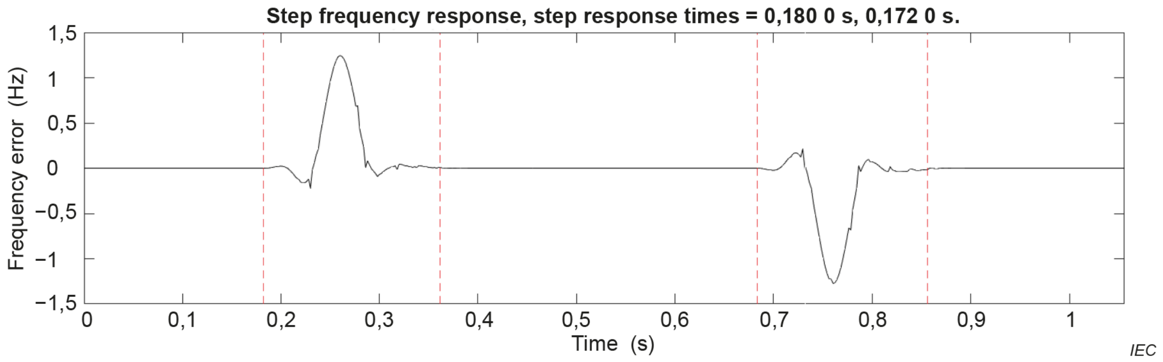


Figure I.1 – Frequency error response to +0,3 radian phase step followed by −0,3 radian step

The red dashed lines indicate the phase step response time of the instrument. The phase was stepped +0,3 radians at approximately 0,18 s, then half a second later, stepped −0,3 radians back to the original phase. The red lines preceding the responses show where the absolute error value exceeds the manufacturer's declared maximum absolute frequency error under steady state conditions (in this case 0,005 Hz). The red lines following the responses show where the absolute error value returns to and remains below the manufacturer's declared maximum absolute error under steady state conditions.

Figure I.2 shows an example from an actual instrument of ROCOF error due to phase steps.

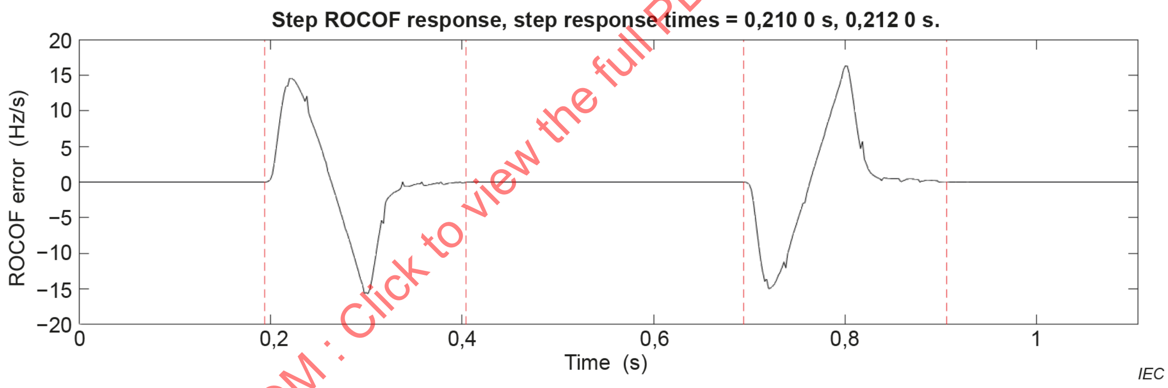


Figure I.2 – ROCOF error response to +0,3 radian phase step followed by −0,3 radian step

The red dashed lines indicate the ROCOF phase step response time of the instrument. The red lines preceding the responses show where the absolute error value exceeds the manufacturer's declared maximum absolute ROCOF error under steady state conditions (in this case 0,04 Hz/s). The red lines following the responses show where the absolute error value returns to and remains below the manufacturer's declared maximum absolute ROCOF error under steady state conditions.

I.2.3 Magnitude step change

I.2.3.1 Test description

The object of this test is to provide common reference for assessing the immunity of a single phase or three phase instrument when subjected to voltage dips and short interruptions as well as over voltage.

For single phase instruments, performance during magnitude change in input signal phase shall be determined by applying the input signal represented in Formula (I.2):

$$X_p(t) = X_c \times \left[1 + k_a \times h1(t)\right] \times \sin\left(2 \times \pi \times f_0 \times t + \varphi_p\right) \quad (I.2)$$

where X_c is the peak amplitude of the input signal, f_0 is the nominal power frequency, $h1(t)$ is the unit step function (see Note 1), k_a is the magnitude step size.

For the positive magnitude step, a step of k_a = +0,1 p.u. shall be evaluated.

For the negative magnitude step, a step of k_a = −0,8 per unit should be applied (See Note 1 and 2).

