BS EN 60469:2013

BSI Standards Publication

Transitions, pulses and related waveforms — Terms, definitions and algorithms

National foreword

This British Standard is the UK implementation of EN 60469:2013. It is identical to IEC 60469:2013. It supersedes BS 5698-1:1989 and BS 5698-2:1989, which are withdrawn.

The UK participation in its preparation was entrusted to Technical Committee PEL/85, Measuring equipment for electrical and electromagnetic quantities.

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

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English version

Transitions, pulses and related waveforms - Terms, definitions and algorithms
(IEC 60469:2013)

Transitions, impulsions et formes d'ondes associées -
Termes, définitions et algorithmes
(CEI 60469:2013)

Übergänge, Impulse und zugehörige Schwingungsabbilder - Begriffe, Definitionen und Algorithmen
(IEC 60469:2013)

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CENELEC
European Committee for Electrotechnical Standardization
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Foreword

The text of document 85/409/CDV, future edition 1 of IEC 60469, prepared by IEC/TC 85 "Measuring equipment for electrical and electromagnetic quantities" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 60469:2013.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2014-02-28
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2016-05-28

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Endorsement notice

The text of the International Standard IEC 60469:2013 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

ISO 9000:2005	NOTE Harmonised as EN ISO 9000:2005 (not modified).
ISO 10012:2003	NOTE Harmonised as EN ISO 10012:2003 (not modified).

CONTENTS

INTRODUCTION

The purpose of this standard is to facilitate accurate and precise communication concerning parameters of transition, pulse, and related waveforms and to establish the techniques and procedures for measuring them. Because of the broad applicability of electrical pulse technology in the electronics industries (such as computer, telecommunication, and test instrumentation industries), the development of unambiguous definitions for pulse terms and the presentation of methods and/or algorithms for their calculation is important for communication between manufacturers and consumers within the electronics industry. The availability of standard terms, definitions, and methods for their computation helps improve the quality of products and helps the consumer better compare the performance of different products. Improvements to digital waveform recorders (including oscilloscopes) have facilitated the capture, sharing, and processing of waveforms. Frequently these waveform recorders have the ability to process the waveform internally and provide pulse parameters. This process is done automatically and without operator intervention. This standard can be applied in many more scientific and engineering applications than mentioned above, such as optics, cosmology, seismology, medicine, etc., and ranging from single events to highly repetitive signals and from signals with bandwidths less than 1 Hz to those exceeding 1 THz. Consequently, a standard is needed to ensure that the definitions and methods of computation for pulse parameters are consistent.

IEC 60469-1 dealt with terms and definitions for describing waveform parameters and IEC 60469-2 described the waveform measurement process. The purpose of this standard is to combine the contents of IEC 60469-1 and IEC 60469-2, update terminology, correct errors, add algorithms for computing values of pulse parameters, and add a newly-developed method for computing state levels. This standard reflects two major changes compared to IEC 60469-1 and IEC 60469-2, which are the parameter definitions and algorithms. Changes to the definitions included adding new terms and definitions, deleting unused terms and definitions, expanding the list of deprecated terms, and updating and modifying existing definitions. This standard contains definitions for approximately 100 terms commonly used to describe the waveform measurement and analysis process and waveform parameters. Many of the terms in standards IEC 60469-1 and IEC 60469-2 have been deleted entirely or deprecated. Deprecated terms were kept in this standard to provide continuity between this standard and IEC 60469-1 and IEC 60469-2. Terms are deprecated whenever they cannot be defined unambiguously or precisely. Development of a set of agreed-upon terms and definitions presented the greatest difficulty because of the pervasive misuse, misrepresentation, and misunderstanding of terms. Legacy issues for instrumentation manufacturers and terms of common use also had to be addressed. This standard also resulted in the development of algorithms for computing the values of certain waveform parameters in all cases where these algorithms could be useful or instructive to the user of the standard. The purpose of adding these algorithms, which are recommended for use, was to provide industry with a common and communicable reference for these parameters and their computation. Heretofore, this was not available and there existed much debate and misunderstanding between various groups measuring the same parameters. Similarly, this is the reason for including several examples of basic waveforms, with formulae, in Annex A. The algorithms focus on the analysis of two-state, single-transition waveforms. The analysis of compound waveforms (waveforms with two or more states and/or two or more transitions) is accomplished by first decomposing the compound waveform into its constituent two-state single-transition waveforms. A method for performing this decomposition is provided.

Algorithms for the analysis of fluctuation and random jitter of waveforms were also introduced into this standard. These algorithms describe the computation of the mean and standard deviation of jitter and fluctuation. This standard also contains methods to estimate the *accuracy* of the standard deviation and to correct its value.

TRANSITIONS, PULSES AND RELATED WAVEFORMS – TERMS, DEFINITIONS AND ALGORITHMS

1 Scope

This International Standard provides definitions of terms pertaining to transitions, pulses, and related waveforms and provides definitions and descriptions of techniques and procedures for measuring their parameters. The waveforms considered in this standard are those that make a number of transitions and that remain relatively constant in the time intervals between transitions. Signals and their waveforms for which this standard apply include but are not limited to those used in: digital communications, data communications, and computing; studies of transient biological, cosmological, and physical events; and electrical, chemical, and thermal pulses encountered and used in a variety of industrial, commercial, and consumer applications.

This standard does not apply to sinusoidally-varying or other continuously-varying signals and their waveforms.

The object of this standard is to facilitate accurate and precise communication concerning parameters of transitions, pulses, and related waveforms and the techniques and procedures for measuring them.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

None.

3 Terms, definitions and symbols

3.1 General

Along with the recommended terms and their definitions, this clause also contains a number of deprecated but widely used terms. These deprecated terms and the reason for their deprecation are given after the definition of the recommended term.

Throughout this standard, time is taken to be an independent variable, symbolized with the letter t. "Waveform value" is used to refer to the dependent variable, symbolized by $y(t)$. For particular waveforms, "waveform value" will be synonymous with terms such as "voltage", "current", "power", or some other quantity. All defined terms are italicized in this document.

3.2 Terms and definitions

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

3.2.1
aberration region

3.2.1.1
post-transition aberration region

interval between a user-specified *instant* and a fixed *instant*, where the fixed *instant* is the first sampling *instant* succeeding the 50 % *reference level instant* for which the corresponding *waveform* value is within the *state boundaries* of the *state* succeeding the 50 % *reference level instant*

Note 1 to entry: The user-specified *instant* occurs after the fixed *instant* and is typically equal to the fixed *instant* plus three times the *transition duration*.

3.2.1.2
pre-transition aberration region

interval between a user-specified *instant* and a fixed *instant*, where the fixed *instant* is the first sampling *instant* preceding the 50 % *reference level instant* for which the corresponding *waveform* value is within the *state boundaries* of the *state* preceding the 50 % *reference level instant*.

Note 1 to entry: The user-specified *instant* occurs before the fixed *instant* and is typically equal to the fixed *instant* minus three times the *transition duration*.

3.2.2
accuracy

closeness of agreement between a measured quantity value and a true quantity value of a measurand

[ISO/IEC Guide 99:2007, 2.13]

3.2.3
amplitude

3.2.3.1
impulse amplitude

difference between the specified *level* corresponding to the *maximum peak* (*minimum peak*) of the positive (negative) *impulse-like waveform* and the *level* of the *state* preceding the first *transition* of that *impulse-like waveform*

3.2.3.2
waveform amplitude

difference between the *levels* of two different *states* of a *waveform*

Note 1 to entry: Two different definitions for *amplitude* are authorized by this standard because they are both in common use (see 3.2.3.2.1.. In all applications of this standard, the chosen definition shall be clearly identified.:

3.2.3.3
signed waveform amplitude,

level of the *state* succeeding a *transition* minus the *level* of the *state* preceding the same *transition*

3.2.3.4
unsigned waveform amplitude

absolute value of the *signed amplitude*

3.2.4
correction

operation combining the results of the conversion operation with the transfer function information to yield a *waveform* that is a more accurate representation of the *signal*

Note 1 to entry: Correction may be effected by a manual process by an operator, a computational process, or a compensating device or apparatus. Correction shall be performed to an *accuracy* that is consistent with the overall *accuracy* desired in the *waveform measurement process*.

Note 2 to entry: See 4.2 concerning the conversion operation.

3.2.5
cycle
portion of a *periodic waveform* with a *duration* of one *period*

3.2.6
delaying
process in which the time of arrival of a *signal* is caused to occur later in time

3.2.7
differentiation
shaping process in which a *waveform* is converted to a *waveform* whose shape is or approximates the time derivative of that *waveform*

3.2.8
duration
difference between two specified *instants*

3.2.9
duty factor
DEPRECATED: duty cycle
unless otherwise specified, for a *periodic pulse train*, the ratio of the *pulse duration* to the *waveform* period

Note 1 to entry: The term duty *cycle* is a deprecated term because the word *cycle* in this standard refers to the *period* of a *signal*.

3.2.10
fluctuation
variation (dispersion) of a *level* parameter of a set of *repetitive waveforms* with respect to a *reference amplitude* or a *reference level*

Note 1 to entry: Unless otherwise specified by a mathematical adjective, root-mean-square (rms) fluctuation is assumed.

3.2.11
frequency
reciprocal of the period

Note 1 to entry: The period is the *waveform period*.

[IEC 60050-103:2009, 103-06-02, modified – the note to entry has been replaced.]

3.2.12
glitch
transient that leaves an initial *state,* enters the boundaries of another *state* for a *duration* less than the *duration* for *state occurrence*, and then returns to the initial *state*

3.2.13
instant
particular time value within a *waveform epoch* that, unless otherwise specified, is referenced relative to the *initial instant* of that *waveform epoch*

3.2.13.1
final instant
last sample *instant* in the *waveform*

3.2.13.2
impulse center instant

instant at which a user-specified approximation to the *maximum peak* (*minimum peak*) of the positive (negative) *impulse-like waveform* occurs

3.2.13.3
initial instant

first sample *instant* in the *waveform*

3.2.13.4
pulse center instant

average of the two *instants* used to calculate the pulse *duration*

3.2.13.5
reference level instant

instant at which the *waveform* intersects a specified *reference level*

3.2.13.6
transition occurrence instant

first 50 % *reference level instant,* unless otherwise specified, on the *transition* of a *step-like waveform*

SEE: Figure 1, Figure 2, Figure 3, and Figure 4.

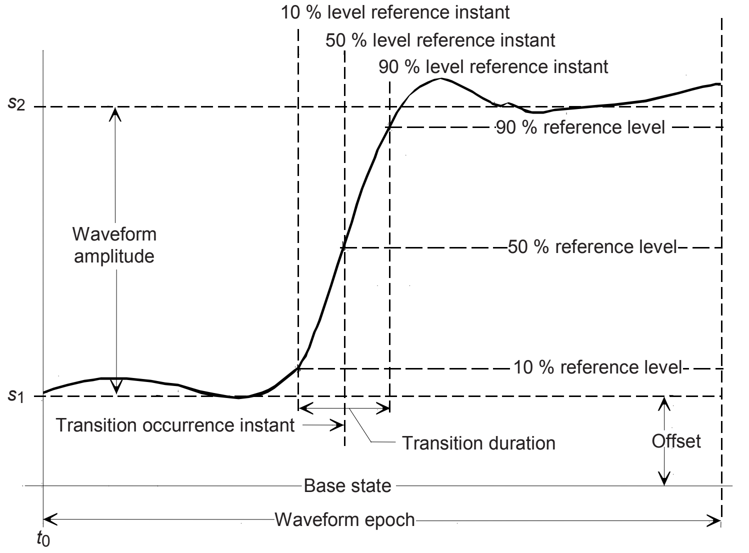


Figure 1 – Single *positive-going transition*

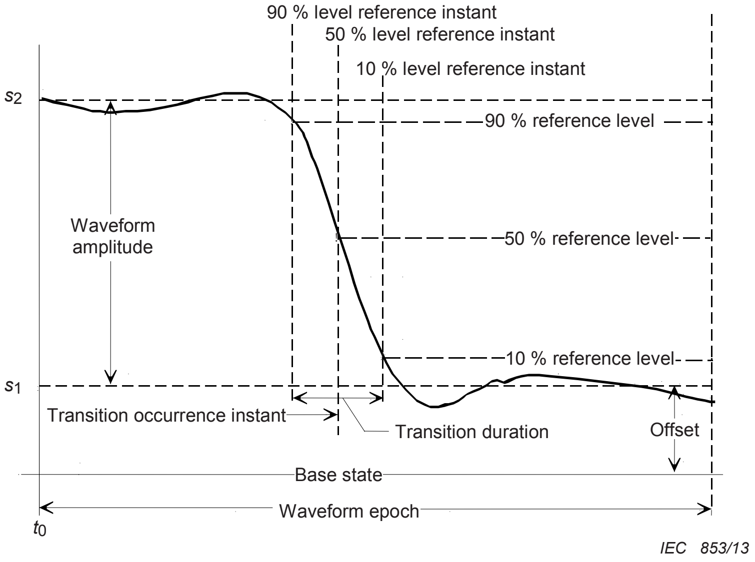


Figure 2 – Single *negative-going transition*

Note 1 to entry: See 5.3.4 concerning *reference level instants.*

3.2.14
integration

shaping process in which a *waveform* is converted to a *waveform* whose shape is or approximates the time integral of that *waveform*

3.2.15
interval

set of all values of time between a first *instant* and a second *instant*, where the second *instant* is later in time than the first.

Note 1 to entry: These first and second *instants* are called the endpoints of the interval. The endpoints, unless otherwise specified, are assumed to be part of the interval.

3.2.16
jitter

variation (dispersion) of a time parameter between successive *cycles* of a repetitive *signal* and/or between successively acquired *waveforms* of a *repetitive signal* for a given *reference level instant* or *duration*.

Note 1 to entry: Unless otherwise specified by a mathematical adjective, rms *jitter* is assumed.

3.2.16.1
cycle-to-*n*th-cycle jitter

jitter between specified *reference level instants* of any two specified *cycles* of a *repetitive signal*

3.2.16.2
period jitter

jitter in the period of a repetitive signal or its waveform

3.2.16.3
pulse duration jitter

jitter in the pulse duration of a signal or its waveform

3.2.16.4
trigger jitter
jitter between a *repetitive signal* and the trigger event that is used to generate or measure that *signal*

3.2.17
level
constant value having the same units as y

3.2.17.1
average level
pertaining to the value of the mean of the *waveform level*

If the *waveform* takes on n discrete values y_j, all equally spaced in time, the *average level* is,

$$\bar{y} = \left(\frac{1}{n}\right)\sum_{j=1}^{n} y_j .$$

If the *waveform* is a continuous function of time $y(t)$,

$$\bar{y} = \left(\frac{1}{t_2 - t_1}\right)\int_{t_1}^{t_2} y(t)dt.$$

Note 1 to entry: The summation or integral extends over the *waveform epoch* for which the average *level* is desired or, if the function is *periodic*, over any integral number of *periodic* repetitions of the function.

3.2.17.2
average absolute level
pertaining to the mean of the absolute *waveform* value

If the *waveform* takes on n discrete values y_j, all equally spaced in time, the average absolute *level* is,

$$\overline{|y|} = \left(\frac{1}{n}\right)\sum_{j=1}^{n} \left|y_j\right|.$$

If the *waveform* is a continuous function of time $y(t)$,

$$\overline{|y|} = \left(\frac{1}{t_2 - t_1}\right)\int_{t_1}^{t_2} \left|y(t)\right|dt.$$

Note 1 to entry: The summation or the integral extends over the *waveform epoch* for which the average absolute *level* is desired or, if the function is *periodic*, over any integral number of *periodic* repetitions of the function.

3.2.17.3
percent reference level
reference level specified by:

$$y_{x\%} = y_{0\%} + \frac{x}{100}\left(y_{100\%} - y_{0\%}\right),$$

where

$0\ \% < x < 100\ \%$

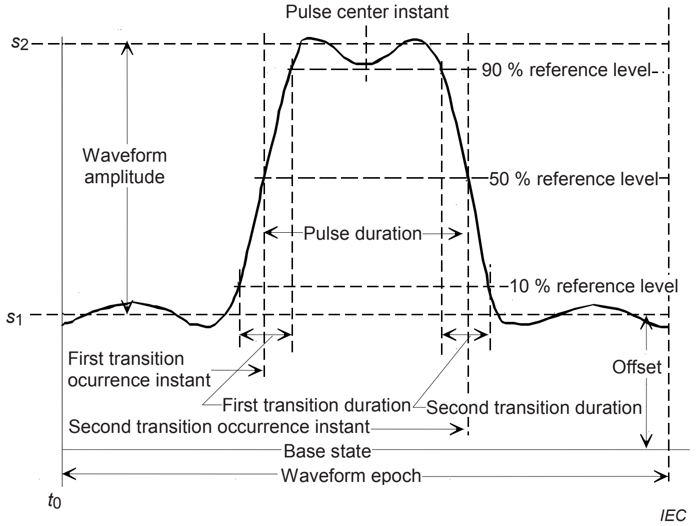
$y_{0\ \%}$ = level of low state

$y_{100\ \%}$ = level of high state

$y_{0\ \%}$, $y_{100\ \%}$, and $y_{x\ \%}$ are all in the same unit of measurement.

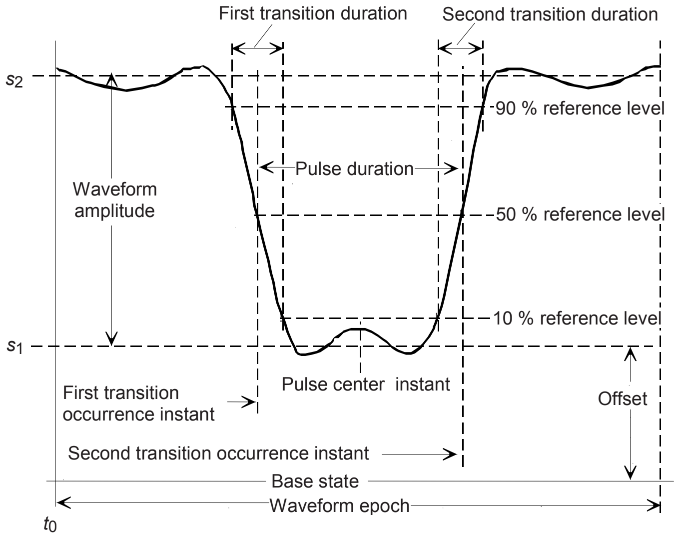
SEE: Figure 1, Figure 2, Figure3, and Figure 4.

Note 1 to entry: Commonly used *reference levels* are: 0 %, 10 % , 50 %, 90 %, and 100 %.



IEC 854/13

Figure 3 – Single *positive pulse waveform*



IEC 855/13

Figure 4 – Single *negative pulse waveform*

3.2.17.4
reference level

DEPRECATED: mesial, proximal, distal
user specified *level* that extends through all *instants* of the *waveform epoch*

Note 1 to entry: *Mesial*, *proximal*, and *distal* lines are deprecated terms because

(a) line refers to consideration of and computations using a *pictorial waveform representation,* whereas *waveforms* today are primarily stored in *digital waveform representations* and computation and viewing are done using a computer;

(b) the terms *mesial*, *proximal*, and *distal* refer to user-defined *reference levels* and it is not necessary to have redundant definitions for these *reference levels*;

(c) the terms *proximal* and *distal* cannot be used unambiguously to describe lines or points on either side of a *transition* of a *step-like waveform* because they depend on whether the *step-like waveform* is for a *positive pulse* or a *negative pulse*. In other words, for (3), the proximal line and points if referenced to the 10 % *reference level* will appear to the left of a *transition* for a p*ositive pulse* and to the right for a *negative pulse*.

