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Edition 4.0 2017-10
REDLINE VERSION

TECHNICAL SPECIFICATION

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BASIC SAFETY PUBLICATION

Effects of current on human beings and livestock – Part 2: Special aspects

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IEC TS 60479-2:2017-10 RLV(en)

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BASIC SAFETY PUBLICATION

Effects of current on human beings and livestock – Part 2: Special aspects

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EFFECTS OF CURRENT ON HUMAN BEINGS AND LIVESTOCK –

Part 2: Special aspects

FOREWORD

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This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

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The main task of IEC technical committees is to prepare International Standards. In exceptional circumstances, a technical committee may propose the publication of a Technical Specification when

- the required support cannot be obtained for the publication of an International Standard, despite repeated efforts, or
- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical Specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 60479-2, which is a Technical Specification, has been prepared by IEC technical committee 64: Electrical installations and protection against electric shock.

This fourth edition cancels and replaces the third edition, published in 2007. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- Changes reflecting the change in applicability of frequency from 1 kHz to 150 kHz have been added.
- The examination of random complex irregular waveforms has been added.
- The handling of successive DC pulses has been clarified.

The text of this Technical Specification is based on the following documents:

Draft TS	Report on voting
64/2143/DTS	64/2166/RVDTS

Full information on the voting for the approval of this Technical Specification can be found in the report on voting indicated in the above table.

This Technical Specification has the status of a basic safety publication in accordance with IEC Guide 104.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 60479 series, published under the general title *Effects of current on human beings and livestock*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- transformed into an International standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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EFFECTS OF CURRENT ON HUMAN BEINGS AND LIVESTOCK –

Part 2: Special aspects

1 Scope

This part of IEC 60479 describes the effects on the human body when a sinusoidal alternating current in the frequency range above 100 Hz passes through it.

The effects of current passing through the human body for:

– alternating sinusoidal current with DC components;
– alternating sinusoidal current with phase control;
– alternating sinusoidal current with multicycle control

are given but are only deemed applicable for alternating current frequencies from 15 Hz up to 100 Hz.

~~NOTE 1 Other waveforms are under consideration.~~

Means of extending the frequency of applicability of pure sinusoids to a frequency of 150 kHz are given, supplementing the data in IEC TS 60479-1.

Means of examining random complex irregular waveforms are given.

This document describes the effects of current passing through the human body in the form of single and multiple successive unidirectional rectangular impulses, sinusoidal impulses and impulses resulting from capacitor discharges.

~~NOTE 2 The effects of sequences of impulses are under consideration.~~

The values specified are deemed to be applicable for impulse durations from 0,1 ms up to and including 10 ms. ~~For impulse durations greater than 10 ms, the values given in Figure 20 of IEC 60479-1 apply.~~

This document only considers conducted current resulting from the direct application of a source of current to the body, as does IEC TS 60479-1 and IEC TS 60479-3. It does not consider current induced within the body caused by its exposure to an external electromagnetic field.

This basic safety publication is primarily intended for use by technical committees in the preparation of standards in accordance with the principles laid down in IEC Guide 104 and ISO/IEC Guide 51. It is not intended for use by manufacturers or certification bodies.

One of the responsibilities of a technical committee is, wherever applicable, to make use of basic safety publications in the preparation of its publications. The requirements, test methods or test conditions of this basic safety publication will not apply unless specifically referred to or included in the relevant publications.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition

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cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC TS 60479-1:2005, *Effects of current on human beings and livestock – Part 1: General aspects*
IEC TS 60479-1:2005/AMD1:2016

~~IEC 60479-3, *Effects of current on human beings and livestock – Part 3: Effects of currents passing through the body of livestock*~~

IEC 60990, *Methods of measurement of touch-current and protective conductor current*

ISO/IEC Guide 51, *Safety aspects – Guidelines for their inclusion in standards*

IEC Guide 104, *The preparation of safety publications and the use of basic safety publications and group safety publications*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 60479-1 and the following apply.

~~NOTE Certain definitions are taken from the IEV. Such references are listed in the bibliography [27], [28].~~

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

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

3.1
frequency factor
F_f
ratio of the threshold current for the relevant physiological effects at the frequency f to the threshold current at 50/60 Hz

Note 1 to entry: The frequency factor differs for perception, let-go and ventricular fibrillation.

3.2
phase control
process of varying the instant within the cycle at which current conduction in an electronic valve device or a valve arm begins

[SOURCE: IEC 60050-551:1998, 551-16-23]

3.3
phase control angle
current delay angle
time expressed in angular measure by which the starting instant of current conduction is delayed by phase control

[SOURCE: IEC 60050-551:1998, 551-16-32, modified — the term "phase control angle" has been added.]

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3.4
multicycle control
process of varying the ratio of the number of cycles which include current conduction to the number of cycles in which no current conduction occurs

[SOURCE: IEC 60050-551:1998, 551-16-31]

3.5
multicycle control factor
p
ratio between the number of conducting cycles and the sum of conducting and non-conducting cycles in the case of multicycle control

SEE Figure 13.

[SOURCE: IEC 60050-551:1998, 551-16-37, modified — the symbol and reference to Figure 13 have been added.]

3.6
specific fibrillating energy
F_e
minimum $I^2 \cdot t$ value of a unidirectional impulse of short duration which under given conditions (current-path, heart-phase) causes ventricular fibrillation with a certain probability

Note 1 to entry: F_e is determined by the form of the impulse as the integral

$$\int_0^{t_i} i^2 dt$$

where t_i is defined in Figure 20 and Figure 21. F_e multiplied by the body resistance gives the energy dissipated in the human body during the impulse.

Note 2 to entry: F_e is expressed in Ws/Ω or A^2s.

3.7
specific fibrillating charge
F_q
minimum $I \cdot t$ value of unidirectional impulse of short duration which under given conditions (current-path, heart-phase) causes ventricular fibrillation with a certain probability

Note 1 to entry: F_q is determined by the form of the impulse as the integral

$$\int_0^{t_i} i dt$$

where t_i is defined in Figure 20 and Figure 21.

Note 2 to entry: F_q is expressed in C or As.

3.8
time constant
time required for the amplitude of an exponentially decaying quantity to decrease to

$$\frac{1}{e} = 0{,}3679$$

times an initial amplitude

[SOURCE: IEC 60050-801:1994, 801-21-45, modified — the definition has been revised.]

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3.9
shock-duration of a capacitor discharge
t_i
time interval from the beginning of the discharge to the time when the discharge current has fallen to 5 % of its peak value

Note 1 to entry: When the time constant of the capacitor discharge is given by T the shock-duration of the capacitor discharge is equal to $3T$. During the shock-duration of the capacitor discharge practically all the energy of the impulse is dissipated.

Note 2 to entry: See Figure 20 and Figure 21.

3.10
shock-duration for complex asymptotic waveform
t_i
shortest duration of that part of the impulse that contains 95 % of the energy over the total impulse

3.11
threshold of perception
minimum value for the charge of electricity which under given conditions causes any sensation to the person through whom it is flowing

3.12
threshold of pain
minimum value for the charge ($I \cdot t$) or specific energy ($I^2 t$) that can be applied as an impulse to a person holding a large electrode in the hand without causing pain

3.13
pain
unpleasant experience such that it is not readily accepted a second time by the subject submitted to it

~~NOTE~~ EXAMPLE: Electric shock above the threshold of pain described in 11.3, the sting of a bee or burn of a cigarette.

4 Effects of alternating currents with frequencies above 100 Hz

NOTE Values for 50/60 Hz are given in IEC TS 60479-1. For frequencies up to 100 Hz the provisions of IEC TS 60479-1 are used.

4.1 General

Electric energy in the form of alternating current at frequencies higher than 50/60 Hz is increasingly used in modern electrical equipment, for example aircraft (400 Hz), power tools and electric welding (mostly up to 450 Hz), electrotherapy (using mostly 4 000 Hz to 5 000 Hz) and switching mode power supplies (20 kHz to 1 MHz).

Little experimental data is available for Clause 4, therefore the information given herein should be considered as provisional only but may be used for the evaluation of risks in the frequency ranges concerned (see Bibliography).

Recent experiments in governmental funded projects are ongoing to exploit and investigate the effects of higher frequencies using the latest technologies and methods to justify existing extrapolation of the frequency factor for ventricular fibrillation (VF) threshold.

Attention is also drawn to the fact that the impedance of human skin decreases approximately inversely proportional to the frequency for touch voltages in the order of some tens of volts, so that the skin impedance at 500 Hz is only about one-tenth of the skin impedance at 50 Hz and may be neglected in many cases. This impedance of the human

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body at such frequencies is therefore reduced to its internal impedance Z_i (see IEC TS 60479-1).

NOTE Use of peak measurements: at current levels that produce physiological responses of perception, startle reaction and inability of let-go, the physiological response from non sinusoidal and mixed frequency periodic current is best indicated by the peak value of an output signal from measuring circuits containing a frequency-weighting network such as those described in IEC 60990.

These frequency weighting networks attenuate the signal according to the frequency factors given in IEC TS 60479-1:2005 and IEC TS 60479-1:2005/AMD1:2016, Clause 4 so that the output signal corresponds to a constant level of physiological response. Attenuation is provided for narrow impulses of current that would produce less physiological response because of the short duration of their peak value. The network output allows a fixed value to be read independent of waveshape or mix of frequencies to be provided for ease of determination of the leakage current and evaluation of the level of hazard present.

Comparable physiological effects are produced by non sinusoidal and sinusoidal current producing the same peak value by this measurement method.

Representative network can be found in IEC 60990 and in bibliographic reference [16] [1].

4.2 Effects of alternating current in the frequency range above 100 Hz up to and including 1 000 Hz

4.2.1 Threshold of perception

For the threshold of perception the frequency factor is given in Figure 1.

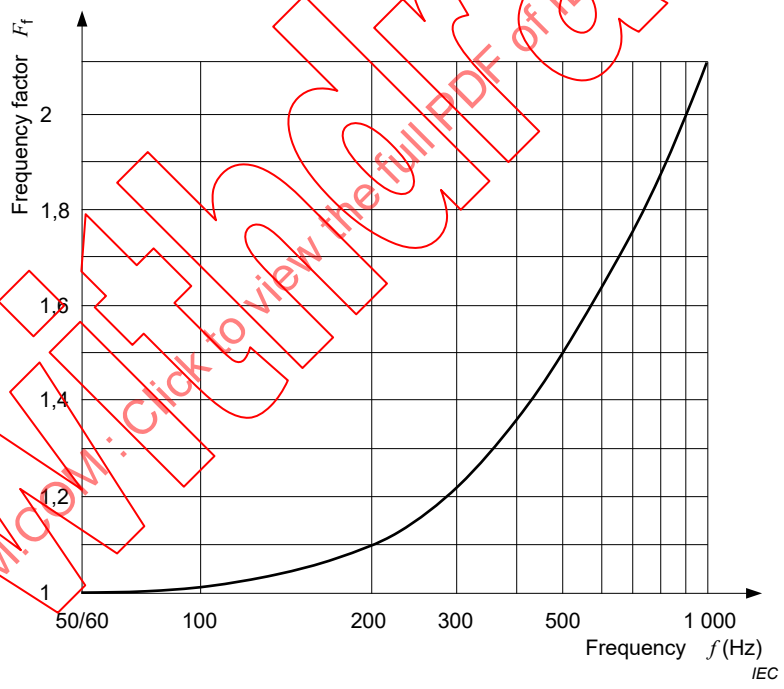

Figure 1 – Variation of the threshold of perception within the frequency range 50/60 Hz to 1 000 Hz

4.2.2 Threshold of let-go

For the threshold of let-go the frequency factor is given in Figure 2.

1 Numbers in square brackets refer to the Bibliography.

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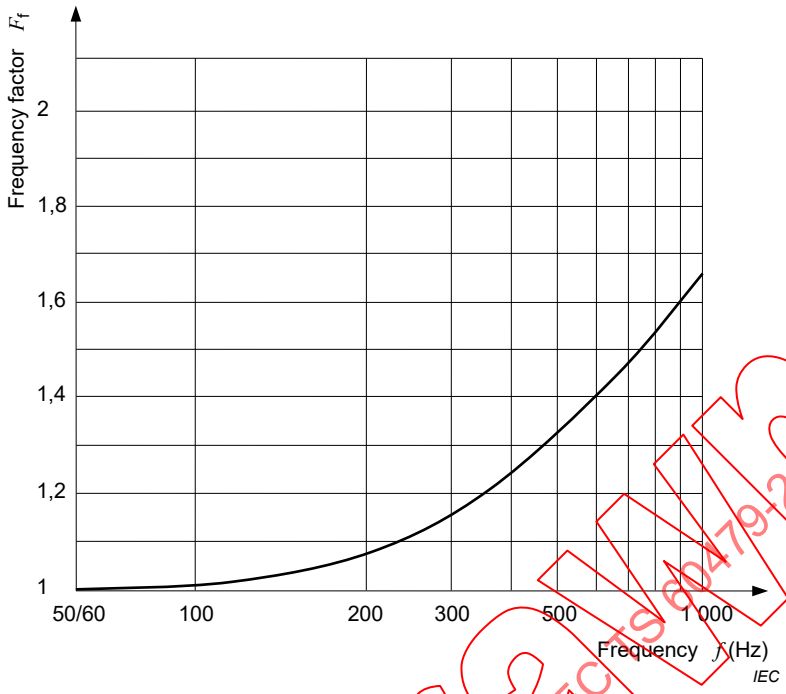

Figure 2 – Variation of the threshold of let-go within the frequency range 50/60 Hz to 1 000 Hz

4.2.3 Threshold of ventricular fibrillation

For shock durations longer than the cardiac cycle, the frequency factor for the threshold of fibrillation for longitudinal current paths through the trunk of the body is given in Figure 3.

For shock durations shorter than the cardiac cycle no experimental data is available on the effects of frequency.

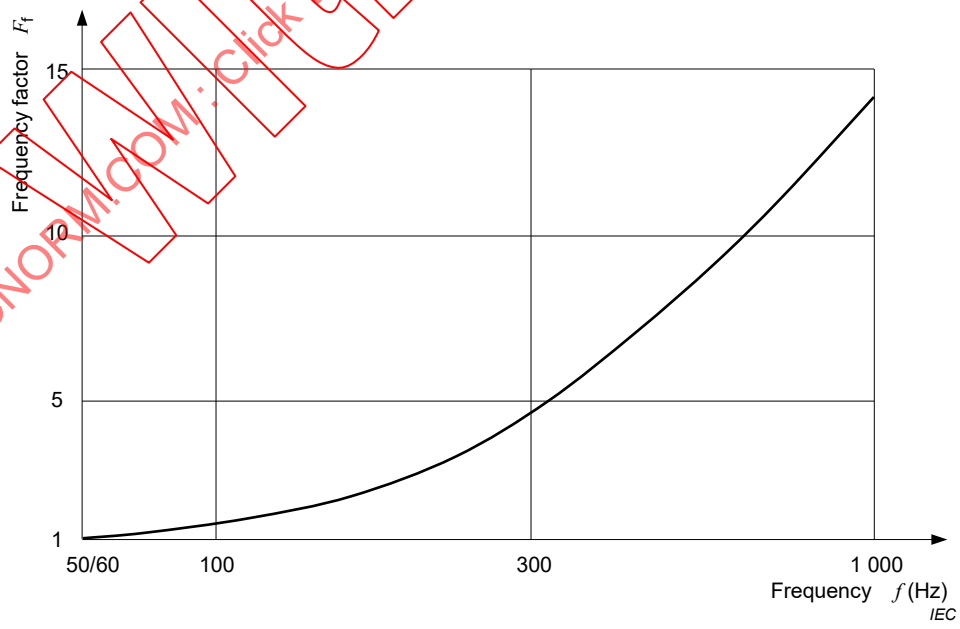

Figure 3 – Variation of the threshold of ventricular fibrillation within the frequency range 50/60 Hz to 1 000 Hz, shock durations longer than one heart period and longitudinal current paths through the trunk of the body

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4.3 Effects of alternating current in the frequency range above 1 000 Hz up to and including 10 000 Hz

4.3.1 Threshold of perception

For the threshold of perception the frequency factor is given in Figure 4.

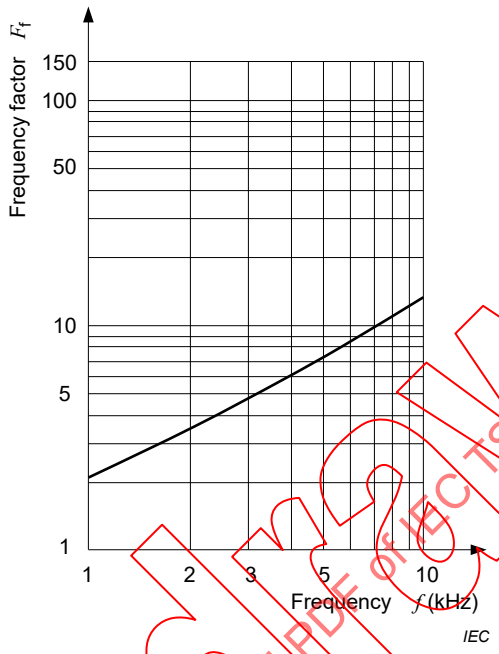

Figure 4 – Variation of the threshold of perception within the frequency range 1 000 Hz to 10 000 Hz

4.3.2 Threshold of let-go

For the threshold of let-go the frequency factor is given in Figure 5.

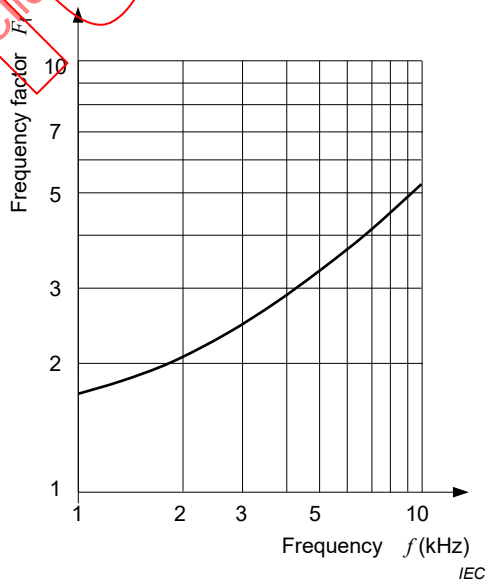

Figure 5 – Variation of the threshold of let-go within the frequency range 1 000 Hz to 10 000 Hz

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4.3.3 Threshold of ventricular fibrillation

~~Under consideration.~~

For frequencies between 1 000 Hz and 10 000 Hz the provisions of 4.4.4 are used.

4.4 Effects of alternating current in the frequency range above 10 000 Hz

4.4.1 General

In 4.4, changes have not been made to the threshold of perception, or the threshold of let-go for higher frequencies. While these are important thresholds, the most dangerous is that of ventricular fibrillation. The fibrillation threshold is therefore given up to 150 kHz. The remaining thresholds may be considered as in the paragraphs below up to the frequency limits shown.

4.4.2 Threshold of perception

For frequencies between 10 kHz and 100 kHz the threshold rises approximately from 10 mA to 100 mA (RMS values).

For frequencies above 100 kHz the tingling sensation characteristic for the perception at lower frequencies changes into a sensation of warmth for current intensities in the order of some hundred milliamperes.

4.4.3 Threshold of let-go

For frequencies above 100 kHz there is neither experimental data nor reported incidents concerning the threshold of let-go.

4.4.4 Threshold of ventricular fibrillation

~~For frequencies above 100 kHz, there is neither experimental data nor reported incidents concerning the threshold of ventricular fibrillation.~~

For shock durations longer than the cardiac cycle, the frequency factor for the threshold of fibrillation for longitudinal current paths through the trunk of the body for the frequency range above 1000 Hz up to and including 150 kHz is given in Figure 6.

For frequencies above 1 kHz, thermal effects are more likely to become dominant.

For shock durations shorter than the cardiac cycle, no experimental data is available.

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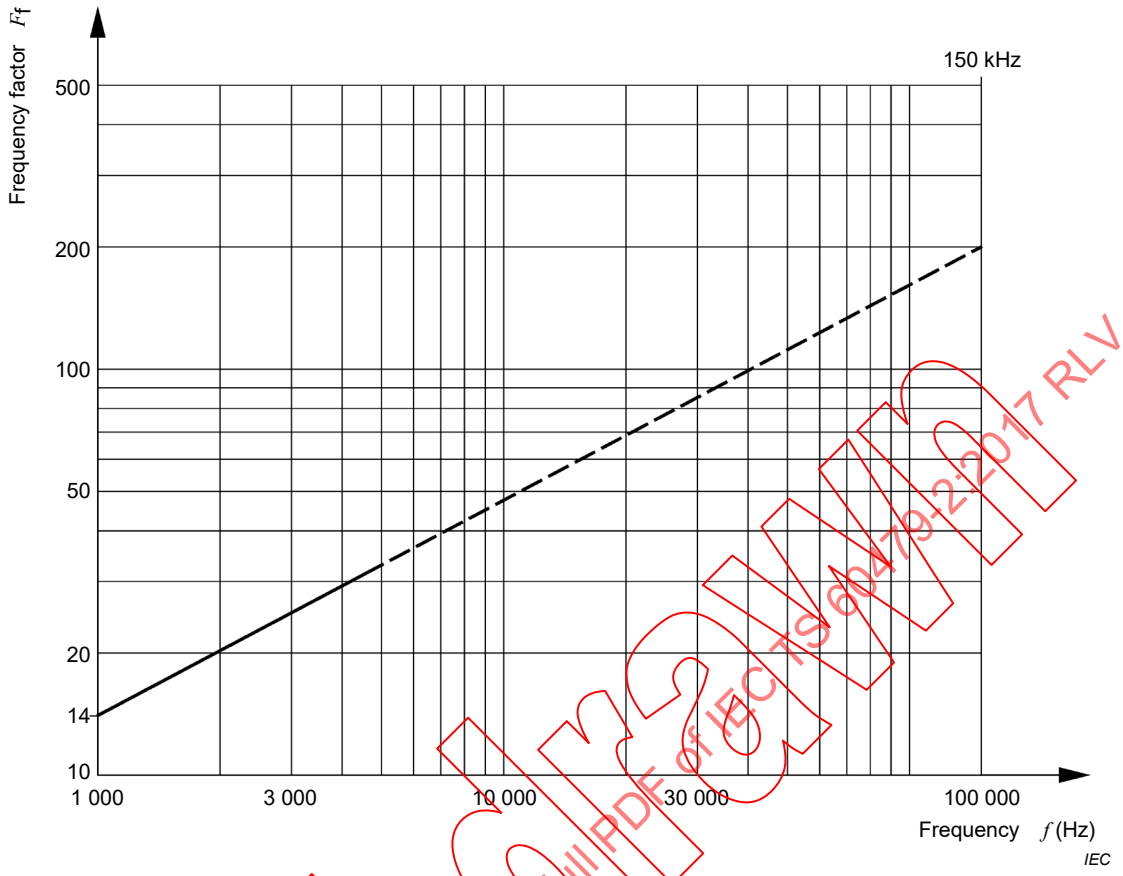

Figure 6 – Variation of the threshold of ventricular fibrillation for continuous sinusoidal current for use from 1 000 Hz to a maximum of 150 kHz

4.4.5 Other effects

Burns may occur at frequencies above 100 kHz and current magnitudes in the order of amperes depending on the duration of the current flow.

5 Effects of special waveforms of current

5.1 General

As is to be expected, the effects of such currents on the human body are between those caused by direct and by alternating current; therefore equivalent current magnitudes with regard to ventricular fibrillation can be established.

Clause 5 describes the effects of current passing through the human body for:

– alternating sinusoidal current with DC components,
– alternating sinusoidal current with phase control,
– alternating sinusoidal current with multicycle control.

NOTE Other waveforms are under consideration.

The information given is deemed applicable for alternating current frequencies from 15 Hz up to 100 Hz.

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5.2 Equivalent magnitude, frequency and threshold

In 5.2 the hazard may be taken as being approximately the same effect as with an equivalent pure alternating sinusoidal current I_{ev} having the following characteristics:

– Magnitude equivalence:

The following current magnitudes have to be distinguished:

I_{RMS} = RMS value of the current of the proposed waveform,

I_p = peak value of the current of the proposed waveform,

I_{pp} = peak-to-peak value of the current of the proposed waveform,

I_{ev} = RMS value of a sinusoidal current presenting the same effect as the waveform concerned.

NOTE The current I_{ev} is used instead of the current I_B in Figures 20 and 22 of IEC TS 60479-1:2005 to estimate the risk of ventricular fibrillation.

Most physiological effects are related to the filtered peak current (in magnitude and in duration) with the natural body filter defined by the frequency factor F. The peak value of the current should be used in all cases except where there is a known relationship between the RMS value and the peak value, i.e. pure sinusoidal current.

– Frequency equivalence

The waveform under study has a time period equal to the period of the equivalent sinusoidal waveform.

– Threshold equivalence

The different current thresholds (perception, inability of let-go and ventricular fibrillation) for waveforms consisting of specific ratio of alternating to direct current is equivalent as for a pure sinusoidal alternating current with a current having the characteristic equal to I_{ev}.

This I_{ev} value is different for each of these thresholds.

5.3 Effects of alternating current with DC components

5.3.1 Waveforms and frequencies and current thresholds

Figure 7 shows typical waveforms which are dealt with in 5.3.1. Pure DC and pure AC are represented as well as combined waveforms of various ratios AC to DC.