The duration of signal before a step change and after a step change shall be at least three (3) times the duration of the declared settling time.

During this test, the response time of the instrument readings will be determined. The response time is the period from when the instrument absolute error first becomes greater than the manufacturer's declared maximum absolute error until the time that the error returns to and remains below the manufacturer's declared maximum absolute error. (See Note 3.)

NOTE 1 "Step" implies an instantaneous change which is not possible with a practical waveform generator. The test can be carried out using a waveform generator and amplifier with a specification as given in 6.1.

NOTE 2 During grid fault conditions, the voltage magnitude depends on many factors such as fault location, fault impedance, etc. A voltage magnitude of 0,8 p.u. is proposed in this test as typical value, which is representative of common case.

NOTE 3 This can be noted as "Not applicable" if the instrument errors are zero.

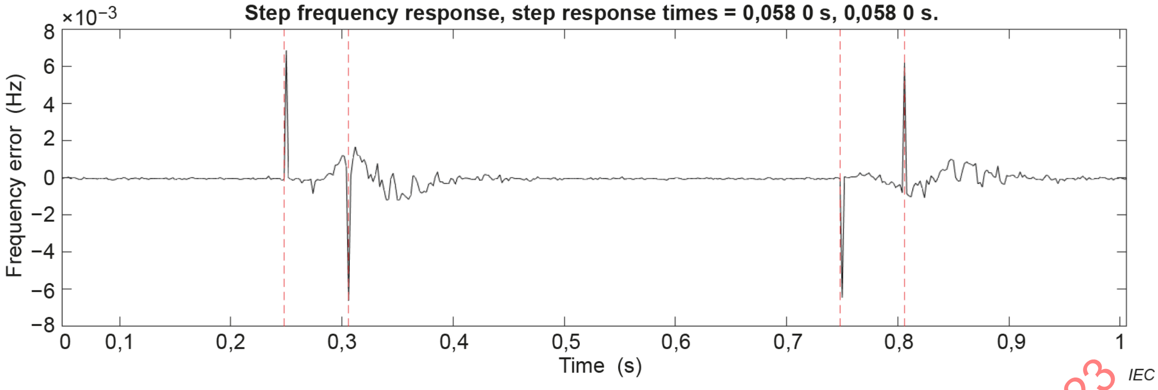
It is likely that the instrument readings will be affected by the finite reporting time of the instrument, in particular, when the reporting rate is long compared to the settling time. Because a magnitude step can occur at any point in the reporting interval (the phase could change at the start of the reporting time, or in the middle, etc.), the error response of the instrument as determined by the subsequent instrument reading(s) will be variable. This variation can be produced systematically using an "equivalent time sampling" technique, where a series of step changes are each separated by an arranged interval. This interval is calculated such that successive steps occur at increasing fractions of the instrument reporting rate. Typically, 10 equivalent time steps per reporting period provide sufficient resolution to determine settling time. Details of this approach are given in Annex G.

For consistency, the input phase in successive test iterations should not change, only the time that the magnitude step occurs. In this manner, the step will occur at different signal phrases between each test iteration.

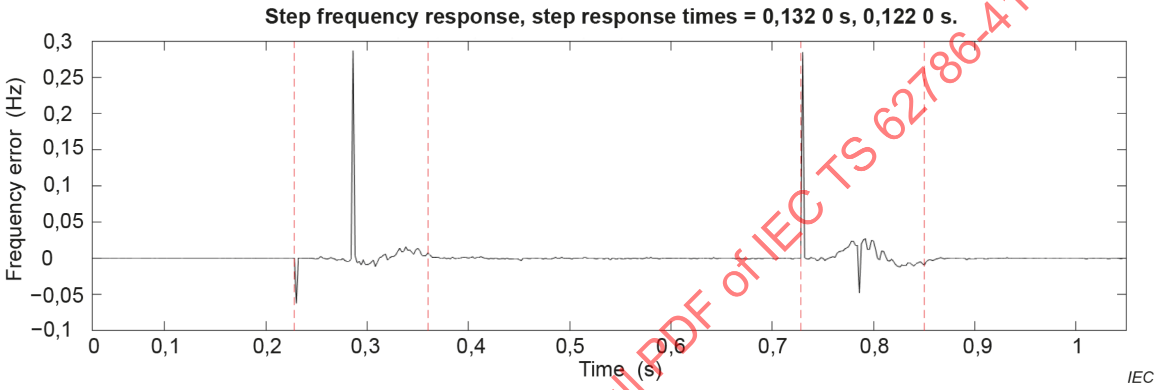
I.2.3.2 Example of magnitude step change

An actual instrument was tested with magnitude step change in accordance with I.2.3 and using the equivalent time sampling techniques described in Clause G.2. Results are shown below.