3.2.17.5
root-mean-square (rms) level
pertaining to the value of the square root of the average of the squares of the *waveform* values

If the *waveform* takes on *n* discrete values y_j, all equally spaced in time, the root-mean-square *level* is,

$$y_{\mathrm{rms}} = \sqrt{\left(\frac{1}{n}\right)\sum_{j=1}^{n} y_j^2}\,.$$

If the *waveform* is a continuous function of time *y(t)*,

$$y_{\mathrm{rms}} = \sqrt{\left(\frac{1}{t_2 - t_1}\right)\int_{t_1}^{t_2} y^2(t)dt}\,.$$

The summation or the integral extends over the *waveform epoch* for which the rms *level* is desired or, if the function is *periodic*, over any integral number of *periodic* repetitions of the function.

3.2.17.6
root sum of squares level
rss level
pertaining to the value of the square root of the arithmetic sum of the squares of the *waveform* values

If the *waveform* takes on *n* discrete values y_j, all equally spaced in time, the root sum of squares *level* is,

$$y_{\mathrm{rss}} = \sqrt{\sum_{j=1}^{n} y_j^2}\,.$$

If the *waveform* is a continuous function of time *y(t)*,

$$y_{\mathrm{rss}} = \sqrt{\int_{t_1}^{t_2} y^2(t)dt}\,.$$

Note 1 to entry: The summation or the integral extends over the *waveform epoch* for which the root sum of squares *level* is desired.

3.2.18
offset
algebraic difference between two specified *levels*.

SEE: Figure 1, Figure 2, Figure 3, and Figure 4.

Note 1 to entry: Unless otherwise specified, the two *levels* are *state* 1 and the *base state*.

3.2.19
overshoot

waveform aberration within a post-transition aberration region or pre-transition aberration region that is greater than the upper state boundary for the associated state level

SEE: Figure 5 and Figure 6.

Note 1 to entry: If more than one such waveform aberration exists, the one with the largest magnitude is the overshoot unless otherwise specified.

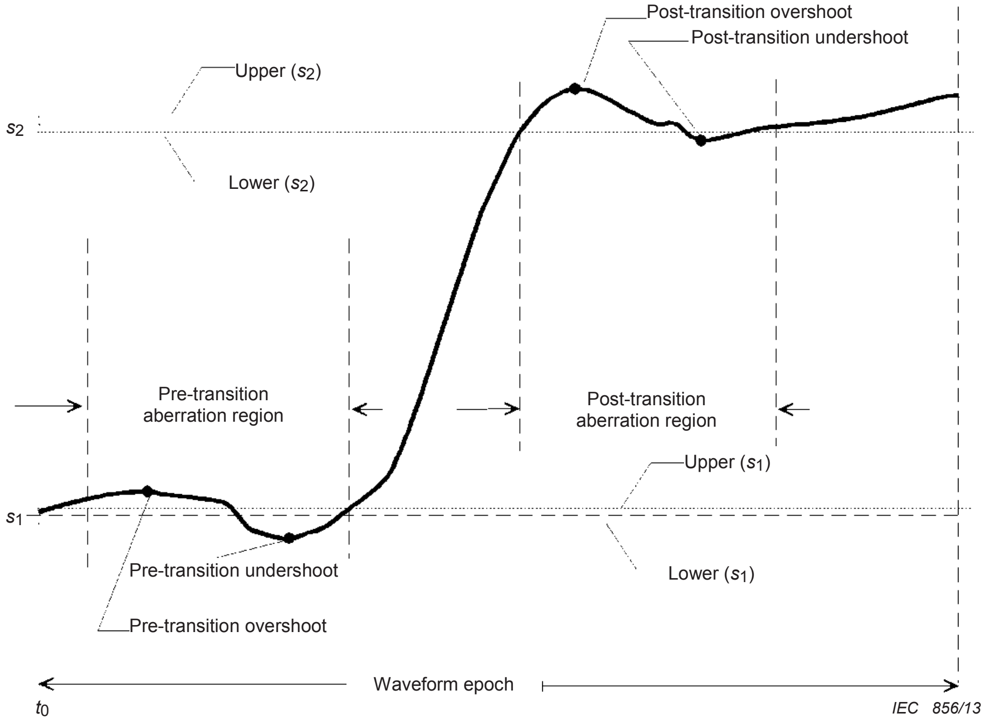


Figure 5 – *Overshoot* and *undershoot* in *single positive-going transition*

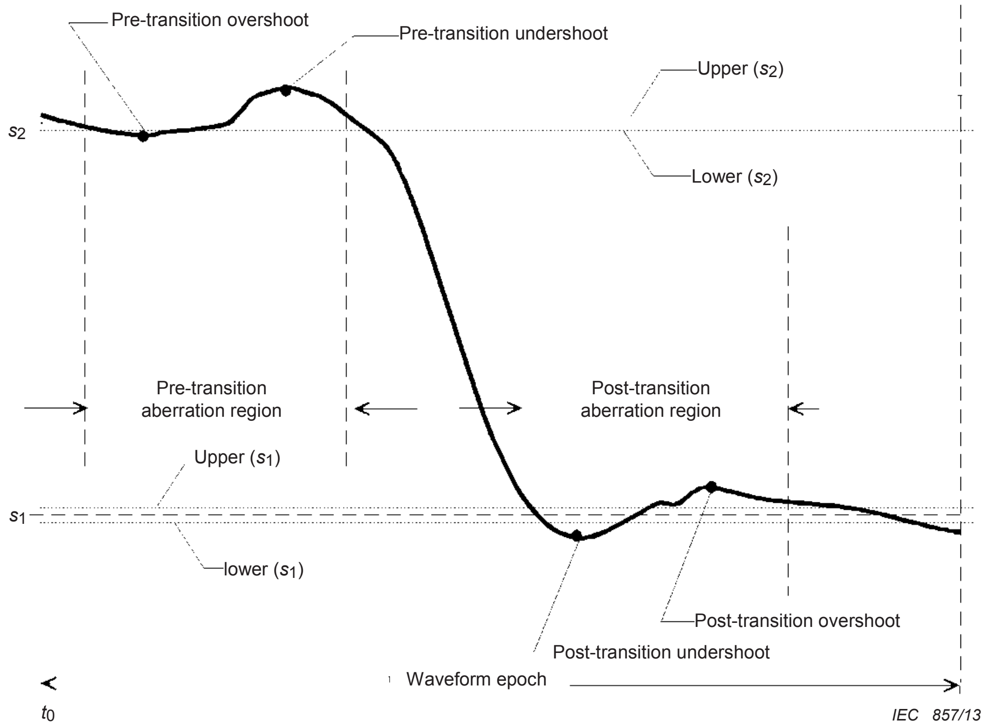


Figure 6 – *Overshoot* and *undershoot* in a *single negative-going transition*

3.2.20
parameter
any value (number multiplied by a unit of measure) that can be calculated from a *waveform*

3.2.20.1
level parameter
parameter whose units are the same as the units of *levels*

3.2.20.2
time parameter
parameter whose units are a unit of time

3.2.21
maximum peak
pertaining to the greatest value of the *waveform*

3.2.22
minimum peak
pertaining to the least value of the *waveform*

3.2.23
peak-to-peak
pertaining to the value of the difference between the extrema of the specified *waveform*

3.2.24
periodic
identically recurring at equal intervals of the independent variable (IEV)

Note 1 to entry: The independent variable is often time.

[IEC 60050-103:2009,103-05-09, modified – the note to entry has been replaced.]

3.2.25
aperiodic
not recurring at equal intervals of the independent variable

Note 1 to entry: The independent variable is often time.

3.2.26
precision
closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions

[ISO/IEC Guide 99:2007, 2.15, modified – the notes in the original definition have been deleted.]

3.2.27
pulse duration
DEPRECATED: pulse width
difference between the first and second *transition occurrence instants*

SEE Figure 3 and Figure 4.

Note 1 to entry *Pulse width,* as well as *full width at half maximum (FWHM)* and *half width at half maximum (HWHM)* are, in general, deprecated terms, because width is a word that denotes a spatial parameter whereas the parameter of interest is time. However, in some applications it may be desireable to discuss the spatial location of a propagating pulse and its spatial distribution, i.e., pulse width in matter or space. FWHM, HWHM, and full duration at half maximum (FDHM) are deprecated terms because of the reference to the maximum value of the *waveform*, where the *waveform amplitude* may be either positive or negative and the *waveform* may contain noise.

3.2.28
pulse separation

duration between the 50 % *reference level instant*, unless otherwise specified, of the second *transition* of one *pulse* in a *pulse train* and that of the first *transition* of the immediately following *pulse* in the same *pulse train*

3.2.29
pulse train

repetitive sequence of *pulse waveforms*. Unless otherwise specified, all of the *pulse waveforms* in the sequence are assumed to be identical

SEE: Figure 7 and Figure A.12.

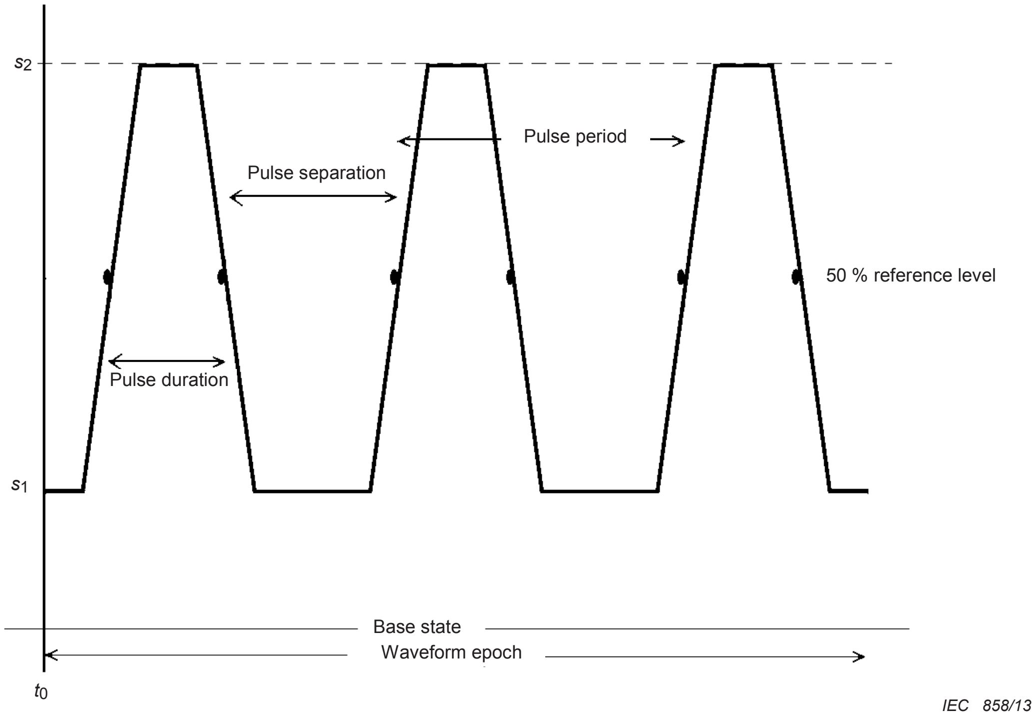


Figure 7 – *Pulse train*

3.2.30
pulse waveform

DEPRECATED: leading edge
DEPRECATED: trailing edge
waveform whose *level* departs from one *state*, attains another *state*, and ultimately returns to the original *state*

SEE: Figures 3 and Figure 4.

Note 1 to entry: As defined here, a pulse waveform consists of two *transitions* and two *states*. (See Clause 4.) Alternatively, a *pulse waveform* can be described as a *compound waveform* consisting of the sum of a positive (negative) *step-like waveform* and a *delayed* negative (positive) *step-like waveform* both having the same *unsigned waveform amplitude*.

Note 2 to entry: *Leading edge* and *trailing edge* are deprecated because 1) the word edge describes the property of a geometric figure, which is not contained by or representative of the physical signal that corresponds to the *waveform* and 2) the terms first and second adequately and unambiguously describe the meanings of leading and trailing.

3.2.30.1
negative pulse waveform
pulse waveform whose first transition is a negative-going transition

SEE: Figure 4.

3.2.30.2
positive pulse waveform
pulse waveform whose first transition is a positive-going transition

SEE: Figure 3.

3.2.31
reference
of or pertaining to a time, *level*, *waveform feature*, or *waveform* that is used for comparison with, or evaluation of, other times*, levels, waveform features*, or *waveforms*.

Note 1 to entry: A *reference* entity may, or may not, be an ideal entity.

3.2.32
repetitive
of or pertaining to a series of specified *waveform features* or *waveforms* that repeat or recur in time

3.2.33
non-repetitive
of or pertaining to a series of specified waveform features or waveforms that do not repeat or recur in time

3.2.34
resolution
smallest distinguishable increment into which a measured quantity is divided

3.2.35
ringing
aberration in the form of a superimposed oscillatory *waveform* that, when present, usually follows a *transition*

3.2.36
runt
transient that leaves an initial *state*, does not attain the *level* of another *state*, and returns to the initial *state*

3.2.37
sampling
the process of taking samples of a signal, usually at equal time intervals

Note 1 to entry: These samples represent *waveform levels* and are taken at selected *instants.*

[IEC 60050-704:1993, 704-23-02, modified – the note to entry has been replaced.]

3.2.38
signal
a physical phenomenon, one or more of whose characteristics may vary to represent information

Note 1 to entry: This phenomenon is a function of time.

[IEC 60050-701:1988, 701-01-02, modified – the note to entry has been replaced.].

3.2.39
spike
transient that leaves an initial *state*, exceeds the farthest *state boundary* of any other state, and returns to the initial *state*

3.2.40
state
particular *level* or, when applicable, particular *level* and upper and lower limits (the upper and lower *state boundaries*) that are referenced to or associated with that *level*

Note 1 to entry: Unless otherwise specified, multiple *states* are ordered from the most negative *level* to the most positive *level*, and the *state levels* are not allowed to overlap. The most negative *state* is called *state* 1. The most positive *state* is called *state n*. The *states* are denoted by s_1, s_2, …, s_n; the *state levels* are denoted by *level*(s_1), *level*(s_2), …, *level*(s_n); the upper *state boundaries* are denoted by upper(s_1), upper(s_2), …, upper(s_n); and the lower *state boundaries* are denoted by lower(s_1), lower(s_2), …, lower(s_n).

Note 2 to entry: *States*, *levels*, and *state boundaries* are defined to accommodate pulse metrology and digital applications. In pulse metrology, the *levels* of a *waveform* are measured and *states* (with or without associated *state boundaries*) are then associated with those *levels*. In digital applications, *states* are defined (with *state boundaries*) and the *waveform* values are determined to either lie within a *state* or not.

3.2.40.1
base state
state of a *waveform* that, unless otherwise specified, possesses a *level* closest to zero

SEE: Figure 1, Figure 2, Figure 3, and Figure 4.

3.2.40.2
high state
the most positive *state* within the *waveform epoch*, unless otherwise specified

Note 1 to entry: For *waveforms* with exactly two *states*, such as the single *transition waveform,* the terms *low state* and *high state* may be used in lieu of the terms *state 1* and *state 2*, respectively.

3.2.40.3
low state
the most negative *state* within the *waveform epoch*, unless otherwise specified

Note 1 to entry: For *waveforms* with exactly two *states*, such as the single *transition waveform,* the terms *low state* and *high state* may be used in lieu of the terms *state 1* and *state 2*, respectively.

3.2.40.4
positive state
state whose *level* is greater than zero

3.2.40.5
negative state
state whose *level* is less than zero

3.2.41
state boundaries
upper and lower limits of the *states* of a *waveform*

Note 1 to entry: All values of a *waveform* that are within the boundaries of a given *state* are said to be in that *state*. The *state boundaries* are defined by the user.

3.2.42
state occurrence
contiguous region of a *waveform* that is bounded by the upper and lower *state boundaries* of a *state*, and whose *duration* equals or exceeds the specified minimum *duration* for state attainment. The state occurrence consists of the entire portion of the *waveform* that remains within the boundaries of that state

Note 1 to entry: State occurrences are numbered as ordered pairs (s,*n*), where s_i refers to the i^{th} *state*, and *n* is the number of the occurrence of that particular *state* within the *waveform epoch*. In a given *waveform epoch*, when the *waveform* first enters a state s_1, that state occurrence is (s_1, 1). If and when the *waveform* exits that *state*, that *state occurrence* is over. If and when the *waveform* next enters and remains in *state* s_1, that *state occurrence* would be labeled (s_1, 2); and so on. Thus, the *state occurrences* for a single *pulse*, as shown in Figures 3 and 4, are (s_1, 1), (s_2, 1), (s_1, 2). The *state occurrences* for the *compound waveform* shown in Figure 8 are (s_2, 1), (s_4, 1), (s_3, 1), (s_5, 1), (s_1, 1). Note that a *waveform* can exit one *state occurrence* without (necessarily) immediately entering another *state occurrence*, that is, the *waveform state* between *state occurrences* can be undefined for some time *interval*, for example, during *transitions* and in the case of *transients* (such as, *runt* pulses).

3.2.43
synchronizing

process of aligning the *transition occurrence instant* of one *pulse* or other event with the *transition occurrence instant* of another *pulse* or event

Note 1 to entry: If two series of events, such as two *pulse trains*, are synchronized, then their *periods* shall be integer multiples of one another.

3.2.44
terminal feature

any contiguous region of a *waveform* that is neither a *state occurrence*, nor a *transient*, nor a *transition*

Note 1 to entry: This feature, if present, occurs only at the beginning and/or end of a *waveform*.

3.2.45
tilt

DEPRECATED: droop

a distortion of a *waveform state* wherein the overall slope over the extent of the *waveform state* is essentially constant and other than zero.

Note 1 to entry: Tilt may be of either polarity.

Note 2 to entry: The term *droop* is a deprecated term because it implies a negative slope and, therefore, cannot be applied unambiguously to both *positive pulse waveforms* and *negative pulse waveforms*.

3.2.46
transient

any contiguous region of a *waveform* that begins at one *state*, leaves and subsequently returns to that *state*, and contains no *state occurrences*

3.2.47
transition

contiguous region of a *waveform* that connects, either directly or via intervening transients, two *state occurrences* that are consecutive in time but are occurrences of different *states*

3.2.47.1
negative-going transition

DEPRECATED: falling edge

a *transition* whose terminating *state* is more negative than its originating state

Note 1 to entry: The endpoints of the *negative-going transition* are the last exit of the *waveform* from the higher *state boundary* and the first entry of the *waveform* into the lower *state boundary*.

Note 2 to entry: *Falling edge* is a deprecated term because 1) the word edge describes the property of a geometric figure, which is not contained by or representative of the physical signal that corresponds to the *waveform* and 2) falling refers to motion or position of physical objects.