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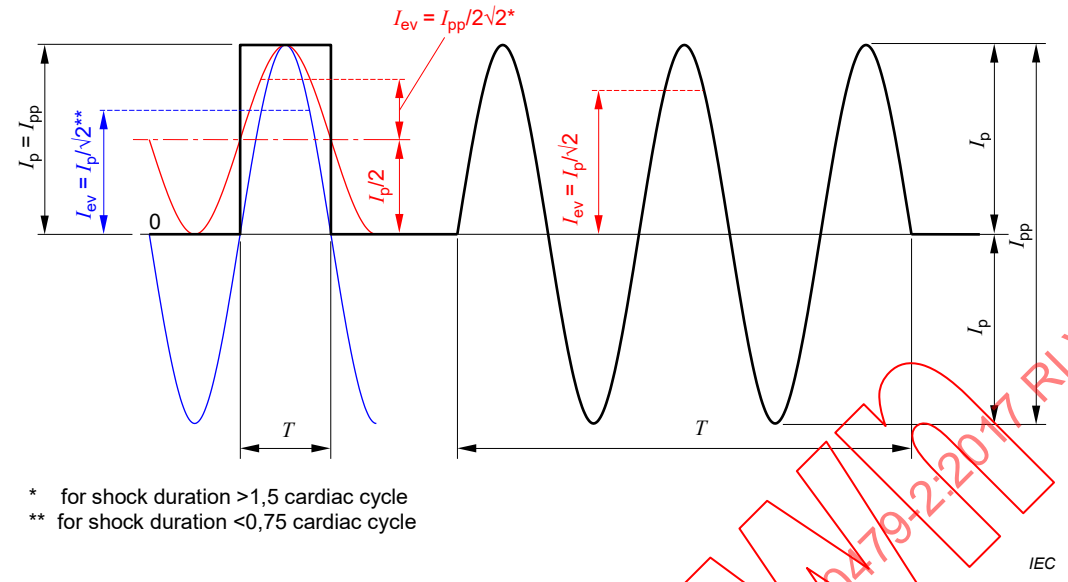
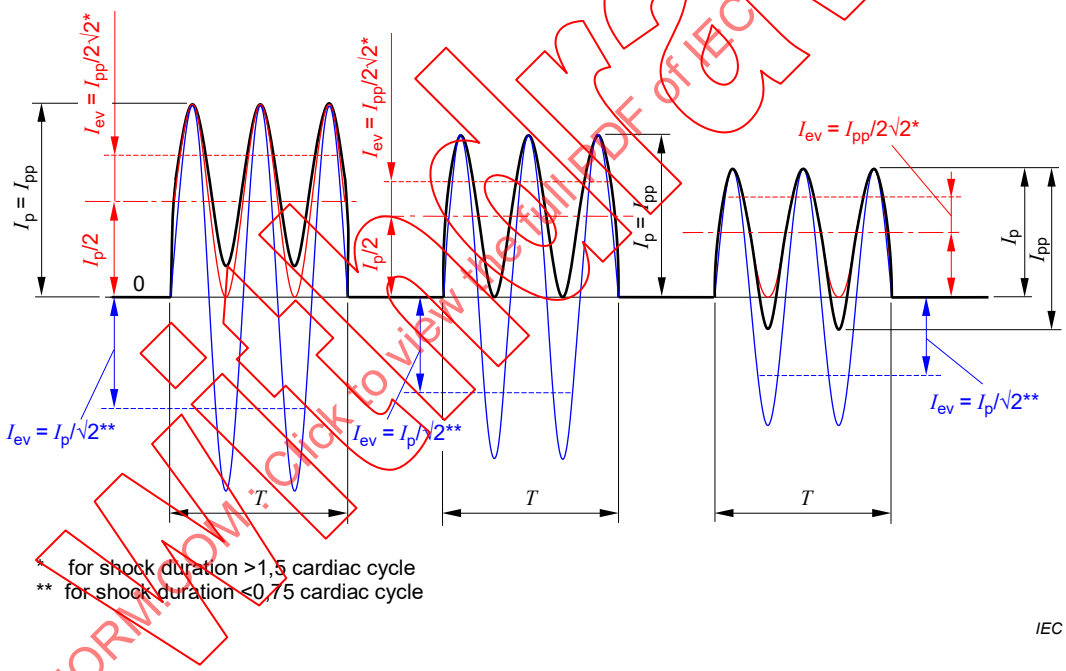


a) Combined waveforms of various ratios AC to DC together with rectangle pulse for shock duration >1,5 and <0,75 of the cardiac cycle



b) Combined waveforms of various ratios AC to DC of mixed frequencies for shock duration >1,5 and <0,75 of the cardiac cycle

Figure 7 – Waveforms of currents

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5.3.2 Threshold of startle reaction

The threshold of startle reaction depends on several parameters such as the area of the body in contact with an electrode (contact area), the conditions of contact (dry, wet, pressure, temperature) and also on the physiological characteristics of the individual.

These effects are related to the peak value of the current [13] and the currents have to be combined frequency by frequency to estimate the total effect. A measurement circuit is described in IEC 60990.

5.3.3 Threshold of let-go

The threshold of let-go depends on several parameters, such as the contact area, the shape and the size of the electrodes and also on the physiological characteristics of the individual.

From the standpoint of let-go (hand contacts with energized circuitry that can last a few seconds), this document uses Figure 5 in the referenced Dalziel paper [17] to determine the let-go current threshold for combinations of alternating current and direct current. The frequency of the alternating current in this case was 60 Hz. 7,07 mA peak AC (5 mA RMS for a sinusoidal current) and 30 mA DC were used as the touch current thresholds for pure AC and DC respectively. These thresholds are considered to be adequate to represent the entire population (including children) from inability to let-go.

The equation, $I_{AC\ peak}$ = 7,176 x exp (– 0,143 4 x DC) – 0,106 1, represents this combined AC and DC case and may be used to calculate the result of any combination of AC and DC in the range specified.

The following Figure 8 illustrates the Dalziel information.

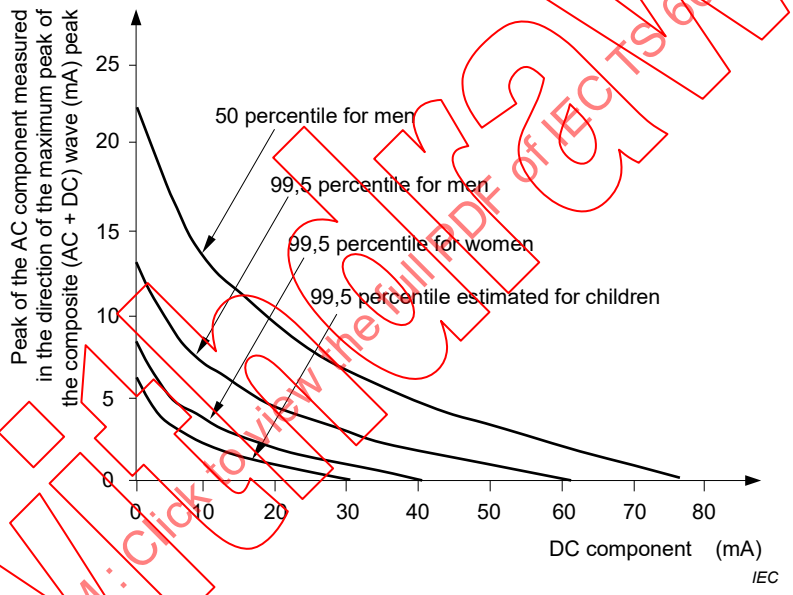

Figure 8 – Let-go thresholds for men, women and children

The above curves can be described by an equation fitted to the data.

The equation, $I_{AC\ peak}$ = 12,890 5 x exp (–0,069 39 x DC) – 0,190 5, represents the 99,5 percentile curve for men.

The equation, $I_{AC\ peak}$ = 8,523 x exp (–0,104 9 x DC) – 0,126, represents the 99,5 percentile curve for women.

The equation, $I_{AC\ peak}$ = 6,394 5 x exp (–0,138 8 x DC) – 0,094 5, represents the 99,5 percentile estimated curve for children.

For practical considerations, some standards allow for some ripple (e.g. up to 10 %) on a DC supply as an exception.

Figure 9 shows the let-go threshold expressed in peak mA for combinations of 50/60 Hz sinusoidal alternating current and direct current. The peak of the composite AC and DC wave

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in mA at the let-go threshold estimated for the population of humans, including children, is shown as a function of the direct current component in mA.

Figure 9 is represented by the equation for the composite ~~d.c.~~ current:

$I_{AC\ peak} + I_{DC} = 7{,}176 \times \exp(-0{,}143\ 4 \times DC) - 0{,}106\ 1 + DC$

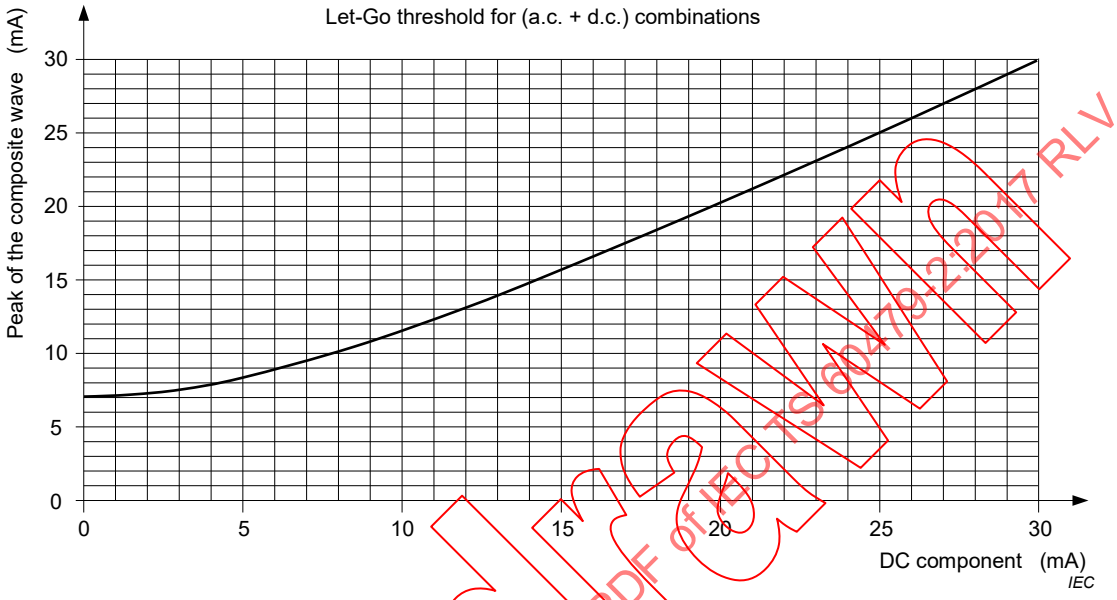

Figure 9 – 99,5 percentile let-go threshold for combinations of 50/60 Hz sinusoidal alternating current and direct current

These effects are related to the peak value of the current [6] and the currents ~~shall~~ have to be combined frequency by frequency to estimate the total effect. A measurement circuit is described in IEC 60990.

5.3.4 Threshold of ventricular fibrillation

5.3.4.1 Waveforms consisting of specific ratios of alternating to direct current

The fibrillation hazard may be taken as being approximately the same as with an equivalent alternating sinusoidal current I_{ev} having the following characteristics:

a) For shock durations longer than approximately 1,5 times the period of the cardiac cycle, I_{ev} is the RMS value of the sinusoidal alternating current having the same peak-to peak value I_{pp} as the current of the waveform concerned.

$$I_{ev} = \frac{I_{pp}}{2\sqrt{2}}$$

b) For shock durations shorter than approximately 0,75 times the period of the cardiac cycle, I_{ev} is the RMS value of the sinusoidal alternating current having the same peak value I_p as the current of the waveform concerned.

$$I_{ev} = \frac{I_p}{\sqrt{2}}$$

NOTE 1 This correlation is ~~less~~ the least applicable the smaller the ratio AC to DC becomes. For pure DC shocks of a duration less than 0,1 s the threshold is equal to the corresponding RMS value of the alternating current (see Figure 20 and Figure 22 in IEC TS 60479-1:2005 respectively).

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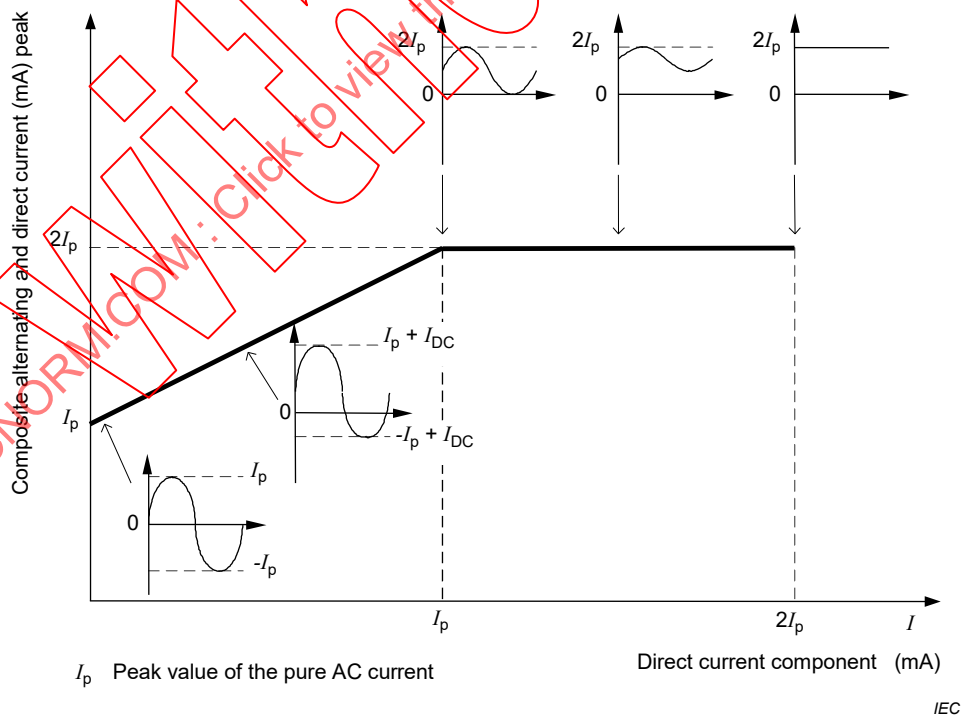
c) In the duration range from 0,75 to 1,5 times the period of the cardiac cycle, the amplitude parameter changes from peak value to peak-to-peak value.

NOTE 2 The details of the nature of the transition that takes place are subject to further studies.

According to Knickerbocker's findings [5], the likelihood of ventricular fibrillation for a combination of 50/60 Hz sinusoidal alternating and direct current lasting a few seconds or more is the same for a purely sinusoidal current of the same duration ~~provided~~ if the following is true. The pure 50/60 Hz sinusoidal alternating current has the same peak-to-peak value as the peak-to-peak value of the combination current waveform. ~~This would be on condition~~ provided that the direct current component ~~were~~ is not large enough to preclude reversal of the instantaneous current (to prevent zero crossing) during each cycle. For example, the combination of a 40 mA RMS 50/60 Hz sinusoidal current combined with direct current up to $40 \cdot \sqrt{2}$ mA has approximately the same likelihood of causing ventricular fibrillation as a 40 mA RMS 50/60 Hz sinusoidal current alone.

Where the exposure is a few seconds or more and the direct current component is large enough so that the instantaneous current does not reverse during each cycle, then the composite of alternating plus direct current has the same likelihood of ventricular fibrillation when the peak value of the composite current is the same as the peak-to-peak value of the 50/60 Hz purely sinusoidal alternating current. For example, the combination of a 50/60 Hz sinusoidal current and direct current with a peak value of $80 \cdot \sqrt{2}$ mA $\left(2 \cdot I_p\right)$ (with no reversal of the instantaneous current during each cycle) has approximately the same likelihood of causing ventricular fibrillation as a 40 mA RMS 50/60 Hz sinusoidal current with no direct current added.

Figure 10 illustrates an example in which the likelihood of ventricular fibrillation for sinusoidal alternating current (including 20 Hz, 50 Hz, and 60 Hz) combined with direct current is the same.



NOTE The peak to peak value I_{pp} remains constant up until the I_p value and then the peak value of the composite remains constant at a value of two times the peak of the AC with no DC component.

Figure 10 – Composite alternating and direct current with equivalent likelihood of ventricular fibrillation

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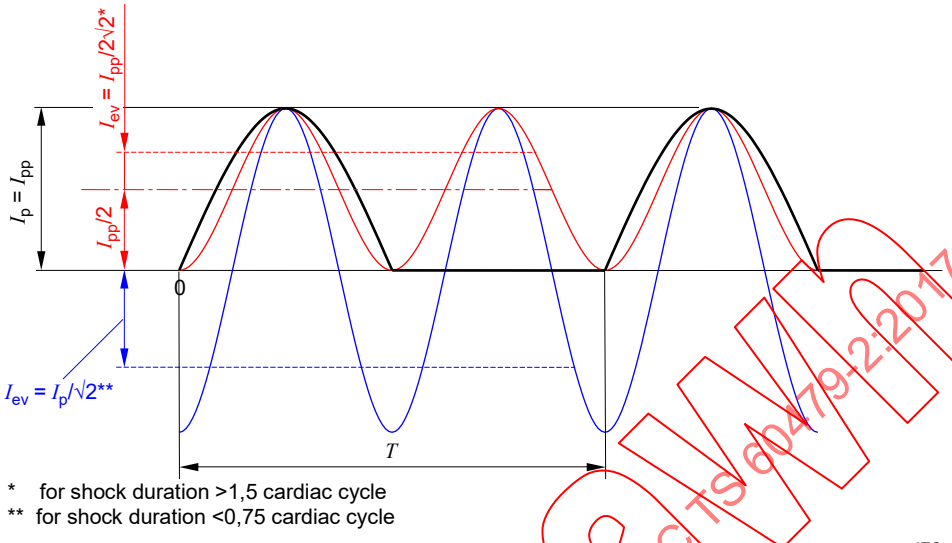
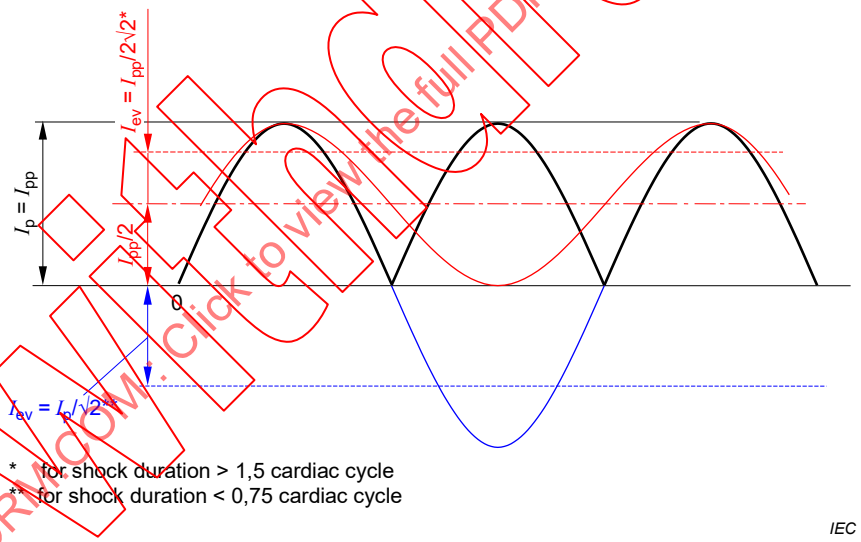
5.3.4.2 Examples of rectified alternating current

Figure 11 shows the waveforms for half wave and full wave rectification. For these waveforms the peak value of the current is identical to its peak-to-peak value.



a) Half wave rectification



b) Full wave rectification

Figure 11 – Waveforms of rectified alternating currents

The equivalent alternating current I_{ev} is determined:

a) for durations longer than 1,5 times the period of the cardiac cycle by:

$$I_{ev} = \frac{I_{pp}}{2\sqrt{2}} = \frac{I_p}{2\sqrt{2}}$$

hence for the half wave rectification, I_{ev} is related to the RMS value of the rectified current I_{RMS} by:

$$I_{ev} = \frac{I_{RMS}}{\sqrt{2}}$$

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and the full wave rectification by:

$$I_{ev} = \frac{I_{RMS}}{2}$$

b) For durations shorter than 0,75 times the period of the cardiac cycle by:

$$I_{ev} = \frac{I_{pp}}{\sqrt{2}} = \frac{I_{p}}{\sqrt{2}}$$

hence for the half wave rectification, I_{ev} is related to the RMS value of the rectified current I_{RMS} by:

$$I_{ev} = \sqrt{2} I_{RMS}$$

and the full wave rectification by:

$$I_{ev} = I_{RMS}$$

In the case of both let-go and ventricular fibrillation, the body current is expected to flow through the limbs and torso for a few seconds. For example, a cadenced ringing signal on a telephone circuit can typically last around two seconds before the signal is interrupted with a pause (between rings). If a person is in contact with a part that is energized by a burst of ringing signal, the person's body might conduct current from the signal for a few seconds. In the case of a cadenced ringing signal, a person might be unable to let go during the time while the signal is “on”. If this occurs, the signal shall not be capable of producing ventricular fibrillation. It ~~is~~ was assumed that when the signal pauses between bursts of the ringing signal, the person can release the conductive part and get away from the circuit.

6 Effects of alternating current with phase control

6.1 Waveforms and frequencies and current thresholds

Figure 12 shows the waveforms for symmetrical and asymmetrical control.

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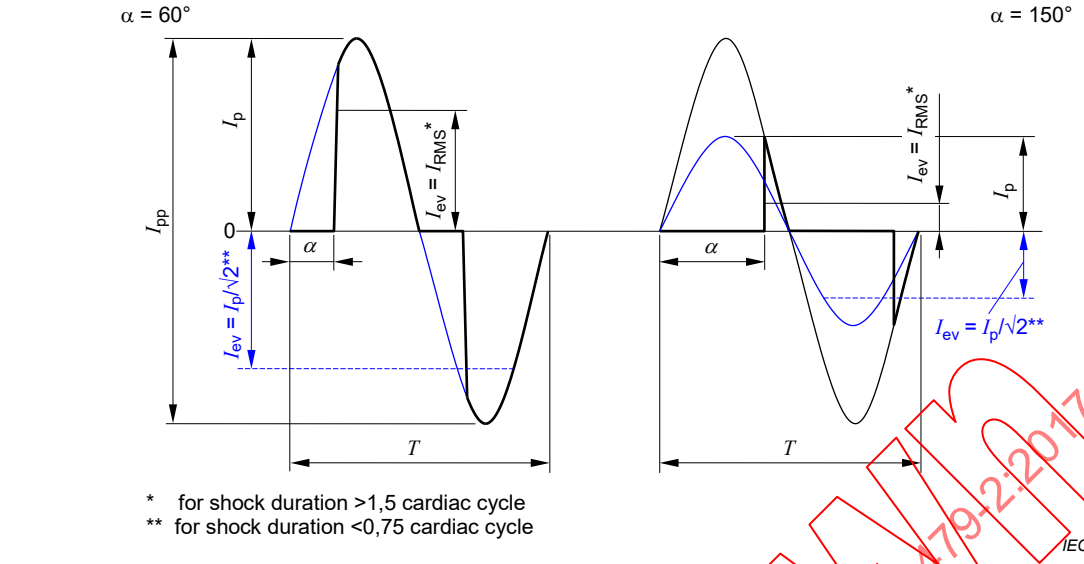
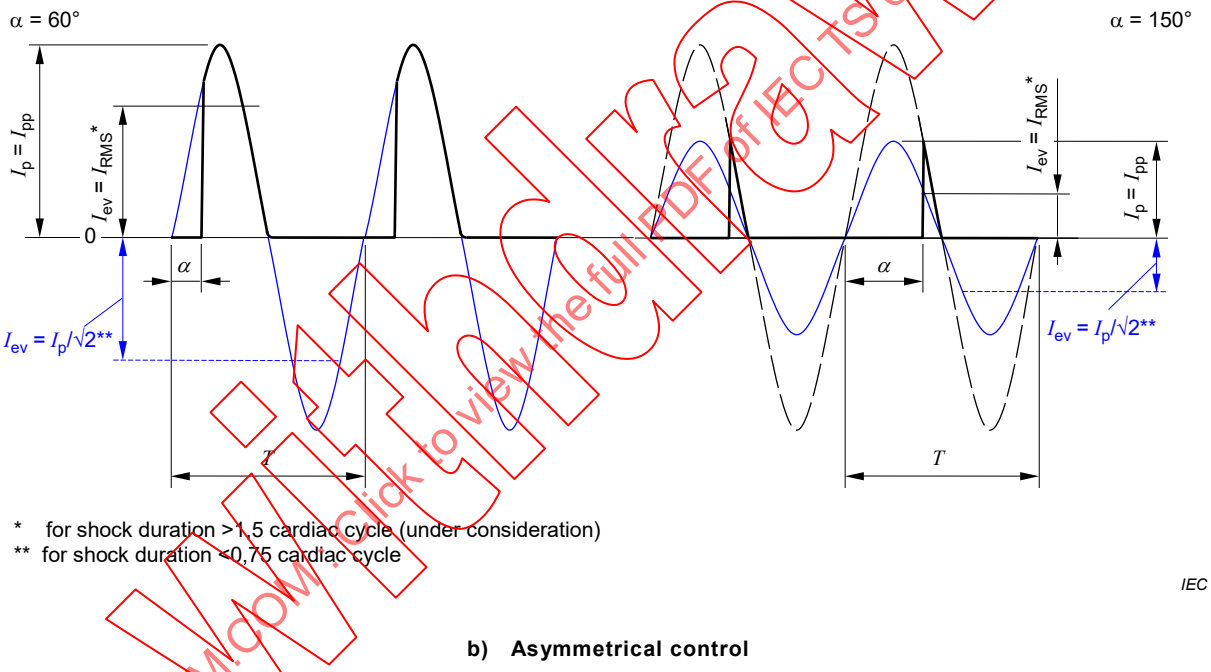


a) Symmetrical control



b) Asymmetrical control

Figure 12 – Waveforms of alternating currents with phase control

6.2 Threshold of startle reaction and threshold of let-go

As described in 5.3.2 and 5.3.3, these thresholds depend on different parameters.

The effects of the current in producing sensation or inhibiting let-go are about equal to a pure AC with the same peak value I_p. For phase control angles above 120° the peak values increase as a consequence of the decreasing duration of the current flow.

These effects are related to the peak value of the current [13] and they have to be combined frequency per frequency to estimate the total effect. This is easily done using the measurement circuit in IEC 60990.

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6.3 Threshold of ventricular fibrillation

6.3.1 General

The thresholds differ for symmetrical and asymmetrical waveforms.

6.3.2 Symmetrical control

The fibrillation hazard may be taken as being approximately the same as with equivalent alternating current I_{ev} having the following characteristics:

a) for shock durations longer than approximately 1,5 times the period of the cardiac cycle, I_{ev} has the same RMS value as the current of the relevant waveform concerned;

b) for shock durations shorter than approximately 0,75 times the period of the cardiac cycle, I_{ev} is the RMS value of a current having the same peak value as the current of the relevant waveform concerned;

NOTE For phase control angles above 120° a rise of the threshold of fibrillation is to be expected.

c) in the duration range from 0,75 to 1,5 times the period of the cardiac cycle, the amplitude parameters change from peak to RMS value.