Figure I.3 shows an actual instrument's frequency error response to magnitude steps of 0,1 p.u. and 0,8 p.u. Figure I.3 a) shows the response to a positive 0,1 p.u. step followed by a negative 0,1 p.u. step. Figure I.3 b) shows the response to a negative 0,8 p.u. step followed by a positive 0,8 p.u. step.



a) 0,1 p.u. magnitude step responses, positive step followed by negative step

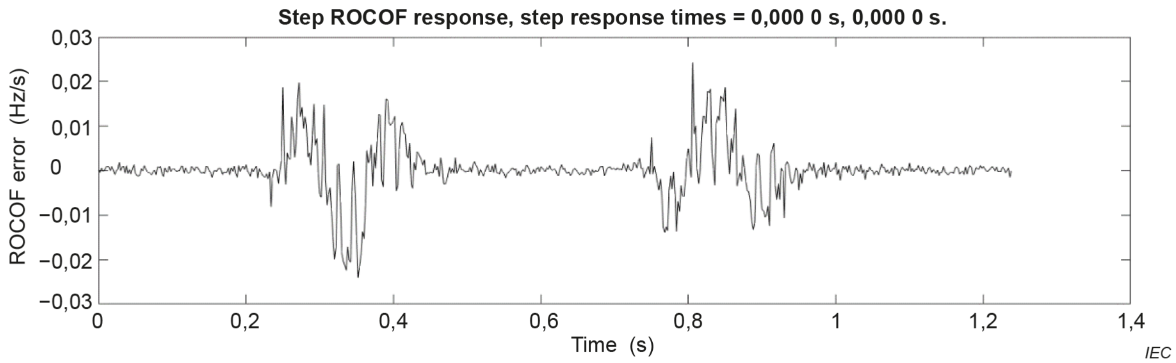


b) 0,8 p.u. magnitude step response, negative step followed by positive step

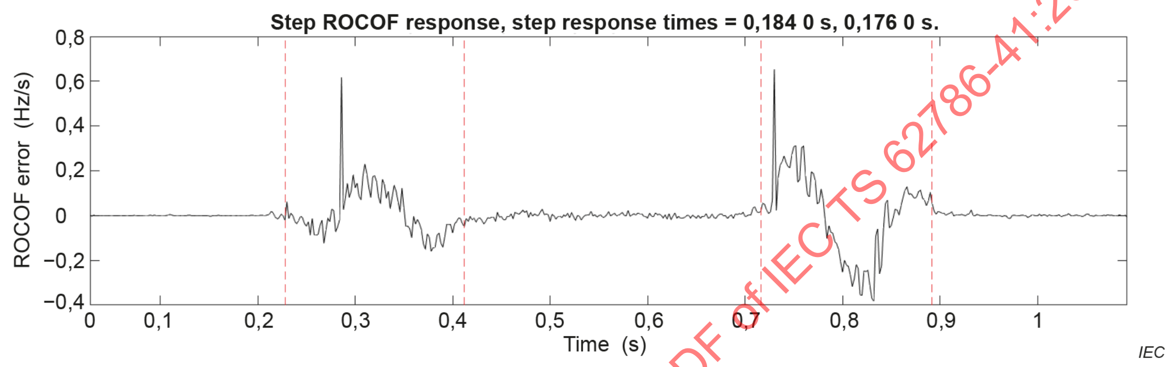
Figure I.3 – Frequency error response to magnitude step changes

The red dashed lines show the magnitude step response times. The red lines preceding the responses show where the absolute error value exceeds the manufacturer's declared maximum absolute frequency error under steady state conditions (in this case, 0,005 Hz). The red lines following the responses show where the absolute error value returns to and remains below the manufacturer's declared maximum absolute frequency error under steady state conditions.

Figure I.4 shows the ROCOF error of an actual instrument in response to steps in magnitude. Figure I.4 a) shows the response to a +0,1 p.u. step on magnitude and Figure I.4 b) shows the response to a −0,8 p.u. step in magnitude.



a) 0,1 p.u. magnitude step responses, positive step followed by negative step



b) 0,8 p.u. magnitude step response, negative step followed by positive step

Figure I.4 – ROCOF error response to steps in magnitude

Red vertical dashed lines show the magnitude step response times of the instrument. In Figure I.4 a), no response time is shown because the ROCOF error never exceeded the manufacturer's declared maximum absolute error for ROCOF (in this case, 0,04 Hz/s). The response time is "not applicable". In Figure I.4 b), the red lines preceding the responses show where the absolute error value exceeds the manufacturer's declared maximum absolute ROCOF error under steady state conditions (in this case, 0,04 Hz/s). The red lines following the responses show where the absolute error value returns to and remains below the manufacturer's declared maximum absolute ROCOF error under steady state conditions.

I.2.4 Combined magnitude and phase step change

I.2.4.1 Test description

This subclause I.2.4 applies to three phase instruments only. Such combined disturbance is familiar for short circuit failure on transmission line, and ability to continue frequency measurement is required.