3.2.47.2
pass through transition

transition from an initial *state* to a non-consecutive *state* through any number of other *states* where the *duration* in these other *states* is less than the *duration* for *state occurrence*

3.2.47.3

positive-going transition

DEPRECATED: rising edge

transition whose terminating *state* is more positive than its originating *state*.

Note 1 to entry: The endpoints of the *positive-going transition* are the last exit of the *waveform* from the lower *state boundary* and the first entry of the *waveform* into the higher *state boundary*.

Note 2 to entry: *Rrising edge* is a deprecated term because 1) the word edge describes the property of a geometric figure, which is not contained by or representative of the physical signal that corresponds to the *waveform* and 2) rising refers to motion or position of physical objects.

3.2.48

transition duration

DEPRECATED: risetime, falltime, transition time

difference between the two *reference level instants* of the same *transition*

SEE: Figure 1 and Figure 2.

Note 1 to entry: Unless otherwise specified, the two *reference levels* are the 10 % and 90 % *reference levels*.

Note 2 to entry: The terms *risetime*, *falltime*, and *transition time*, although widely used, are deprecated because they are ambiguous and confusing. First, the use of the word time in this standard refers exclusively to an *instant* and not an *interval*. Also, if the *first transition* of a *waveform* within a *waveform epoch* happens to be a *negative transition*, some users may refer to its *transition duration* as its *risetime*, and some others may refer to its *transition duration* as its *falltime*. If the use of these deprecated terms is required, then *risetime* is synonymous with the *transition duration* of a *positive-going transition*, and *falltime* is synonymous with the *transition duration* of a *negative-going transition*. If the upper and lower *state boundaries* of the two *states* are not the user-defined *reference levels* (for example, the 10 % and 90 % *reference levels*), then the *duration* of a *transition* is not equal to the *transition duration.*

3.2.49

transition settling duration

DEPRECATED: settling time

time interval between the 50 % *reference level instant*, unless otherwise specified, and the final *instant* the waveform crosses the *state boundary* of a specified *state* in its approach to that *state*

Note 1 to entry: The term *settling time* is a deprecated term because the word time in this standard refers exclusively to an *instant* and not an *interval*.

3.2.50

transition settling error

maximum error between the *waveform* value and a specified *reference level* within a user-specified *interval* of the *waveform epoch*. The *interval* starts at a user-specified *instant* relative to the 50 % *reference level instant*

3.2.51

triggering

process in which a *step-like waveform*, *pulse*, or *compound waveform* initiates a predetermined event or response

3.2.52

true value

quantity value consistent with the definition of a quantity

[SOURCE: ISO/IEC Guide 99:2007, definition 2.11, modified – the wording of the definition has been changed and the original notes to the definition have not been retained.]

3.2.53
undershoot

DEPRECATED: preshoot

waveform aberration within a *post-transition aberration region* or *pre-transition aberration region* that is less than the lower *state boundary* for the associated *state level*. If more than one such *waveform aberration* exists, the one with the largest magnitude is the undershoot unless otherwise specified

SEE: Figure 5 and Figure 6.

Note 1 to entry: Preshoot is a deprecated term because "pre" is a temporal prefix and "shoot," in this context, refers to a *level parameter*.

3.2.54
waveform

representation of a *signal* (for example, a graph, plot, oscilloscope presentation, discrete time series, equations, or table of values).

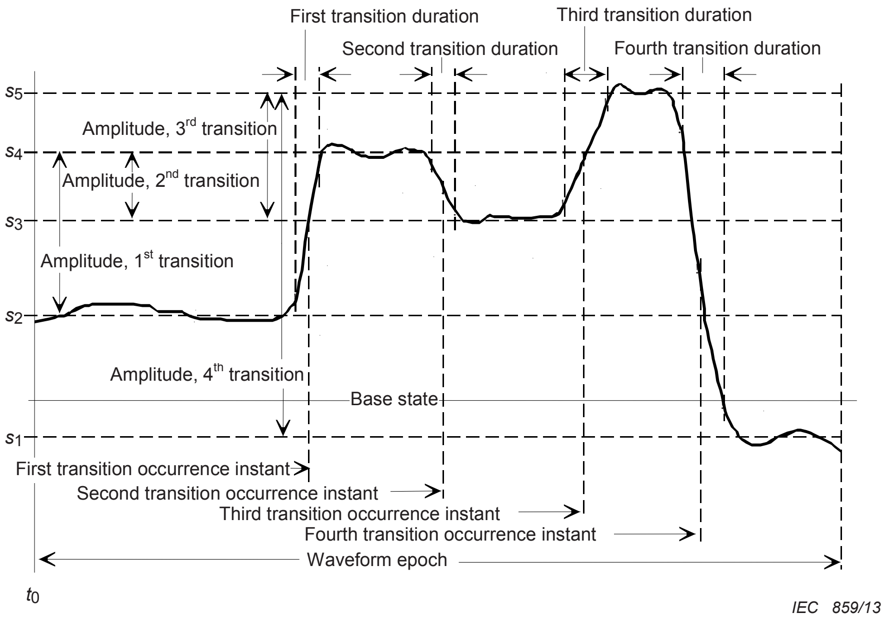
SEE: Figure 1, Figure 2, Figure 3, Figure 4, and the figures of Annex A.

Note 1 to entry: Note that the term *waveform* refers to a measured or otherwise-defined estimate of the physical phenomenon or *signal*.

3.2.54.1
compound waveform

waveform which may be completely represented by *m states* and *n transitions* where $(m + n) \geq 4$

SEE: Figure 8.



IEC 859/13

The dots indicate the intersection of the *waveform* with the 10 %, 50 %, and 90 % *reference levels*. The term "amplitude" is used in place of the defined term *waveform amplitude* because of space constraints. References to t*ransition durations* and *transition occurrence instants* for the *transitions* are abbreviated by, for example, "second transition duration" instead of the more accurate reference "*transition duration*, second *transition*."

Figure 8 – *Compound waveform*

Note 1 to entry: Any *compound waveform* can be parsed (see 5.5) into *n* two-state *waveforms*.

3.2.54.2
impulse-like waveform

waveform that, when convolved with an ideal step, yields a step-like waveform

SEE: Figure A.4.

3.2.54.3
reference waveform

waveform against which other *waveforms* are compared.

Note 1 to entry: Clause 7 contains figures that depict different *reference waveforms*.

3.2.54.4
step-like waveform

waveform whose *level* departs from one *state* and attains another *state*.

SEE: Figure 1 and Figure 2.

Note 1 to entry: Unless otherwise specified, multiple *transitions* are ordered from the earliest *transition occurrence instant* to the latest occurrence in time.

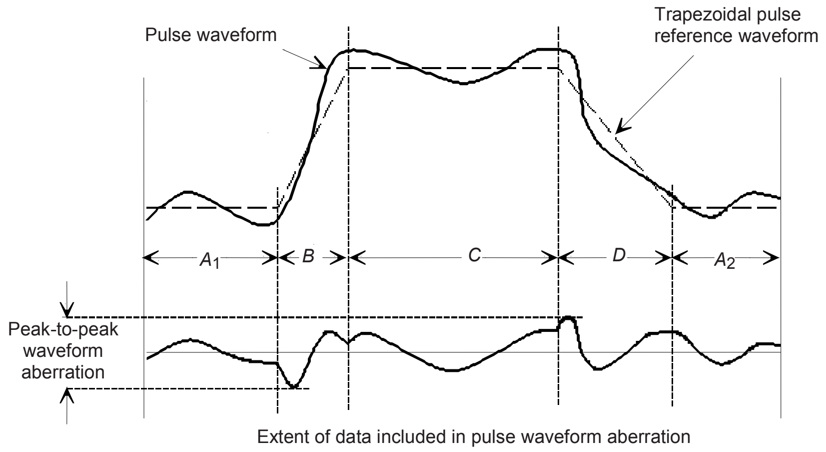
3.2.54.5
transition waveform

waveform consisting of a *transition* and the two *states* joined by that *transition*

3.2.55
waveform aberration

algebraic difference in *waveform* values between all corresponding *instant*s in time of a *waveform* and a *reference waveform* in a specified *waveform epoch*

SEE: Figure 9.



Extent of data included in pulse waveform aberration
A_1 and A_2 state occurrences of s_1
B transition, s_1 to s_2
C state occurrence of s_2
D Transition, s_2 to s_1

IEC 860/13

Figure 9 – Calculation of *waveform aberration*

3.2.55.1
percent waveform aberration

for a two-state *waveform*, the *waveform aberration* expressed as a percentage of the *waveform amplitude* of the *reference waveform*, unless otherwise specified

Note 1 to entry: *Compound waveforms* may be parsed (see 5.5) into a set of two-state *waveforms* after which *percent waveform aberration* may be defined for each two-state *waveform* of that set.

3.2.56
waveform delay (advance)
duration between the first *transition occurrence instant* of two *waveform*s

3.2.57
waveform epoch
interval to which consideration of a *waveform* is restricted for a particular calculation, procedure, or discussion. Except when otherwise specified, the waveform epoch is assumed to be the span over which the *waveform* is measured or defined

SEE: Figure 1, Figure 2, Figure 3, and Figure 4.

3.2.58
waveform feature
specified portion or segment of a *waveform*

3.2.59
waveform measurement process
realization of a method of waveform measurement in terms of specific devices, apparatus, instruments, auxiliary equipment, conditions, operators, and observers

Note 1 to entry: In this process, a value (a number multiplied by a unit) of measurement is assigned to the elements of the *waveform*.

3.2.60
waveform period
the minimum *duration* after which a *periodic waveform* repeats

Note 1 to entry: The period of a repetitive two-*state waveform* is the *duration* between specified *reference level instants* for the same *transition*, either the *negative-going transition* or the *positive-going transition,* of two consecutive *pulses* in a *pulse train*. The period is equal to the sum of the *pulse separation* and the *pulse duration*.

3.2.61
waveform representation

3.2.61.1
pictorial waveform representation
graph, plot, or display in which a *waveform* is presented for observation or analysis

Note 1 to entry: Any of the *waveform* formats defined in 3.2.61.2 to 3.2.61.2.2 may be presented in the pictorial format.

3.2.61.2
sampled waveform representation
waveform which is a series of *sample* numerical values taken sequentially or nonsequentially as a function of time

Note 1 to entry: It is assumed that nonsequential samples may be rearranged in time sequence to yield either *aperiodically sampled waveform representations* (3.2.61.2.1) or *periodically sampled waveform representations* (3.2.61.2.2).

3.2.61.2.1
aperiodically sampled waveform representation,
format which is identical to the *periodically sampled format*, above, except that the sampling in real time is not *periodic* and wherein the data exists as coordinate *instant* pairs, t_1 , $y_{1;}$ t_2, y_2; ...; t_n , y_n

3.2.61.2.2
periodically sampled waveform representation

a finite sequence of *levels* y_0 , y_1 , y_2 , ... , y_n each of which represents the value of the *waveform* at times t_0, $t_0 + \Delta t$, $t_0 + 2\Delta t$, ... , $t_0 + n\Delta t$, respectively, wherein the data may exist in a pictorial format or as a list or table of numbers

3.3 Symbols

A:	*waveform amplitude*
d_f:	*duty factor*
i:	discrete time index
n:	number of elements in a *waveform*
O_post:	*overshoot* in the *post-transition aberration region of a waveform*
O_pre:	*overshoot* in the *pre-transition aberration region of a waveform*
s_k:	*state level k*
t:	continuous time
$t_{\mathrm{x}\,\%}$:	*x % reference level instant*
t_0:	*initial instant*
T:	*waveform period*
t_d:	*transition duration*
T_D:	*waveform delay*
T_p:	*pulse duration*
T_s:	*pulse separation*
U_post:	*undershoot* in the *post-transition aberration region* of a *waveform*
U_pre:	*undershoot* in the *pre-transition aberration region* of a *waveform*
W_a:	*waveform aberration*, given as percentage of *waveform amplitude*
$y(\mathrm{t})$:	*waveform amplitude* values for a continuous-time signal
y_i:	*waveform amplitude* values for a discrete-time *waveform*, with discrete time index i
y_rms:	*root-mean-square* (rms) *level* (see 3.2.17.5)
y_rss:	*root sum of squares* (rss) *level* (see 3.2.17.6)
$y_{\mathrm{x}\,\%}$:	*x % reference level*
$\bar{y}$:	*average level* (see 3.2.17.1)
$\bar{y}_i$:	mean over a collection of *waveforms* $y_{\mathrm{k,i}}$, where *k* is the *waveform* index
Σ_i:	the standard deviation of a set of standard deviations

3.4 Deprecated terms

The terms listed below on the left are the deprecated terms in alphabetical order and the terms on the right are the accepted terms:

Droop	*tilt*
Duty cycle	*duty factor*
Preshoot	*overshoot* or *undershoot* in the *pre-transition aberration region*
Pulse width	*pulse duration*
Falltime (fall time)	*transition duration*
Falling edge	*negative-going transition*
Leading edge	*first transition*
Risetime (rise time)	*transition duration*

Rising edge	*positive-going transition*
Trailing edge	*second transition*
Transition	*transition duration*,

NOTE *transition* is deprecated when used to refer to an *interval* within a *waveform epoch*. *Transition*, when referring to an event, as defined in 3.44, is not deprecated.

4 Measurement and analysis techniques

4.1 General

This clause provides descriptions of the techniques and procedures for time-domain waveform measurements. The descriptions provided are independent of specific devices, apparatus, instruments, or computing devices that may be used in these measurements and are prerequisite to:

a) efficient communication of the results of *transition*, *pulse*, and *compound waveform* measurements;

b) development and use of physical artifact standards for *transition*, *pulse*, and *compound waveform* apparatus;

c) development and use of procedures for apparatus that employ *transition*, *pulse*, and *compound waveform* techniques.

4.2 Method of waveform measurement

A method of making a *waveform* measurement comprises:

a) the complete specification of all relevant functional characteristics of the devices, apparatus, instruments, and auxiliary equipment to be used:

b) the specification of all essential corrections required to compensate or adjust for departure of the measurement process from ideality;

c) the procedures to be used in making essential corrections;

d) the operations to be performed and their sequence;

e) the conditions under which all operations are to be carried out.

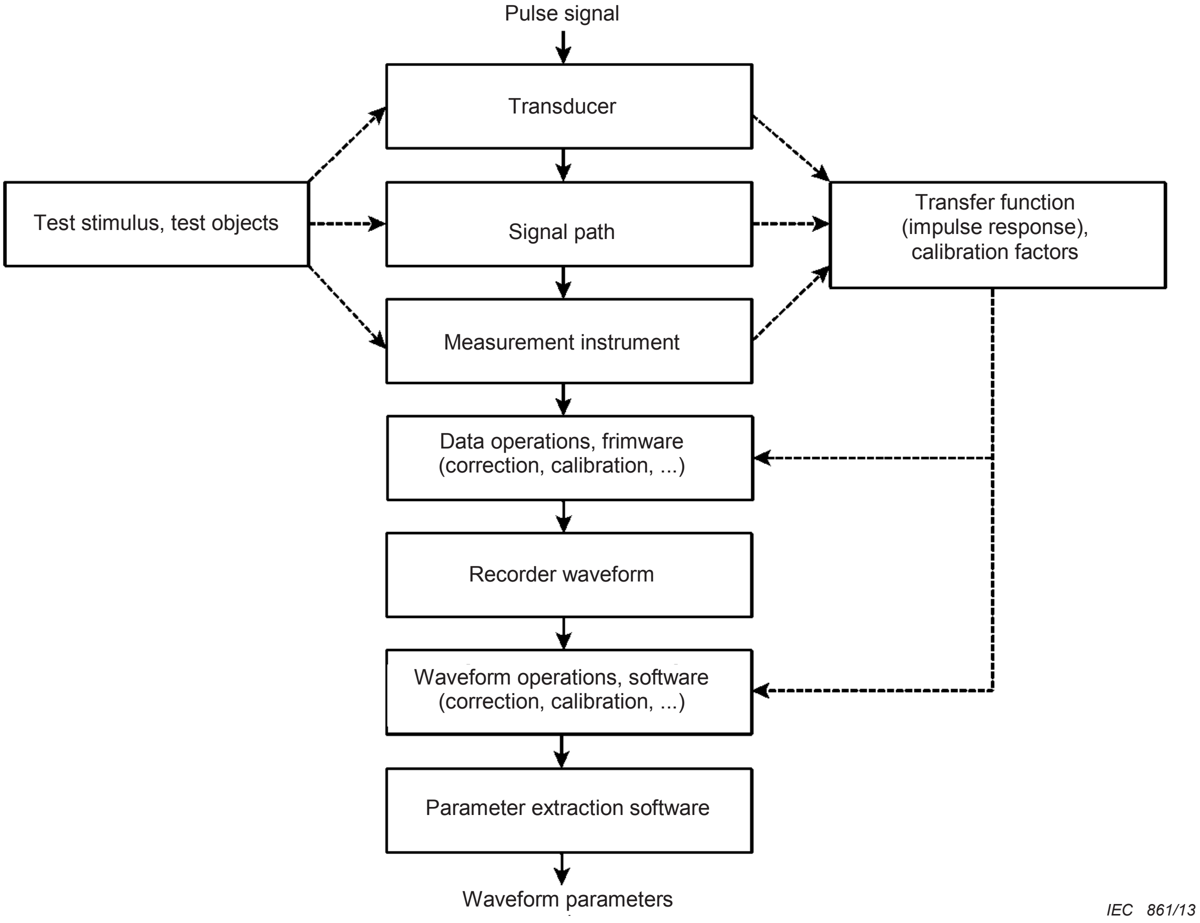


Figure 10 – Waveform acquisition and measurement process

4.3 Description of the waveform measurement process

The object of any *waveform measurement process* is the determination to some *accuracy*, either expressed or implied, of the value of one or more *parameters* of a *waveform*. Figure 10 shows the constituent steps of any *waveform measurement process* where, as indicated, the process involves two distinct sequential subprocesses: *signal*-to-*waveform* conversion and *waveform* analysis. Thus, the *waveform measurement process* involves:

a) the conversion of a *signal* into its transform, which is called its *waveform;*

b) analysis of the *waveform* to determine the value of one or more *parameters;*

c) the assertion or assumption that the value of the *waveform parameter* thus determined is, to some *accuracy*, identical to the value of the *signal parameter*.

The validity of the final assertion or assumption is dependent on the combined validity of the first two steps.

The vast array of devices, apparatus, instruments, and techniques which may be configured in virtually limitless combinations to provide *signal*-to-*waveform* conversion renders the discussion of specific implementations beyond the scope of this standard. Such discussion is deferred to other standards, documents, or specifications that describe or define the characteristics or methods of specific devices, apparatus, instruments, or techniques.

4.4 Waveform epoch determination

4.4.1 Selection of waveform epoch

A *waveform epoch* shall contain the *waveform features* under analysis. The *waveform epoch* shall contain sufficient data to yield all necessary *state levels* to the desired *accuracy* prescribed in the measurement process. These data may be augmented by *reference levels* that are determined using another *waveform epoch*.

4.4.2 Exclusion of data from analysis

A *waveform* may include *waveform features* or events that are non-pertinent in the circumstances of, or to the application of, the *waveform*. Non-pertinent data may be excluded from analysis, however, the basis for any such exclusion shall be stated.