6.3.3 Asymmetrical control

The fibrillation hazard may be taken as being approximately the same as with the equivalent alternating current I_{ev} having the following characteristics:

For shock durations shorter than approximately 0,75 times the period of the cardiac cycle, I_{ev} is the RMS value of a current having the same peak value as the current of the relevant waveform concerned.

NOTE 1 For phase control angles above 120° a rise of the threshold of fibrillation is to be expected.

NOTE 2 Currents caused by asymmetrical control (see IEC 60050-551:1998, 551-16-25) ~~may~~ can also have DC components.

7 Effects of alternating current with multicyle control

7.1 Waveforms and frequencies

Figure 13 shows the waveforms for a degree of power control of p = 0,67.

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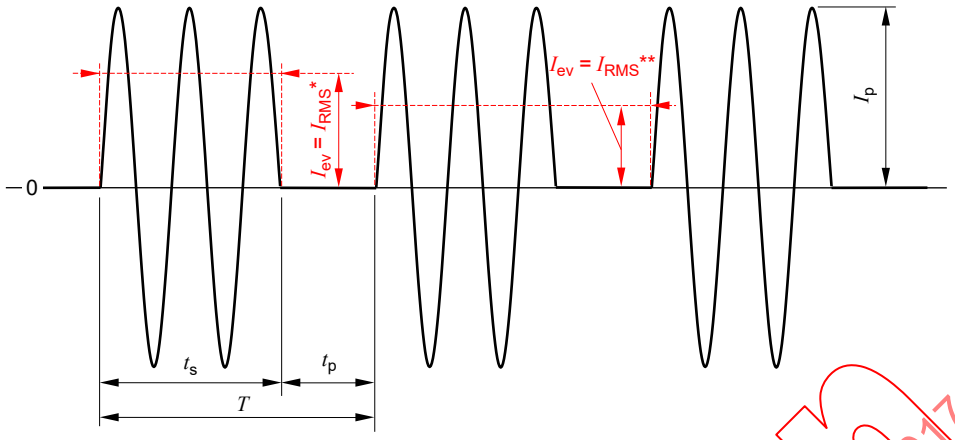

* for shock duration >1,5 cardiac cycle and p <<1 or shock duration < 0,75 cardiac cycle
** for shock duration <0,75 cardiac cycle and $p \approx 1$

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Key

$$p = \frac{t_s}{t_s + t_p}$$

where

t_s = conducting time
$T_s + t_p$ = working period
t_p = non-conducting time
p = degree of power control

$I_{1RMS} = \frac{I_p}{\sqrt{2}}$ = RMS value of current during current conduction.

NOTE I_{1RMS} is not to be confused with the RMS value of current during the working period $I_{2RMS} = I_{RMS}\sqrt{p}$.

Figure 13 – Waveforms of alternating currents with multicycle control

7.2 Threshold of startle reaction and threshold of let-go

As described in 5.3.2, 5.3.3 and 6.2, these thresholds depend on different parameters.

These effects are related to the peak value of the current [13] and the currents have to be combined frequency by frequency to estimate the total effect.

7.3 Threshold of ventricular fibrillation

7.3.1 General

Depending on the duration of shock and the degree of power control, alternating currents with multicycle control are equally or less dangerous than ~~alternative~~ alternating currents of the same shock duration and current magnitude.

Figure 14 shows the variation of the ventricular fibrillation threshold for various degrees of power control from experiments with pigs [7].

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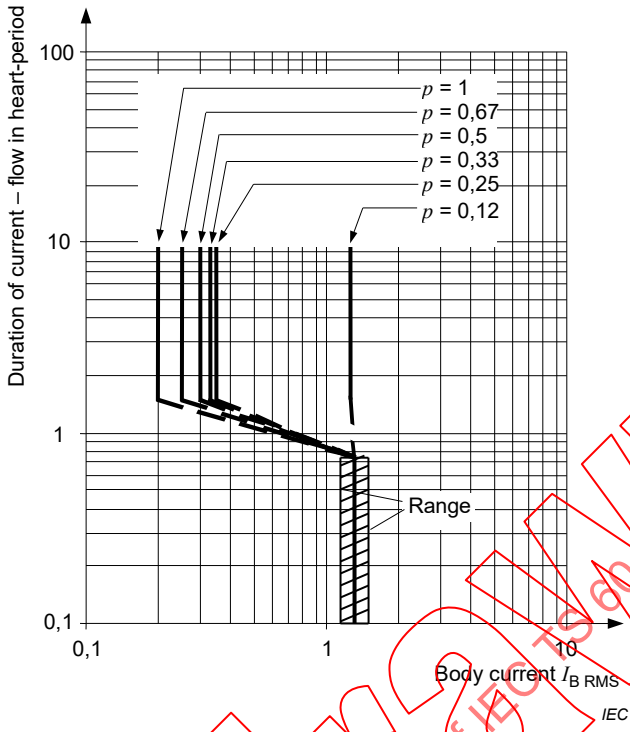

NOTE Body current I_{BRMS} is the RMS value of the current during current conduction I_{1RMS}.

Figure 14 – Threshold of ventricular fibrillation (average value) for alternating current with multicycle control for various degrees of controls (results of experiments with young pigs)

7.3.2 Shock durations ~~exceeding~~ longer than 1,5 times the period of the cardiac cycle

For shock durations longer than approximately 1,5 times the period of the cardiac cycle, the threshold depends on the degree of power control p. For p near the unity, it has the same RMS value as the sinusoidal alternating current of the same duration. For p near 0,1 the RMS value of the current during current conduction, I_{1rms} is the same as the threshold for alternating current of a duration below 0,75 times the period of the cardiac cycle.

NOTE For intermediate values of p, the fibrillation threshold rises from the low level shown in Figure 20 in IEC TS 60479-1:2005 to the high level indicated for shock duration below 0,1 s.

7.3.3 Shock durations less than 0,75 times the period of the cardiac cycle

For shock durations shorter than approximately 0,75 times the period of the cardiac cycle, the RMS value of the current during the current conduction, I_{1RMS} is the same as that for a sinusoidal alternating current of ~~the same~~ 0,1 s duration.

8 Estimation of the equivalent current threshold for mixed frequencies

8.1 Threshold of perception and let-go

These effects are related to the peak value of the current [13] and the currents have to be combined frequency by frequency to estimate the total effect.

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8.2 Threshold of ventricular fibrillation

The ventricular fibrillation hazard caused by a current having multiple frequencies may be estimated as a rough approximation as equivalent to the hazard caused by a pure alternating current having the following characteristics:

– fundamental frequency,

– with an amplitude I_{ev} equivalent to the quadratic summation of all component amplitudes individually affected by the appropriate frequency factor as provided in Figure 3

$$I_{ev} = \sqrt{\sum_{i=1}^{n}\left(\frac{I_i}{F_i}\right)^2}$$

This result of combining waveforms presumes only a relationship between the peak value and the RMS value of the composite waveform. The physiological effect depends on the phase angle relationship among the contributing frequencies which needs to be known and is not considered in this estimate.

9 ~~The effect of repeated pulses (bursts) of current on the threshold of ventricular fibrillation~~ Effects of current pulse bursts and random complex irregular waveforms

9.1 Ventricular fibrillation threshold of multiple ~~bursts~~ pulses of current separated by ~~1 s~~ 300 ms or more

Ventricular fibrillation can be considered unlikely to occur from the passage of a single~~, non-repetitive burst~~ pulse of current through the heart if the combination of magnitude and duration is below the c_1 curve shown in Figure~~s 20 and~~ 22 of IEC TS 60479-1:2005. ~~Figure 20 pertains to single non-repetitive bursts of sinusoidal current of 15 Hz to 100 Hz, while Figure 22 pertains to a single, non-repetitive burst of direct current with no significant a.c. components.~~ These considerations also apply to a single pulse of direct current with no significant AC component.

~~Bursts~~ Pulses of current that are separated from each other by an interval that is equal to or greater than ~~the period of a normal heartbeat cycle~~ 300 ms do not have cumulative effects on the heart and may therefore be treated individually as if they were single, non-repetitive ~~bursts~~ pulses of current. When the ~~bursts~~ pulses of current in a series are separated from each other by at least ~~1 s~~ 300 ms, a comparison of the magnitude and duration of each ~~burst~~ pulse of current individually to the c_1 curve may be used to determine the ventricular fibrillation hazard. ~~A typical heartbeat rate for humans is 70 beats per minute; therefore, the period of a human heartbeat cycle is slightly less than approximately 1 s.~~

9.2 Ventricular fibrillation threshold of multiple ~~bursts~~ pulses of current separated by less than ~~1 s~~ 300 ms

9.2.1 General

~~Bursts~~ Pulses of current through the heart that are separated by less than ~~the period of a normal heartbeat (less than approximately 1 s between consecutive bursts)~~ 300 ms can create disturbances in the heart with cumulative effects. These cumulative effects can lead to ventricular fibrillation even though each ~~burst~~ pulse of current in the series is significantly lower than the threshold for ventricular fibrillation applicable to each of the single ~~burst~~ pulse of current occurring alone.

Short pulses of current through the heart that are separated by less than 300 ms can launch activation wavefronts with increasing heterogeneity. The cumulative effect of these wavefronts is an increase of wave splitting which leads to VF. However, with pulse spacing of less than 100 ms the effect is very definite [32], [33].

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The first ~~burst~~ pulse of current in a series can be evaluated using Figure 20 or Figure 22 of IEC TS 60479-1:2005, whichever is appropriate. The threshold for ventricular fibrillation applicable to the second ~~burst~~ pulse of current can be as low as approximately 65 % of the threshold applicable to the first ~~burst~~ pulse. This process can continue until the threshold reaches a minimum after several ~~bursts~~ pulses. The minimum threshold ~~reached can~~ may only be approximately 10 % or less of the threshold applicable to the first current ~~burst~~ pulse [14], [18], [19], [20].

Table 1 provides an estimate of the threshold of ventricular fibrillation that ~~might be~~ is applicable to current ~~burst~~ pulse in a series as a worst case. The quiet times between the current ~~bursts~~ pulses, if less than 300 ms, ~~is~~ are insufficient to allow the effects of the previous current ~~bursts~~ pulses, to fully subside. Each ~~burst~~ pulse of current is sufficient in magnitude and duration to excite the heart tissue, and it is assumed that the threshold of ventricular fibrillation decreases by 35 % after each ~~burst~~ pulse of current if the spacing is < 100 ms.

Table 1 – Example of estimate for ventricular fibrillation threshold after each burst of current in a series of pulses each of which excited the heart tissue

~~Burst~~ Pulse of current in a series of ~~bursts~~ pulses separated by less than ~~1 s~~ 100 ms, where the first current ~~burst~~ pulse is in the AC-3 or DC-3 region of Figure 20 or Figure 22 of IEC TS 60479-1:2005	Example estimate of the ventricular fibrillation threshold after each ~~burst~~ pulse of current in a series of pulses each of which excited the heart tissue %
First current pulse	100
Second current pulse	65
Third current pulse	42
Fourth current pulse	27
Fifth current pulse	18
Sixth current pulse	12
Seventh and subsequent current ~~bursts~~ pulses	10 or less

9.2.2 Examples

Example 1 – Four pulses separated by 500 ms, with little risk from the first, and no cumulation

Consider a series of four rectangular pulses (see Figure 15) of unidirectional current passing through a person's body between the left hand and both feet, where each pulse has a magnitude of 100 mA peak and a duration of 0,01 s. Suppose the pulses are separated from each other by 0,5 s of "off-time". In this example ~~it will be established if~~ there is a risk of ventricular fibrillation when the pulse current flows upward (feet positive) through the body.

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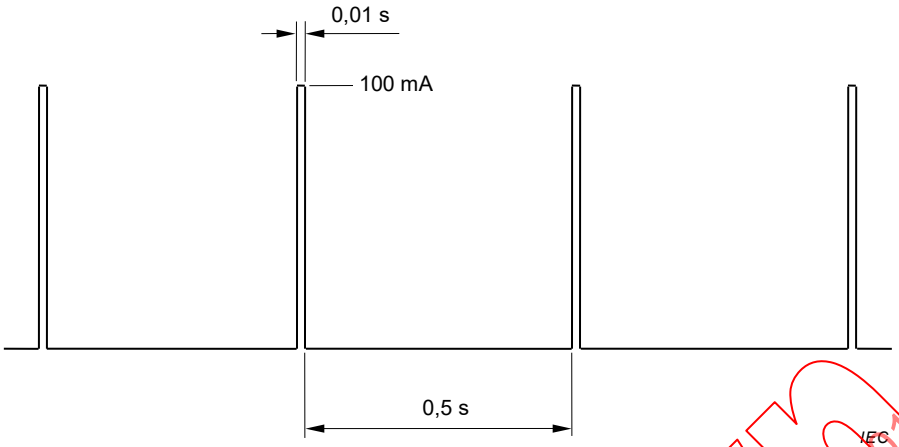

Figure 15 – Series of four rectangular pulses of unidirectional current

According to Figure 22 of IEC TS 60479-1:2005, each of the 0,01 s or 100 mA pulses by itself have no harmful physiological effects (DC-2 region) and are also separated by more than 300 ms. ~~If the four pulses that are 0,5 s apart were each to have the most cumulative effects that can be expected to lower the ventricular fibrillation threshold, the fourth and last pulse might have a threshold that is as low as 27 % of 500 mA, i.e. 135 mA. Therefore, it is doubtful that the pulses in this series would be able to produce disturbances that could escalate into a dangerous situation, even though the current bursts are separated by only 0,5 s.~~ The risk of ventricular fibrillation in this case could be considered low.

Example 2 – Four pulses separated by 500 ms, with significant risk from the first, and no cumulation

Consider another series of four rectangular pulses (see Figure 16) of unidirectional current passing in the same direction (feet positive) through a person's body between the left hand and both feet.

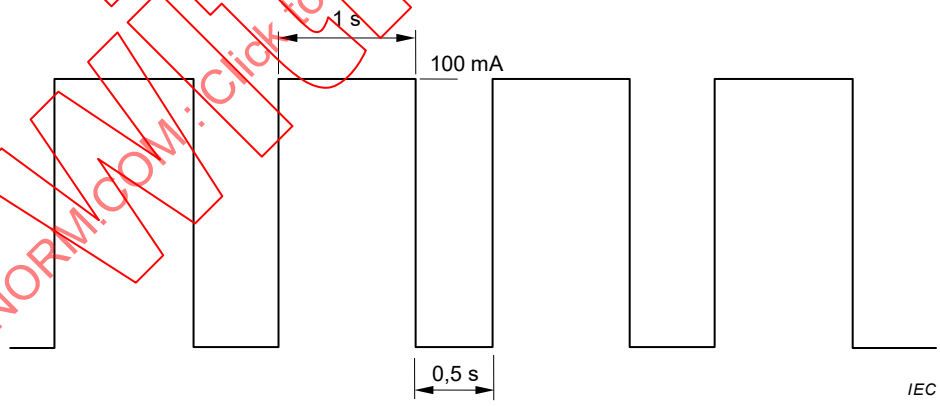

Figure 16 – Series of four rectangular pulses of unidirectional current

Each pulse has the same magnitude of 100 mA peak, but the duration of each pulse "on-time" is increased to 1 s. The separation between pulses is still 0,5 s. ~~Is there a risk of ventricular fibrillation?~~

According to Figure 22 of IEC TS 60479-1:2005, each of the pulses by itself is capable of inducing reversible disturbances of formation and conduction of impulses in the heart (DC-3 region). ~~Until these disturbances subside, the ventricular fibrillation threshold is reduced to a lower level, making ventricular fibrillation more likely. A single, non repetitive pulse of 1 s duration might have a ventricular fibrillation threshold as low as approximately 150 mA (the c_1~~

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~~line). If the first pulse caused disturbances that lowered the ventricular fibrillation by 35 %, then the ventricular fibrillation threshold for the second pulse would be 65 % of 150 mA, i.e. 98 mA. The third pulse could have a ventricular fibrillation threshold of 65 % of 98 mA, i.e. 63 mA, and the fourth pulse could have a ventricular fibrillation threshold as low as 41 mA. In this case, the first pulse is unlikely to cause ventricular fibrillation, but the second, third and fourth pulses have an increasing risk of ventricular fibrillation. This is due to the cumulative effect of the disturbances caused by the previous pulses in the series without sufficient time between pulses for the effects to subside.~~

The pulses are still however separated by more than 300 ms and so the risk of cumulation is low. The pulses may be considered as individual pulses under the same criteria as the first, thus suggesting that each pulse is equally harmful.

Example 3 – Four pulses separated by less than 300 ms, with significant risk from the first, and cumulation

Finally, consider another series of four rectangular pulses of unidirectional current passing in the same direction (feet positive) through a person's body between the left hand ~~to~~ and both feet. Each pulse has the same magnitude of ~~100~~ 200 mA peak and ~~1 s~~ 100 ms duration, but with ~~1 s~~ 50 ms between pulses instead of 0,5 s (see Figure 17). In this example, ~~it will be established if~~ there is a risk of ventricular fibrillation.

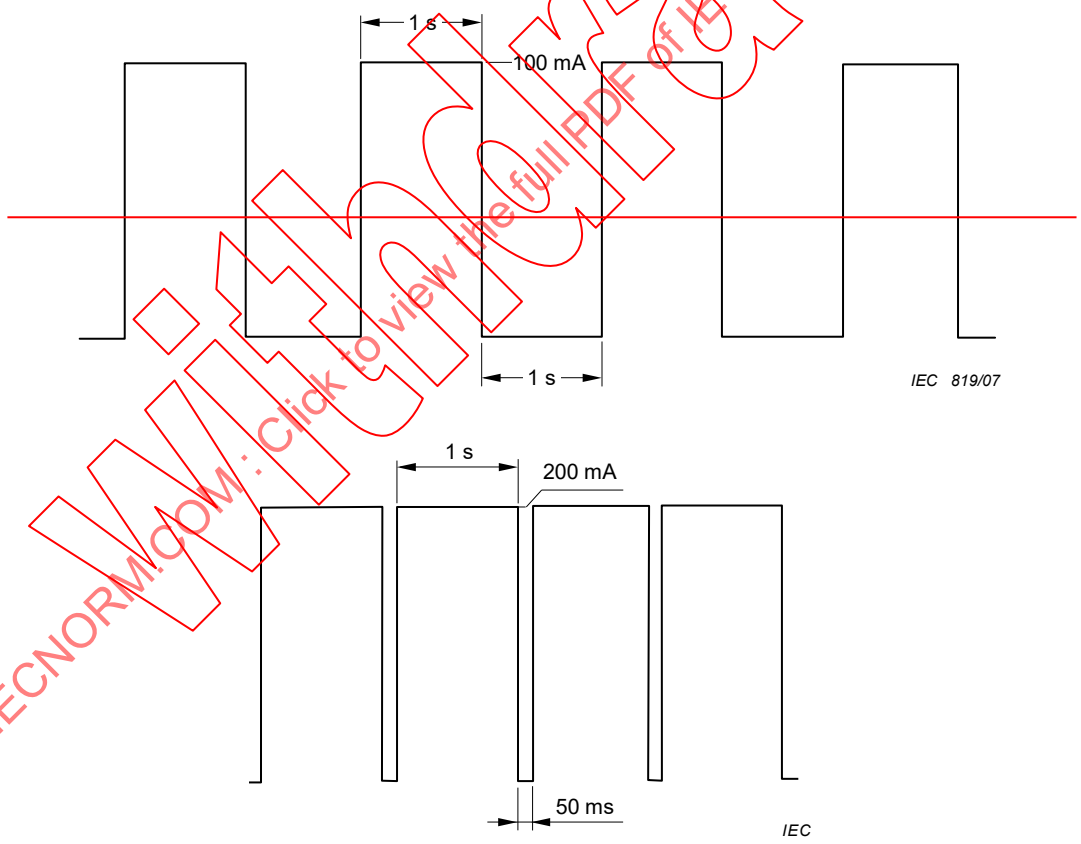

Figure 17 – Series of four rectangular pulses of unidirectional current

According to Figure 22 of IEC TS 60479-1:2005, each of the pulses by itself is capable of inducing reversible disturbances in the heart (DC-3 region), ~~but the 1 s~~ and the 200 ms quiet interval between the pulses does not allow~~s~~ the disturbances to subside before the onset of the next pulse occurs in the series. Therefore, ~~there is little or no cumulative effect, and the risk of ventricular fibrillation for this series of pulses is low~~ there is a full cumulative effect,

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with the magnitude threshold of the seventh pulse being less than 10 % of the original and the risk of ventricular fibrillation for this series of pulses is high.

~~**9.2.3 Example 2**~~

~~If one considers a continuous stream of interrupted direct current with a 50 % duty cycle, the likelihood of ventricular fibrillation is estimated for this pulse stream compared to the likelihood for a single, non repetitive rectangular pulse with the same duration as one of the pulses in the pulse stream.~~

~~According to Figure 20 of IEC 60479-1, a continuous sinusoidal alternating current of, e.g. 200 mA r.m.s. or 283 mA peak has a specific likelihood of ventricular fibrillation. According to Kouwenhoven's observations [18] which compared the likelihood of ventricular fibrillation for sinusoidal a.c. and interrupted d.c. with the same 60 Hz fundamental frequency, the ratio of amplitudes of a continuous series of d.c. pulses having the same likelihood of ventricular fibrillation would be 1,7/1. This ratio between measured ventricular fibrillation thresholds for a.c. and interrupted d.c. with the current applied directly to the heart of a dog (1,06 mA peak / 0,62 mA peak = 1,7). The interrupted d.c. causes ventricular fibrillation at a lower value than the sinusoidal a.c.~~

~~According to Figure 20 of IEC 60479-1, the likelihood of ventricular fibrillation for a single, non repetitive rectangular impulse of unidirectional current with duration equal to half the period of a 60 Hz repetitive pulse train ((1/60) / 2 = 8,3 ms) is about ten times higher than for the continuous sinusoidal alternating current.~~

~~The ratio between the likelihood of ventricular fibrillation for one single impulse of 8,3 ms duration and for the 60 Hz series of 50 % duty cycle pulses (the same rectangular shape and the same duration) is therefore about 1 / (2 830 mA / 166 mA) = 1 / 17. This significant difference between the likelihood of ventricular fibrillation is caused by the cumulative effects of the pulses on the heart when many pulses occur in rapid succession.~~

9.2.3 Random complex irregular waveforms

In some applications a random complex irregular waveform requires assessment. This type of waveform is not amenable to assessment using other clauses of this document. Such a waveform may arise, for example, in the current crossing a polluted insulator.

In particular, "random" and "complex" imply that

a) there is no observable repetition or pattern to irregularities;

b) the waveform cannot easily be described mathematically;

c) the waveform cannot easily be reduced to examination by harmonic analysis.

An example of a segment of such a waveform is shown in Figure 18. This waveform can be digitally recorded using, for example, an oscilloscope, or a digital acquisition system. The electronic record of the waveform segment may then be assessed for VF danger using digital processing according to an appropriate method. Tasks of this kind may be solved by commonly used mathematical methods like Convolution, Fourier transformation or Wavelet analysis but these approaches are often not convenient for ordinary users. Here a simple, reliable and conservative procedure which transforms the results into Figure 20 of IEC TS 60479-1:2005 is used. The method is that proposed by Pratt [29].

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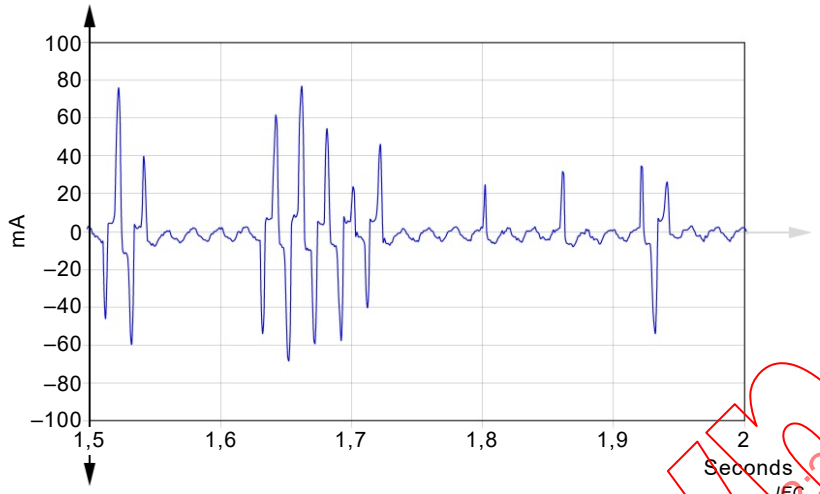

Figure 18 – Example of current versus elapsed time over a contaminated insulator

Data from vulnerability studies on patients implanted with cardiac defibrillators showed that the VF vulnerable interval extended over approximately 60 ms about the peak of the T wave [36] [37]. The analysis of random complex waveforms (RCWs) has been conducted from such perspective. The goal of the analysis was to understand the worst-case stimulation scenarios from the perspective of the extent of the cardiac vulnerable period. Ideally, the worst case scenario would be analysed using moving windows of shapes resembling the shock-strength-vulnerable-period profiles [36]. A simpler, but more conservative, modality employed rectangular windows shifted along the RCW such that the worst-case stimulation strengths were determined. As described below, consistent with the vulnerability theory, various window sizes were used to transverse the RCW, to then find the worst-case stimuli strengths and, finally, to generate a probable current curve.

The method considers both the effects of the magnitude of the complex exposure to the human and the duration of the complex exposure. It assumes that the human contact could occur at any point in a waveform and for an unspecified time duration. The current to be assessed for risk for any given exposure duration is the largest found for that duration. The method then considers all possible exposure durations in the chosen waveform segment and the maximum magnitude in each to determine the VF danger.

The combination that is the largest in any given duration interval is called the "probable current" (PC), for that interval. The PC is generated from the processing of the digitized waveform according to the method shown in Annex A. When all possible probable currents are found for all possible duration intervals, a PC curve is found. The overall worst case in the waveform segment is therefore found and may be assessed.

The PC is in a format that can be compared with 50 Hz data for which experimental data is available. It is plotted on the same axes as Figure 20 of IEC TS 60479-1:2005. It may therefore be considered that this method is a transform method to map a random complex waveform onto the RMS curve satisfying Figure 20. Prior to assessing the random complex waveform segment it should first be low pass filtered, using a 100 Hz upper frequency cut-off, as Figure 20 is considered valid to 100 Hz.

