



BSI Standards Publication

Distributed energy resources connection with the grid

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

National foreword

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A list of organizations represented on this committee can be obtained on request to its committee manager.

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TECHNICAL SPECIFICATION



**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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ELECTROTECHNICAL
COMMISSION

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distributed energy resources (DER) and loads****FOREWORD**

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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	$\pm 0,005$ Hz	$\pm 0,06$ Hz
ROCOF	0,012 Hz/s	$\pm 0,04$ Hz/s	$\pm 2,3$ 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.

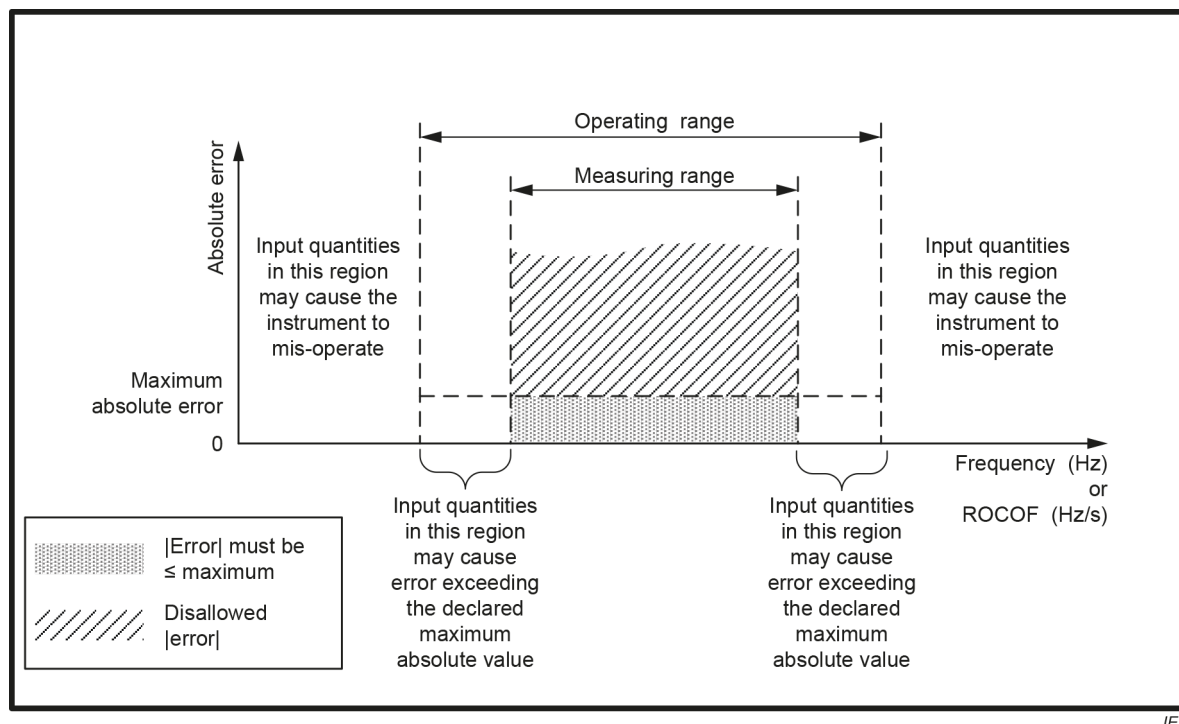
The manufacturer shall declare the maximum absolute error for frequency and ROCOF under steady state and dynamic operating conditions. This is the absolute value of the worst-case measurement error allowed by the instrument operating within its measuring range as described in 4.5. Frequency and ROCOF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