When data within a *waveform epoch* are excluded from analysis the following shall be specified:

a) the extent, in time or waveform value, of the excluded data;
b) the basis for excluding the data;
c) whether the excluded data is ignored (that is, the *waveform* that is analyzed is discontinuous) or replaced (that is, the excluded data are replaced with other assumed or derived data).

5 Analysis algorithms for *waveforms*

5.1 Overview and guidance

The analysis of a two-*state waveform* requires the sequential determination of the following:

a) low or first *state level* and high or second *state level;*
b) *transition* or *waveform amplitude;*
c) necessary *percent reference levels* and corresponding *reference level instants* (unless otherwise specified, these are assumed to be the 10 %, 50 %, and 90 % *reference levels* and *reference level instants*);
d) values of all other *waveform parameters* as computed from *level* or *instant* pairs;
e) parameters contributing to the uncertainty in the computation of the *waveform parameters* should be identified and their relative importance assessed.

5.2 Selecting *state levels*

5.2.1 General

In the following sections, algorithms for determining *state levels* are described. There is no requirement that the same algorithm be used for determining different *state levels*. (These algorithms are described for single *transition waveforms* or single *pulse waveforms*, but they may also be applied to *compound waveforms* if desired.)

5.2.2 Data-distribution-based methods - Histograms

5.2.2.1 General

A histogram is an amplitude density representation of a *signal* whereas, for comparison, a *waveform* is an amplitude-versus-time representation of a *signal*. The amplitude density representation shows the number of occurrences of a given amplitude versus amplitude. To generate a histogram, the amplitude range must be divided into *M* unique, but not necessarily equal, amplitude intervals. For simplicity, however, we will consider only the equal-amplitude-interval case. The amplitude interval is called the histogram bin width and *M* is the number of bins or the histogram size. The histogram is formed by counting the number of times a *waveform* value fits within a particular histogram bin; this is referred to as the bin count.

5.2.2.2 Algorithm:

a) Determine the maximum and minimum amplitude values, $y_{\max}$ and $y_{\min,}$ of the *waveform* or data using a)1) or a)2).

   1) Search the *waveform* or data for $y_{\min}$ and $y_{\max}$.

   2) Set $y_{\min}$ and $y_{\max}$ from criteria specified by the user of this standard or knowledge of the *waveform* or data.

b) Calculate the amplitude range, y_{R}, of the *waveform* or data using: $y_R = y_{\max} - y_{\min}$.

c) Calculate the bin width:

   1) For equal sized bins, Δy is found by dividing y_{R} by M (selection of M is discussed below):

$$\Delta y = \frac{y_R}{M} = \frac{y_{\max} - y_{\min}}{M}, \tag{1}$$

   where

Δy	is the histogram bin width
M	is the number of histogram bins,
$y_{\max}$	is the maximum amplitude value of the signal, y
$y_{\min}$	is the minimum amplitude value of the signal, y,
y_{R}	is the range of the signal values.

   2) For unequal-sized bins, the user of this standard specifies an array of bin widths, Δy_i.

d) Initially set $B_j = 0$ for $j = 1 \ldots M$, where B_j is the count for the j^{th} histogram bin. Sort through the *waveform* or data values, y_i, $i = 1$, N, where N is the number of *waveform* values, and if y_i lies within the range of a bin, that is if: $(y_{\min} + [j-1]\Delta y) < y_i < (y_{\min} + j\Delta y)$ for $1 \le j \le M$, for equal size bins, or $(y_{\min} + \Delta y_j) < y_i < (y_{\min} + \Delta y_{j+i})$ for $1 \le j \le M$ for unequal-size bin widths, then set $B_j = B_j + 1$, where B_j is the count in the j^{th} histogram bin. If a data value equals the value of a bin boundary, that data value must be assigned to one of the bins located on either side (below or above) of that bin boundary. The side that is selected must be consistently applied to all such data values and specified by the user of this standard.

5.2.2.3 Selection of the number of histogram bins, M

5.2.2.3.1 General

Two methods are described in this section to select M for a waveform that exhibits a bimodal amplitude distribution and contains one *transition*. N_{S}*-state waveforms* ($N_{\mathrm{S}} > 2$) and N_{T}*-transition waveforms* ($N_{\mathrm{T}} > 1$) can also be operated on with the techniques mentioned here, however, these techniques will require that the *waveform* be parsed (see 5.5) into subwaveforms where each subwaveform contains one *transition* and two *states*. The limitations of each method for determining M are indicated. All of these methods are based on the requirement that the extracted pulse parameters agree with observation. The value of M has an upper and lower limit. The value of M should be large enough so that the desired amplitude resolution of the parameters that are derived from the histogram is not degraded or reduced. The value of M should not be so large that the histogram bin width is smaller than the amplitude quantization of the waveform. The amplitude quantization is dependent on the input range of the instrument over which the input range of the analog-to-digital converter (ADC) is applied, the number of bits in the ADC, and whether or not signal averaging was performed.

If the data for which a histogram is being made is obtained from an ADC, then it is usually important to make the histogram bin width compatible with the width of the quantization bins of the analog-to-digital converter. The width of the quantization bin of an analog-to-digital converter is the interval of input values that produce a single output value, that is, the interval between transition *levels* of the analog-to-digital converter. If the data is the average of N readings of the analog-to-digital converter, then each analog-to-digital-converter bin is effectively divided into N equal-sized smaller bins. (Averaging effectively reduces the bin size of the analog-to-digital converter.)

Each histogram bin width shall be an integer number of ADC bin widths. If the histogram bin width used in 5.2.2.2 is equal to ($n + x$) analog-to-digital-converter bin widths, where n is an integer and x is less than 1, then each histogram bin will actually have a width of either n analog-to-digital-converter bin widths or ($n + 1$) analog-to-digital-converter bin widths. If n is very large, so that the relative difference between n and $n + 1$ is small, then this error in histogram bin width is not important.

There is an additional consideration if the selection of *state levels* is based on the mode of a histogram. Bin widths, which are intended to be equal, can be unequal due to the differential nonlinearity of the analog-to-digital converter. In this case, the mode may occur in the widest bin rather than in its correct bin. When this is a possibility, the histogram counts (the number of *waveform* values that lie within each histogram bin) should be corrected for the bin widths before the histogram is analyzed.

5.2.2.3.2 Method 1

Select a fixed value of M. The selection of M may be based on observation, common practice, or some other valid means.

5.2.2.3.3 Method 2

A large (or small) value of M is selected as initial value. The value of M is then decremented (or incremented) until a particular histogram criterion is attained. One criterion that has been used is that the least populated of the two mode bins contains a count that is equal to at least 1 % of the number of elements, N_e, in the *waveform*. This method assumes the *waveform* exhibits a bimodal amplitude distribution and that it is positioned such that the bin corresponding to *level*(s_2) and *level*(s_1) has a count greater than or equal $0.01N_e$. Typically this latter requirement is assured by positioning the *waveform* such that either the *duration* of *level*(s_2) or *level*(s_1) is no less than 10 % of the *waveform epoch*. (Although shorter *durations* may work, this has not been tested.) This method can be adapted to apply to *waveforms* containing more than one *transition* and more than two modes in the amplitude distribution if the *waveform* is appropriately parsed. However, for each segment, the *duration* of the the *level*(s_2) or *level*(s_1) in that *waveform* segment must provide at least $0{,}01N_e$ amplitude occurrences. If this method is implemented automatically, that is, without operator intervention, it requires that the *level*(s_2) and *level*(s_1) are located in opposite halves of y_R. An implementation of this method using equal sized bins is described in [1][1], which also shows the effects of varying bin width on computed pulse parameters.

5.2.2.4 Splitting the bimodal histogram into two parts (subhistograms)

This procedure conceptually separates the histogram, computed as described in 5.2.2, into upper and lower histograms from which the modes for each are computed and subsequently used to determine *waveform state levels*. This procedure is based on the values of two *parameters*, f_1 and f_2, where $f_1 \le f_2$, defined by the user of this standard Typical values for this pair of variables are (f_1, f_2) = (0,5, 0,5) or (f_1, f_2) = (0,4, 0,6). Let B_j, for $j = 1 \ldots M$, be the bin counts in a histogram as defined in 5.2.2. Let j_{low} be the smallest value of j for which $B_j > 0$, and let j_{high} be the largest value of j for which $B_j > 0$. The range of the lower histogram is $j_{low} \le j \le f_1\left(j_{high} - j_{low}\right)$. The range of the upper histogram is $\left(j_{low} + f_2\left[j_{high} - j_{low}\right]\right) \le j \le j_{high}$.

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

Waveform aberrations and/or other spurious artifacts may adversely affect the ability of automated algorithms to find the appropriate *waveform level* around which the histogram is split. On the other hand, manual (operator) selection of the appropriate *waveform level* will not be confounded by spurious content

5.2.2.5 Determining state levels from the histogram

Split the bimodal histogram into two parts as described in 5.2.2.4. Find the means or modes of the two subhistograms found in 5.2.2.4. The low state level is given by the mode or mean of the lower histogram and the high state level is given by the mode or mean of the upper histogram. Solomon et al [2] examine the effect of different histogram methods on the values of the state levels.

5.2.3 Data-distribution-based methods - Shorth estimator

This discussion will address *step-like waveforms*. The shorth of a finite collection of data values is the shortest interval comprising a certain fraction, f_S, of the data values. The fraction f_S = ½ unless otherwise specified. The shorth estimator is a location estimator, similar to the least median of squares (LMS) estimator [3]. The first step in the shorth estimator method is to label or group *waveform* values as belonging to a particular *state*. The *k*-means method (4) is an effective approach for grouping the *waveform* values. In this method, the *waveform* values are grouped according to their difference relative to a particular *average level*, where in this case *average levels* are computed for the two *state occurrences* of the *step-like waveform*.

a) Grouping *waveform* values:

   1) Initialize the *average levels*, $\bar{y}_1$ and $\bar{y}_2$, for the two *states occurrences,* (s_1,1) and (s_2,1) (note that in a *step-like waveform*, there are only two *state occurrences*):

      i) $\bar{y}_1 = y_{\min,}$ or as otherwise specified by the user of this standard

      ii) $\bar{y}_2 = y_{\max,}$ or as otherwise specified by the user of this standard,
      where $y_{\min}$ and $y_{\max}$ are the minimum and maximum amplitude values of the *waveform, y*.

   2) Segregate each *waveform* value, y_i, into (s_1,1) or (s_2,1) based on the difference in amplitude between y_i and the *average levels*. The *average levels* are then updated by calculating the average values of the y_i assigned to each *state occurrences*. The process continues until the y_i values no longer switch *state occurrences*, or, equivalently, until the *average levels* no longer change. The following algorithm is now given:

```
do
    $\bar{y}_{1,old} = \bar{y}_1$
    $\bar{y}_{2,old} = \bar{y}_2$
    for $i$ = 1 .. $N$
        if $| y_i - \bar{y}_1 | < | y_i - \bar{y}_2 |$ then assign $y_i$ to ($s_1$,1)
        else assign $y_i$ to ($s_2$,1)
    endfor
    $\bar{y}_1$=average level of ($s_1$,1)
    $\bar{y}_2$= average level of ($s_2$,1)
while $\bar{y}_1 - \bar{y}_{1,old} \neq 0$ and $\bar{y}_2 - \bar{y}_{2,old} \neq 0$
```

   where N is the number of samples in y.

   After the algorithm converges, typically in two or three iterations, it yields (s_1,1) and (s_2,1), the two *state occurrences* of the *step-like waveform*.. The set of N_1 *waveform* values in (s_1,1) (the first *state occurrence*) is given by $(s_1,1)=\{y_1^{(1)},y_2^{(1)},\ldots,y_{N_1}^{(1)}\}$ and the set of N_2 *waveform* values in (s_2,1) is given by $(s_2,1)=\{y_1^{(2)},y_2^{(2)},\ldots,y_{N_2}^{(2)}\}$.

The next step in this process is to obtain the shorth and the corresponding shorth collection for both (s_1,1) and (s_2,1). The shorth collection comprises the data values that are contained in the shorth. As used here, the shorth of the i^{th} *state occurrence* is the shortest *interval* containing the specified fraction of the values assigned to the i^{th} *state occurrence*.

b) Determining the shorth collection. The shorth collection is computed independently for (s_1,1) and (s_2,1) per the following procedure:

1) Reorder (s_1,1) into a non-decreasing sequence to give $(s_1,1)_{nd}=y_{(1)}^{(1)}\le y_{(2)}^{(1)}\le\ldots\le y_{(N_1)}^{(1)}$,

2) Reorder (s_2,1) into a non-decreasing sequence to give $(s_2,1)_{nd}=y_{(1)}^{(2)}\le y_{(2)}^{(2)}\le\ldots\le y_{(N_2)}^{(2)}$,

where

N_1 is the number of samples in (s_1,1) and

N_2 is the number of samples in (s_2,1). For clarity, $y_i^{(1)}$ is not necessarily equal to $y_{(i)}^{(1)}$ and $y_i^{(2)}$ is not necessarily equal to $y_{(i)}^{(2)}$.

3) Perform the following to compute the shorth collection for (s_1,1):

```
$h=\lfloor f_s N_1 \rfloor+1$, where $\lfloor x \rfloor$ is the greatest integer less than or equal to $x$
$d = N_1 - h + 1$
$min\_diff = 10^9$
for $i$ = 1 .. $d$
$diff = y_{(h+i-1)}^{(1)} - y_{(i)}^{(1)}$
if ($diff < min\_diff$) then
    $min\_diff = diff$
    $m = i$
endif
endfor
The shorth collection for ($s_1$,1): = $\left(y_{(m)}^{(1)},\ldots,y_{(h+m-1)}^{(1)}\right)$
```

4) Perform the following to compute the shorth collection for (s_2,1):

```
$k=\lfloor f_s N_2 \rfloor+1$
$d = N_2 - k + 1$
$min\_diff = 10^9$
for $i$ = 1 .. $d$
$diff = y_{(k+i-1)}^{(2)} - y_{(i)}^{(2)}$
if ($diff < min\_diff$) then
    $min\_diff = diff$
    $n = i$
endif
endfor
The shorth collection for ($s_2$,1): = $\left(y_{(n)}^{(2)},\ldots,y_{(k+n-1)}^{(2)}\right)$
```

NOTE The algorithm in Steps 3 and 4 produces a shorth collection that, if two or more successive intervals qualify for the shorth, selects the first interval. If the user of this standard implements a shorth collection criterion different from that used here, the user of this standard shall indicate the criterion used.

c) Finally, the mean of the value, unless otherwise specified, of the shorth collection is used to estimate *levels* of each *state*(5).

   1) The *level* of s_1 is computed using: $level(s_1) = \frac{1}{h}\sum_{j=m}^{h+m-1} y_{(j)}^{(1)}$.

   2) The *level* of s_2 is computed using: $level(s_2) = \frac{1}{k}\sum_{j=n}^{k+n-1} y_{(j)}^{(2)}$.

   As a simple illustration, suppose N_1 = 11 and

$$\left(y_{(1)}^{(1)},\ldots,y_{(N_1)}^{(1)}\right) = (10,45,50,53,56,58,60,62,63,65,75).$$

   Then, $h = \lfloor 11/2 \rfloor + 1 = 6$, and the smallest of the differences in the corresponding set of differences, 58-10, 60-45, 62-50, 63-53, 65-56, and 75-58 is 9, which corresponds to the interval (56, 65), which is the shorth. The values contained in the shorth are 56, 58, 60, 62, 63, and 65. *Level*(s_1) is calculated as *level*(s_1) = (56+58+60+62+63+65)/6 = 60,67.

5.2.4 Other methods

5.2.4.1 Peak magnitude

Determine the *maximum peak* and *minimum peak* values of the single *transition waveform* or the single *pulse waveform*:

a) take the *minimum peak* value as the low or first *state level;*

b) take the *maximum peak* value as the high or second *state level*.

This algorithm is best suited to the analysis of waveforms with *state levels* of negligible or relatively short *duration*.

5.2.4.2 Initial (final) instant

For a single *transition waveform*, determine the values of the *initial instant* and the *final instant.* Take the value at either the *initial instant* or the *final instant, which*ever is the more *negative,* as the *low* or *first state level.* Then, take the value at either the *initial instant* or the *final instant,* whichever is the more *positive*, as the *high* or *second state level*.

For a single *pulse waveform*, only one of the two *state levels* can be determined by the initial (final) instant method. In this case, determine the value of the *initial (final) instant*. For a *positive pulse waveform* take this value as the *low* or *first state level*. For a *negative pulse waveform* take this value as the *high* or *second state level*.

5.2.4.3 User defined

This method is based on assumptions made by, or expectations of, the user of this standard regarding the behavior of the waveform generator. These assumptions or expectations should be based on knowledge of, for example, the waveform generator circuitry, the interaction between the waveform generator and the load (measurement instrument), and/or previous observations. Using this information, the user of this standard states what the values are for the *low* and *high states* of the *waveform*.

5.2.4.4 Use of other waveform epochs

Two or more *waveform epochs* may be necessary because the *waveform* from which a given *parameter* is to be computed may not contain enough information for that computation. For example, in computing *transition duration*, if the *waveform* has not settled to its final or initial *states* within a shorter *waveform epoch* from which *transition duration* can be computed, and the *waveform* of longer *epoch*(s) does not have the temporal resolution required to accurately compute the *transition duration*, then two or more *epochs* are necessary to compute *transition duration*. At least two *waveforms* will be required, one or more having a long *epoch* from which the *state levels* will be obtained, and one having a short *epoch* from which the *transition duration* will be computed.

a) Identify the *waveform epochs* to be used, E_1, E_2 and possibly E_3. Three *waveforms* are necessary if the *low state* and *high state* are to be computed from different *waveforms*.

b) Acquire the *waveform(s)* from which the *low state* and *high state* are to be determined.

c) Compute the *low state* and *high state* of the appropriate *waveforms* by a method specified by the user of this standard.

The *low state* and *high state* thus determined are the *low state* and *high state* of the *waveform*.

5.2.4.5 Static levels

This method requires that the pulse generator used to generate the *step-like waveform* can be operated such that it also provides two static (constant-valued) *levels*, one corresponding to the *low state* of the pulse to be measured and the other to the *high state* of the same pulse. Furthermore, these static *levels* shall be supplied at the same connector from which the pulse is output and that these *levels* can be uniquely selected.

a) Operate the pulse generator so that it outputs a static *level* that is equal to the *level* of the *low state* of the pulse.

b) Acquire a *waveform* of this *low state level* and compute its value by a method specified by the user of this standard; this is the *low state* of the *waveform*.

c) Operate the pulse generator to output a static *level* that is equal to the *high state* of the pulse and measure this *level*.

d) Acquire a *waveform* of this *high state level* and compute its value by a method specified by the user of this standard; this is the *high state* of the *waveform*.

5.2.5 Algorithm switching

The above methods may be dynamically chosen based upon the input *waveform*. For example, some algorithms use a histogram method or a peak magnitude method depending upon the shape of the histogram. If several methods are combined or employed, the criteria for when a particular method is used should be stated.

5.3 Determination of other single *transition waveform* parameters

5.3.1 General

After the *low* or *state* 1 *level* and the *high* or *state* 2 *level* of a single *transition waveform* or a single *pulse waveform* have been determined, all other *transition* or *pulse waveform parameters* defined in this standard are calculable directly from the definitions of those *parameters* presented in this standard.