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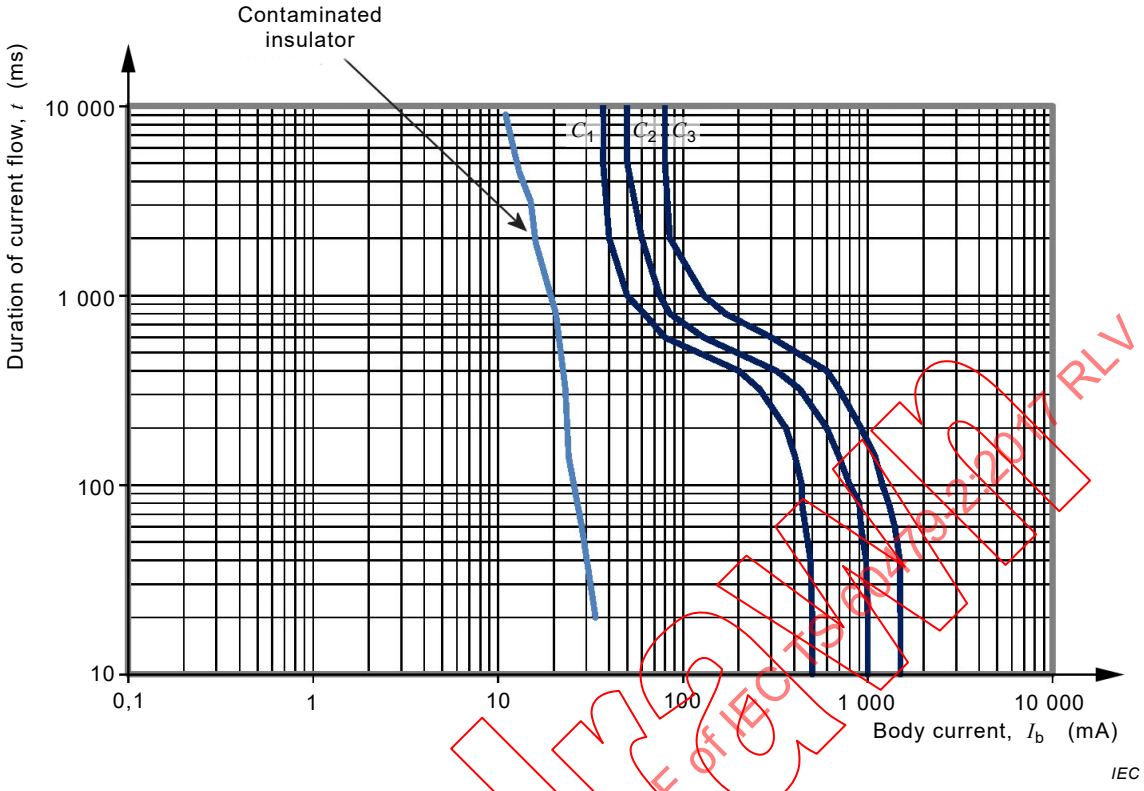

Figure 19 – PC plotted on the AC time current curves
(Figure 20 of IEC TS 60479-1:2005)

The waveform is unlikely to cause VF if the PC curve, plotted on Figure 20, lies below a "justified current" (JC) curve. Choosing the JC curve will be examined in Annex A.

See also [32], [33], [38].

10 Effects of electric current through the immersed human body

10.1 General

Clause 10 discusses the effects of electric current through the human body when the body is immersed in water of various levels of conductivity. Sinusoidal frequencies of 50/60 Hz and direct current are discussed, but the effects of other frequencies might be estimated by applying the information given in other parts of IEC 60479.

NOTE 1 Unless otherwise specified, voltage and current are sinusoidal, and the values are expressed in terms of RMS.

NOTE 2 For the purposes of this document, the term "water" is used to describe pure water as well as solutions of pure water with salts and other impurities in solution.

10.2 Resistivity of water solutions and of the human body

Pure water is essentially non conductive, but when impurities such as salts are added to water, the resistivity of the solution can decrease significantly. Table 2 shows values of resistivity for examples of typical water solutions in which people can be partially or totally immersed.

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Table 2 – Resistivity of water solutions [24], [25]

Water solution	Resistivity Ω·cm
Rain water	254 to 420 000
“Standard” hard water	1 780
Tap water (USA)	1 290 to 16 000
Laundry water (tap water with detergent added)	520
“Swimming pool water”	300
Isotonic (normal) saline solution	60
Sea water (Atlantic Ocean, near New York)	22
NOTE Conductivity values in this table are approximate for solutions at room temperature, and will vary with changes in temperature.	

When the human body is immersed in water that conducts an electric current, the path of the electric current through the water is affected by the relative resistivity of the body, which is not homogeneous, and the water. If the water is less resistive than the immersed body (e.g. sea water), much of the current that would have been flowed through the water displaced by the body will flow around the body rather than through it. However, if the water is more resistive than the body (e.g. fresh lake water), a larger portion of the current will take the path of least resistance and “collect” or “concentrate” through the body. The presence of the body distorts the electric field and paths of current flow in the water. The least distortion of the electric fields and current paths will occur when the resistivity of the water is nearly the same as the resistivity of the body parts displacing the water. However, since the body is not homogeneous, the presence of a body in the water will always distort the electric field and current paths to some extent.

The strength of the electric field (in V/cm) is equal to the resistivity (in Ω·cm) times the current density (in A/cm^2). Therefore, for two parallel paths with the same electric field across them, the path with the lower resistivity will carry a proportionately higher current density.

Table 3 shows approximate values of resistivity for examples of various human body parts at normal body temperature [22], [23]. The values apply for low-frequency alternating current or direct current.

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Table 3 – Resistivity of human body tissues

Human body tissue	Resistivity Ω·cm
Blood	62,9 [a]
Cerebrospinal fluid	64,6
Arm (body segment)	160
Skeletal muscle	240
Neck (body segment)	280
Fingers and hand (body segment)	280
Thorax (body segment)	375 to 455
Trunk (body segment)	415
Brain	588
Head (body segment)	840
Cardiac muscle	925 to 1 150
Bone	16 000

~~NOTE~~ The human body is non uniform in its composition and therefore also in its resistivity. The values given in the table, particularly for the body segments, should be considered as a kind of "average" value.

[a] This value applies to plasma with no cells in the sample. As the number of cells in the sample is increased, the resistivity increases to a value as high as almost 300 Ω·cm.

10.3 Conducted current through immersed body

The output impedance of an electrical source supplying current to the water can be high or low, depending on the nature and design of the source. If the source has a low output impedance relative to the impedance of the water and immersed body, the source behaves like a constant voltage source. In this case, the current through the body and water is determined more by the impedance of the various parallel pathways in the water, and is not limited by the output impedance of the source. The current through the body is not significantly influenced by the presence of current pathways in parallel with the body. Due to the low output impedance of the source, each of the parallel paths can be supplied with current from the source that is essentially based on the impedance of each of the many individual paths.

If the electrical source has a high output impedance relative to the combined impedance of the body and the water in which it is immersed, it behaves like a constant current source. In this case, the magnitude of the total current from the source that flows through the body and the water is determined by the source voltage divided by the source impedance. The impedance outside the source is low relative to the source impedance and has little influence. The current in the water divides between the body and paths around the body. Most of the current flows through the paths of least resistance. In the extreme case, if the water were a perfect conductor, the immersed body would conduct none of the current because all of the current would flow around the body through the highly conductive water. In the other extreme, if the water were highly resistive, then almost all of the current in the water would concentrate through the body.

Table 4 qualitatively illustrates the relative interaction between the resistivity of the water solution (relative to the resistivity of the immersed body), and the impedance characteristic of the electrical source (the source impedance relative to the impedance of the solution and immersed body).

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Table 4 – Relative interaction between the resistivity of water solution and the impedance characteristic of the electrical source

	High resistivity solution	Low resistivity solution
Constant voltage source (low source impedance relative to the impedance of the combination of the immersed body and the water)	Body current is determined by the source voltage and the impedance of the body "in series with" the water that is between the body and the electrodes. The higher the water resistivity in series with the body, the less current through the body.	Body current is determined by the source voltage and the impedance of the body "in series with" the water that is between the body and the electrodes. The lower the resistivity of the water in series with the body, the more current through the body.
Constant current source (high source impedance relative to the impedance of the combination of the immersed body and the water)	Total current is determined by the source voltage divided by the source impedance. Body current is determined by the relative impedances of the immersed body and the water "in parallel with" the body. The higher the resistivity of the water, the more current through the body.	Total current is determined by the source voltage divided by the source impedance. Body current is determined by the relative impedances of the immersed body and the water "in parallel with" the body. The lower the resistivity of the water, the less current through the body.

10.4 Physiological effects of current through the immersed body

Perception and startle reaction are unlikely to occur when the body is totally immersed in water. With the entire body immersed ~~and conducting current~~, the current density through the skin is usually low even though the current that accumulates in the body and flows through some of the internal body tissue (muscle, blood, nerves, etc.) can be significant. Because of the low current density in the skin, harmful levels of current can flow through the internal parts of an immersed person without the sensation normally associated with an electric shock.

Physiological effects of body current that involve muscle tetanization (immobilization) can be particularly hazardous when the body is immersed since it can interfere with the person's ability to swim, or can interfere with the ability to keep the head above the surface of the water. Drowning can result from the interference with normal muscle control.

Ventricular fibrillation can occur when current of sufficient magnitude flows through the body in the region of the heart. The orientation of the body with respect to an electric field in water is not necessarily fixed and can be continually changing. Therefore, it ~~must~~ shall be assumed that current can enter and exit the body in ways that can maximize the current density in the heart and can flow in the most adverse direction. For example, current can flow directly into the chest and exit through the left arm depending on the location of the body with respect to the electrodes in the water.

A person immersed in a body of water that is electrically isolated from earth and that is elevated in potential by an electrical source with respect to earth, but where there is no differences in potential in the water (no electric field in the water), might have no current flowing through the body until that person reaches out of the water and touches a conductive part connected to earth. In this case, current will flow from the water, into the body over a large area of immersed skin, and out through the limb touching or grasping the earthed part. The person might be unable to let go the part, and if the current through the torso is sufficiently high, the current can interfere with breathing or cause ventricular fibrillation.

Electrical burn injuries are less likely when the body is immersed because of the cooling of the skin provided by the water.

If a person is completely immersed in the water, current that flows through the head can produce a number of other physiological effects [24]. Low currents can produce a prickling or stinging sensation on the skin. Higher currents can stimulate facial muscles. Yet higher currents can stimulate the optic nerves to create phosphenes. Phosphenes are visual images of light produced by an external stimulus not involving light – in this case electric current.

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(Mechanical pressure exerted on the closed eye can also produce phosphenes.) Although phosphenes themselves are not ~~harmful~~ injurious, they can be frightening to an unsuspecting person, and might cause a thoughtless response, or even a panic reaction, that could lead to other hazards including drowning. The direct effects of the current are immediately reversible when the current stops; however, higher current can cause pain in the upper facial area. This pain is reversible in a few minutes to a few hours. The sense of balance can be affected by these currents. This effect is reversible but can last as long as a few days.

10.5 Threshold values of current

The current threshold of physiological effects for a person's body immersed in water is not a unique value. There are too many variables that can continuously change the "body impedance", and continuously change each pathway and magnitude of current in each pathway as the body moves relative to the source electrodes in the water. The following values have been used for conservative current limits in applications where a person's body is immersed in low resistivity water. The tests to determine these values were performed with 22 Ω·cm water, representing sea water, prepared by adding NaCl to tap water [25].

In general, if a 50/60 Hz current exceeding 5 mA enters and flows through the body of an immersed person, it may lead to muscle tetanization which can interfere with the ability to swim, interference with breathing or even ventricular fibrillation. When a person is immersed, current can enter the chest directly from the water, without flowing through limbs. In addition, retaining control of muscles is important to be able to avoid drowning. The 5 mA value is not related to curve b in Figure 20 of IEC TS 60479-1:2005. Immersed conditions are different from the typical electric shock scenario, and different considerations apply.

A 50 Ω resistor is sometimes specified to measure the current available from high output impedance electrical sources in water. However, this value can be too high to be a suitable body impedance model. This becomes important when the source has a low output impedance. In this case, the value of the body impedance model influences the current to a larger extent and should more accurately represent the body.

When 5 mA enters a child's body through the area of the chest, a 50/60 Hz current density of 30 μA/cm^2 may occur [26].

10.6 Intrinsically "safe" voltage values

It has been the practice of product standards to limit current rather than voltage in applications such as swimming pools and spas where body immersion occurs. If an intrinsically "safe" voltage value were ~~to be~~ specified, it would have to be very low, perhaps in the order of only a few volts, because of the very low impedance pathways that can exist through the immersed body.

11 Effects of unidirectional single impulse currents of short duration

11.1 General

Unidirectional single impulse currents of short duration in the form of rectangular and sinusoidal impulses or capacitor discharges may be a source of danger in the case of an insulation fault of an electric appliance containing electronic components or when touching live parts of such equipment. It is therefore important to establish the danger limits for these types of currents.

For a shock duration of 10 ms and longer, the effects described in Clause 11 correspond to those given in IEC TS 60479-1 ~~so that IEC 60479-1 and IEC 60479-2 cover the whole range of shock durations from 0,1 ms to 10 s for nearly all current waveforms which are of technical interest. The content of this clause is based on the assumption derived from scientific research that the principal factor for the initiation of ventricular fibrillation for the various~~

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~~forms of unidirectional impulse currents is the $I \times t$ or $I^2 \times t$ value for shocks of up to 10 ms duration [8].~~

Subclauses 11.2 to 11.4 apply to the range 1,0 ms to 10 ms and waveforms which are of technical interest. The content of these subclauses is based on the assumption derived from scientific research that the principal factor for the initiation of ventricular fibrillation for the various forms of unidirectional impulse currents is the $I \cdot t$ or $I^2 \cdot t$ value.

In the region 1 µs to 100 µs, the data of Bridges [31] and of Pearce [43] have been used to provide an extrapolation of Figure 20. Pearce et al. emphasize that charge transferred to a membrane is the most significant parameter in membrane depolarization. The value of current and the width of a pulse when applied to stimulate a membrane of time constant T, (i.e the area under the I-t curve of Figure 20 c)) are the significant parameters in specifying charge and, therefore, in causing the induction of VF.

Work by Osypka [42], Biegelmeier [41], Geddes [40] and others established that the amount of electrical charge, not the current as root-mean-square (RMS) calculation, is most representative of the effects of cardiac stimulation. See also Panescu [38].

11.2 Effects of unidirectional impulse currents of short duration

11.2.1 Waveforms

Figure 20 shows the forms of currents for rectangular impulses, sinusoidal impulses and for capacitor discharges. The following current magnitudes have to be distinguished:

I_{DC} = magnitude of the current of the rectangular impulse,

$I_{AC,RMS}$ = RMS value of the current of the sinusoidal impulse,

$I_{AC(p)}$ = peak value of the current of the sinusoidal impulse,

I_{CRMS} = RMS value of the current of the capacitor discharge for a duration of $3T$,

$I_{C(p)}$ = peak value of the capacitor discharge.

NOTE If U_e is the voltage of the capacitor at the beginning of the discharge through the human body and R_e the initial body resistance, $I_{C(p)}$ is determined by:

$$I_{C(p)} = \frac{U_e}{R_i}$$

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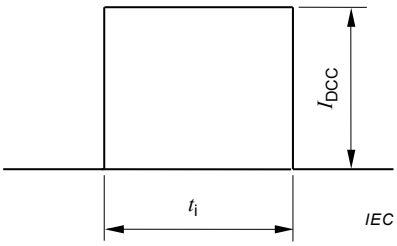
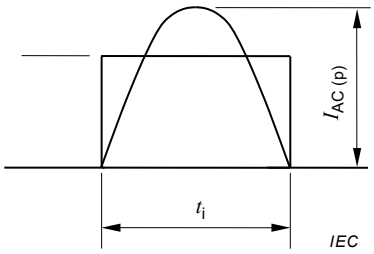
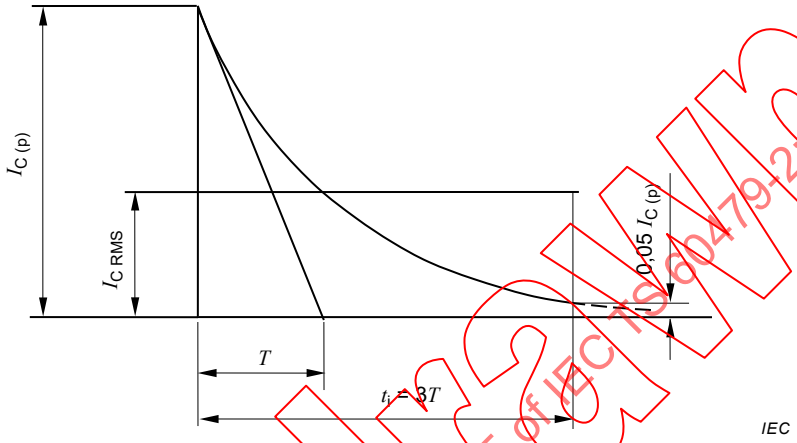


a) Rectangular impulses



b) Sinusoidal impulses



c) Capacitor discharges

Figure 20 – Forms of current for rectangular impulses, sinusoidal impulses and for capacitor discharges

11.2.2 Determination of specific fibrillating energy F_e

The specific fibrillating energy F_e for the different forms of impulses dealt with in 11.2.2, is determined:

a) for rectangular impulses by:

$$F_e = I_{DC}^2 t_i$$

b) for sinusoidal impulses by:

$$F_e = \frac{I_{AC(p)}^2}{2} t_i = I_{ACRMS}^2 t_i$$

c) for a capacitor discharge with a time-constant T by:

$$F_e = I_{C(p)}^2 \frac{T}{2} = I_{CRMS}^2 t_i$$

Figure 21 compares the current magnitudes for rectangular impulses, sinusoidal impulses and a capacitor discharge with the time constant T having the same specific fibrillating energy F_e and the same shock-duration t_i. In this case the following relationship exists:

$$I_{DC} = \frac{I_{AC(p)}}{\sqrt{2}} = \frac{I_{C(p)}}{\sqrt{6}}$$

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NOTE The relationship $I_{DC} = \frac{I_{C(p)}}{\sqrt{6}}$ is derived as follows:

$$F_e = I^2_{C(p)} \int_0^\infty e^{-\frac{2t}{T}} dt = I^2_{C(p)} \frac{T}{2}$$

$$I^2_{CRMS} 3T = I^2_{DC} 3T = I^2_{C(p)} \frac{T}{2}$$

$$I_{CRMS} = I_{DC} = I_{C(p)} \frac{1}{\sqrt{6}}$$

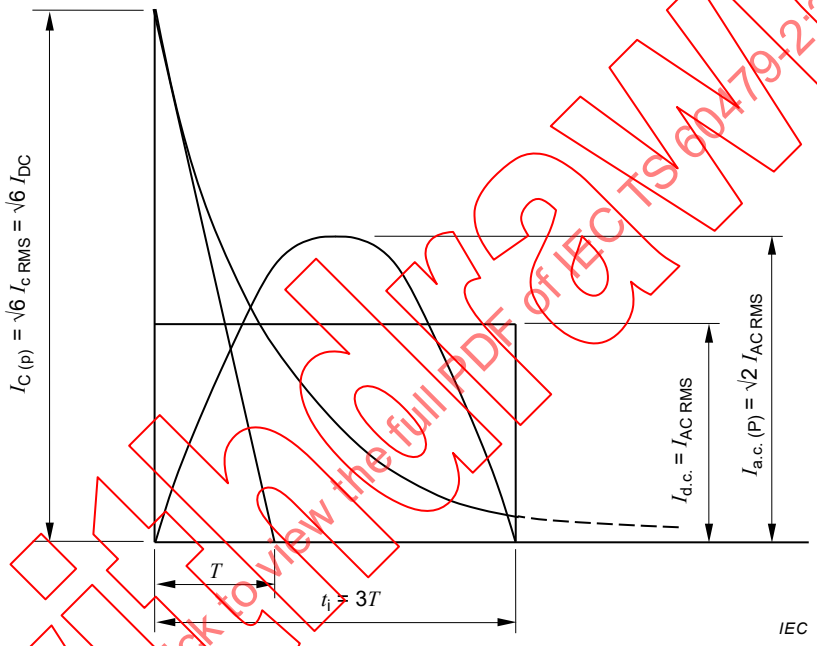

Figure 21 – Rectangular impulse, sinusoidal impulse and capacitor discharge having the same specific fibrillating energy and the same shock-duration

11.3 Threshold of perception and threshold of pain for capacitor discharge

The thresholds depend on the form of the electrodes, on the charge of the impulse and on its peak current value. Figure 22 shows the threshold of perception and the threshold of pain as a function of the charge and the charging voltage of the capacitor for a person holding large electrodes with dry hands.

The threshold of pain in terms of specific energy is in the order of 50 A^2s to $100 \cdot 10^{-6}$ A^2s for current paths through the extremities and large contact areas.

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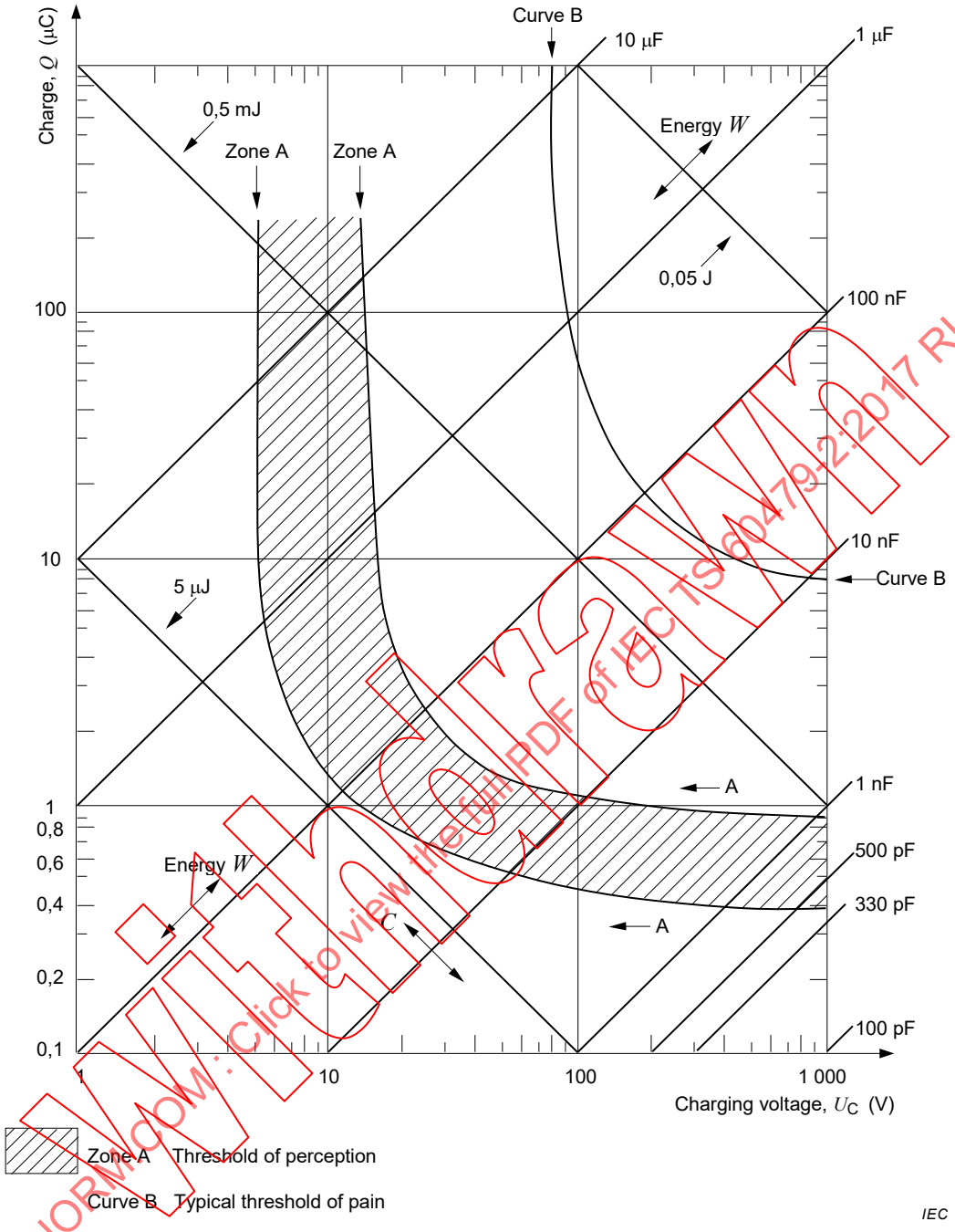

Zone A: Threshold of perception. Curve B: Typical threshold of pain

NOTE The diagonal axes are scaled for capacitance (C) and energy (W). From the intersection of the co-ordinates for charging voltage and capacitance the charge and the energy of the impulse can be read on the appropriate axes.

Figure 22 – Threshold of perception and threshold of pain for the current resulting from the discharge of a capacitor (dry hands, large contact area)

11.4 Threshold of ventricular fibrillation

11.4.1 General

The threshold of ventricular fibrillation depends on the form, duration and magnitude of the current of the impulse, the heart phase in which the impulse starts, the current path in the human body and on the physiological characteristics of the person.

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Experiments on animals show:

– that for impulses of short-duration and relatively low pulse energies, ventricular fibrillation in general results only if the impulse falls within the vulnerable period of the cardiac cycle;

NOTE With high energy pulses occurring outside the vulnerable period, fibrillation can also occur even minutes after the original event.

– the specific fibrillating charge F_q ~~or the specific fibrillating energy F_e~~ determines the initiation of ventricular fibrillation for unidirectional impulses for shock durations shorter than 10 ms.

Thresholds for ventricular fibrillation are shown in Figure 23. For 50 % probability of fibrillation, F_q is of the order of 0,005 As and F_e rises from about 0,01 A^2s at an impulse duration t_i = 4 ms to 0,02 A^2s for t_i = 1 ms.