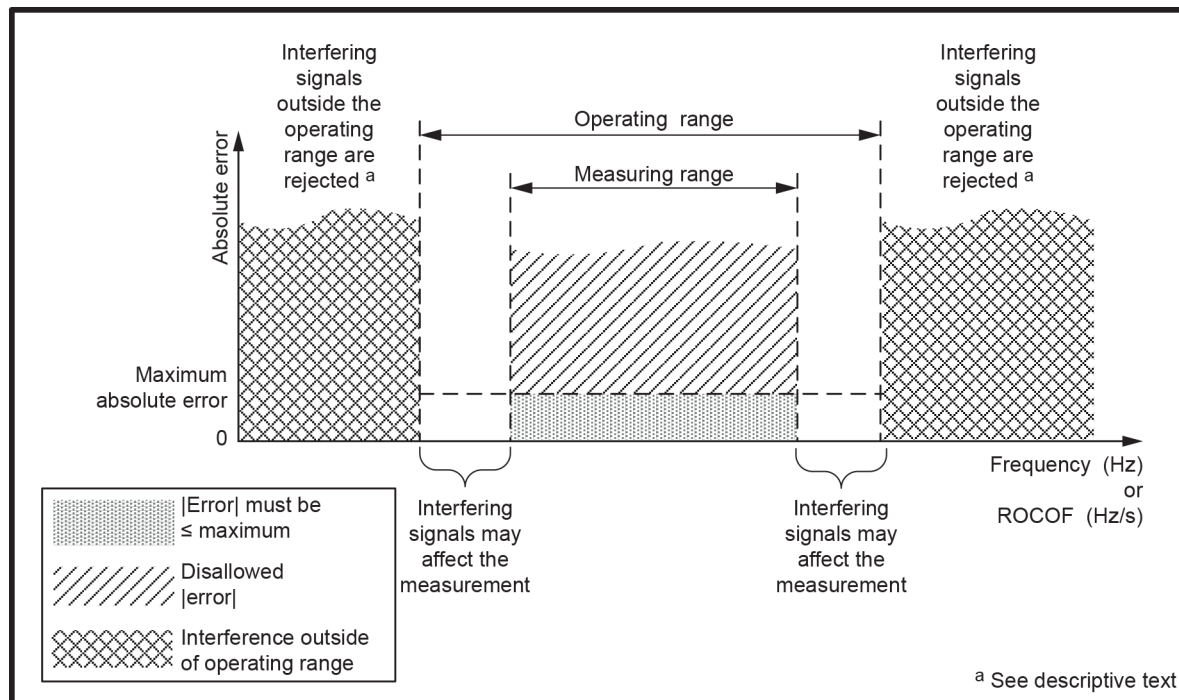
The operating range of the instrument is extended beyond the measuring range, to ensure input frequency or ROCOF in the operating range does not cause the instrument to enter any form of saturation mode that requires a recovery time when the input returns into the measuring range.

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.



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Figure 1 – Measuring range and operating range without interfering signals



^a See descriptive text

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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 $f_n \pm 5$ 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 $f_n \pm f_n/2$ (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 $|\pm 0,005 \text{ Hz}|$ error under steady state conditions and $|0,06 \text{ Hz}|$ 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 $|\pm 0,005 \text{ Hz}|$ 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 ($d f/dt = 0$, 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.