Some *waveform* recorders contain internal hardware or firmware for calculating *waveform parameters*. In the process of calculating these *waveform parameters*, the recorder may filter the *waveform* prior to interpolation. Consequently, the user of this standard should be aware of any internal filtering performed by the *waveform* recorder because this filtering may affect the value of the *parameter*. If filtering is performed in the process of calculating *waveform parameters*, the type of filter and its defining variables shall be specified.

5.3.2 Algorithm for calculating signed waveform amplitude

a) Determine s_1 and s_2 using a method described in 5.2.

b) The *waveform amplitude*, *A*, is the difference between *level*(s_2) and *level*(s_1)

1) For positive-going transitions, A is given by:

$$A = level(\mathrm{s}_2) - level(\mathrm{s}_1), \tag{2}$$

where

A	is the amplitude of the *waveform*,
$level(\mathrm{s}_1)$	is the *state level* of s_1, and
$level(\mathrm{s}_2)$	is the *state level* of s_2.

2) For negative-going transitions, A is given by:

$$A = level(\mathrm{s}_1) - level(\mathrm{s}_2). \tag{3}$$

5.3.3 Algorithm for calculating percent reference levels

a) Calculate the *waveform amplitude, A,* as described in 5.3.2.

b) Calculate the value for the *percent reference level*, $y_{x\,\%}$, using:

$$y_{x\%} = level(\mathrm{s}_1) + \frac{|A|}{100}x\%, \tag{4}$$

where

$y_{x\,\%}$,	is the value of the *percent reference level*,
x	represents the percentage for the *percent reference level* specified by the user of this standard, and
$level(\mathrm{s}_1)$	is the *state level* of s_1.

NOTE $y_{x\,\%}$ may or may not equal the value of a sample in the *waveform*.

5.3.4 Algorithms for calculating reference level instants

5.3.4.1 General

The algorithms for calculating *reference level instants* use linear interpolation between the *instants* at which the *waveform* is sampled. If the *interval* between successive *waveform* samples is too large for linear interpolation to be sufficiently accurate, the *accuracy* of the computed *reference levels* and associated *reference level instants* will be reduced. If this limitation causes errors in parameter values that are larger than a tolerance specified by the user of this standard, then a more sophisticated interpolation method based on more than two adjacent samples may be used. The selection of an alternate interpolation method depends on knowledge of the *waveform* and is beyond the scope of this standard. The interpolation method and the conditions in which it is used shall be specified.

5.3.4.2 Algorithm for calculating the 50 % *reference level instant*

a) Calculate the 50 % *reference level* as described in 5.3.3.

b) Calculate the 50 % *reference level instant* for $y_{50\,\%}$ using linear interpolation:

$$t_{50\%} = t_{50\%-} + \left(\frac{t_{50\%+} - t_{50\%-}}{y_{50\%+} - y_{50\%-}}\right)(y_{50\%} - y_{50\%-}) \tag{5}$$

where

$t_{50\,\%}$	is the 50 % *reference level instant*,
$t_{50\,\%-}$ and $t_{50\,\%+}$	are two consecutive sampling *instants* corresponding to data nearest in value to $y_{50\,\%}$ such that $y_{50\,\%-} \le y_{50\,\%} \le y_{50\,\%+}$, and

$y_{50\,\%-}$ and $y_{50\,\%+}$ are the two consecutive *waveform* values corresponding to $t_{50\,\%-}$ and $t_{50\,\%+}$.

If there is more than one 50 % *reference level instant*, the first one is the 50 % *reference level instant*, unless otherwise specified.

5.3.4.3 Algorithm for calculating other *reference level instants*

a) Supply a *reference level*, $y_{x\,\%}$, by either calculating the $y_{x\,\%}$ as described in 5.3.3 for a value of x or of $y_{x\,\%}$ specified or provided by the user of this standard

b) Calculate the *reference level instant* for $y_{x\,\%}$ using linear interpolation:

$$t_{x\%} = t_{x\%-} + \left(\frac{t_{x\%+} - t_{x\%-}}{y_{x\%+} - y_{x\%-}}\right)\left(y_{x\%} - y_{x\%-}\right), \tag{6}$$

where

$t_{x\,\%}$ is the *reference level instant* for the *reference level* selected by the user of this standard,

$y_{x\,\%}$ is the *reference level* specified by the user of this standard

$t_{x\,\%-}$ and $t_{x\,\%+}$ are two consecutive sampling *instants* corresponding to data nearest in value to $y_{x\,\%}$ such that $y_{x\,\%-} \leq y_{x\,\%} \leq y_{x\,\%+}$, and

$y_{x\,\%-}$ and $y_{x\,\%+}$ are the two consecutive *waveform* values corresponding to $t_{x\,\%-}$ and $t_{x\,\%+}$.

If there is more than one *reference level instant*, the *reference level instant* closest to the 50 % *reference level instant* (see 5.3.4.2) is used, unless otherwise specified.

5.3.5 Algorithm for calculating transition duration between x1 % and x2 % reference levels

a) Calculate the *reference level instant*, $t_{x1\,\%}$, for the $x1$ % *reference level* in accordance with 5.3.4 that is nearest to the 50 % *reference level instant*, unless otherwise specified.

b) Calculate the *reference level instant*, $t_{x2\,\%}$, for the $x2$ % *reference level* in accordance with 5.3.4 that is nearest to the 50 % *reference level instant*, unless otherwise specified.

c) Calculate the *transition duration*, $t_{x1\,\%\text{-}x2\,\%}$:

$$t_{x1\%-x2\%} = \left|t_{x1\%} - t_{x2\%}\right|, \tag{7}$$

where

$t_{x1\,\%\text{-}x2\,\%}$ is the duration between the $x1$ % *reference level* and the $x2$ % *reference level*,

$t_{x1\,\%}$, is the *reference level instant* for the $x1$ % *reference level*, and

$t_{x2\,\%}$, is the *reference level instant* for the $x2$ % *reference level*.

5.3.6 Algorithm for calculating the undershoot and overshoot aberrations of step-like waveforms

a) Determine *level*(s_1) and *level*(s_2) using a method described in 5.2 and define the *upper boundary* and *lower boundary* for the *states* corresponding to these levels.

b) Determine the maximum and minimum *waveform* values, y_{max} and y_{min}.

c) Calculate the *waveform amplitude, A,* as described in 5.3.2.

d) Calculate the $x1$ % and $x2$ % *reference levels* and the 50 % *reference level* as described in 5.3.3. Typically used *reference levels* are the 10 % and 90 % *reference levels*.

e) Calculate the *reference level instants*, $t_{x1\,\%}$, $t_{50\,\%}$and $t_{x2\,\%}$, as described in 5.3.4, for the *reference levels* determined in step (d).

f) Calculate the *transition duration,* for the *reference levels instants* determined in step (e), as described in 5.3.5.

g) Calculating the *overshoot* and *undershoot* in the *pre-transition aberrations region*.

   1) Calculate the last *instant*, t_{pre}, which occurs before $t_{50\,\%}$ when the *waveform* exits the upper (lower) *state boundary* of the *low state* (*high state*) for a *positive-going* (*negative-going*) *transition* using the method described in 5.3.4.

   2) Define the *pre-transition aberration region* as that between t_{pre} - $3t_{10\,\%\text{-}90\,\%}$ and t_{pre} (or as specified by the user of this standard).

   3) Search the *pre-transition aberration* region for the maximum value, $y_{\mathrm{max,pre}}$, and the minimum value, $y_{\mathrm{min,pre}}$. $y_{\mathrm{max,pre}}$ is the maximum y_i in the *pre-transition aberration region* and $y_{\mathrm{min,pre}}$ is the minimum y_i in the *pre-transition aberration region*.

   4) If $y_{\mathrm{max,pre}}$ is equal to or less than the upper *state boundary* of s_1 (s_2) for a *positive-going* (*negative-going*) *transition* then the *overshoot* in the *pre-transition aberration region*, O_{pre}, is zero; otherwise compute the percentage *overshoot* in the *pre-transition aberration region* using:

$$O_{pre}(\%) = \frac{y_{\mathrm{max},pre} - level(\mathrm{s}_k)}{|\mathrm{A}|}100\%, \tag{8}$$

   where

   O_{pre} is the *overshoot* value in the *pre-transition aberration region*,

   $y_{\mathrm{max,pre}}$ is the maximum *waveform* value in the *pre-transition aberration region*,

   A is the *waveform amplitude*,

   level(s_k) is the state level of the k^{th} state. Level(s_k) = level(s_1) for a positive-going transition and level(s_k)= level(s_2) for a negative-going transition.

   5) If $y_{\mathrm{min,pre}}$ is equal to or greater than the lower *state boundary* s_1 (s_2) for a *positive-going* (*negative-going*) *transition*, then the *undershoot* in the *pre-transition aberration region*, U_{pre}, is zero, otherwise compute the percentage *undershoot* in the *pre-transition aberration region* using:

$$U_{\mathrm{pre}}(\%) = \frac{level(\mathrm{s}_k)\text{ - }y_{\mathrm{min,pre}}}{|A|}100\%, \tag{9}$$

   where

   U_{pre} is the *undershoot* value in the *pre-transition aberration region*,

   $y_{\mathrm{min,pre}}$ is the minimum *waveform* value in the *pre-transition aberration region*,

   A is the *waveform amplitude*,

   level(s_k) is the state level of the k^{th} state. Level(s_k) = level(s_1) for a positive-going transition and level(s_k)= level(s_2) for a negative-going transition.

h) Calculating the overshoot and undershoot in the post-transition aberration region.

   1) Calculate the first *instant*, t_{post}, that occurs after $t_{50\,\%}$ when the *waveform* enters the lower (upper) *state boundary* of the *high state* (*low state*) for a *positive-going* (*negative-going*) *transition* using the method described in 5.3.4.

   2) Define the *post-transition aberration region* as that between t_{post} and t_{post} + $3t_{10\,\%\text{-}90\,\%}$ (or as specified by the user of this standard).

   3) Search the *post-transition aberration* region for the maximum value, $y_{\mathrm{max,post}}$ and the minimum value, $y_{\mathrm{min,post}}$. $y_{\mathrm{max,post}}$ is the maximum y_{i} in the *post-transition aberration region* and $y_{\mathrm{min,post}}$ is the minimum y_i in the *post-transition aberration region*.

4) If $y_{\text{max,post}}$ is equal to or less than the upper *state boundary* of s_2 (s_1) for a *positive-going* (*negative-going*) *transition* then the *overshoot* in the *post-transition aberration region*, O_{post}, is zero, otherwise compute the percentage *overshoot* in the *post-transition aberration region* using:

$$O_{post}(\%) = \frac{y_{\max,post} - level(s_k)}{|\mathrm{A}|}100\%, \tag{10}$$

where

O_{post} is the *overshoot* value in the *post-transition aberration region*,
$y_{\text{max,pre}}$ is the maximum *waveform* value in the *post-transition aberration region*,
A is the *waveform amplitude*,

level(s_k) is the state level of the k$^{\text{th}}$ state. Level(s_k) = level(s_1) for a positive-going transition and level(s_k)= level(s_2) for a negative-going transition.

5) If $y_{\text{min,post}}$ is equal to or greater than the lower *state boundary* s_2 (s_1) for a *positive-going* (*negative-going*) *transition*, then the *undershoot* in the *post-transition aberration region*, U_{post}, is zero, otherwise compute the percentage *undershoot* in the *post-transition aberration region* using:

$$U_{\text{post}}(\%) = \frac{level(s_k) - y_{\text{min,post}}}{|A|}100\%, \tag{11}$$

where

U_{post} is the *undershoot* value in the *post-transition aberration region*,
$y_{\text{max,pre}}$ is the minimum *waveform* value in the *post-transition aberration region*,
A is the *waveform amplitude*,

level(s_k) is the state level of the k$^{\text{th}}$ state. Level(s_k) = level(s_1) for a positive-going transition and level(s_k)= level(s_2) for a negative-going transition.

5.3.7 Algorithm for calculating waveform aberrations

a) Calculate the $x1$ % and $x2$ % *reference levels* as described in 5.3.3. Typically used *reference levels* are the 10 % and 90 % *reference levels*.

b) Calculate the *reference level instants*, $t_{x1\ \%}$ and $t_{x2\ \%}$, as described in 5.3.4, for the *reference levels* determined in step (a).

c) Determine the *pre-transition aberration region* and *post-transition aberration region* as described in 5.3.6 and exclude those regions in the calculation of *waveform aberration*.

d) Calculate the parameters for generating the *reference waveform*, *r(t)*. Unless otherwise specified, the trapezoidal *pulse waveform* (see Fig. A.6) will be used as the *reference waveform* for calculating *waveform aberrations*.

   1) Calculate the slope through the *reference levels* and *reference level instants* of the *waveform* using:

$$S = \left(\frac{y_{x2\%} - y_{x1\%}}{t_{x2\%} - t_{x1\%}}\right).$$

   2) Calculate the *reference level instants*, $t_{0\ \%}$ and $t_{100\ \%}$, that will be used to generate *r*(*t*) in step (e).

      i) The *reference levels* and their associated *reference level instants* of the *reference waveform* should be chosen such that the slope of the line through these points is a close fit to the corresponding *waveform* values.

      ii) Compute the $t_{100\ \%}$ *reference level instant* using:

$$t_{100\%} = t_{x2\%} + \frac{level(\mathrm{s}_2) - y_{x2\%}}{S}.$$

iii) Compute the $t_{0\,\%}$ *reference level instant* using:

$$t_{0\%} = t_{x1\%} + \frac{level(\mathrm{s}_1) - y_{x1\%}.}{S}$$

e) Generate the trapezoidal *reference waveform*, *r*(*t*), using:

$$r(t_n) = \begin{cases} y_{0\%}, & \text{for } t_{0\%} \\ S(t_n - t_{0\%}) + y_{0\%}, & \text{for } t_{0\%} \le t_\mathrm{n} \le t_{100\%}\,. \\ y_{100\%}, & \text{for } t_\mathrm{n} > t_{100\%} \end{cases}$$

f) The *waveform aberrations* are calculated as the maximum positive and negative deviation of the measured *waveform* from the *reference waveform* and are presented as a percentage of the *waveform amplitude*. Calculate *waveform aberration* using:

$$W_\mathrm{a} = \begin{cases} \left(\dfrac{\max\left\{y_\mathrm{n} - r(t_\mathrm{n})\right\}_{T_\mathrm{ab}}}{y_{100\%} - y_{0\%}}\right) 100\% \\ \left(\dfrac{\min\left\{y_\mathrm{n} - r(t_\mathrm{n})\right\}_{T_\mathrm{ab}}}{y_{100\%} - y_{0\%}}\right) 100\% \end{cases}, \tag{12}$$

where

W_a	is the *waveform aberration*,
max{...}	return the maximum value of its argument,
min{…}	returns the minimum value of its argument,
$y_{100\,\%}$	is the value of the 100 % *reference level*,
$y_{0\,\%}$	is the value of the 0 % *reference level*,
$r(t_n)$	is the *reference waveform*,
n	is the discrete time index of the *waveform*,
T_ab	is the *interval* over which the *waveform aberration* is being calculated.

5.3.8 Algorithm for calculating transition settling duration

a) Calculate the 50 % *reference level*, as described in 5.3.3.

b) Calculate the 50 % *reference level instant* as described in 5.3.4.

c) Specify the *state boundaries* of the specified *state* (usually state 2).

d) Determine the *instant* at which the *waveform* enters and subsequently remains within the specified *state boundary*.

   1) Starting at the end of the waveform epoch, check each waveform value against the specified state boundaries.

   2) Record the sampling instant of the first waveform value encountered that is found outside the state boundary.

   3) Calculate the instant that the waveform crosses the state boundary using the method described in 5.3.4.

   4) Calculate the transition settling duration by finding the difference between the instant determined in step (d)3) and the 50 % reference level instant determined in step (a).

5.3.9 Algorithm for calculating transition settling error

a) Calculate the 50 % *reference level instant* as described in 5.3.4.2.

b) Specify which *state level*, *level*(s$_1$) or *level*(s$_2$), will be used to compute the *transition settling error*.

c) Specify the *instant,* t_s, for $t_s > t_{50\,\%}$, and its corresponding *waveform* sample index, i_s, at which *interval* over which the *transition settling error* is to be determined starts.

d) Specify the *instant* t_f after t_s, and its corresponding *waveform* sample index, i_f, at which *interval* over which the *transition settling error* is to be determined ends.

e) *Transition settling error,* E_{settling}, is determined using:

$$E_{\text{settling}} = \max\left\{\left|\frac{y_i - level(\mathrm{s}_k)}{level(\mathrm{s}_2) - level(\mathrm{s}_1)}\right|\right\}, i_s \le i \le i_f, \tag{13}$$

where

E_{settling}, is the *transition settling error*,

max{...} returns the maximum value of its argument,

level(s$_k$) is the *state level* of the k^{th} *state*,

k = 1 or 2 depending on whether the *state level* selected in step (b) was s$_1$ or s$_2$.

5.4 Analysis of single and repetitive pulse waveforms

5.4.1 General

The algorithms in 5.4 assume the *repetitive pulse waveform* is a *compound waveform* comprised of either *positive pulse waveforms* or *negative pulse waveforms*. In either case, the user of this standard shall specify whether the computed parameters of the *repetitive pulse waveform* were based on it being comprised of *positive pulse waveforms* or *negative pulse waveforms.*

5.4.2 Algorithm for calculating pulse duration

a) Select a *waveform epoch* or subepoch that contains exactly one *pulse waveform*.

b) Select the *x* % *reference level*. Typically the $y_{50\,\%}$ is used.

c) Calculate the *reference level instant*, $t_{1,\mathrm{x}\,\%}$, for the *x* % *reference level* in accordance with 5.3.4 for the *positive-going* (*negative-going*) *transition* of the *waveform* selected in step (a).

d) Calculate the *reference level instant*, $t_{2,\mathrm{x}\,\%}$, for the *x* % *reference level* in accordance with 5.3.4 for the *negative-going* (*positive-going*) *transition* of the *waveform* used in step (c) above.

e) The *pulse duration*, T_{P}, is the absolute value of the difference between the *reference level instants* found in steps (c) and (d):

$$T_P = \left|t_{2,x\%} - t_{1,x\%}\right|, \tag{14}$$

where

T_{P} is the *pulse duration*,

$t_{1,\mathrm{x}\,\%}$ and $t_{2,\mathrm{x}\,\%}$ are the *reference level instants*.

5.4.3 Algorithm for calculating waveform period

a) Select a *waveform epoch* or subepoch that contains exactly two *pulse waveforms* within that *waveform epoch*.

b) Determine *level*(s$_1$) and *level*(s$_2$) using a method from 5.2.

c) Select the $y_{\mathrm{x}\ \%}$ *reference level*. Typically the $y_{50\ \%}$ is used.

d) Calculate the *reference level instant*, $t_{1,\mathrm{x}\ \%}$, for the $y_{\mathrm{x}\ \%}$ *reference level* in accordance with 5.3.4 for either the *positive-going* (or *negative-going) transition* on a *pulse* in the *waveform.*

e) Calculate the *reference level instant*, $t_{2,\mathrm{x}\ \%}$, for the $y_{\mathrm{x}\ \%}$ *reference level* in accordance with 5.3.4 for either the *positive-going* (or *negative-going) transition* (consistent with the choice made in step (d)) on a *pulse* immediately following or preceding the *pulse* used in step (d) above.

f) The *period*, *T*, is the difference between the *reference level instants* found in steps (d) and (e):

$$T = \left| t_{2,x\%} - t_{1,x\%} \right|, \tag{15}$$

where

T is the *period*,

$t_{1,\mathrm{x}\ \%}$ and $t_{2,\mathrm{x}\ \%}$ are the *reference level instants*.