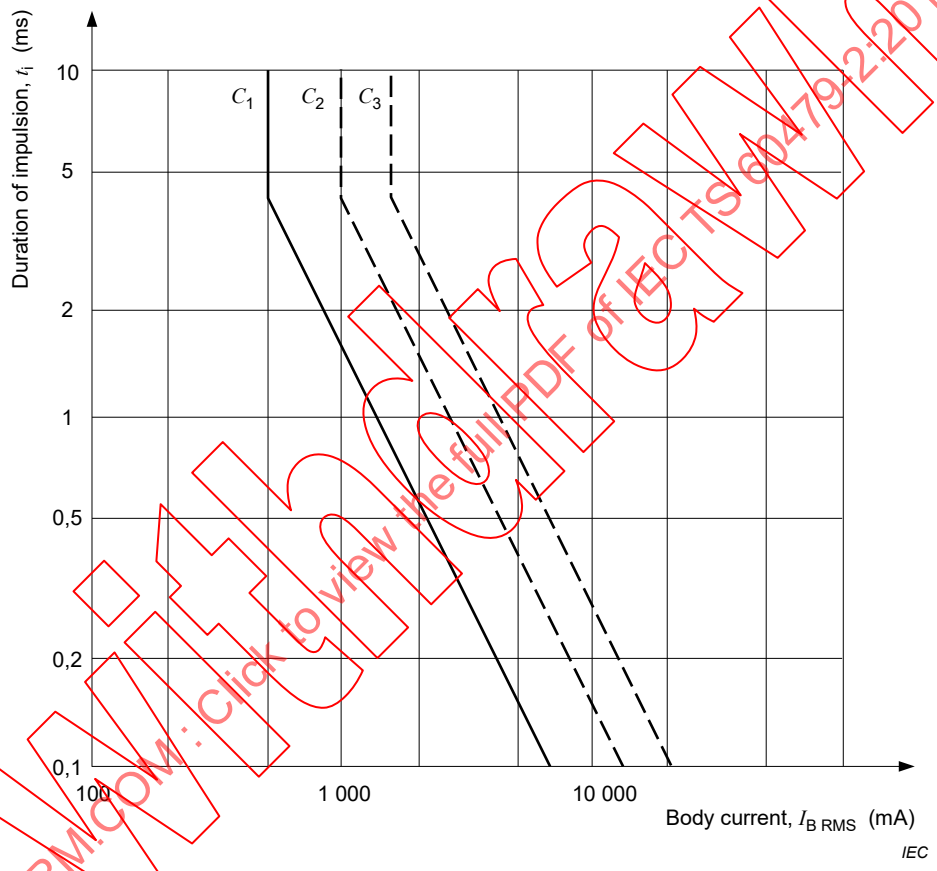

Figure 23 – ~~Threshold of ventricular fibrillation~~ Probability of fibrillation risks for current flowing in the path left hand to feet

The curves indicate the probability of fibrillation risks for current flowing ~~through the body from~~ in the path left hand to ~~both~~ feet. For other current path~~s~~, see 5.9 in IEC TS 60479-1:2005.

Below C_1: no fibrillation,

Above C_1 up to C_2: low risk of fibrillation (up to 5 probability);

Above C_2 up to C_3: average risk of fibrillation (up to 50% of probability);

Above C_3: high risk of fibrillation (more than 50 % probability).

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11.4.2 Examples

In order to explain the practical application of the relationships described in 11.4.1, two examples are given. The first example deals with a capacitor discharge with a time constant of T = 1 ms and a shock duration t_i = 3T = 3 ms and is within the scope of this document. In the second example, the time constant is T = 10 ms, i.e. t_i = 30 ms which means that the limits for ventricular fibrillation are those given in Figure 20 of IEC TS 60479-1:2005.

Example 1

Effects of capacitor discharge on the human body:

Capacitor C = 1 µF, charging voltages 10 V, 100 V, 1 000 V and 10 000 V

Current-path: hand to foot, initial body resistance assumed to be R_i = 1 000 Ω (see footnote in Table 5).

Time constant T = 1 ms, i.e. shock-duration t_i = 3T = 3 ms

Specific fibrillating energy $F_e = I^2_{CRMS} t_i \approx \frac{W_C}{R_i}$

Table 5 – Effects of shocks

Charging voltage U_e V	**10**	**100**	**1 000**	**10 000**
Discharge current Peak value $I_{C(p)}$ (A)	0,01	0,1	1	10
Discharge current RMS value (A) $I_{CRMS} = \frac{I_{C(p)}}{\sqrt{6}}$	0,004 1	0,041	0,41	41
Specific charge F_q (~~As~~ C)	$0{,}01 \cdot 10^{-3}$	$0{,}1 \cdot 10^{-3}$	10^{-3}	$10 \cdot 10^{-3}$
Discharge energy W_c (~~Ws~~ J)	$0{,}05 \cdot 10^{-3}$	$5 \cdot 10^{-3}$	0,5	50
Specific fibrillating energy F_e (R_i = 1 000 Ω) (A^2s)[a]	$0{,}05 \cdot 10^{-6}$	$5 \cdot 10^{-6}$	$0{,}5 \cdot 10^{-3}$	$50 \cdot 10^{-3}$
Physiological effects	Slight	Disagreeable	Painful	Ventricular fibrillation likely

NOTE 1 F_q is expressed in C or As.

NOTE 2 W_c is expressed in J or WS.

[a] The value of R_i of 1 000 Ω has been arbitrarily chosen for the purpose of this example. It is not to be confused with the value of R_i for the 5 % percentile rank of Clause 4 of IEC TS 60479-1:2005.

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Example 2

Effects of capacitor discharge on the human body:

Capacitor C = 20 µF, charging voltages 10 V, 100 V, 1 000 V and 10 000 V.

Current-path: hand trunk, initial body resistance assumed to be R_i = 500 Ω. (see footnote "a" in Table 6).

Time constant T = 10 ms, i.e. shock-duration $t_i = 3T$ = 30 ms (see footnote "b" in Table 6).

Specific fibrillating energy $F_e = I^2_{CRMS} t_i \approx \frac{W_C}{R_i}$

Table 6 – Effects of shocks

Charging voltage U_e V	**10**	**100**	**1 000**	**10 000**
Discharge current Peak value $I_{C(p)}$ (A)	0,02	0,2	2	20
Discharge current RMS value (A) $I_{CRMS} = \frac{I_{C(p)}}{\sqrt{6}}$	0,008	0,08	0,8	8
Specific charge F_q (~~As~~ C)	$0{,}2 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	$20 \cdot 10^{-3}$	$200 \cdot 10^{-3}$
Discharge energy W_c (~~Ws~~ J)	10^{-3}	0,1	10	1 000
Specific fibrillating energy F_e (R_i = 500 Ω) (A^2s)[a,b]	-	-	-	-
Physiological effects	Slight	Painful	Dangerous but ventricular fibrillation unlikely	Dangerous, and ventricular fibrillation likely

NOTE 1 F_q is expressed in C or As

NOTE 2 W_c is expressed in J or WS

[a] The value of R_i of 500 Ω has been arbitrarily chosen for the purpose of this example. Not to be confused with the value of R_i for 5 % percentile rank of Clause 4 of IEC TS 60479:2005.

[b] As the shock duration t_i is longer than 10 ms, fibrillation thresholds are to be taken from Figure 20 in IEC TS 60479-1:2005.

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Annex A
(informative)

Random complex irregular waveform analysis

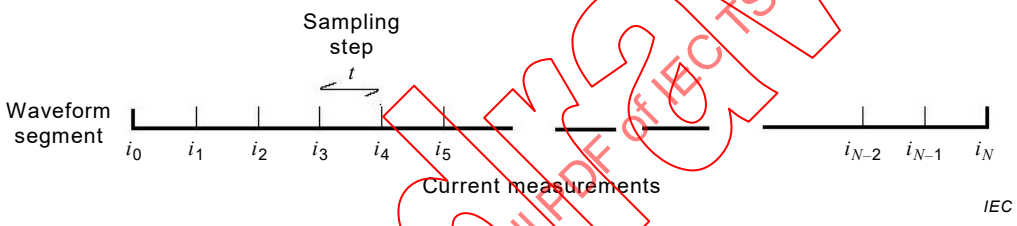
A.1 General

The detail of this method is that of Pratt [29]. It is assumed a waveform has been sampled and filtered as stated in 9.3.

A formal statement of the method follows, and then examples are used to make the method plainer.

A.2 Formal theoretical statement of the method

Consider a waveform segment, digitized at time steps t, of length N samples. This is shown in Figure A.1.



Key

N is the number of samples in the waveform segment

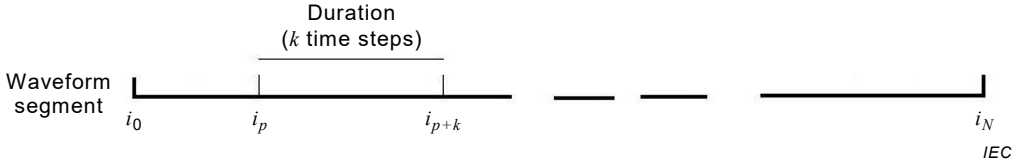
t is the sampling step size in seconds

i is the instantaneous current at any point

Figure A.1 – Definition of a segment of a random complex waveform

The segment therefore has N+1 data points, and is Nt seconds in duration. There is no immediate necessity for t to be constant, though in practice it generally will be. Should it vary, the formulae below, particularly with respect to interval length, should be modified. The following formulation is restricted to a constant sampling period t.

Consider duration within this segment of length k time steps. There are k+1 data points for this duration. The sample begins at data point p. It thus extends to include, and end on, data point $p + k$. This is shown in Figure A.2.



Key

k is the length of the duration under consideration in time steps

p is the starting position of the duration

Figure A.2 – Definition of a duration within a sample

The RMS value of the current over this duration is given by

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$$i_{\text{interval}}^{\text{RMS}} = \sqrt{\frac{1}{k+1}\sum_{m=p}^{p+k} i_m^2}$$

The RMS value for all possible durations of length k within the segment are calculated and the maximum value found. To generate the RMS value for all possible durations of length k, take the duration starting at point i_0 and ending at i_k, and find the RMS of this duration. Steps are then taken through successive durations of length k, successively beginning at i_1 i_2 i_3 until there are no further durations of length k. The final duration of length k will begin at $i_{N\text{-}k}$ and end at i_N, and a further step of length k is not possible. This flags the stopping point for consideration of all durations of length k.

The maximum RMS of these durations gives the probable current (PC) point corresponding to the time kt. That is:

$$\text{PC}_{kt} = \text{MAX}_{p=0}^{N-k} \left(\sqrt{\frac{1}{k+1}\sum_{m=p}^{p+k} i_m^2} \right)$$

This is then repeated for all values of k from 1 to N. That is,

$$\text{PC}_{kt} = \text{MAX}_{p=0}^{N-k} \ldots \left(\sqrt{\frac{1}{k+1}\sum_{m=p}^{p+k} i_m^2} \right) \quad \forall k = 1 \ldots N$$

This may be computationally intensive, and while the complete definition of the PC curve is given by this relation, individual users may wish simply to select a subset of the values of k to identify a smaller number of points on the PC curve.

In summary, the PC curve is found by processing sequential portions of the data of a given time duration to obtain the RMS current in each duration. This is achieved by stepping through the data, beginning one data digit later each time, until all RMS current values for this time duration are generated. The maximum RMS current, for this time duration, is chosen and gives one point on the PC curve corresponding to this given time duration. The process is then repeated for successively longer time durations to provide sufficient points for a PC curve (maximum RMS current versus time duration) on the graph (the method is therefore not a moving average RMS as the time-length durations are controlled and successively increased).

The application of the technique is shown in more detail in the following demonstration and examples.

In particular, comments are made on the comparison curve with which the PC is compared, and also on the choice of t, the sample step size.

A.3 Demonstration of the calculation

A.3.1 General

Consider a segment of a given waveform digitized with t = 20 ms, the sample step size.

In this demonstration ten current values at 20 ms sampling steps (20 ms, 40 ms, 60 ms … 200 ms) are sequentially 5 mA, 7 mA, 8 mA, 4 mA, 9 mA, 11 mA, 9 mA, 7 mA, 3 mA, and 1 mA. The PC ("probable current") is to be extracted for all possible durations for successively longer durations. At each duration considered, the maximum RMS, for that duration, is chosen

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as the PC point for that duration. The points thus found for succeeding durations form the PC curve.

1) The method proceeds as follows.
2) To obtain the RMS values, the current values are initially squared so the current squared at sampling steps (20 ms, 40 ms, 60 ms …200 ms) are sequentially 25 mA^2, 49 mA^2, 64 mA^2, 16 mA^2, 81 mA^2, 121 mA^2, 81 mA^2, 49 mA^2, 9 mA^2, and 1 mA^2. Squaring the values also ensures that positive and negative excursions are considered equally.
3) The first duration chosen is 20 ms, there is thus only one sample in this duration. The maximum value is 121 mA^2. Therefore the PC value for all possible 20 ms durations is the maximum 11 mA, and is plotted at 20 ms (see Figure A.3).
4) The next duration chosen is 60 ms, therefore three samples in each such duration. The PC value for each 60 ms duration is calculated thus, recalling the division by the number of points (3) in the time duration:
   a) (25 + 49 + 64) $mA^2/3$ = 46,0 mA^2
   b) (49 + 64 + 16) $mA^2/3$ = 43,0 mA^2
   c) (64 + 16 + 81) $mA^2/3$ = 53,7 mA^2
   d) (16 + 81 + 121) $mA^2/3$ = 72,7 mA^2
   e) (81 + 121 + 81) $mA^2/3$ = 94,3 mA^2
   f) (121 + 81 + 49) $mA^2/3$ = 83,7 mA^2
   g) (81 + 49 + 9) $mA^2/3$ = 46,3 mA^2
   h) (49 + 9 + 1) $mA^2/3$ = 19,7 mA^2

The maximum value is 94,3 mA^2 therefore the PC value for three data point groups is 9,7 mA, plotted at 60 ms (see Figure A.3).

The next duration chosen is 120 ms, there are therefore six samples in each such duration. The PC value for each 120 ms duration is calculated thus, recalling the division by the number of points (6) in the time duration:

a) (25 + 49 + 64 + 16 + 81 + 121) $mA^2/6$ = 59,3 mA^2
b) (49 + 64 + 16 + 81 + 121 + 81) $mA^2/6$ = 68,7 mA^2
c) (64 + 16 + 81 + 121 + 81 + 49) $mA^2/6$ = 68,7mA^2
d) (16 + 81 + 121 + 81 + 49 + 9) $mA^2/6$ = 59,5mA^2
e) (81 + 121 + 81 + 49 + 9 + 1) $mA^2/6$ = 57,0 mA^2

The maximum value is 68,7 mA^2 therefore the PC value is 8,3 mA, and is plotted at 120 ms (see Figure A.3).

The PC curve is derived from these values and is plotted in Figure A.3.

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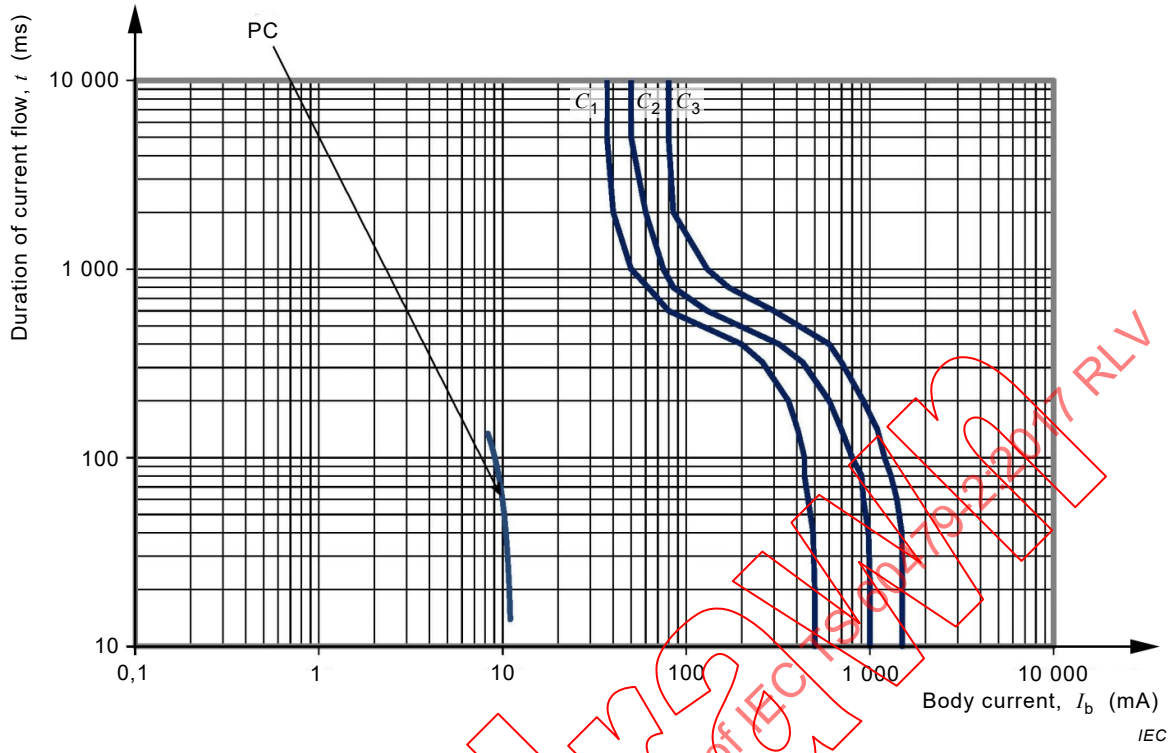

Figure A.3 – PC for demonstration example of the random complex waveform method plotted against time-current curves for RMS AC

The justified current (JC) in this demonstration was chosen as c_1. At no time does the PC exceed the JC so this situation is considered acceptably safe on the criteria specified.

A.3.2 Choice of justified current

This method allows data to be reduced and compared with traditional RMS data found in Figure 20 of IEC TS 60479-1:2005. The appropriate level for justified current to make this comparison shall be chosen.

In various applications a more conservative value than c_1 might be deemed necessary, for example, a product committee may wish to design a specific application. They may choose a justified current value of less than c_1. In any case, c_1 should not exceed the justified current.

It should be noted that the method does not take into account the reduction in VF threshold for closely succeeding pulses. If these pulses are suspected then a lesser value for the justified current can be chosen recognizing repeated burst analysis as described elsewhere in IEC TS 60479-2.

A.3.3 Choice of sampling step size

The choice of sampling step size t is made after scrutiny of the waveform. In one sense, the sample value i might be considered best as the RMS value of the maximum in that period. This however implies a much faster sampling interval, and substantial processing of the samples before an output at any chosen step p. It is considered this adds a greater degree of complexity than warranted. It also requires a much more complex sampling regime than is usually available.

Thus the current i_p are instantaneous values at any step p, given the chosen sampling step size t. Should this be considered to “hide” important detail, a smaller t should be chosen.

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As with all choices regarding the waveform, the analysis may be revisited with different choices.

A.4 Examples 1 and 2

Two examples of the use of the method in more real circumstances follow. The waveform that is used in these examples is a waveform that is close to that for which the method would be used in real analysis. The waveforms have been generated on a Monte Carlo basis.

The typical appearance of the random complex waveform examples which are generated as described below is as follows (see Figures A.4, A.5 and A.6).

Example 1

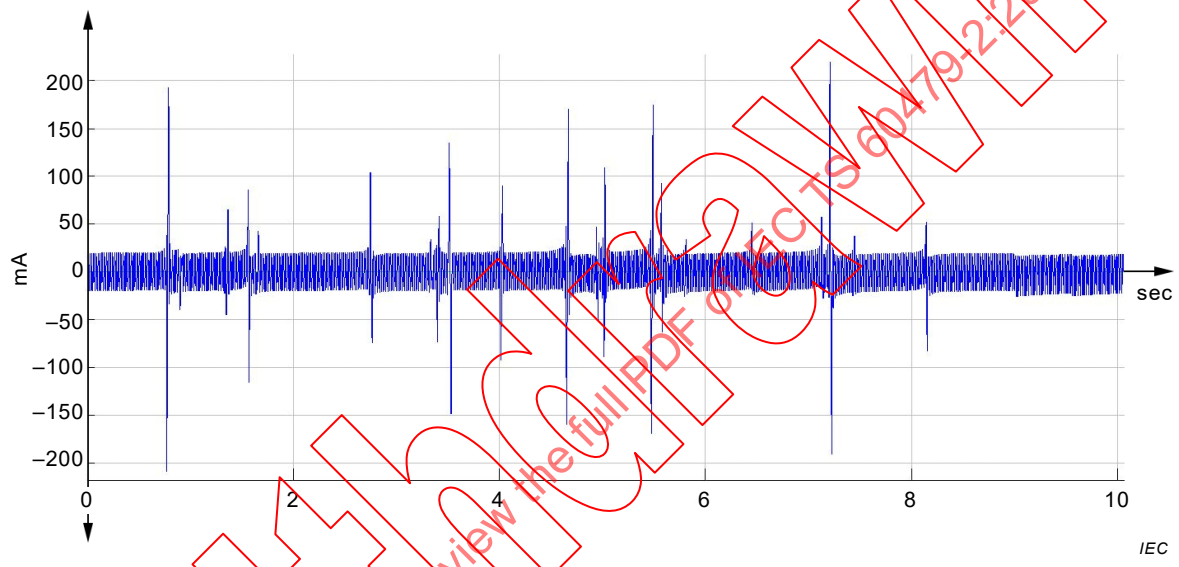

Figure A.4 – Random complex waveform typical of those used in Example 1

Example 1 uses a random complex waveform with the following parameters:

i) A 50 Hz current waveform, safe from the viewpoint of not causing VF, forms a background wave. It is a 20 mA RMS waveform. The length of the data segment is 10 s.

ii) Into this sample, 50 pulses, in random positions within the 10 s, of random width up to 10 ms, are added. The set of pulses are inserted with amplitude randomly up to 200 mA. Reference to Figure 22 of IEC TS 60479-1:2005 should convince us that these are also safe.

iii) Adjustment: for the sake of these examples only, and this will not be the case in “real” analysis, every pulse is matched by an equal and opposite pulse occurring immediately after. This is simply to ensure that the DC mean of the pulses is zero. It will be appreciated that if the DC mean is not zero, this mean will accumulate throughout the analysis especially in longer segments, and will affect the PC. This may well be what is required in “real” situations, but zero mean is used here so that the expected effects of the pulses versus a cumulating DC offset can be isolated.

iv) The signals are filtered by low pass filter (LPF), with cut-off 100 Hz. The filter is a high order LPF, using digital filtering techniques. The RMS values of the segments are found.

The nine second segment is examined at time durations of 20 ms, 50 ms, 100 ms, 200 ms, 500 ms, 1 000 ms, 2 000 ms, and 5 000 ms.

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The PC is calculated at each of these durations, and is plotted with the c_1, c_2, c_3-curves of Figure 20 of IEC TS 60479-1:2005 and shown in Figure A.6 below.

In comparison with a JC taken as c_1, this waveform is not likely to cause VF.

Example 2

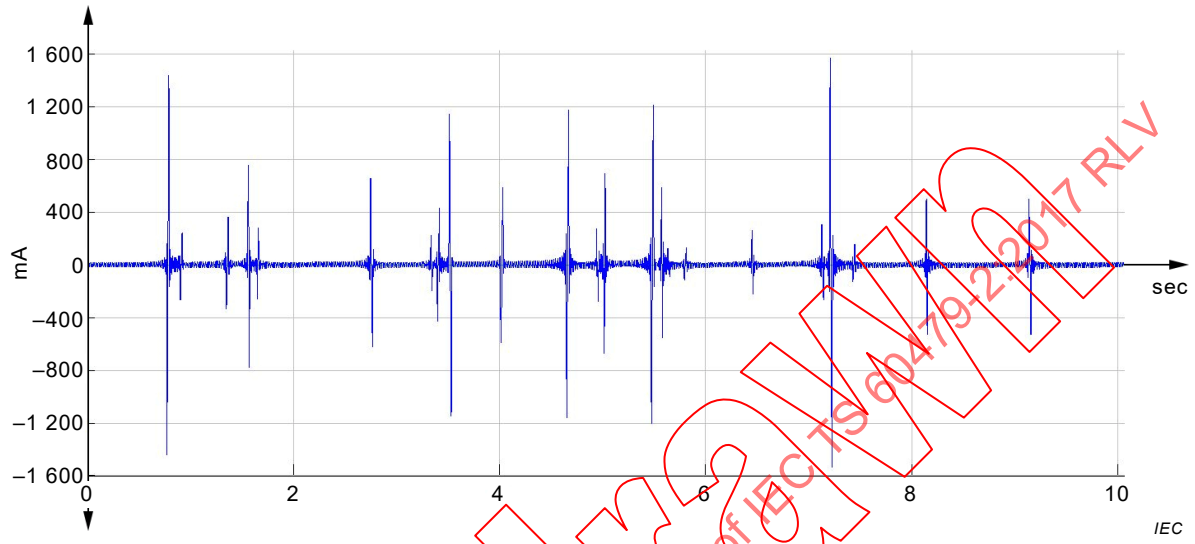

Figure A.5 – Random complex waveform typical of those used in Example 2

Example 2 is a random complex waveform with the following parameters

i) A 50 Hz current waveform, safe from the viewpoint of not causing VF, forms a background wave. It is a 20 mA RMS waveform. The length of the data segment is 10 s.

ii) Into this sample, 50 pulses, in random positions within the 10 s, of random width up to 10 ms, are added. The set of pulses are inserted with amplitude randomly up to 1 500 mA. Reference to Figure 22 of IEC TS 60479-1:2005 should convince us that these are likely to cause VF.

iii) Adjustment: A similar adjustment for clarity is made as in Example 1.

iv) The signals are filtered by low pass filter (LPF), with cut-off 100 Hz, in the same manner as in Example 1.

v) Same value as in Example 1.

The nine second sample is examined at time durations of 20 ms, 50 ms, 100 ms, 200 ms, 500 ms, 1 000 ms, 2 000 ms, and 5 000 ms.

The PC is calculated at each of these durations, and is plotted with the c_1, c_2, c_3-curves of Figure 20 of Figure 20 of IEC TS 60479-1:2005 and shown in Figure A.6 below.

In comparison with a JC taken as c_1, for this waveform VF induction cannot be excluded.

Both these examples therefore yield results in accord with expectations.