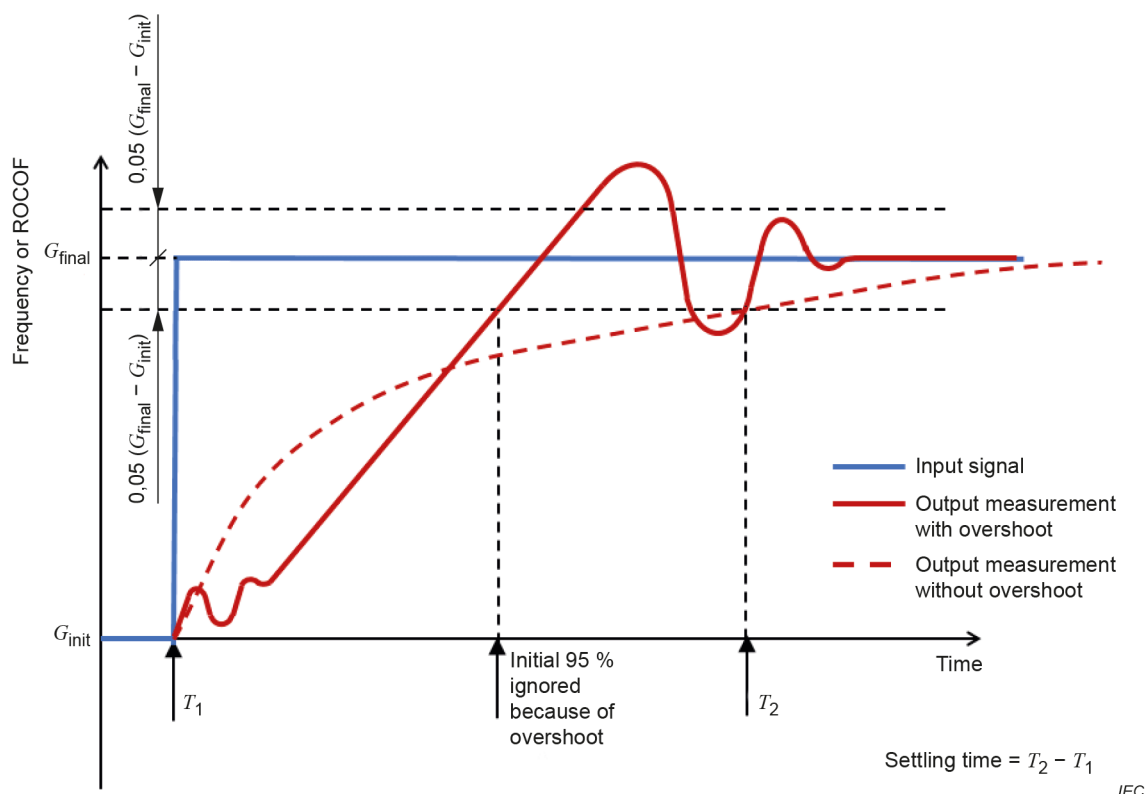


Figure 3 – Settling time description with input signal added

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	A
						100 ms	B
	200 ms	C					
	1 s	D					
	1 s	D					
	1 s	D					
	1 s	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):

$$X_p(t) = X_c \times \sin(2 \times \pi \times f_0 \times t + \varphi_p + K_m \times \sin(2 \times \pi \times f_m \times t)) \quad (1)$$

where

$X_p(t)$ 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 $\Delta f = \pm 5$ 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).

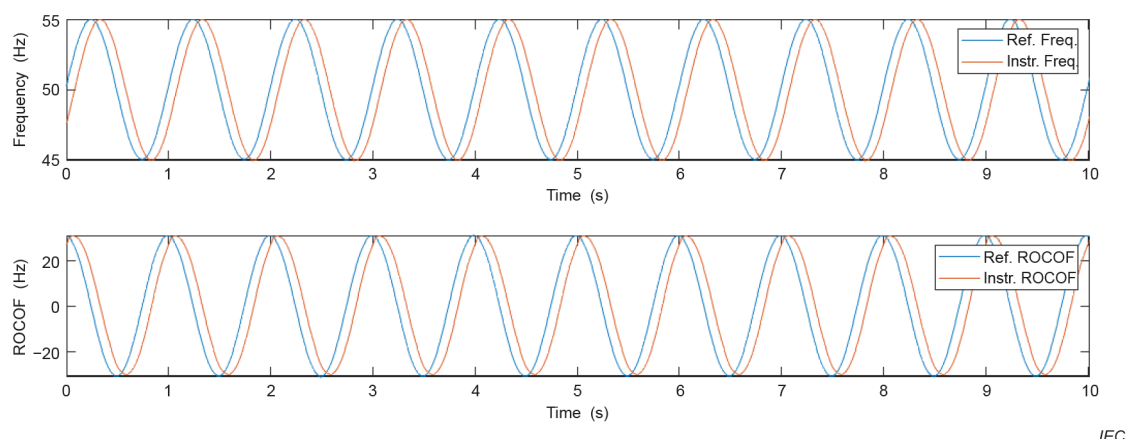


Figure 4 – Example of frequency delay time validation: measurement of delay time for a power frequency of 50 Hz

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.