The instrument performance during a step change in input signal magnitude and a step change in signal phase shall be determined by applying the input signal represented in Formula (I.3):

$$X_{\text{p}}(t) = X_{\text{c}} \times \left[1 + k_{\text{a}} \times h1(t)\right] \times \sin\left(2 \times \pi \times f_0 \times t + \varphi_{\text{p}} + k_{\text{p}} \times h2(t)\right) \tag{I.3}$$

where X_{c} is the peak amplitude of the input signal, f_0 is the nominal power frequency, $h1(t)$ and $h2(t)$ are unit step functions (see Note 1), k_{a} is the magnitude step size and k_{p} is the phase step size.

φ_p is defined in 6.1 for the three phase signals. Performance during step changes in magnitude shall be determined by applying balanced three-phase magnitude step changes to balanced three-phase input signals.

The combined magnitude and phase step test is made with two separate unbalanced conditions (see Note):

a) k_a = −0,8 on one phase at a time, with the remaining two phases experiencing magnitude step with k_a = −0,13 and phase jump of 24°. The three phase voltage vectors are described in Table I.2 and in Figure I.5.

Table I.2 – Test case a) for combined magnitude and phase step change

Voltage signal	State 1	State 2	State 3
U_{AG}	1 p.u. V, φ_p = −30,0°	0,87 p.u. V, φ_p = −6,59°	1 p.u. V, φ_p = −30,0°
U_{BG}	1 p.u. V, φ_p = −150,0°	0,87 p.u. V, φ_p = −173,4°	1 p.u. V, φ_p = −150,0°
U_{CG}	1 p.u. V, φ_p = 90,0°	0,2 p.u. V, φ_p = 90,0°	1 p.u. V, φ_p = 90,0°

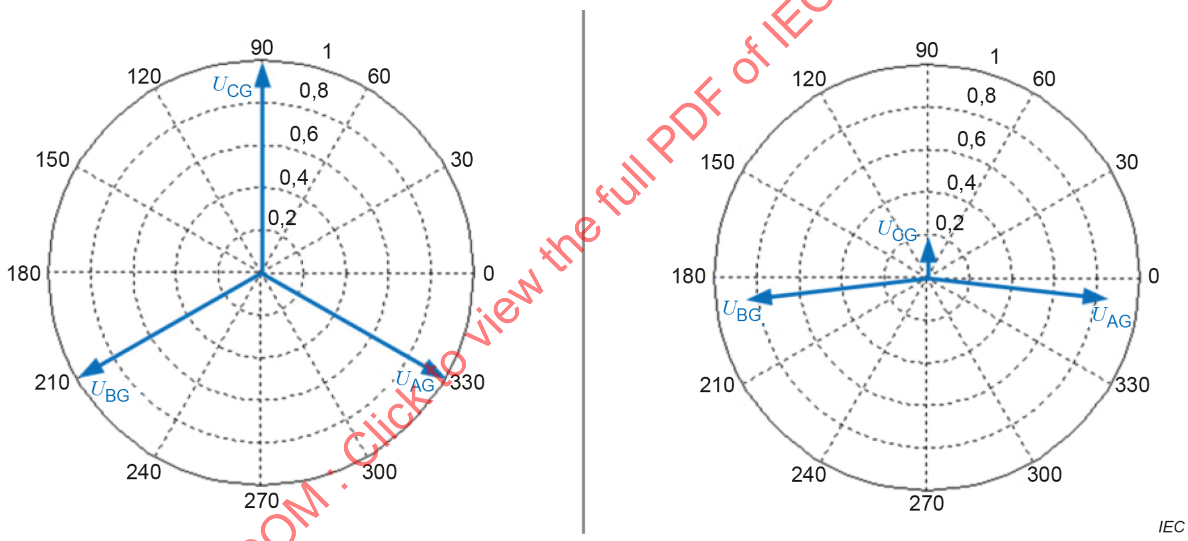


Figure I.5 – Voltage vectors for test case a)

b) k_a = −0,48 on two phases at a time, with the remaining one phase staying unchanged and phase jump of 41°. The three phase voltage vectors are described in Table I.3 and in Figure I.6.

Table I.3 – Test case b) for combined magnitude and phase step change

Voltage signal	State 1	State 2	State 3
U_{AG}	1 p.u. V, φ_p = 0,0°	1 p.u. V, φ_p = 0°	1 p.u. V, φ_p = 0,0°
U_{BG}	1 p.u. V, φ_p = −120,0°	0,52 p.u. V, φ_p = −160,9°	1 p.u. V, φ_p = −120,0°
U_{CG}	1 p.u. V, φ_p = 120,0°	0,52 p.u. V, φ_p = 160,9°	1 p.u. V, φ_p = 120,0°