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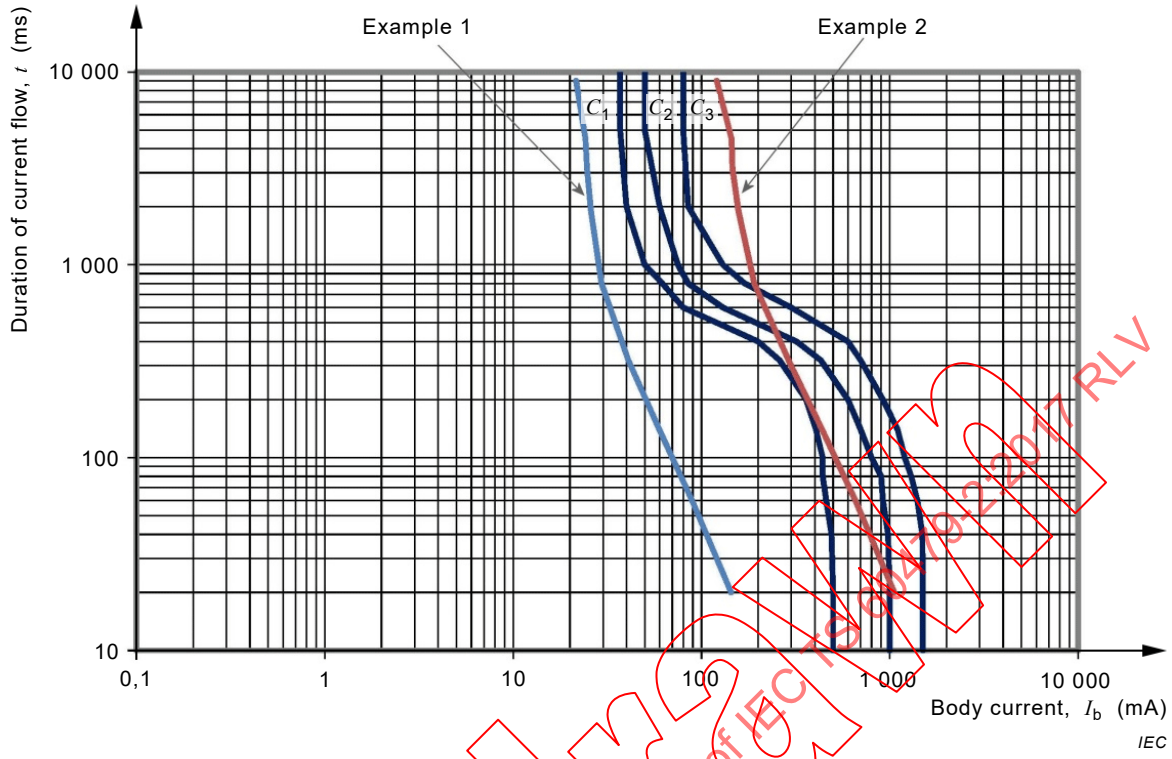

Figure A.6 – PC for Examples 1 and 2 of the random complex waveform method plotted against time-current curves for RMS AC

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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EFFECTS OF CURRENT ON HUMAN BEINGS AND LIVESTOCK –

Part 2: Special aspects

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- the required support cannot be obtained for the publication of an International Standard, despite repeated efforts, or
- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical Specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 60479-2, which is a Technical Specification, has been prepared by IEC technical committee 64: Electrical installations and protection against electric shock.

This fourth edition cancels and replaces the third edition, published in 2007. This edition constitutes a technical revision.

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This edition includes the following significant technical changes with respect to the previous edition:

- Changes reflecting the change in applicability of frequency from 1 kHz to 150 kHz have been added.
- The examination of random complex irregular waveforms has been added.
- The handling of successive DC pulses has been clarified.

The text of this Technical Specification is based on the following documents:

Draft TS	Report on voting
64/2143/DTS	64/2166/RVDTS

Full information on the voting for the approval of this Technical Specification can be found in the report on voting indicated in the above table.

This Technical Specification has the status of a basic safety publication in accordance with IEC Guide 104.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 60479 series, published under the general title *Effects of current on human beings and livestock*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- transformed into an International standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

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EFFECTS OF CURRENT ON HUMAN BEINGS AND LIVESTOCK –

Part 2: Special aspects

1 Scope

This part of IEC 60479 describes the effects on the human body when a sinusoidal alternating current in the frequency range above 100 Hz passes through it.

The effects of current passing through the human body for:

– alternating sinusoidal current with DC components;
– alternating sinusoidal current with phase control;
– alternating sinusoidal current with multicycle control

are given but are only deemed applicable for alternating current frequencies from 15 Hz up to 100 Hz.

Means of extending the frequency of applicability of pure sinusoids to a frequency of 150 kHz are given, supplementing the data in IEC TS 60479-1.

Means of examining random complex irregular waveforms are given.

This document describes the effects of current passing through the human body in the form of single and multiple successive unidirectional rectangular impulses, sinusoidal impulses and impulses resulting from capacitor discharges.

The values specified are deemed to be applicable for impulse durations from 0,1 ms up to and including 10 ms.

This document only considers conducted current resulting from the direct application of a source of current to the body, as does IEC TS 60479-1 and IEC TS 60479-3. It does not consider current induced within the body caused by its exposure to an external electromagnetic field.

This basic safety publication is primarily intended for use by technical committees in the preparation of standards in accordance with the principles laid down in IEC Guide 104 and ISO/IEC Guide 51. It is not intended for use by manufacturers or certification bodies.

One of the responsibilities of a technical committee is, wherever applicable, to make use of basic safety publications in the preparation of its publications. The requirements, test methods or test conditions of this basic safety publication will not apply unless specifically referred to or included in the relevant publications.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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IEC TS 60479-1:2005, *Effects of current on human beings and livestock – Part 1: General aspects*
IEC TS 60479-1:2005/AMD1:2016

IEC 60990, *Methods of measurement of touch-current and protective conductor current*

ISO/IEC Guide 51, *Safety aspects – Guidelines for their inclusion in standards*

IEC Guide 104, *The preparation of safety publications and the use of basic safety publications and group safety publications*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 60479-1 and the following apply.

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

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

3.1
frequency factor
F_f
ratio of the threshold current for the relevant physiological effects at the frequency f to the threshold current at 50/60 Hz.

Note 1 to entry The frequency factor differs for perception, let-go and ventricular fibrillation.

3.2
phase control
process of varying the instant within the cycle at which current conduction in an electronic valve device or a valve arm begins

[SOURCE: IEC 60050-551:1998, 551-16-23]

3.3
phase control angle
current delay angle
time expressed in angular measure by which the starting instant of current conduction is delayed by phase control

[SOURCE: IEC 60050-551:1998, 551-16-32, modified — the term "phase control angle" has been added.]

3.4
multicycle control
process of varying the ratio of the number of cycles which include current conduction to the number of cycles in which no current conduction occurs

[SOURCE: IEC 60050-551:1998, 551-16-31]

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3.5
multicycle control factor
p
ratio between the number of conducting cycles and the sum of conducting and non-conducting cycles in the case of multicycle control

SEE Figure 13.

[SOURCE: IEC 60050-551:1998, 551-16-37, modified — the symbol and reference to Figure 13 have been added.]

3.6
specific fibrillating energy
F_e
minimum $I^2 \cdot t$ value of a unidirectional impulse of short duration which under given conditions (current-path, heart-phase) causes ventricular fibrillation with a certain probability

Note 1 to entry: F_e is determined by the form of the impulse as the integral

$$\int_0^{t_i} i^2 dt$$

where t_i is defined in Figure 20 and Figure 21. F_e multiplied by the body resistance gives the energy dissipated in the human body during the impulse.

Note 2 to entry: F_e is expressed in Ws/Ω or A^2s.

3.7
specific fibrillating charge
F_q
minimum $I \cdot t$ value of unidirectional impulse of short duration which under given conditions (current-path, heart-phase) causes ventricular fibrillation with a certain probability

Note 1 to entry: F_q is determined by the form of the impulse as the integral

$$\int_0^{t_i} i dt$$

where t_i is defined in Figure 20 and Figure 21.

Note 2 to entry: F_q is expressed in C or As.

3.8
time constant
time required for the amplitude of an exponentially decaying quantity to decrease to

$$\frac{1}{e} = 0{,}3679$$

times an initial amplitude

[SOURCE: IEC 60050-801:1994, 801-21-45, modified — the definition has been revised.]

3.9
shock-duration of a capacitor discharge
t_i
time interval from the beginning of the discharge to the time when the discharge current has fallen to 5 % of its peak value

Note 1 to entry: When the time constant of the capacitor discharge is given by T the shock-duration of the capacitor discharge is equal to $3T$. During the shock-duration of the capacitor discharge practically all the energy of the impulse is dissipated.

Note 2 to entry: See Figure 20 and Figure 21.

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3.10
shock-duration for complex asymptotic waveform
t_i
shortest duration of that part of the impulse that contains 95 % of the energy over the total impulse

3.11
threshold of perception
minimum value for the charge of electricity which under given conditions causes any sensation to the person through whom it is flowing

3.12
threshold of pain
minimum value for the charge ($I \cdot t$) or specific energy ($I^2 \cdot t$) that can be applied as an impulse to a person holding a large electrode in the hand without causing pain

3.13
pain
unpleasant experience such that it is not readily accepted a second time by the subject submitted to it

EXAMPLE: Electric shock above the threshold of pain described in 11.3, the sting of a bee or burn of a cigarette.

4 Effects of alternating currents with frequencies above 100 Hz

NOTE Values for 50/60 Hz are given in IEC TS 60479-1. For frequencies up to 100 Hz the provisions of IEC TS 60479-1 are used.

4.1 General

Electric energy in the form of alternating current at frequencies higher than 50/60 Hz is increasingly used in modern electrical equipment, for example aircraft (400 Hz), power tools and electric welding (mostly up to 450 Hz), electrotherapy (using mostly 4 000 Hz to 5 000 Hz) and switching mode power supplies (20 kHz to 1 MHz).

Little experimental data is available for Clause 4, therefore the information given herein should be considered as provisional only but may be used for the evaluation of risks in the frequency ranges concerned (see Bibliography).

Recent experiments in governmental funded projects are ongoing to exploit and investigate the effects of higher frequencies using the latest technologies and methods to justify existing extrapolation of the frequency factor for ventricular fibrillation (VF) threshold.

Attention is also drawn to the fact that the impedance of human skin decreases approximately inversely proportional to the frequency for touch voltages in the order of some tens of volts, so that the skin impedance at 500 Hz is only about one-tenth of the skin impedance at 50 Hz and may be neglected in many cases. This impedance of the human body at such frequencies is therefore reduced to its internal impedance Z_i (see IEC TS 60479-1).

NOTE Use of peak measurements: at current levels that produce physiological responses of perception, startle reaction and inability of let-go, the physiological response from non sinusoidal and mixed frequency periodic current is best indicated by the peak value of an output signal from measuring circuits containing a frequency-weighting network such as those described in IEC 60990.

These frequency weighting networks attenuate the signal according to the frequency factors given in IEC TS 60479-1:2005 and IEC TS 60479-1:2005/AMD1:2016, Clause 4 so that the output signal corresponds to a constant level of physiological response. Attenuation is provided for narrow impulses of current that would produce less physiological response because of the short duration of their peak value. The network output allows a fixed value to be read independent of waveshape or mix of frequencies to be provided for ease of determination of the leakage current and evaluation of the level of hazard present.

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Comparable physiological effects are produced by non sinusoidal and sinusoidal current producing the same peak value by this measurement method.

Representative network can be found in IEC 60990 and in bibliographic reference [16][1].

4.2 Effects of alternating current in the frequency range above 100 Hz up to and including 1 000 Hz

4.2.1 Threshold of perception

For the threshold of perception the frequency factor is given in Figure 1.

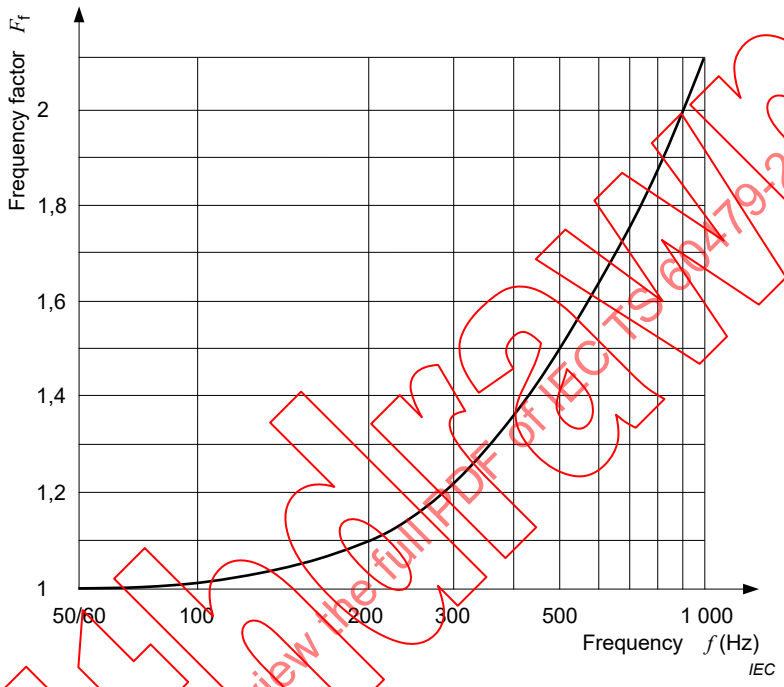

Figure 1 – Variation of the threshold of perception within the frequency range 50/60 Hz to 1 000 Hz

4.2.2 Threshold of let-go

For the threshold of let-go the frequency factor is given in Figure 2.

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1 Numbers in square brackets refer to the Bibliography.

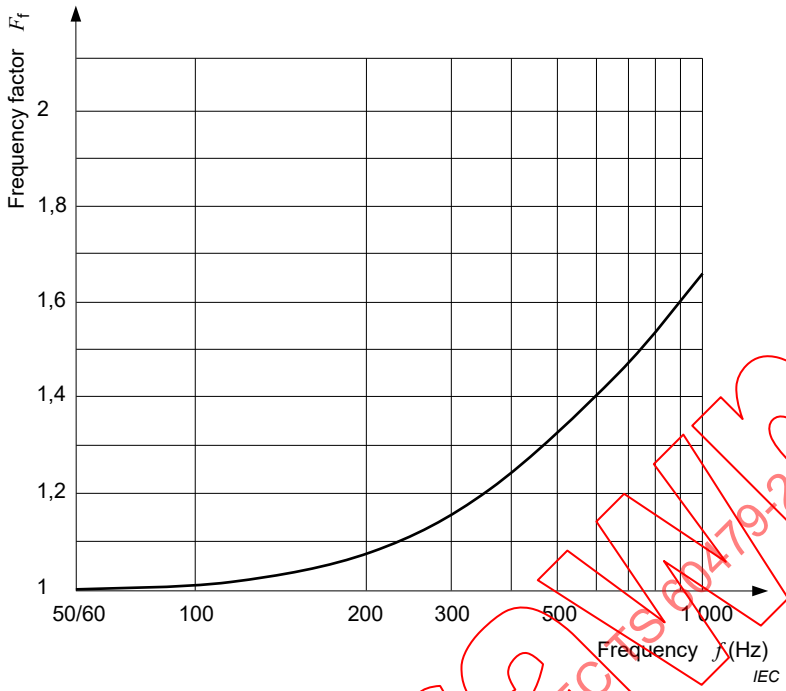

Figure 2 – Variation of the threshold of let-go within the frequency range 50/60 Hz to 1 000 Hz

4.2.3 Threshold of ventricular fibrillation

For shock durations longer than the cardiac cycle, the frequency factor for the threshold of fibrillation for longitudinal current paths through the trunk of the body is given in Figure 3.

For shock durations shorter than the cardiac cycle no experimental data is available on the effects of frequency.

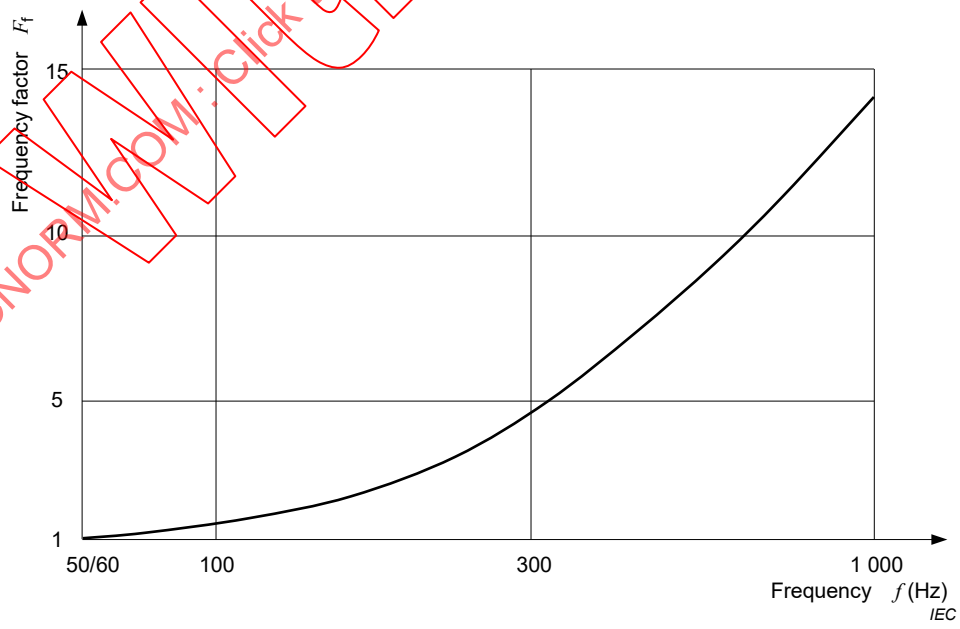

Figure 3 – Variation of the threshold of ventricular fibrillation within the frequency range 50/60 Hz to 1 000 Hz, shock durations longer than one heart period and longitudinal current paths through the trunk of the body

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4.3 Effects of alternating current in the frequency range above 1 000 Hz up to and including 10 000 Hz

4.3.1 Threshold of perception

For the threshold of perception the frequency factor is given in Figure 4.

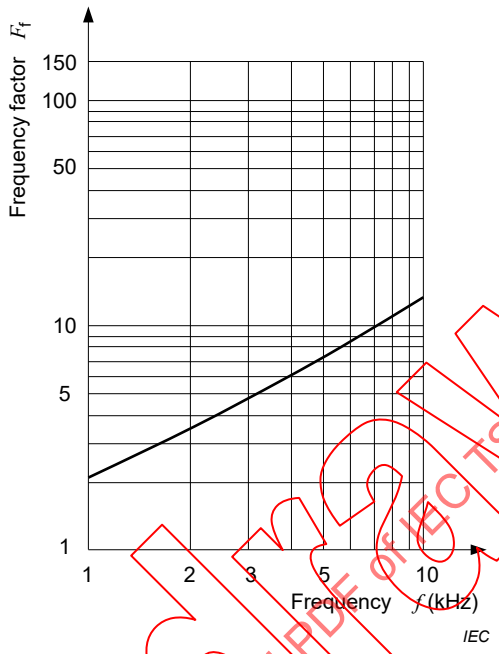

Figure 4 – Variation of the threshold of perception within the frequency range 1 000 Hz to 10 000 Hz

4.3.2 Threshold of let-go

For the threshold of let-go the frequency factor is given in Figure 5.

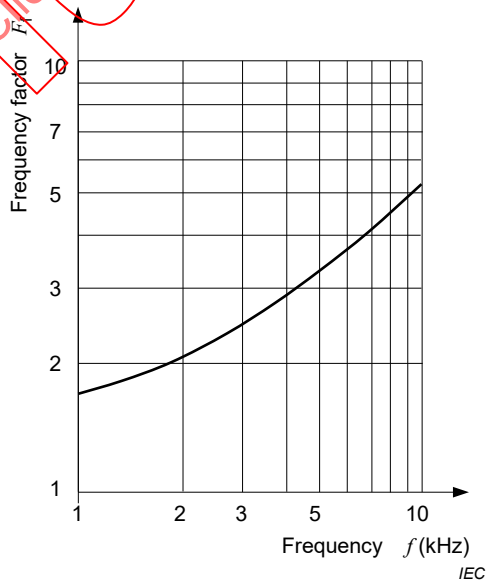

Figure 5 – Variation of the threshold of let-go within the frequency range 1 000 Hz to 10 000 Hz

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4.3.3 Threshold of ventricular fibrillation

For frequencies between 1 000 Hz and 10 000 Hz the provisions of 4.4.4 are used.

4.4 Effects of alternating current in the frequency range above 10 000 Hz

4.4.1 General

In 4.4, changes have not been made to the threshold of perception, or the threshold of let-go for higher frequencies. While these are important thresholds, the most dangerous is that of ventricular fibrillation. The fibrillation threshold is therefore given up to 150 kHz. The remaining thresholds may be considered as in the paragraphs below up to the frequency limits shown.

4.4.2 Threshold of perception

For frequencies between 10 kHz and 100 kHz the threshold rises approximately from 10 mA to 100 mA (RMS values).

For frequencies above 100 kHz the tingling sensation characteristic for the perception at lower frequencies changes into a sensation of warmth for current intensities in the order of some hundred milliamperes.

4.4.3 Threshold of let-go

For frequencies above 100 kHz there is neither experimental data nor reported incidents concerning the threshold of let-go.

4.4.4 Threshold of ventricular fibrillation

For shock durations longer than the cardiac cycle, the frequency factor for the threshold of fibrillation for longitudinal current paths through the trunk of the body for the frequency range above 1000 Hz up to and including 150 kHz is given in Figure 6.

For frequencies above 1 kHz, thermal effects are more likely to become dominant.

For shock durations shorter than the cardiac cycle, no experimental data is available.

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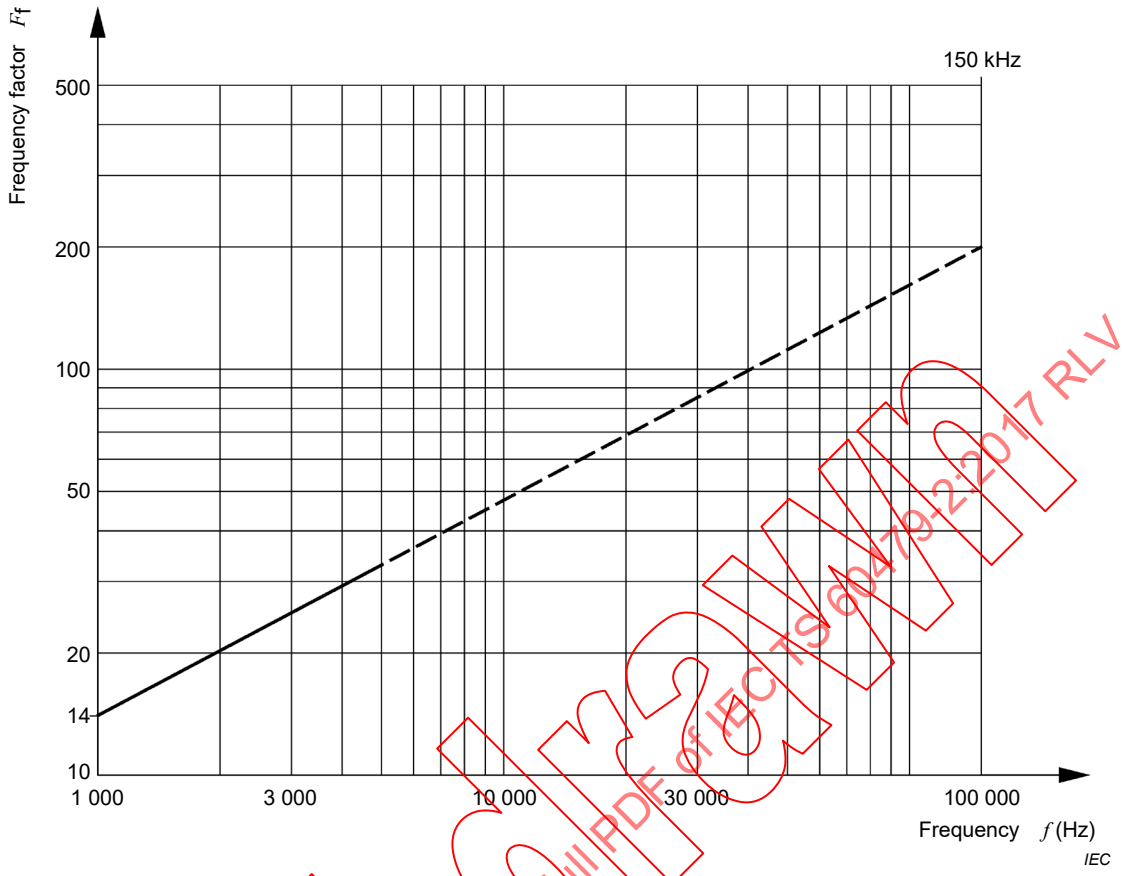

Figure 6 – Variation of the threshold of ventricular fibrillation for continuous sinusoidal current for use from 1 000 Hz to a maximum of 150 kHz

4.4.5 Other effects

Burns may occur at frequencies above 100 kHz and current magnitudes in the order of amperes depending on the duration of the current flow.

5 Effects of special waveforms of current

5.1 General

As is to be expected, the effects of such currents on the human body are between those caused by direct and by alternating current; therefore equivalent current magnitudes with regard to ventricular fibrillation can be established.

Clause 5 describes the effects of current passing through the human body for:

– alternating sinusoidal current with DC components,
– alternating sinusoidal current with phase control,
– alternating sinusoidal current with multicycle control.

NOTE Other waveforms are under consideration.

The information given is deemed applicable for alternating current frequencies from 15 Hz up to 100 Hz.

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5.2 Equivalent magnitude, frequency and threshold

In 5.2 the hazard may be taken as being approximately the same effect as with an equivalent pure alternating sinusoidal current I_{ev} having the following characteristics:

– Magnitude equivalence:

The following current magnitudes have to be distinguished:

I_{RMS} = RMS value of the current of the proposed waveform,

I_p = peak value of the current of the proposed waveform,

I_{pp} = peak-to-peak value of the current of the proposed waveform,

I_{ev} = RMS value of a sinusoidal current presenting the same effect as the waveform concerned.

NOTE The current I_{ev} is used instead of the current I_B in Figures 20 and 22 of IEC TS 60479-1:2005 to estimate the risk of ventricular fibrillation.