5.4.4 Algorithm for calculating pulse separation

There are two methods given here for calculating pulse separation.

a) Method 1

  1) Select a *waveform epoch* or subepoch that contains exactly two *pulse waveforms* within that *waveform epoch*.
  2) Determine *level*(s_1) and *level*(s_2) using a method from 5.2.
  3) Select the $y_{\mathrm{x}\ \%}$ *reference level*. Typically the $y_{50\ \%}$ is used.
  4) Calculate the *reference level instant*, $t_{1,\mathrm{x}\ \%}$, for the $y_{\mathrm{x}\ \%}$ *reference level* in accordance with 5.3.4 for the second (or first) *transition* of a *pulse* in the *waveform.*
  5) Calculate the *reference level instant*, $t_{2,\mathrm{x}\ \%}$, for the $y_{\mathrm{x}\ \%}$ *reference level* in accordance with 5.3.4 for the first (or second) *transition* on the *pulse* immediately following or preceding the *pulse* used in step (a)4) above.
  6) The *pulse separation*, T_{S}, is the difference between the *reference level instants* found in step a)4) and step (a)5):

$$T_{\mathrm{S}} = \left| t_{2,x\%} - t_{1,x\%} \right|, \tag{16}$$

where

T_{S} is the pulse separation,

$t_{1,\mathrm{x}\ \%}$ and $t_{2,\mathrm{x}\ \%}$ are the *reference level instants*.

b) Method 2

  1) Calculate the *pulse duration* according to 5.4.2.
  2) Calculate the *waveform period* according to 5.4.3.
  3) The *pulse separation*, T_{S}, is the difference between the *waveform period* and the *pulse duration*:

$$T_{\mathrm{S}} = T - T_{\mathrm{P}}, \tag{17}$$

where

T_{S} is the pulse separation,

T is *pulse period* determined in 5.4.3,

T_{P} is *pulse period* determined in 5.4.2.

5.4.5 Algorithm for calculating duty factor

a) Calculate the *pulse duration* according to 5.4.2.

b) Calculate the *waveform period* according to 5.4.3.

c) The *duty factor*, d_f, is given by the ratio of the *pulse duration* to the *waveform period*:

$$d_f = \frac{T_P}{T}, \tag{18}$$

where

d_f is the duty factor,

T is *pulse period* determined in 5.4.3,

T_P is *pulse period* determined in 5.4.2.

5.5 Analysis of compound waveforms

5.5.1 General

Typically, the analysis of a *compound waveform* involves three steps. The first step is to decompose the *waveform epoch* of the *compound waveform* into subepochs, where each subepoch contains an elementary component of the *waveform* (see Figure 11). An elementary component includes those defined in this standard (*transitions*, *state levels*, *runts*, *spikes*, *transients*, *terminal features*) and those that may be defined by the user of this standard. This decomposition of the *waveform epoch* into appropriate subepochs is the parsing process. The second step of *compound waveform* analysis is to classify or categorize the *waveform* subepochs. This process involves identifying each subepoch as containing a specific elementary component of a *waveform*. The last step in compound waveform analysis is to recombine those subepochs required to compute the desired waveform parameter. In any analysis of *compound waveforms,* the algorithms or procedures used in these processes shall be specified.

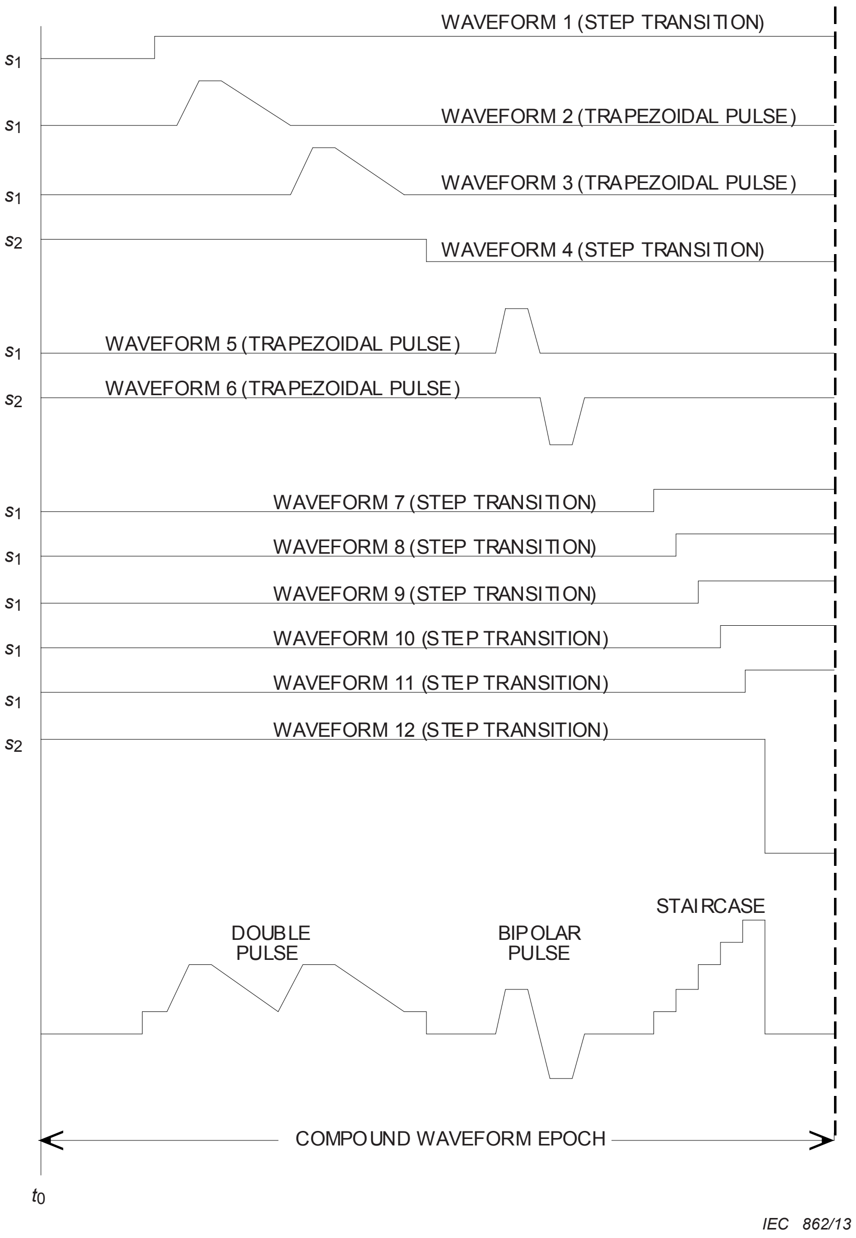


Figure 11 – Generation of a *compound waveform*

5.5.2 Waveform parsing

This subclause contains a set of algorithms for decomposing the *compound waveform* into subepochs that contain either *transitions*, *transients*, *terminal features*, or *state levels*. The inputs for this process are:

- *y*[] is the array containing the *waveform* amplitude values
- *i* is the *waveform* sample index, *i* = 1, .. *N_samples*
- *N_samples* is the number of samples in the *compound waveform*
- *state_upper*[] is the array containing the values defined by the user of this standard for the upper *boundary* for each *state* in the *waveform*
- *state_lower*[] is the array containing the values defined by the user of this standard for the lower *boundary* for each *state* in the *waveform*

- *j* is the *state* index, *j* = 1,.., *N_states*. *j* = 1 is the *base state* (see 3.2.40.1).
- *N_states* is the number of states in the *compound waveform*. For example, for a *pulse train* of *pulses* having equal *pulse amplitude*, *N_states* = 2.
- d_{min} is the minimum *duration* (given in number of samples) required for a *state occurrence*

The outputs of this decomposition process are:

- *assigned_state*[] is an integer array containing *state* assignments for each sample of the *waveform*. These assignments are necessary to complete the parsing process.
- *N_sub* is the number of subepochs determined
- *sub_start*[] is the array containing the starting *waveform* sample index for each subepoch
- *sub_end*[] is the array containing the ending *waveform* sample index for each subepoch
- *k* is the subepoch index, *k* = 1, .. *N_sub*
- *sub_type*[] is an array containing a temporary subepoch classification index.

If *sub_type*[*k*] is a positive integer, then the associated subepoch contains a *state occurrence* and the value of *sub_type*[*k*] is the state number. The value of *sub_type* = 0 is used as a temporary classification to indicate that a subepoch is not a *state occurrence* but has not yet been further classified.

The first step in the parsing process assigns *state levels* to each *waveform* value by comparing the *waveform* value to the upper and lower *boundaries* of all the *states* defined for the *compound waveform*. If the *waveform* value is contained within *state boundaries* of a *state*, then that *waveform* value is assigned a *state level* indicator, such as “1” for s_1, “2” for s_2, etc. If the *waveform* value is not within the *state boundaries* of any *state*, then the value of its associated *assigned_state*[] is set to zero. Once this step is completed, each *waveform* value has an associated value in the array *assigned_state*[].

```
for i = 1 .. N_samples
    assigned_state[i] = 0
    for j = 1 .. N_states
        if(state_lower[j] <= y[i] <= state_upper[j]) assigned_state[i] = j
    endfor
endfor
```

The following algorithm decomposes the *compound waveform* into subepochs based on values in the array *assigned_state*[]. This is the second step in parsing the *compound waveform*. The subepochs provided at the end of this step are not the final subepochs because they may contain parts of *transitions* or *transients*. These parts will be recombined in a subsequent step (as described later). Once this step is complete, each temporary subepoch has an associated starting *waveform* sample index (found in *sub_start*[]), an associated ending *waveform* sample index (found in *sub_end*[]), and an assigned classification (found in *sub_type*[]).

```
i = 1
k = 1
do
    current_assignment = assigned_state[i]
    sub_start[k] = i
    sub_type[k] = current_assignment
    while( (assigned_state[i] = current_assignment) and i < N_samples) i = i + 1 endwhile
    sub_end[k] = i -1
    if(sub_end[k] – sub_start[k] < $d_{\text{min}}$ -1) sub_type[k] = 0
    k = k + 1
    i = i + 1
while(i < N_samples)
N_sub = k -1
```

The next step in parsing the *compound waveform* is to examine the temporary subepochs created in the previous step and merge those temporary subepochs that together form a *transition* or a *transient*. This step is performed by the following algorithm.

```
$j$ = 1
while($j < N\_sub$)
    if ($sub\_type[j] = 0$)
        while ($sub\_type[j+1] = 0$) Merge($j$) endwhile
    endif
    $j = j + 1$
endwhile
```

This algorithm uses the function Merge(*j*), which merges the j^{th} and $(j+1)^{st}$ subepochs into one subepoch. This function is given by:

```
Merge($j$)
    $sub\_end[j] = sub\_end[j+1]$
    $N\_sub = N\_sub - 1$
    for $i = j+1$ .. $N\_sub$
        $sub\_start[i] = sub\_start[i+1]$
        $sub\_end[i] = sub\_end[i+1]$
        $sub\_type[i] = sub\_type[i+1]$
    endfor
end Merge
```

Once this parsing process is complete, the *compound waveform* has been decomposed into subepochs containing either *state levels*, *terminal features*, *transients*, and/or *transitions*. The next step in the analysis of the *compound waveform* is to classify the subepochs.

5.5.3 Subepoch classification

The subepochs found using the process described in 5.5.1 will be classified. The following algorithm provides a classification scheme. This classification scheme will only classify subepochs as either *terminal features*, *state levels*, *transients*, or *transitions*. Subepochs that contain a *state occurrence* are given a number corresponding to the *state level* numbering described in 3.2.42, in which the number is related to the *level* of the *state*. When this process is complete, each subepoch will be uniquely defined by its classification and stop and start indices. The input for this algorithm is array *sub_type*[] and output is the array *sub_class*[]. The array *sub_class*[] contains the final classification of each subepoch.

```
terminal = -1
transient = -2
transition = -3
if ($sub\_type[1] = 0$) $sub\_class[1]$ = terminal
if ($sub\_type[N\_sub] = 0$) $sub\_class[N\_sub]$  = terminal
for $k = 2 .. N\_sub - 1$
    if (($sub\_type[k] = 0$) and ($sub\_type[k+1] \neq sub\_type[k-1]$)) then $sub\_class[k]$ = transition
        else $sub\_class[k]$ = transient
        endif
if ($sub\_type[k] \neq 0$) $sub\_class[k] = sub\_type[k]$
endfor
```

5.5.4 Waveform reconstitution

Once the original *waveform epoch* has been parsed into subepochs and these subepochs appropriately classified, the appropriate sequential subepochs shall be selected for calculating the desired *waveform parameters*. These sequential subepochs create a new *waveform*, which is a subset of the original *waveform* and that has a *duration* shorter than the original *waveform*. For example, if the first *transition duration* of the n^{th} *pulse* in a *pulse train* of *positive pulses* is desired, where this *transition* is located in the j^{th} subepoch, then the $(j-1)^{th}$, j^{th}, and $(j+1)^{th}$ subepochs are selected to create the new *waveform*, which starts at *sub_start*[*j*-1] and ends at *sub_end*[*j*+1]. The algorithms for computing the *transition duration* (see 5.3.5) are then applied to this new *waveform*.

5.6 Analysis of impulse-like waveforms

5.6.1 Algorithm for calculating the impulse amplitude

a) Determine *level*(s_1) using a method described in 5.2.

b) Determine the maximum *waveform* value and the sampling *instant* at which it occurs.

c) Fit a parabola (or function specified by the user of this standard) to five (or a number specified by the user of this standard) points of the *waveform* with the third (middle) point being the maximum *waveform* value determined in step (b).

d) The *impulse amplitude* is the value of the fitted parabola at the vertex.

5.6.2 Algorithm for calculating impulse center instant

a) Determine the *amplitude* of the *impulse-like waveform* as described in 5.6.1.

b) The *impulse center instant* is the instant associated with the vertex of the fitted parabola.

5.7 Analysis of time relationships between different waveforms

5.7.1 General

The time relationships between different *waveforms* may be analyzed by:

a) applying the methods described earlier in the analysis of the different *waveforms* and;

b) determining the time relationships between different *waveforms* as computed *intervals* or *durations* as described in 5.3.5 and 5.4.2.

5.7.2 Algorithm for calculating delay between different waveforms

a) Calculate $t_{50\ \%}$ for each *waveform* as described earlier in the algorithm for calculating *transition duration* between the *x*1 % and *x*2 % *reference levels*.

b) Calculate the *delay* as the difference between $t_{50\ \%}$ for the different *waveforms*:

$$T_D = t_{mid,W1} - t_{mid,W2}, \tag{19}$$

where

T_D is the delay,

$t_{mid,W1}$ is the 50 % *reference level instant* for one of the *waveforms,*

$t_{mid,W2}$ is the 50 % *reference level instant* for the other *waveforms*.

NOTE *Delay* can be either positive or negative (negative *delay* can also be called "advance").

5.8 Analysis of waveform aberration

The analysis of *waveform aberration* (See 5.3.7.) entails the determination of the differences between a *waveform* and a *reference waveform*. In any *aberration* determination the type of *reference waveform* shall be specified.

The *reference waveform* shall be properly located, in time and in *level*, relative to the *waveform* being analyzed.

5.9 Analysis of *fluctuation* and *jitter*

5.9.1 General

The analysis of *fluctuation* and *jitter* involves making repeated independent measurements of the same quantity and evaluating the standard deviation of the results. In many cases, the measurement of *fluctuation* and *jitter* includes the *fluctuation* and *jitter* of the instrument used for the measurements, and this should be taken into account. Also, in many cases the result of a measurement of either *fluctuation* or *jitter* is influenced by the presence of the other. The correct determination of *fluctuation* and *jitter* often requires multiple measurements taken under different conditions and the solution of simple algebraic equations to determine the individual *parameters*.

5.9.2 Determining standard deviations

5.9.2.1 General

There are two commonly used methods for determining the standard deviations required for *fluctuation* and *jitter* analysis: the direct method and the histogram method. Both will be described here. Any method of measuring a standard deviation includes an inherent statistical error. An estimate of that error will be given here. This subclause also gives the standard method for correcting standard deviation results for the contributions from interfering sources.

5.9.2.2 Standard deviation – Direct method

A number, M, of independent measurements are made of the same *parameter*, p_i. The standard deviation of these measurements is determined as follows:

a) Calculate the mean value, $\overline{p}$, using the following formula:

$$\overline{p} = \frac{1}{M}\sum_{i=1}^{M} p_i , \tag{20}$$

where

M is the number of independent measurements,

p_i is the value of the i^{th} measurement of the parameter.

b) Calculate the standard deviation using the following formula:

$$\sigma_p = \sqrt{\frac{1}{M-1}\sum_{i=1}^{M}\left(p_i - \overline{p}\right)^2} . \tag{21}$$

5.9.2.3 Standard deviation -- Histogram method

The histogram method has the advantage that it does not require storage of each of the M measurement values. This method is often incorporated into instruments. In this method, a histogram is generated of the M measurement values using the method of 5.2.2.2 if applicable. The histogram is comprised of B histogram bins numbered from 1 through B. The value at the center of the k^{th} histogram bin is denoted by v_{k}, and the count in the k^{th} bin is denoted by c_{k}. The standard deviation is calculated as follows:

a) Determine the mean of the *parameter* value by using:

$$\overline{p} = \frac{1}{M}\sum_{k=1}^{B} c_k v_k , \tag{22}$$

where

c_{k} is the count in the k^{th} bin,

v_{k} is the center of the k^{th} bin,

B is the number of histogram bins.

b) Calculate the standard deviation of the parameter value using:

$$\sigma_p = \sqrt{\left(\frac{1}{M-1}\sum_{k=1}^{B} v_k^2 c_k\right) - \overline{p}^2}. \tag{23}$$

For these results to be valid, there are restrictions on the histogram parameters. First, the bin width, that is the value of v_k - v_{k-1}, should be small compared to the value determined for the standard deviation. The histogram calculation of the standard deviation can be as large as one-half of the bin width. Second, the values associated with the most negative bin and with the most positive bin should be sufficient to include the tails of the distribution. If the bins include $\overline{p} \pm 3\sigma$, this error will be less than 3 % of σ.

5.9.2.4 *Accuracy* of standard deviation

The value of the standard deviation calculated by either of the above methods is a random variable and has an inherent statistical error. Under the assumption that the values of the *parameter* for which the standard deviation was found have normal distributions, the standard deviation of the calculated standard deviation is given by:

$$\Sigma_p = \sigma_p \sqrt{1 - \frac{2}{M-1}\left(\frac{\Gamma\left(\frac{M}{2}\right)}{\Gamma\left(\frac{M-1}{2}\right)}\right)^2}, \tag{24}$$

where

Σ_p is the standard deviation of the calculated standard deviation,

σ_p is the calculated standard deviation (see 5.9.2.2 and 5.9.2.3), and

Γ is the gamma function.