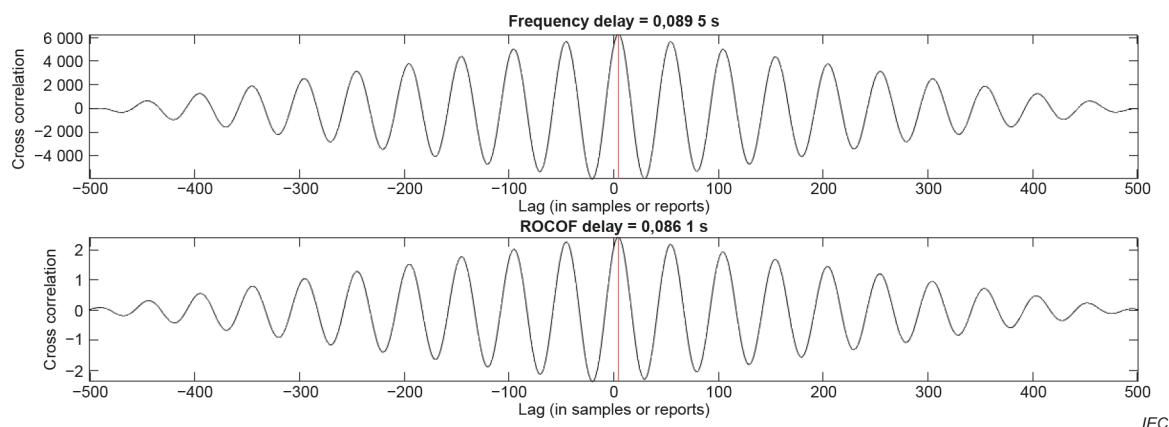


Figure 5 – Example of cross-correlations of the normalized frequencies and ROCOF

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):

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

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

$$t_d = \left(\left(k - 1 - \text{floor} \left(\frac{m}{2} \right)_r \right) - \frac{\theta}{\omega} \right) dT \quad (6)$$

where

t_d is the delay time;

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

dT 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 $10/f_m$. 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 n th 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:

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

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}).

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

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].

$$E_{res} = \frac{R_{rms}}{P_{meas}} \times M_{range} \quad (12)$$

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.

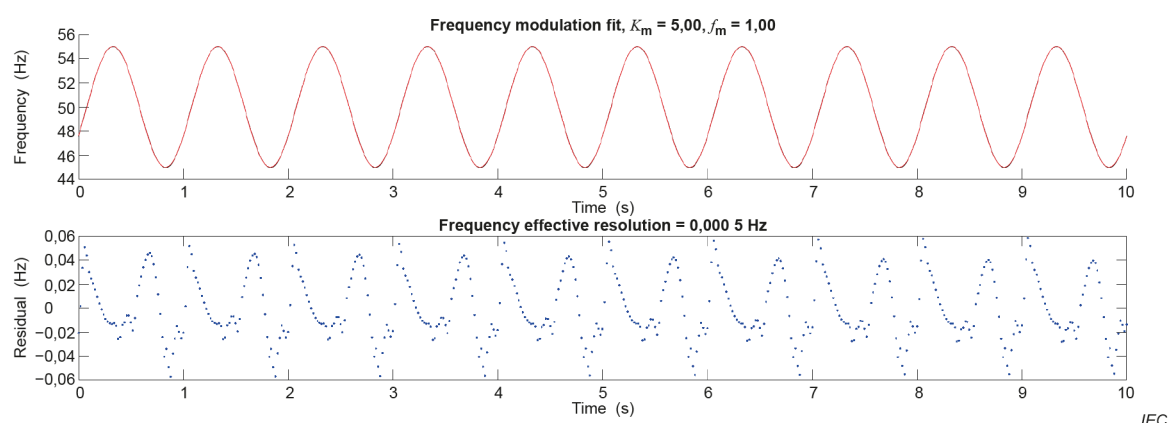


Figure 6 – Example of frequency modulation used to determine frequency effective resolution