Most physiological effects are related to the filtered peak current (in magnitude and in duration) with the natural body filter defined by the frequency factor F. The peak value of the current should be used in all cases except where there is a known relationship between the RMS value and the peak value, i.e. pure sinusoidal current.

– Frequency equivalence

The waveform under study has a time period equal to the period of the equivalent sinusoidal waveform.

– Threshold equivalence

The different current thresholds (perception, inability of let-go and ventricular fibrillation) for waveforms consisting of specific ratio of alternating to direct current is equivalent as for a pure sinusoidal alternating current with a current having the characteristic equal to I_{ev}.

This I_{ev} value is different for each of these thresholds.

5.3 Effects of alternating current with DC components

5.3.1 Waveforms and frequencies and current thresholds

Figure 7 shows typical waveforms which are dealt with in 5.3.1. Pure DC and pure AC are represented as well as combined waveforms of various ratios AC to DC.

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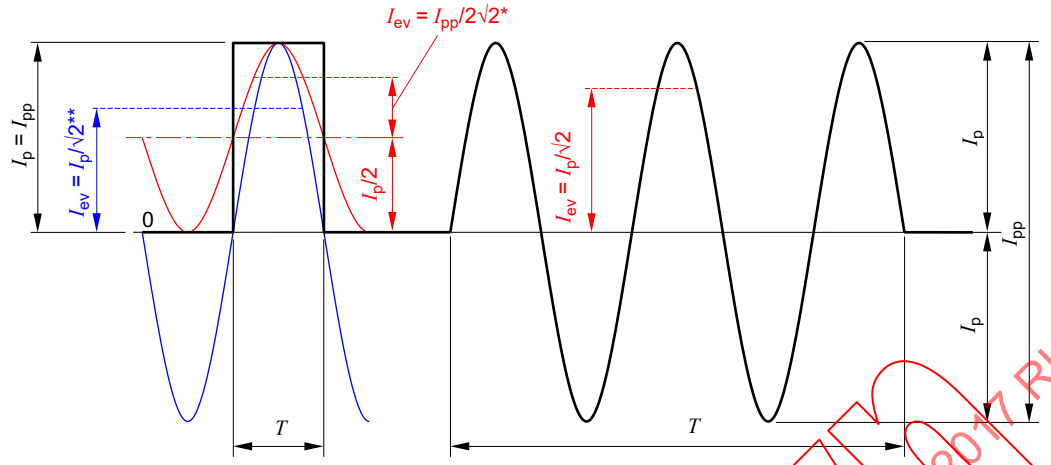
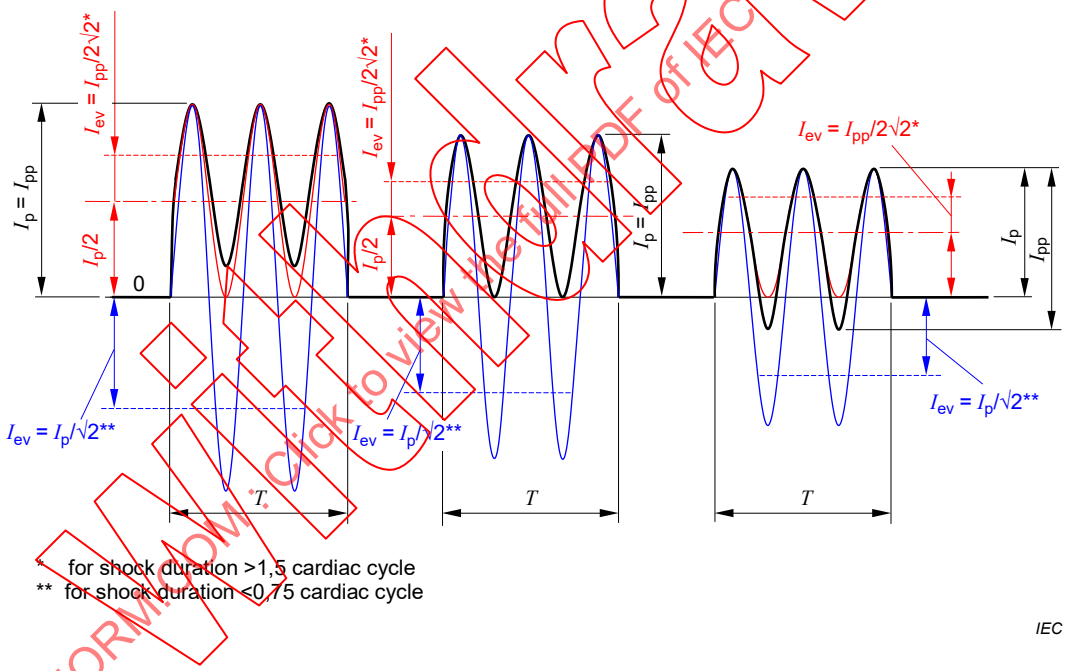


a) Combined waveforms of various ratios AC to DC together with rectangle pulse for shock duration >1,5 and <0,75 of the cardiac cycle



b) Combined waveforms of various ratios AC to DC of mixed frequencies for shock duration >1,5 and <0,75 of the cardiac cycle

Figure 7 – Waveforms of currents

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5.3.2 Threshold of startle reaction

The threshold of startle reaction depends on several parameters such as the area of the body in contact with an electrode (contact area), the conditions of contact (dry, wet, pressure, temperature) and also on the physiological characteristics of the individual.

These effects are related to the peak value of the current [13] and the currents have to be combined frequency by frequency to estimate the total effect. A measurement circuit is described in IEC 60990.

5.3.3 Threshold of let-go

The threshold of let-go depends on several parameters, such as the contact area, the shape and the size of the electrodes and also on the physiological characteristics of the individual.

From the standpoint of let-go (hand contacts with energized circuitry that can last a few seconds), this document uses Figure 5 in the referenced Dalziel paper [17] to determine the let-go current threshold for combinations of alternating current and direct current. The frequency of the alternating current in this case was 60 Hz. 7,07 mA peak AC (5 mA RMS for a sinusoidal current) and 30 mA DC were used as the touch current thresholds for pure AC and DC respectively. These thresholds are considered to be adequate to represent the entire population (including children) from inability to let-go.

The equation, $I_{AC\ peak}$ = 7,176 x exp (– 0,143 4 x DC) – 0,106 1, represents this combined AC and DC case and may be used to calculate the result of any combination of AC and DC in the range specified.

The following Figure 8 illustrates the Dalziel information.

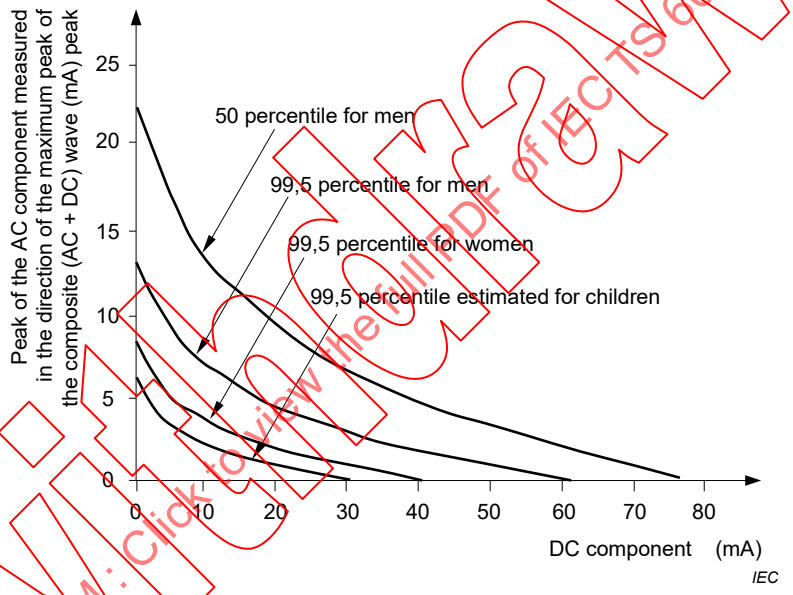

Figure 8 – Let-go thresholds for men, women and children

The above curves can be described by an equation fitted to the data.

The equation, $I_{AC\ peak}$ = 12,890 5 x exp (–0,069 39 x DC) – 0,190 5, represents the 99,5 percentile curve for men.

The equation, $I_{AC\ peak}$ = 8,523 x exp (–0,104 9 x DC) – 0,126, represents the 99,5 percentile curve for women.

The equation, $I_{AC\ peak}$ = 6,394 5 x exp (–0,138 8 x DC) – 0,094 5, represents the 99,5 percentile estimated curve for children.

For practical considerations, some standards allow for some ripple (e.g. up to 10 %) on a DC supply as an exception.

Figure 9 shows the let-go threshold expressed in peak mA for combinations of 50/60 Hz sinusoidal alternating current and direct current. The peak of the composite AC and DC wave

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in mA at the let-go threshold estimated for the population of humans, including children, is shown as a function of the direct current component in mA.

Figure 9 is represented by the equation for the composite current:

$I_{AC\ peak} + I_{DC} = 7{,}176 \times \exp(-0{,}143\ 4 \times DC) - 0{,}106\ 1 + DC$

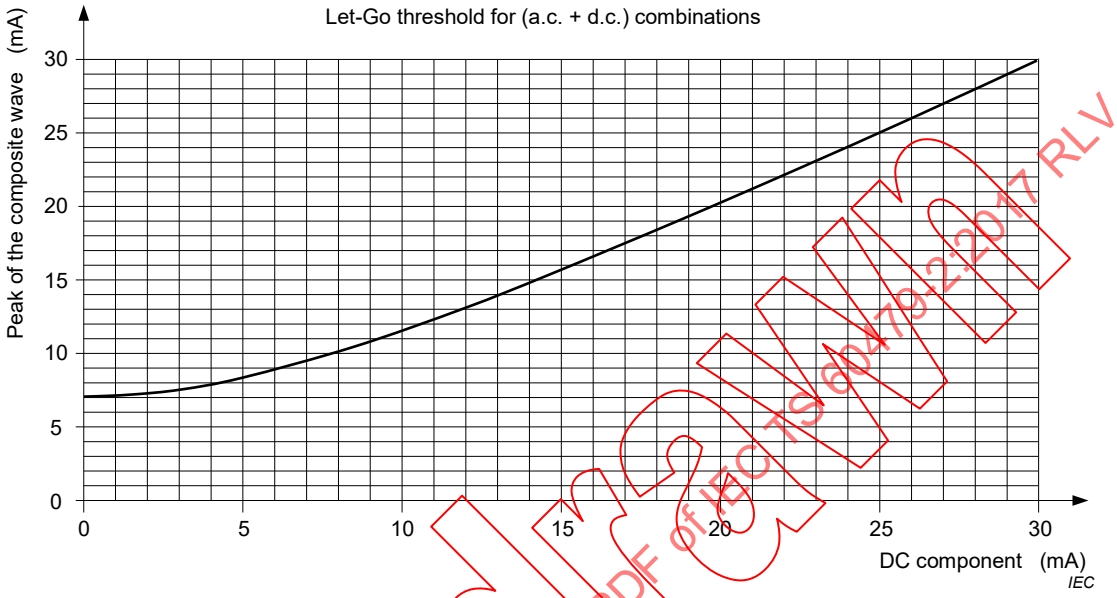

Figure 9 – 99,5 percentile let-go threshold for combinations of 50/60 Hz sinusoidal alternating current and direct current

These effects are related to the peak value of the current [6] and the currents have to be combined frequency by frequency to estimate the total effect. A measurement circuit is described in IEC 60990.

5.3.4 Threshold of ventricular fibrillation

5.3.4.1 Waveforms consisting of specific ratios of alternating to direct current

The fibrillation hazard may be taken as being approximately the same as with an equivalent alternating sinusoidal current I_{ev} having the following characteristics:

a) For shock durations longer than approximately 1,5 times the period of the cardiac cycle, I_{ev} is the RMS value of the sinusoidal alternating current having the same peak-to peak value I_{pp} as the current of the waveform concerned.

$$I_{ev} = \frac{I_{pp}}{2\sqrt{2}}$$

b) For shock durations shorter than approximately 0,75 times the period of the cardiac cycle, I_{ev} is the RMS value of the sinusoidal alternating current having the same peak value I_p as the current of the waveform concerned.

$$I_{ev} = \frac{I_p}{\sqrt{2}}$$

NOTE 1 This correlation is the least applicable the smaller the ratio AC to DC becomes. For pure DC shocks of a duration less than 0,1 s the threshold is equal to the corresponding RMS value of the alternating current (see Figure 20 and Figure 22 in IEC TS 60479-1:2005 respectively).

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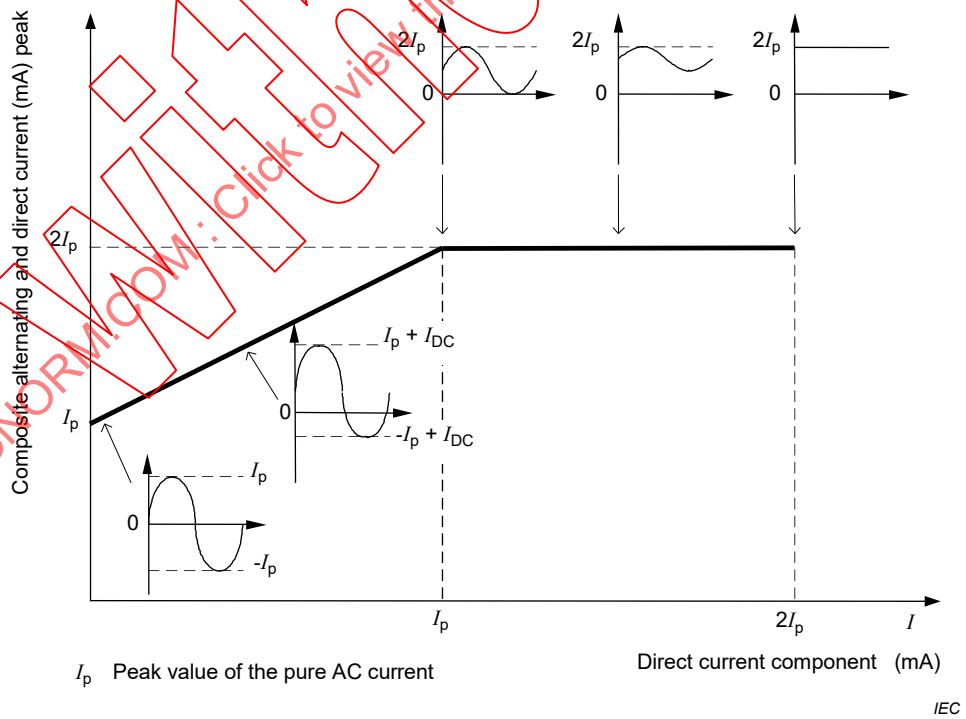
c) In the duration range from 0,75 to 1,5 times the period of the cardiac cycle, the amplitude parameter changes from peak value to peak-to-peak value.

NOTE 2 The details of the nature of the transition that takes place are subject to further studies.

According to Knickerbocker's findings [5], the likelihood of ventricular fibrillation for a combination of 50/60 Hz sinusoidal alternating and direct current lasting a few seconds or more is the same for a purely sinusoidal current of the same duration if the following is true. The pure 50/60 Hz sinusoidal alternating current has the same peak-to-peak value as the peak-to-peak value of the combination current waveform provided that the direct current component is not large enough to preclude reversal of the instantaneous current (to prevent zero crossing) during each cycle. For example, the combination of a 40 mA RMS 50/60 Hz sinusoidal current combined with direct current up to $40 \cdot \sqrt{2}$ mA has approximately the same likelihood of causing ventricular fibrillation as a 40 mA RMS 50/60 Hz sinusoidal current alone.

Where the exposure is a few seconds or more and the direct current component is large enough so that the instantaneous current does not reverse during each cycle, then the composite of alternating plus direct current has the same likelihood of ventricular fibrillation when the peak value of the composite current is the same as the peak-to-peak value of the 50/60 Hz purely sinusoidal alternating current. For example, the combination of a 50/60 Hz sinusoidal current and direct current with a peak value of $80 \cdot \sqrt{2}$ mA $\left(2 \cdot I_p\right)$ (with no reversal of the instantaneous current during each cycle) has approximately the same likelihood of causing ventricular fibrillation as a 40 mA RMS 50/60 Hz sinusoidal current with no direct current added.

Figure 10 illustrates an example in which the likelihood of ventricular fibrillation for sinusoidal alternating current (including 20 Hz, 50 Hz, and 60 Hz) combined with direct current is the same.



NOTE The peak to peak value I_{pp} remains constant up until the I_p value and then the peak value of the composite remains constant at a value of two times the peak of the AC with no DC component.

Figure 10 – Composite alternating and direct current with equivalent likelihood of ventricular fibrillation

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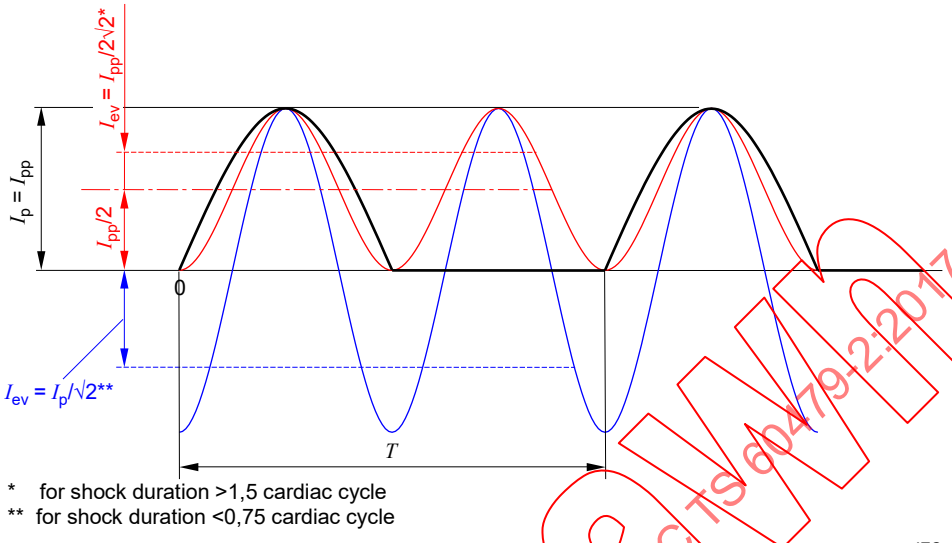
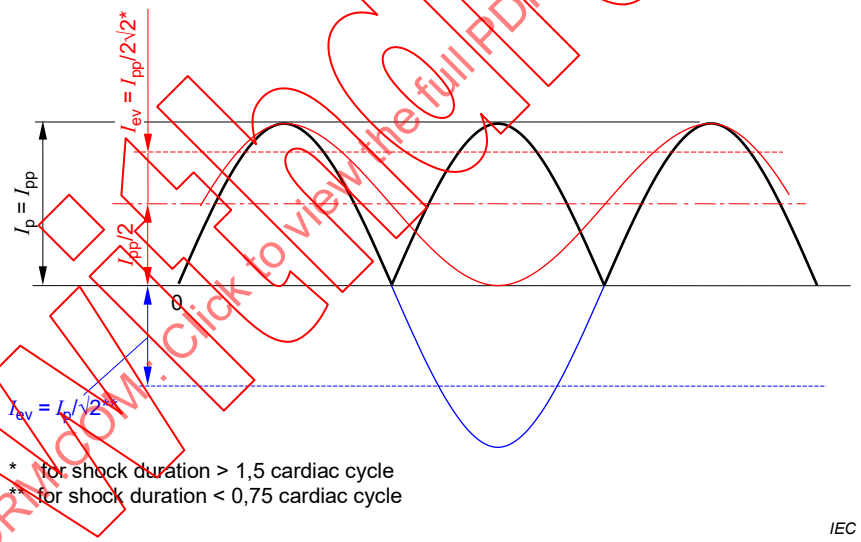
5.3.4.2 Examples of rectified alternating current

Figure 11 shows the waveforms for half wave and full wave rectification. For these waveforms the peak value of the current is identical to its peak-to-peak value.



a) Half wave rectification



b) Full wave rectification

Figure 11 – Waveforms of rectified alternating currents

The equivalent alternating current I_{ev} is determined:

a) for durations longer than 1,5 times the period of the cardiac cycle by:

$$I_{ev} = \frac{I_{pp}}{2\sqrt{2}} = \frac{I_p}{2\sqrt{2}}$$

hence for the half wave rectification, I_{ev} is related to the RMS value of the rectified current I_{RMS} by:

$$I_{ev} = \frac{I_{RMS}}{\sqrt{2}}$$

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and the full wave rectification by:

$$I_{ev} = \frac{I_{RMS}}{2}$$

b) For durations shorter than 0,75 times the period of the cardiac cycle by:

$$I_{ev} = \frac{I_{pp}}{\sqrt{2}} = \frac{I_{p}}{\sqrt{2}}$$

hence for the half wave rectification, I_{ev} is related to the RMS value of the rectified current I_{RMS} by:

$$I_{ev} = \sqrt{2} I_{RMS}$$

and the full wave rectification by:

$$I_{ev} = I_{RMS}$$

In the case of both let-go and ventricular fibrillation, the body current is expected to flow through the limbs and torso for a few seconds. For example, a cadenced ringing signal on a telephone circuit can typically last around two seconds before the signal is interrupted with a pause (between rings). If a person is in contact with a part that is energized by a burst of ringing signal, the person's body might conduct current from the signal for a few seconds. In the case of a cadenced ringing signal, a person might be unable to let go during the time while the signal is "on". If this occurs, the signal shall not be capable of producing ventricular fibrillation. It was assumed that when the signal pauses between bursts of the ringing signal, the person can release the conductive part and get away from the circuit.

6 Effects of alternating current with phase control

6.1 Waveforms and frequencies and current thresholds

Figure 12 shows the waveforms for symmetrical and asymmetrical control.

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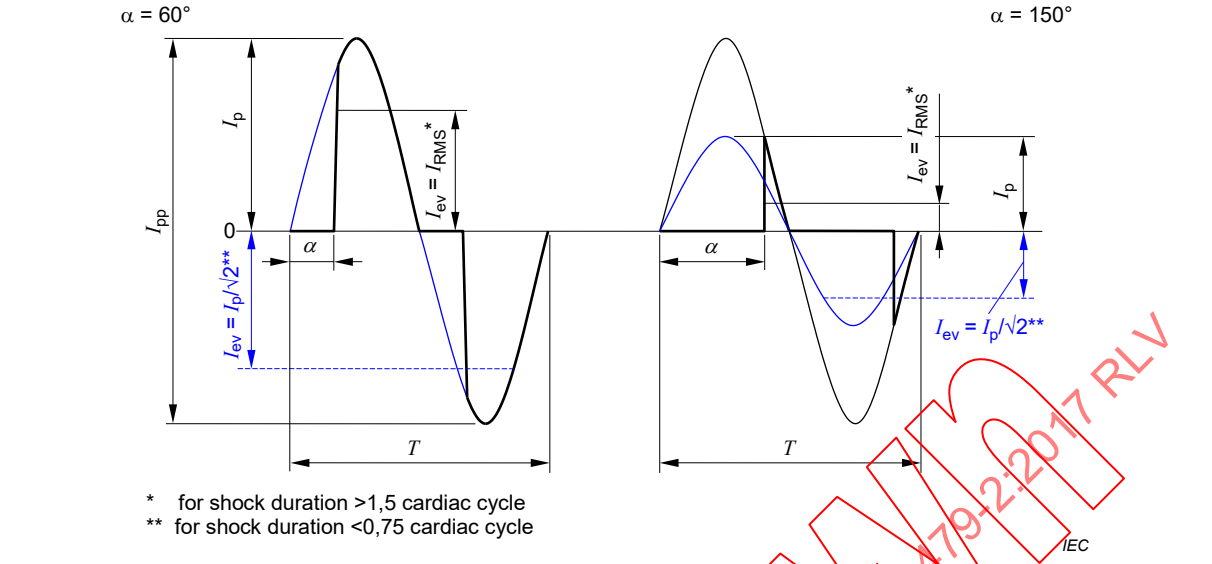
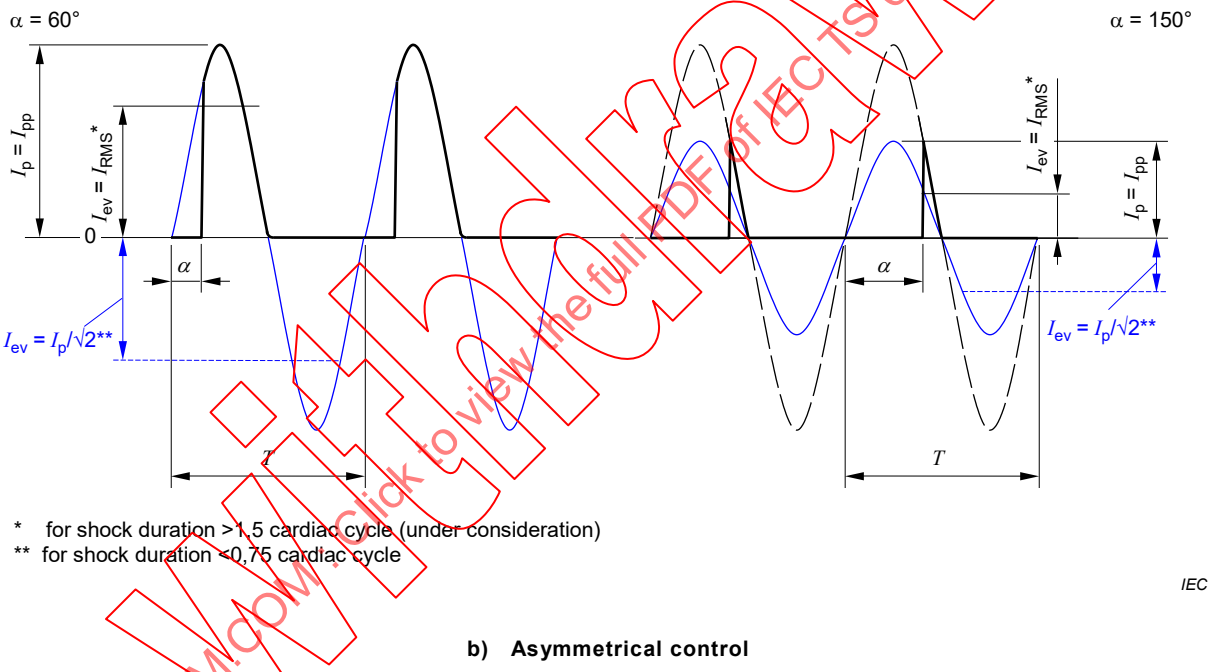


a) Symmetrical control



b) Asymmetrical control

Figure 12 – Waveforms of alternating currents with phase control

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6.2 Threshold of startle reaction and threshold of let-go

As described in 5.3.2 and 5.3.3, these thresholds depend on different parameters.