This formula can be approximated by the following:

$$\Sigma_p \cong \frac{\sigma_p}{\sqrt{2(M-1)}}. \tag{25}$$

Table 1 shows the ratio of Σ_p calculated using Equation (24) to that calculated using Equation (25):

Table 1 – Comparison of the results from the exact and approximate formulas for computing the standard deviation of the calculated standard deviations

M	Σ_p calculated using [24]	Σ_p calculated using [25]	ratio
5	$0{,}341063\sigma_p$	$0{,}353553\sigma_p$	0,965
10	$0{,}232197\sigma_p$	$0{,}235702\sigma_p$	0,985
20	$0{,}161225\sigma_p$	$0{,}162221\sigma_p$	0,994
50	$0{,}100756\sigma_p$	$0{,}101015\sigma_p$	0,997
100	$0{,}070943\sigma_p$	$0{,}071067\sigma_p$	0,998

5.9.2.5 Correcting the standard deviation

Often the measured standard deviation for the *parameter* of interest will have a contribution due to interfering sources. Examples will be given later. This section gives the standard method for correcting for the interference. If σ_{obs} is the observed standard deviation and σ_I is the contribution to the standard deviation from the interfering source, then the estimate for the true standard deviation is

$$\sigma_p = \sqrt{\sigma_{\text{obs}}^2 - \sigma_I^2}, \tag{26}$$

where

σ_p is the estimated standard deviation,

σ_I is the contribution to the standard deviation from the interfering source,

σ_{obs} is the observed standard deviation.

If the values of σ_{obs} and σ_I are close to each other, then one should assure that the error in each is sufficiently small, as described in 5.9.2.6. If there are n different interfering sources, each with standard deviation σ_j, then the value for σ_I is given by the square root of the sum of their squares:

$$\sigma_I = \sqrt{\sum_{j=1}^{n} \sigma_j^2}, \tag{27}$$

where

σ_j is the standard deviation from each j^{th} interfering source,

n is the number of interfering sources.

5.9.2.6 Errors in the corrected standard deviation

The standard deviation of the corrected standard deviation is given by:

$$\frac{\Sigma_p}{\sigma_p} = \frac{\sqrt{\sigma_{\text{obs}}^2 \Sigma_{\text{obs}}^2 + \sigma_I^2 \Sigma_I^2}}{\sigma_p^2}, \tag{28}$$

where

σ_p is the calculated standard deviation,

Σ_I is the standard deviation of the standard deviation of the interfering sources,

Σ_{obs} is the standard deviation of the observed standard deviation of the parameter.

If there are n different interfering sources contributing to σ_I, each with standard deviation σ_j that has standard deviation Σ_j, then the value for Σ_I is given by:

$$\Sigma_I = \frac{\sqrt{\sum_{j=1}^{n} \sigma_j^2 \Sigma_j^2}}{\sigma_I}.$$

If the ratio, Σ_p/σ_p, is not small, then there is significant error in the calculated value of σ_p. In the case that both of the standard deviations in the right hand side of Equation (28) were determined with the same number of measurements, M, this reduces to a simpler relation, namely,

$$\frac{\Sigma_p}{\sigma_p} \le \frac{\alpha}{\sqrt{M}}, \tag{29}$$

where

M is the number of measurements,

$$\alpha = \max\left(\frac{\sigma_{\text{obs}}}{\sigma_p}, \frac{\sigma_I}{\sigma_p}\right),$$

where

max{..} returns the maximum value of its argument,

all other variables have been defined for Equation (28).

5.9.3 Measuring fluctuation and jitter of an instrument

5.9.3.1 General

Before using an instrument to measure the *fluctuation* and *jitter* of a *signal* source one should determine the *fluctuation* and *jitter* of the instrument. The instrument will typically be some form of digital oscilloscope. It is most convenient to measure *fluctuation* first.

5.9.3.2 Measuring *fluctuation* of an instrument

5.9.3.2.1 General

The measurement of the *fluctuation* of the instrument depends on the *level parameter* of interest and on the algorithm that will be used to determine the *level parameter*. The *parameter* calculations performed in the instrument *fluctuation* measurements shall be made with essentially the same algorithm as will be used for the *parameter* calculations in the *signal* source *fluctuation* measurements. Two approaches are presented in 5.9.3.2.2 and 5.9.3.2.3.

5.9.3.2.2 Measuring *fluctuation* of an instrument -- Simulation approach

This approach requires a input *signal* that is similar to the *signal* source to be tested and is known to have a *fluctuation* less than one-quarter of the *fluctuation* of the *signal* to be measured.

a) Record M *waveforms* of the input *signal*.
b) Calculate the value of the *level parameter* for each recorded *waveform* using one of the algorithms described in s 5.2 and 5.3, if applicable.
c) Determine the standard deviation, σ_{obs}, of the values obtained in step (b) by any of the methods described in 5.9.2.

If the input *signal* does not have negligible *fluctuation* compared to that of the instrument, and if the instrument *fluctuation* will subsequently be used to correct the measured *fluctuation* value of a device under test, then the corrected *fluctuation* of the device under test will be underestimated.

5.9.3.2.3 Measuring *fluctuation* of an instrument – Constant *signal* approach

a) Record *M* records of a constant *signal*.

b) Calculate the value of the *level parameter* for each record obtained in step (a) using an algorithm essentially equivalent (see 5.2 and 5.3 if applicable) to the algorithm that will be used to determine the *level parameter* for the *signal* source.

c) Determine the standard deviation of the values obtained in step (b) by any of the methods of 5.9.2.

Use of this method is valid with the assumption that the instrument's contribution to *fluctuation* is caused by additive random noise, which is often the case.

In step (b) it may not be possible to use the exact same algorithm to calculate the *level parameter* for a constant *signal* that will be used for the actual time-varying *signal*. For example, if the *level parameter* is the *amplitude* of a *transition*, the algorithm may involve taking a histogram of the entire record, separating it into two separate histograms based on the two modes, and taking the difference of the means, medians or modes of the two histograms. With the *waveform* of a constant *signal*, a bimodal histogram is not obtained. Therefore, a different method shall be supplied to obtain two separate histograms, one histogram each for the two constant-*signal waveforms*. Each of these two histograms should come from approximately the same time interval in the record, have the same histogram bin width, and have approximately the same number of total counts as the corresponding histogram for the time varying *signal*. The calculations done on these two histograms should be identical to those that will be done when a time-varying *signal* is present.

5.9.3.3 Measuring *jitter* of an instrument

5.9.3.3.1 General

There are two distinct kinds of *jitter*: *trigger jitter* and relative *jitter*. For an instrument, (as opposed to a *signal* source) *trigger jitter* refers to the variation between the *instant* the trigger *signal* occurs and the *instant* that a given *waveform* sample is taken. Relative *jitter* refers to the variation in the *interval* between two sample *instants* in the same record. Relative *jitter* may be dependent on the time *interval* between the two sample *instants*. *Trigger jitter* may depend on the *instant*, within the *waveform epoch*, of the sample used in the measurement. The interval between the trigger *instant* and the sample *instant* should be chosen to be as short as possible.

5.9.3.3.2 Measuring *trigger jitt*er of an instrument

The measurement requires a *signal* with a rapid *transition*. How rapid will be discussed later. The *signal* is passively split into two *signals*, one to provide the trigger and one to be recorded on the instrument under test. The *signal* to be recorded may have to be *delayed* (with a passive *delay* line) in order to record, in the *waveform*, the rapid *transition* of the *signal*.

a) Record *M waveforms*, each containing the rapid *transition* of the *signal*.

b) Calculate the average, $\overline{y}_i$, of the *M waveforms* for every *instant* of the *waveform* using:

$$\overline{y}_i = \frac{1}{M}\sum_{m=1}^{M} y_{m,k}, \qquad [30]$$

where

$\overline{y}_i$ is the average,

$y_{\mathrm{m,k}}$ are the *waveform* values,

M is the number of *waveforms*,

m is the *waveform* index,

k is the *waveform* sample index.

c) Using $\overline{y}_i$, determine a *level*, v_0, at which the instantaneous slope, S, in the *transition* of the *signal* is large and determine the value of S at v_0 by a method specified by the user of this standard.

d) For each of the M *waveforms*, determine the *instant* at which the *waveform* value crosses v_0 using the method of 5.3.4.

e) Determine the standard deviation, $\sigma_{\tau\mathrm{obs}}$, of the *instants* obtained in step (d).

f) Correct the result found in step (d) for *fluctuation* using the following formula:

$$\sigma_{ITJ} = \sqrt{\sigma_{\tau,obs}^2 - \left(\sigma_{IF}/S\right)^2} \qquad [31]$$

where

σ_{ITJ} is the corrected standard deviation (corrected *trigger jitter*),

$\sigma_{\tau,\mathrm{obs}}$ is the observed standard deviation of the *instants*(observed *trigger jitter*),

σ_{IF} is the rms *fluctuation* of individual values from the instrument,

S is the instantaneous slope in the *transition* of the *signal*.

To verify the result, the standard deviation of σ_τ should be calculated using the method of 5.9.2.6.

5.9.3.3.3 Measuring relative *jitter* of an instrument

This measurement requires a test *signal* with two rapid *transitions*, such as a *rectangular pulse.* The *interval* between the two *transitions* of the test *signal* should have *jitter* less than one-fourth of the *jitter* to be measured and be approximately the same as the *interval* over which the relative *jitter* is to be measured.

a) Record M *waveforms*, each containing the two rapid *transitions* of the *signal*.

b) Calculate the average, $\overline{y}_i$, of the M *waveforms* for every *instant* of the *waveform* as described in step (b) of 5.9.3.3.2.

c) Using $\overline{y}_i$, determine *levels*, v_1 and v_2, (one on each *transition*) at which the slope, S, in the *transition* of the *signal* is large. Determine S_1 for v_1 and S_2 for v_2 by a method specified by the user of this standard.

d) Determine the *instant*, t_1, when v_1 occurs using the method described in 5.3.4.

e) Determine the *instant*, t_2, when v_2 occurs using the method described in 5.3.4.

f) For each of the *waveforms* from step (a) calculate the difference, $t_2 - t_1$.

g) Determine the standard deviation, $\sigma_{\tau\mathrm{obs}}$, of the time differences calculated in step (f).

h) Correct the result found in step (g) for *fluctuation* using the following formula*:*

$$\sigma_{\tau,IJ,rel} = \sqrt{\sigma_{\tau,obs}^2 - \left(\sigma_{IF}/S_1\right)^2 - \left(\sigma_{IF}/S_2\right)^2} \qquad [32]$$

where

$\sigma_{\tau,\mathrm{IJ,rel}}$ is the relative jitter of the instrument,

S_1 and S_2 are the instantaneous slopes in the *transitions* of the *signal*.

To verify the result, the standard deviation of σ_{T} should be calculated using the method of 5.9.2.6.

5.9.4 Measuring *fluctuation* and *jitter* of a *signal* source

5.9.4.1 General

The measurements for a *signal* source are identical to those for an instrument except that the *signal* source is used instead of a test *signal*. The *signal* source measurements have an additional correction for the *fluctuation* and *jitter* of the instrument.

5.9.4.2 Measuring *fluctuation* of a *signal* source

a) Perform steps (a) through (c) of 5.9.3.2.2.

b) Determine the corrected standard deviation, $\sigma_p = \sqrt{\sigma_{\mathrm{obs}}^2 - \sigma_I^2}$, where σ_I is the fluctuation of the instrument as determined by one of the methods of 5.9.3.2. To verify the result, the standard deviation of σ_{p} should be calculated using the method of 5.9.2.65.

5.9.4.3 Measuring the *trigger jitter* of a *signal* source

This requires triggering the oscilloscope with the trigger generated by the *signal* source and recording a rapid transition of the *signal* source on the oscilloscope.

a) Perform steps (a) through (e) of 5.9.3.3.2.

b) Correct the result found in step (a) for *fluctuation* of the *signal* source and *jitter* and *fluctuation* of the instrument using the following formula:

$$\sigma_{\tau,STJ} = \sqrt{\sigma_{\tau,obs}^2 - \sigma_{ITJ}^2 - \left(\sigma_{IF}/S\right)^2 - \left(\sigma_F/S\right)^2} \qquad [33]$$

where

$\sigma_{\tau,\mathrm{STJ}}$ is the trigger *jitter* of the *signal* source,

σ_{F} is the *fluctuation* of the instrument *signal* source,

To verify the result, the standard deviation of σ_{T} should be calculated using the method of 5.9.1.5.

5.9.4.4 Measuring a relative jitter of a signal source

There are several *jitter* values that involve the *interval* between two *instants*: *cycle-to-cycle jitter*, *period jitter*, and *pulse duration jitter*. The measurement method is the same for all of them.

a) Record *M waveforms* containing the two relevant *instants*.

b) Perform steps (b) through (e) of 5.9.3.3.3 for the *parameter* of interest.

c) Correct the result of step (b) for *fluctuation* and the relative *jitter* in the instrument using the following formula:

$$\sigma_{\tau,SJ,rel} = \sqrt{\sigma_{\tau,obs}^2 - \sigma_{ITJ}^2 - \left(\sigma_{IF}^2/S_1\right)^2 - \left(\sigma_{IF}^2/S_2\right)^2} \qquad [34]$$

where

$\sigma_{\tau,\mathrm{SJ,rel}}$ is the relative *jitter* of the *signal* source,

To verify the result, the standard deviation of σ_{T} should be calculated using the method of 5.9.2.6.

Annex A
(informative)

Waveform examples

A.1 Reference *waveform* examples

A.1.1 General

A reference *waveform* is a *waveform* that is used for comparison (quantitatively or qualitatively) with, or in evaluation of other *waveforms*. A reference *step-like waveform* may, or may not, be a *step waveform*. Some *waveforms* that are commonly used as *reference waveforms* are defined below (see Figures A.1 to A.8).

A.1.2 *Step-like waveform*

Figure A.1 shows a *waveform* defined by

$$y(t) = \begin{cases} \mathrm{s}_1 & t < t_1 \\ \mathrm{s}_2 & t \geq t_1 \end{cases}$$

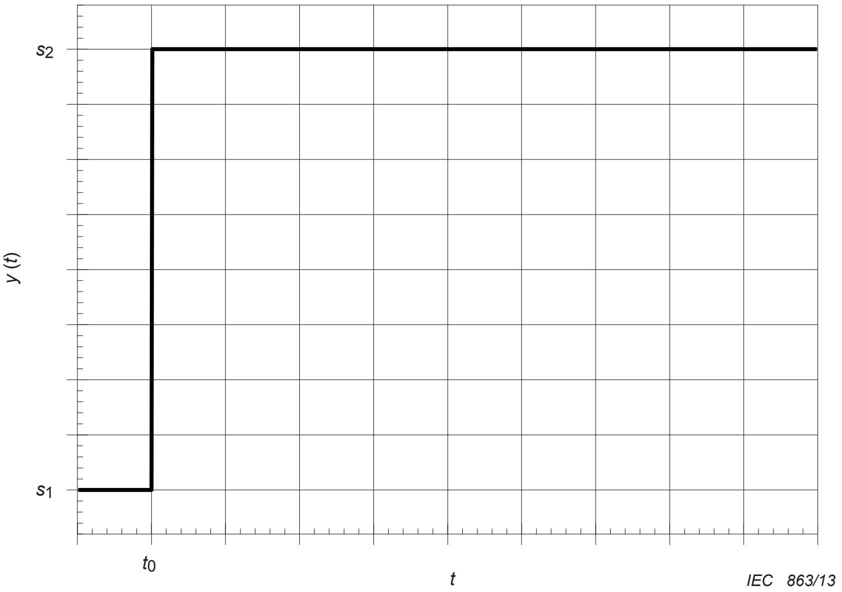


Figure A.1 – *Step-like waveform*

A.1.3 Linear *transition waveform*

Figure A.2 shows a *waveform* defined by

$$y(t) = \begin{cases} s_1 & t < t_1 \\ s_1 + \dfrac{s_2 - s_1}{t_2 - t_1}(t - t_1) & t_1 \le t \le t_2 \\ s_2 & t > t_2 \end{cases}$$

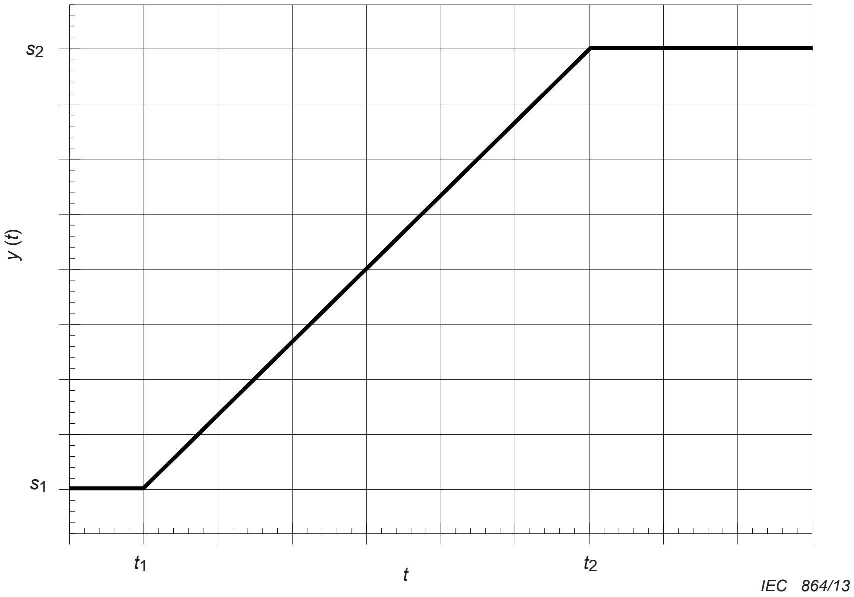


Figure A.2 – Linear *transition waveform*

A.1.4 Exponential *waveform*

Figure A.3 shows a transition waveform defined by

$$y(t) = \begin{cases} \mathrm{s}_1 & t < t_1 \\ s_1 + (\mathrm{s}_2 - \mathrm{s}_1)\left[1 - e^{-(t-t_1)/b}\right] & t \geq t_1 \end{cases}$$

where

$b =$ exponential time constant.