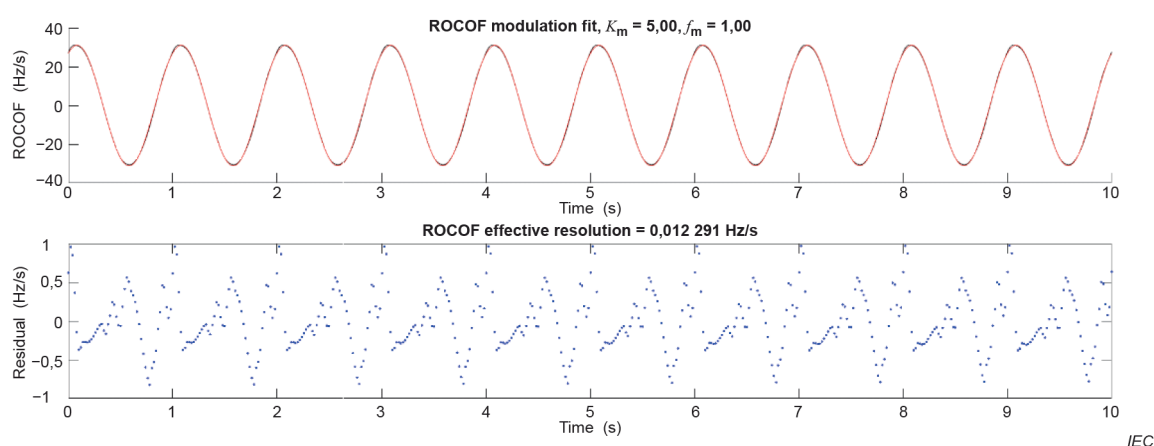


Figure 7 – Example of frequency modulation used to determine ROCOF effective resolution

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).

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

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 $f_n \pm 5$ Hz (45 Hz to 55 Hz for 50 Hz nominal frequency). The operating range was declared at $f_n \pm f_n/2$ (25 Hz to 75 Hz). The maximum absolute frequency error was given by the manufacturer to be $|\pm 0,005$ Hz| and the maximum absolute ROCOF error was given by the manufacturer to be $|\pm 0,04$ 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.

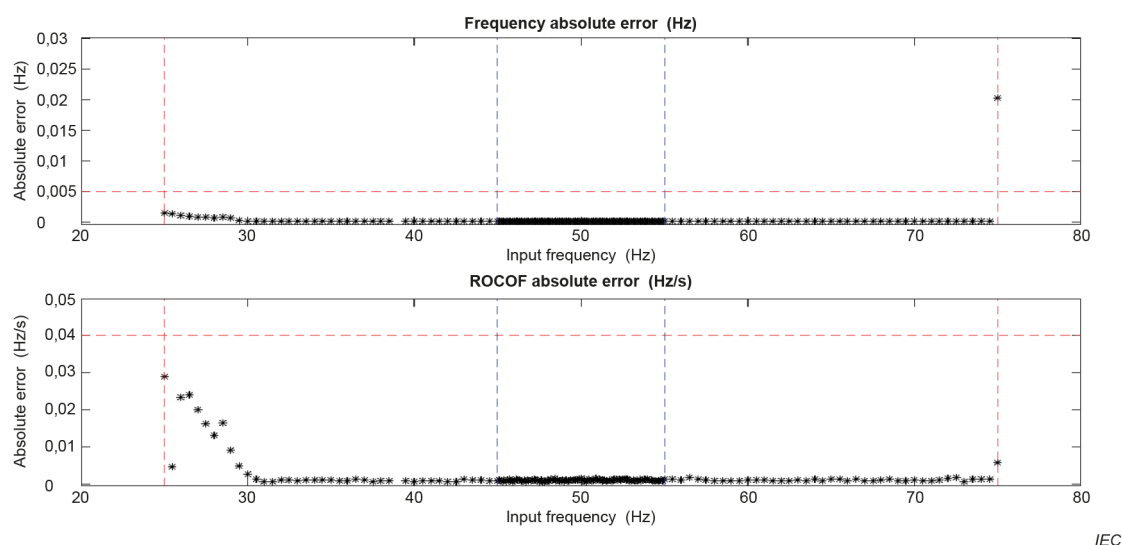


Figure 8 – Example of verification of measurement bandwidth under steady state conditions

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 that 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 ($\text{ROCOF}_{\text{peak}}$) reached by the input signal are functions of both K_m and f_m as shown in Formulas (15) and (16).

$$f_{\text{peak}} = f_0 + K_m \times f_m \quad (15)$$