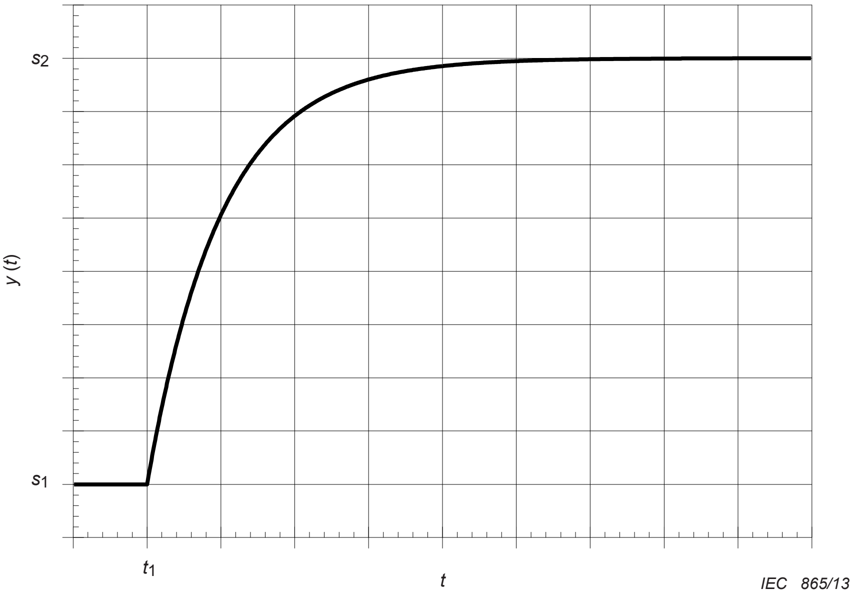


Figure A.3 – Exponential *waveform*

A.1.5 *Impulse-like waveform*

Figure A.4 shows a pulse waveform defined as

$$y(t)=\begin{cases} s_1 & t \neq t_1 \\ s_2 & t = t_1 \end{cases}$$

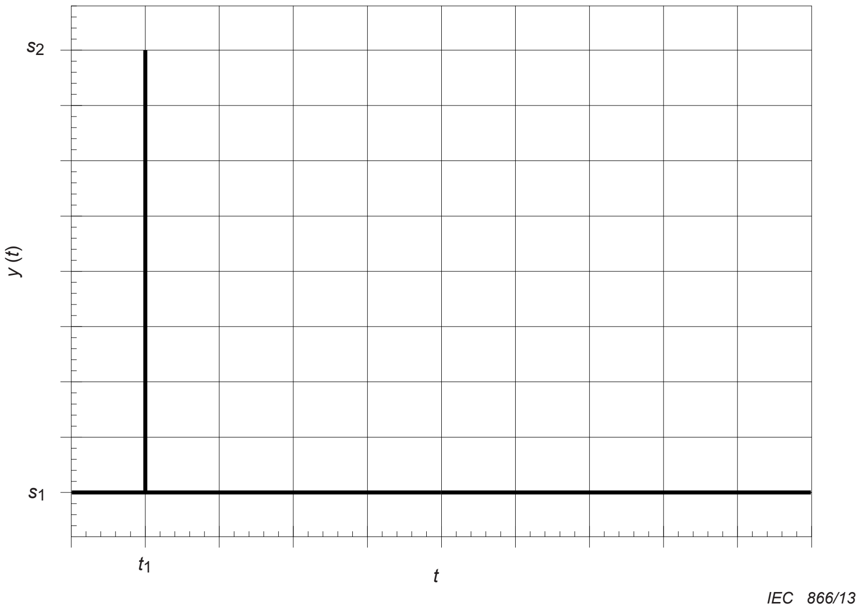


Figure A.4 – *Impulse-like waveform*

A.1.6 Rectangular *pulse waveform*

Figure A.5 shows a pulse waveform defined as

$$y(t) = \begin{cases} s_1 & t < t_1 \\ s_2 & t_1 \le t \le t_2 \\ s_1 & t > t_2 \end{cases}$$

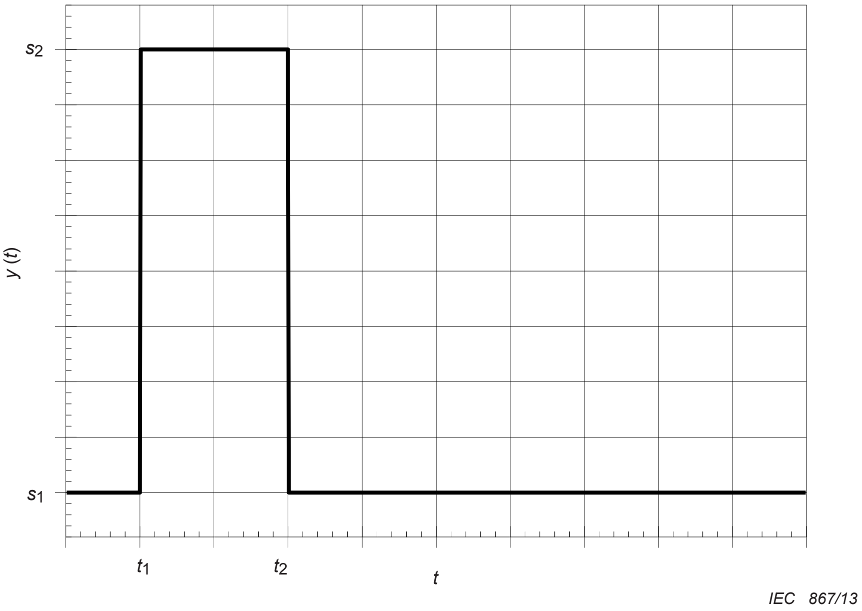


Figure A.5 – Rectangular *pulse waveform*

A.1.7 Trapezoidal pulse waveform

Figure A.6 shows a pulse waveform defined as

$$y(t)=\begin{cases} s_1 & t<t_1 \\ s_1+\dfrac{s_2-s_1}{t_2-t_1}(t-t_1) & t_1\le t\le t_2 \\ s_2 & t_2<t<t_3 \\ s_1-\dfrac{s_2-s_1}{t_4-t_3}(t-t_4) & t_3\le t\le t_4 \\ s_1 & t>t_4 \end{cases},$$

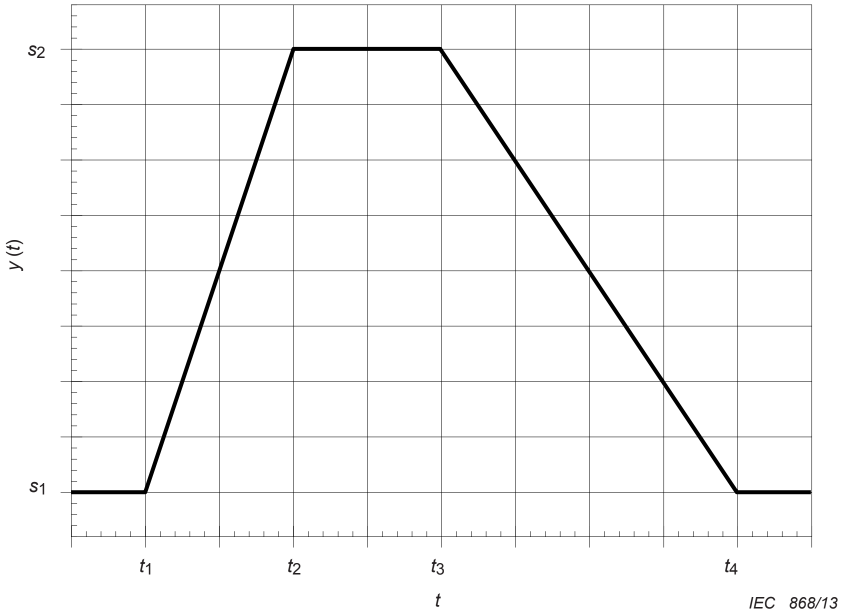
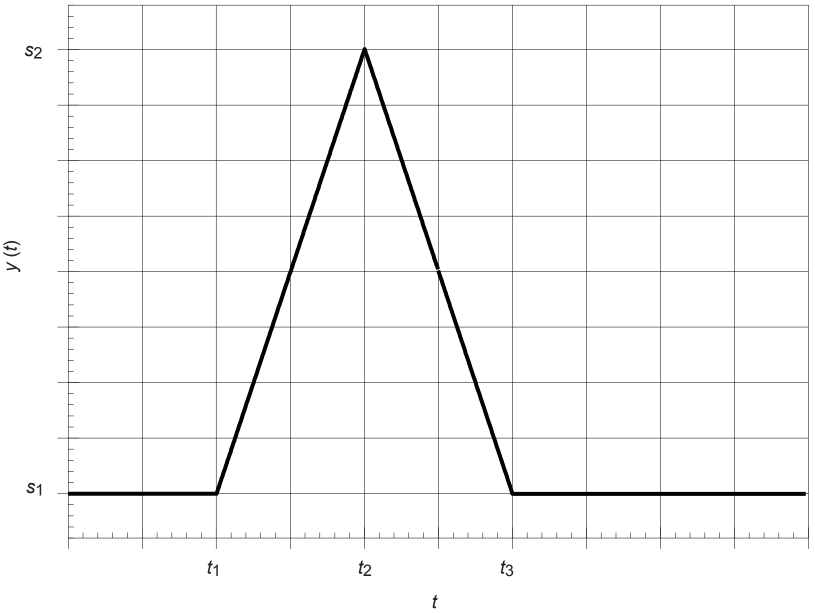


Figure A.6 – Trapezoidal *pulse waveform*

A.1.8 Triangular pulse waveform

Figure A.7 shows a *pulse waveform defined as*

$$y(t) = \begin{cases} s_1 & t < t_1 \\ s_1 + \dfrac{s_2 - s_1}{t_2 - t_1}(t - t_1) & t_1 \le t < t_2 \\ s_2 & t = t_2 \\ s_1 - \dfrac{s_2 - s_1}{t_3 - t_2}(t - t_3) & t_2 < t \le t_3 \\ s_1 & t > t_3 \end{cases}$$



IEC 869/13

Figure A.7 – Triangular *pulse waveform*

A.1.9 Exponential p*ulse waveform*

Figure A.8 shows a pulse waveform defined as

$$y(t) = \begin{cases} s_1 & t < t_1 \\ s_1 + (s_2 - s_1)\left[1 - e^{-(t-t_1)/b}\right] & t_1 \le t \le t_2 \\ s_1 + (s_2 - s_1)\left[1 - e^{-(t-t_1)/b}\right] e^{-(t-t_2)/c} & t > t_2 \end{cases}$$

where

b = time constant of first *transition* and

c = time constant of second *transition.*

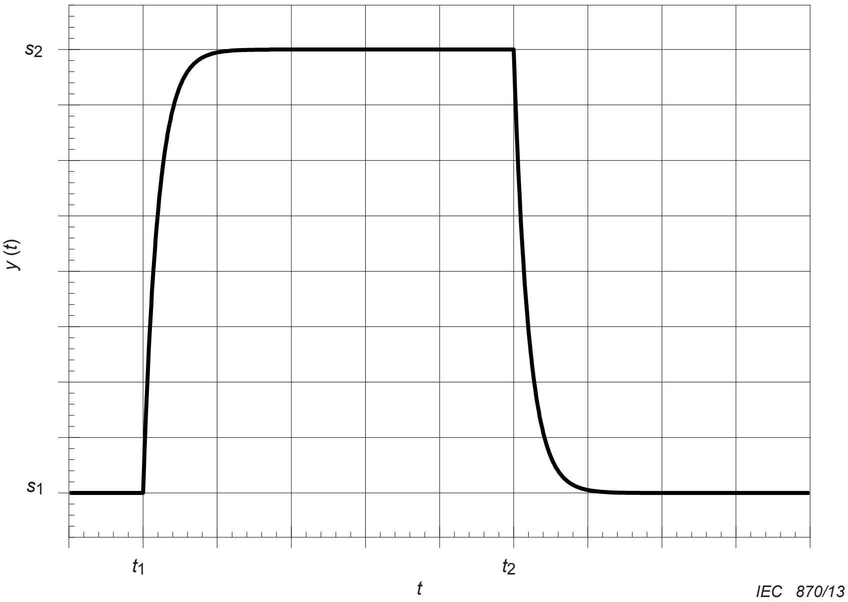


Figure A.8 – Exponential *pulse waveform*

A.2 Compound waveform examples

A.2.1 General

A *compound waveform* can be generated by concatenating or summing a finite number of single *step-like waveforms*, each of which is defined over an appropriate part of the *waveform epoch*. Examples of some *waveforms* of this type are defined here.

A.2.2 Double *pulse waveform*

Figure A.9 illustrates:

a) the summation of two *pulse waveforms* of the same polarity that are adjacent in time and that are considered or treated as a single *waveform*;

b) two pulses with the same polarity, *waveform amplitude* and *base level* that are not overlapping and are treated as a single *waveform*. A c*ompound waveform* with two *states* and four *transitions*.

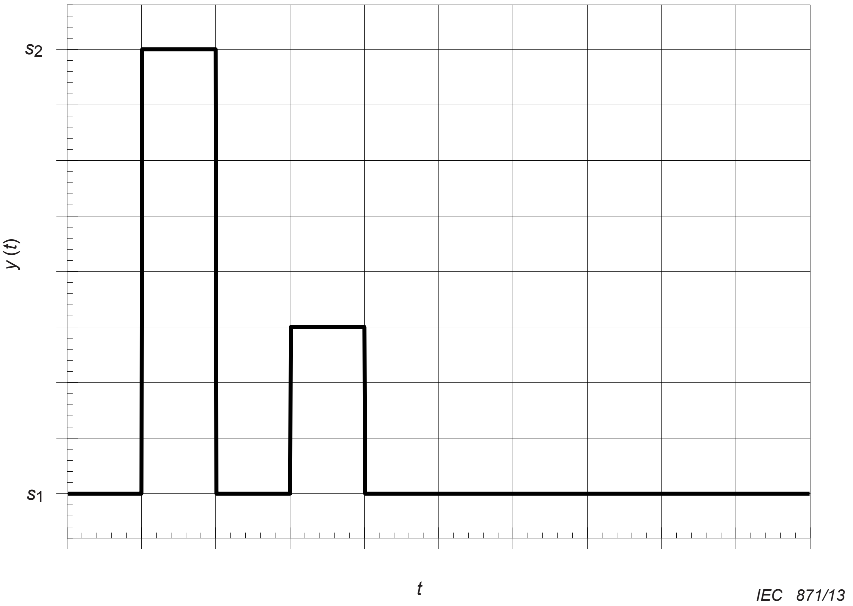


Figure A.9 – Double *pulse waveform*

A.2.3 Bipolar *pulse waveform*

Figure A.10 illustrates:

1) The summation of two *pulse waveforms* of opposite polarity that are adjacent in time and that are considered or treated as a single *waveform*.
2) Use a figure that stresses the order of the *states*. As an example, the order of the *states* for the figure below is s_2, s_3, s_2, s_1, s_2. The *states* of the tri-state *waveform* in this example have the ordering (s_2, 1) (s_3, 1) (s_2, 2) (s_1, 1) (s_2, 3).

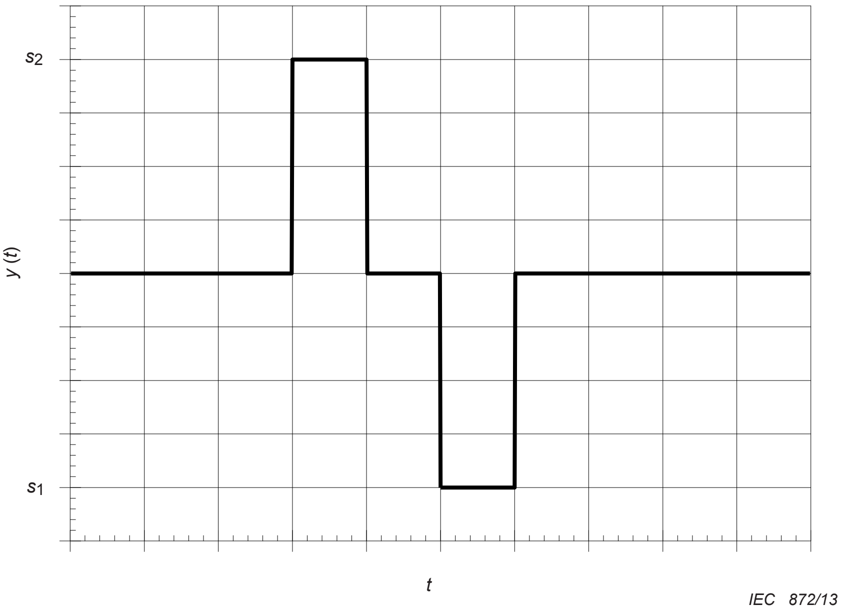


Figure A.10 – Bipolar *pulse waveform*

A.2.4 Staircase *waveform*

Figure A.11 illustrates the summation of a finite sequence of *step-like waveforms* of the same polarity.

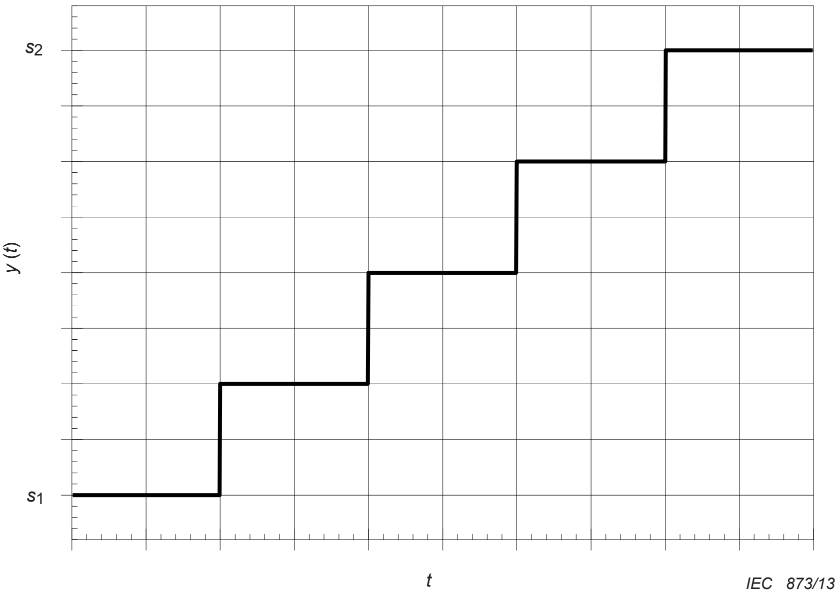


Figure A.11 – Staircase *waveform*

A.2.5 *Pulse* train

Figure A.12 illustrates a repetitive sequence of *pulse waveforms*. Unless otherwise specified, all of the *pulse waveforms* in the sequence are assumed to be identical.

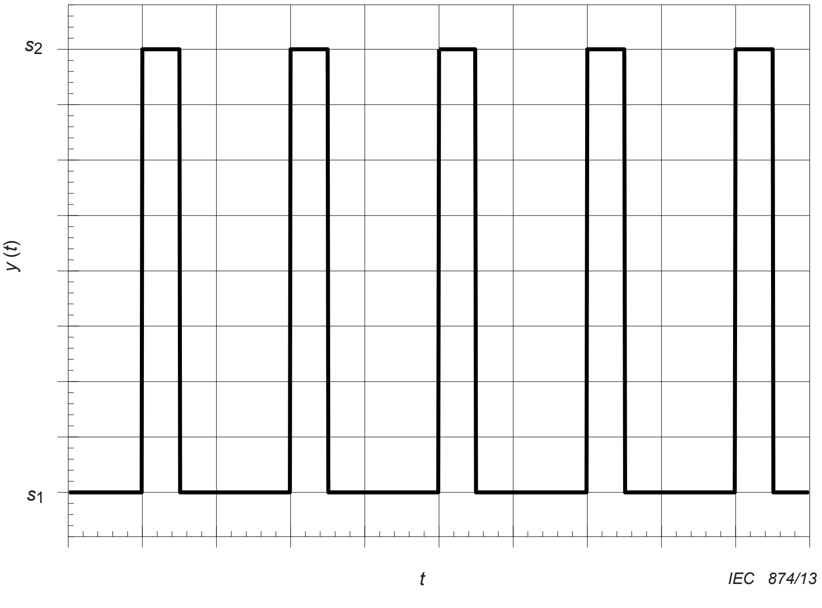


Figure A.12 – *Pulse train*

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