The effects of the current in producing sensation or inhibiting let-go are about equal to a pure AC with the same peak value I_p. For phase control angles above 120° the peak values increase as a consequence of the decreasing duration of the current flow.

These effects are related to the peak value of the current [13] and they have to be combined frequency per frequency to estimate the total effect. This is easily done using the measurement circuit in IEC 60990.

6.3 Threshold of ventricular fibrillation

6.3.1 General

The thresholds differ for symmetrical and asymmetrical waveforms.

6.3.2 Symmetrical control

The fibrillation hazard may be taken as being approximately the same as with equivalent alternating current I_{ev} having the following characteristics:

a) for shock durations longer than approximately 1,5 times the period of the cardiac cycle, I_{ev} has the same RMS value as the current of the relevant waveform concerned;

b) for shock durations shorter than approximately 0,75 times the period of the cardiac cycle, I_{ev} is the RMS value of a current having the same peak value as the current of the relevant waveform concerned;

NOTE For phase control angles above 120° a rise of the threshold of fibrillation is to be expected.

c) in the duration range from 0,75 to 1,5 times the period of the cardiac cycle, the amplitude parameters change from peak to RMS value.

6.3.3 Asymmetrical control

The fibrillation hazard may be taken as being approximately the same as with the equivalent alternating current I_{ev} having the following characteristics:

For shock durations shorter than approximately 0,75 times the period of the cardiac cycle, I_{ev} is the RMS value of a current having the same peak value as the current of the relevant waveform concerned.

NOTE 1 For phase control angles above 120° a rise of the threshold of fibrillation is to be expected.

NOTE 2 Currents caused by asymmetrical control (see IEC 60050-551:1998, 551-16-25) can also have DC components.

7 Effects of alternating current with multicyle control

7.1 Waveforms and frequencies

Figure 13 shows the waveforms for a degree of power control of p = 0,67.

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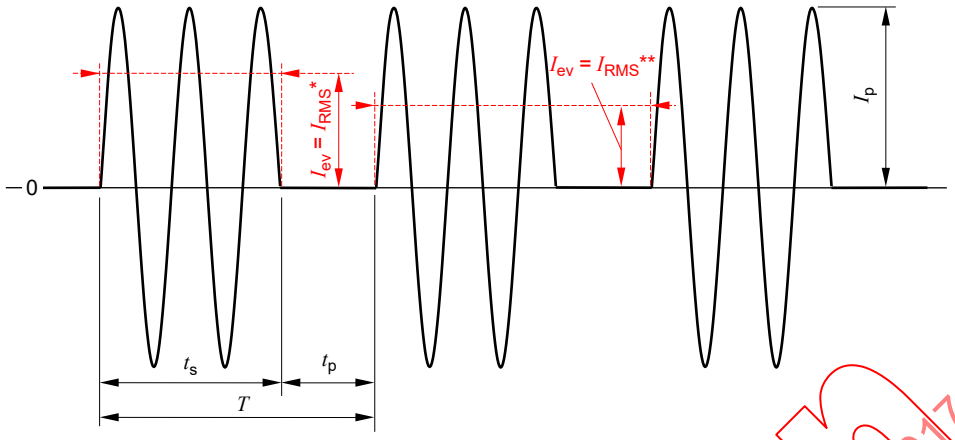

* for shock duration >1,5 cardiac cycle and p <<1 or shock duration < 0,75 cardiac cycle

** for shock duration <0,75 cardiac cycle and $p \approx 1$

Key

$$p = \frac{t_s}{t_s + t_p}$$

where

t_s = conducting time

t_p = non-conducting time

$T_s + t_p$ = working period

p = degree of power control

$I_{1RMS} = \frac{I_p}{\sqrt{2}}$ = RMS value of current during current conduction.

NOTE I_{1RMS} is not to be confused with the RMS value of current during the working period $I_{2RMS} = I_{RMS}\sqrt{p}$.

Figure 13 – Waveforms of alternating currents with multicycle control

7.2 Threshold of startle reaction and threshold of let-go

As described in 5.3.2, 5.3.3 and 6.2, these thresholds depend on different parameters.

These effects are related to the peak value of the current [13] and the currents have to be combined frequency by frequency to estimate the total effect.

7.3 Threshold of ventricular fibrillation

7.3.1 General

Depending on the duration of shock and the degree of power control, alternating currents with multicycle control are equally or less dangerous than alternating currents of the same shock duration and current magnitude.

Figure 14 shows the variation of the ventricular fibrillation threshold for various degrees of power control from experiments with pigs [7].

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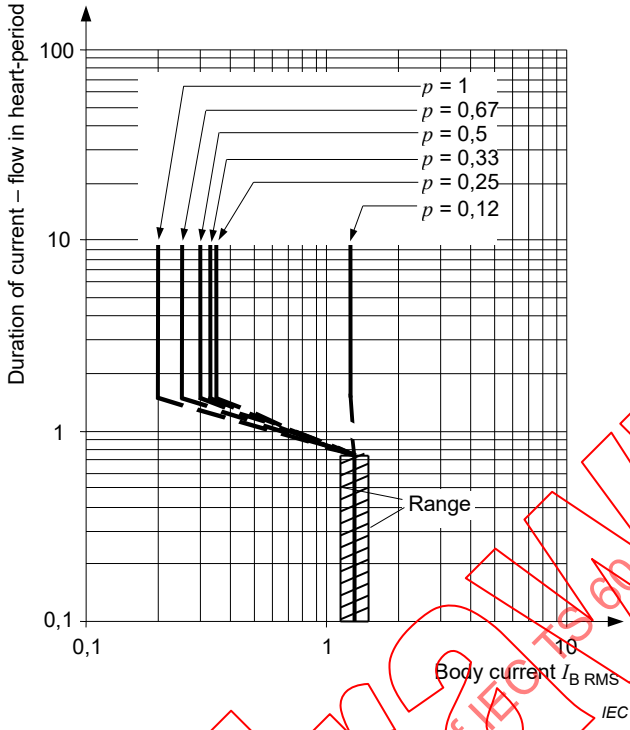

NOTE Body current I_{BRMS} is the RMS value of the current during current conduction I_{1RMS}.

Figure 14 – Threshold of ventricular fibrillation (average value) for alternating current with multicycle control for various degrees of controls (results of experiments with young pigs)

7.3.2 Shock durations longer than 1,5 times the period of the cardiac cycle

For shock durations longer than approximately 1,5 times the period of the cardiac cycle, the threshold depends on the degree of power control p. For p near the unity, it has the same RMS value as the sinusoidal alternating current of the same duration. For p near 0,1 the RMS value of the current during current conduction, I_{1rms} is the same as the threshold for alternating current of a duration below 0,75 times the period of the cardiac cycle.

NOTE For intermediate values of p, the fibrillation threshold rises from the low level shown in Figure 20 in IEC TS 60479-1:2005 to the high level indicated for shock duration below 0,1 s.

7.3.3 Shock durations less than 0,75 times the period of the cardiac cycle

For shock durations shorter than approximately 0,75 times the period of the cardiac cycle, the RMS value of the current during the current conduction, I_{1RMS} is the same as that for a sinusoidal alternating current of 0,1 s duration.

8 Estimation of the equivalent current threshold for mixed frequencies

8.1 Threshold of perception and let-go

These effects are related to the peak value of the current [13] and the currents have to be combined frequency by frequency to estimate the total effect.

8.2 Threshold of ventricular fibrillation

The ventricular fibrillation hazard caused by a current having multiple frequencies may be estimated as a rough approximation as equivalent to the hazard caused by a pure alternating current having the following characteristics:

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– fundamental frequency,
– with an amplitude I_{ev} equivalent to the quadratic summation of all component amplitudes individually affected by the appropriate frequency factor as provided in Figure 3

$$I_{ev} = \sqrt{\sum_{i=1}^{n}\left(\frac{I_i}{F_i}\right)^2}$$

This result of combining waveforms presumes only a relationship between the peak value and the RMS value of the composite waveform. The physiological effect depends on the phase angle relationship among the contributing frequencies which needs to be known and is not considered in this estimate.

9 Effects of current pulse bursts and random complex irregular waveforms

9.1 Ventricular fibrillation threshold of multiple pulses of current separated by 300 ms or more

Ventricular fibrillation can be considered unlikely to occur from the passage of a single pulse of current through the heart if the combination of magnitude and duration is below the c_1 curve shown in Figure 22 of IEC TS 60479-1:2005. These considerations also apply to a single pulse of direct current with no significant AC component.

Pulses of current that are separated from each other by an interval that is equal to or greater than 300 ms do not have cumulative effects on the heart and may therefore be treated individually as if they were single, non-repetitive pulses of current. When the pulses of current in a series are separated from each other by at least 300 ms, a comparison of the magnitude and duration of each pulse of current individually to the c_1 curve may be used to determine the ventricular fibrillation hazard.

9.2 Ventricular fibrillation threshold of multiple pulses of current separated by less than 300 ms

9.2.1 General

Pulses of current through the heart that are separated by less than 300 ms can create disturbances in the heart with cumulative effects. These cumulative effects can lead to ventricular fibrillation even though each pulse of current in the series is significantly lower than the threshold for ventricular fibrillation applicable to each of the single pulse of current occurring alone.

Short pulses of current through the heart that are separated by less than 300 ms can launch activation wavefronts with increasing heterogeneity. The cumulative effect of these wavefronts is an increase of wave splitting which leads to VF. However, with pulse spacing of less than 100 ms the effect is very definite [32], [33].

The first pulse of current in a series can be evaluated using Figure 20 or Figure 22 of IEC TS 60479-1:2005, whichever is appropriate. The threshold for ventricular fibrillation applicable to the second pulse of current can be as low as approximately 65 % of the threshold applicable to the first pulse. This process can continue until the threshold reaches a minimum after several pulses. The minimum threshold may only be approximately 10 % or less of the threshold applicable to the first current pulse [14], [18], [19], [20].

Table 1 provides an estimate of the threshold of ventricular fibrillation that is applicable to current pulse in a series as a worst case. The quiet times between the current pulses, if less than 300 ms, are insufficient to allow the effects of the previous current pulses to fully subside.

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Each pulse of current is sufficient in magnitude and duration to excite the heart tissue, and it is assumed that the threshold of ventricular fibrillation decreases by 35 % after each pulse of current if the spacing is < 100 ms.

Table 1 – Example of estimate for ventricular fibrillation threshold after each burst of current in a series of pulses each of which excited the heart tissue

Pulse of current in a series of pulses separated by less than 100 ms, where the first current pulse is in the AC-3 or DC-3 region of Figure 20 or Figure 22 of IEC TS 60479-1:2005	Example estimate of the ventricular fibrillation threshold after each pulse of current in a series of pulses each of which excited the heart tissue %
First current pulse	100
Second current pulse	65
Third current pulse	42
Fourth current pulse	27
Fifth current pulse	18
Sixth current pulse	12
Seventh and subsequent current pulses	10 or less

9.2.2 Examples

Example 1 – Four pulses separated by 500 ms, with little risk from the first, and no cumulation

Consider a series of four rectangular pulses (see Figure 15) of unidirectional current passing through a person's body between the left hand and both feet, where each pulse has a magnitude of 100 mA peak and a duration of 0,01 s. Suppose the pulses are separated from each other by 0,5 s of "off-time". In this example there is a risk of ventricular fibrillation when the pulse current flows upward (feet positive) through the body.

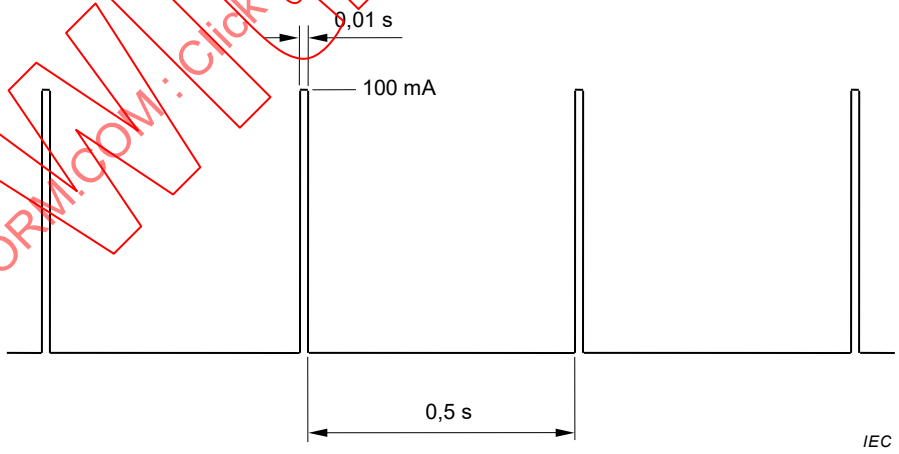

Figure 15 – Series of four rectangular pulses of unidirectional current

According to Figure 22 of IEC TS 60479-1:2005, each of the 0,01 s or 100 mA pulses by itself have no harmful physiological effects (DC-2 region) and are also separated by more than 300 ms. The risk of ventricular fibrillation in this case could be considered low.

Example 2 – Four pulses separated by 500 ms, with significant risk from the first, and no cumulation

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Consider another series of four rectangular pulses (see Figure 16) of unidirectional current passing in the same direction (feet positive) through a person's body between the left hand and both feet.

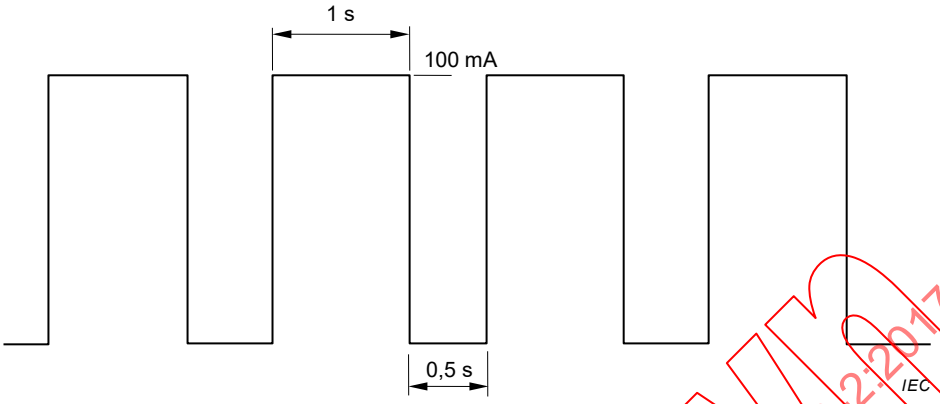

Figure 16 – Series of four rectangular pulses of unidirectional current

Each pulse has the same magnitude of 100 mA peak, but the duration of each pulse "on-time" is increased to 1 s. The separation between pulses is still 0,5 s.

According to Figure 22 of IEC TS 60479-1:2005, each of the pulses by itself is capable of inducing reversible disturbances of formation and conduction of impulses in the heart (DC-3 region).

The pulses are still however separated by more than 300 ms and so the risk of cumulation is low. The pulses may be considered as individual pulses under the same criteria as the first, thus suggesting that each pulse is equally harmful.

Example 3 – Four pulses separated by less than 300 ms, with significant risk from the first, and cumulation

Finally, consider another series of four rectangular pulses of unidirectional current passing in the same direction (feet positive) through a person's body between the left hand and both feet. Each pulse has the same magnitude of 200 mA peak and 100 ms duration, but with 50 ms between pulses instead of 0,5 s (see Figure 17). In this example, there is a risk of ventricular fibrillation.

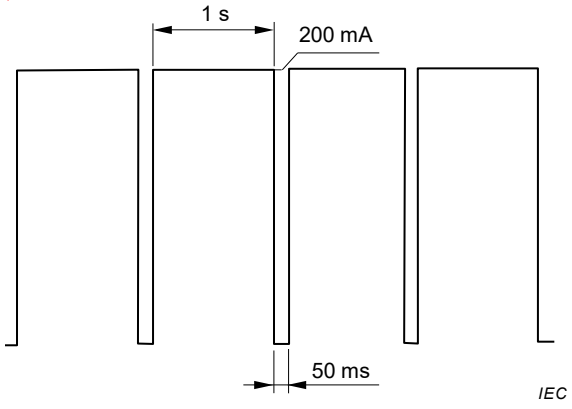

Figure 17 – Series of four rectangular pulses of unidirectional current

According to Figure 22 of IEC TS 60479-1:2005, each of the pulses by itself is capable of inducing reversible disturbances in the heart (DC-3 region), and the 200 ms quiet interval

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between the pulses does not allow the disturbances to subside before the onset of the next pulse occurs in the series. Therefore, there is a full cumulative effect, with the magnitude threshold of the seventh pulse being less than 10 % of the original and the risk of ventricular fibrillation for this series of pulses is high.

9.2.3 Random complex irregular waveforms

In some applications a random complex irregular waveform requires assessment. This type of waveform is not amenable to assessment using other clauses of this document. Such a waveform may arise, for example, in the current crossing a polluted insulator.

In particular, “random” and “complex” imply that

a) there is no observable repetition or pattern to irregularities;

b) the waveform cannot easily be described mathematically;

c) the waveform cannot easily be reduced to examination by harmonic analysis.

An example of a segment of such a waveform is shown in Figure 18. This waveform can be digitally recorded using, for example, an oscilloscope, or a digital acquisition system. The electronic record of the waveform segment may then be assessed for VF danger using digital processing according to an appropriate method. Tasks of this kind may be solved by commonly used mathematical methods like Convolution, Fourier transformation or Wavelet analysis but these approaches are often not convenient for ordinary users. Here a simple, reliable and conservative procedure which transforms the results into Figure 20 of IEC TS 60479-1:2005 is used. The method is that proposed by Pratt [29].

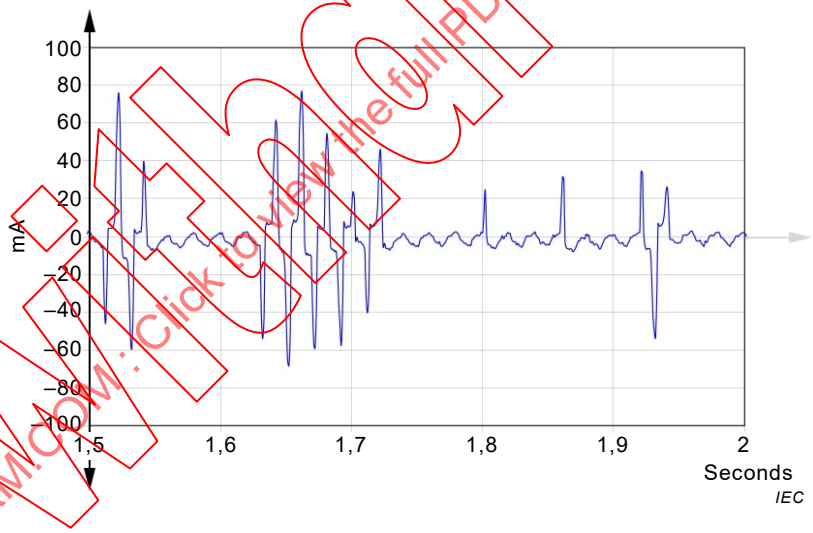

Figure 18 – Example of current versus elapsed time over a contaminated insulator

Data from vulnerability studies on patients implanted with cardiac defibrillators showed that the VF vulnerable interval extended over approximately 60 ms about the peak of the T wave [36] [37]. The analysis of random complex waveforms (RCWs) has been conducted from such perspective. The goal of the analysis was to understand the worst-case stimulation scenarios from the perspective of the extent of the cardiac vulnerable period. Ideally, the worst case scenario would be analysed using moving windows of shapes resembling the shock-strength-vulnerable-period profiles [36]. A simpler, but more conservative, modality employed rectangular windows shifted along the RCW such that the worst-case stimulation strengths were determined. As described below, consistent with the vulnerability theory, various window sizes were used to transverse the RCW, to then find the worst-case stimuli strengths and, finally, to generate a probable current curve.

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The method considers both the effects of the magnitude of the complex exposure to the human and the duration of the complex exposure. It assumes that the human contact could occur at any point in a waveform and for an unspecified time duration. The current to be assessed for risk for any given exposure duration is the largest found for that duration. The method then considers all possible exposure durations in the chosen waveform segment and the maximum magnitude in each to determine the VF danger.

The combination that is the largest in any given duration interval is called the "probable current" (PC), for that interval. The PC is generated from the processing of the digitized waveform according to the method shown in Annex A. When all possible probable currents are found for all possible duration intervals, a PC curve is found. The overall worst case in the waveform segment is therefore found and may be assessed.

The PC is in a format that can be compared with 50 Hz data for which experimental data is available. It is plotted on the same axes as Figure 20 of IEC TS 60479-1:2005. It may therefore be considered that this method is a transform method to map a random complex waveform onto the RMS curve satisfying Figure 20. Prior to assessing the random complex waveform segment it should first be low pass filtered, using a 100 Hz upper frequency cut-off, as Figure 20 is considered valid to 100 Hz.

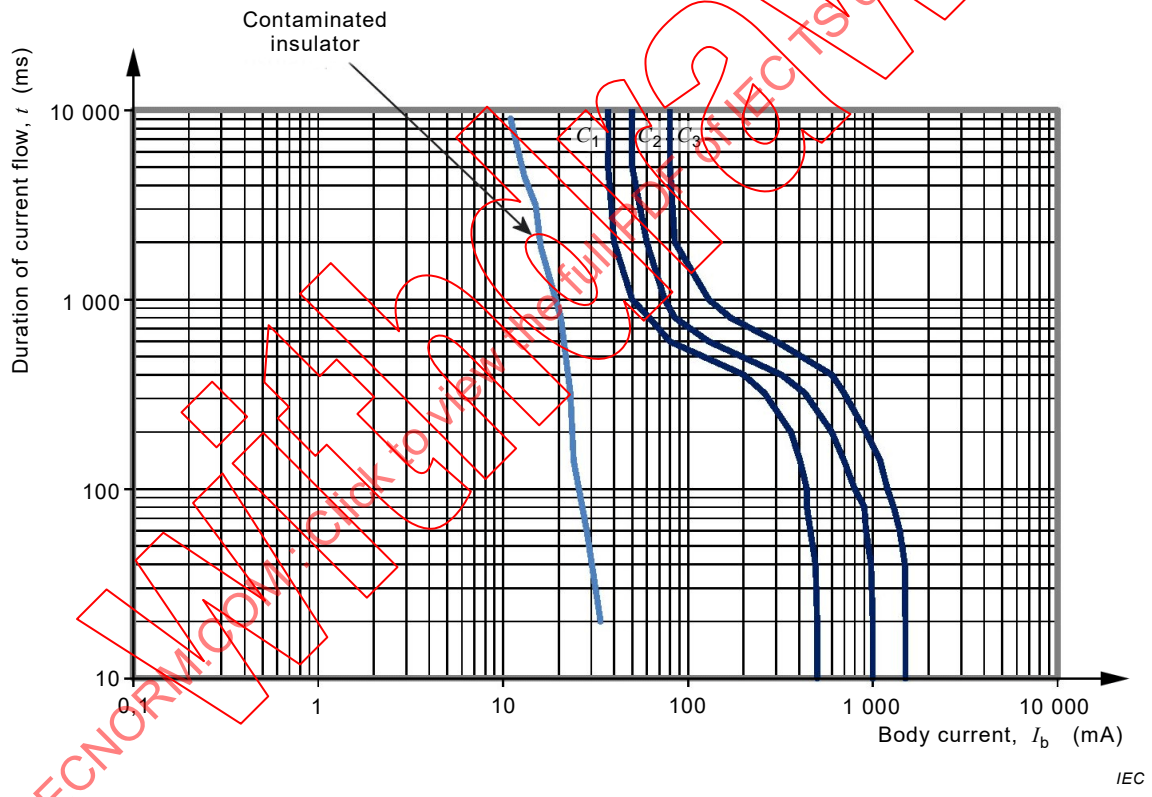

Figure 19 – PC plotted on the AC time current curves (Figure 20 of IEC TS 60479-1:2005)

The waveform is unlikely to cause VF if the PC curve, plotted on Figure 20, lies below a "justified current" (JC) curve. Choosing the JC curve will be examined in Annex A.

See also [32], [33], [38].

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10 Effects of electric current through the immersed human body

10.1 General

Clause 10 discusses the effects of electric current through the human body when the body is immersed in water of various levels of conductivity. Sinusoidal frequencies of 50/60 Hz and direct current are discussed, but the effects of other frequencies might be estimated by applying the information given in other parts of IEC 60479.

NOTE 1 Unless otherwise specified, voltage and current are sinusoidal, and the values are expressed in terms of RMS.

NOTE 2 For the purposes of this document, the term “water” is used to describe pure water as well as solutions of pure water with salts and other impurities in solution.

10.2 Resistivity of water solutions and of the human body

Pure water is essentially non conductive, but when impurities such as salts are added to water, the resistivity of the solution can decrease significantly. Table 2 shows values of resistivity for examples of typical water solutions in which people can be partially or totally immersed.

Table 2 – Resistivity of water solutions [24], [25]

Water solution	Resistivity Ω·cm
Rain water	254 to 420 000
“Standard” hard water	1 780
Tap water (USA)	1 290 to 16 000
Laundry water (tap water with detergent added)	520
“Swimming pool water”	300
Isotonic (normal) saline solution	60
Sea water (Atlantic Ocean, near New York)	22
NOTE Conductivity values in this table are approximate for solutions at room temperature, and will vary with changes in temperature.	

When the human body is immersed in water that conducts an electric current, the path of the electric current through the water is affected by the relative resistivity of the body, which is not homogeneous, and the water. If the water is less resistive than the immersed body (e.g. sea water), much of the current that would have been flowed through the water displaced by the body will flow around the body rather than through it. However, if the water is more resistive than the body (e.g. fresh lake water), a larger portion of the current will take the path of least resistance and “collect” or “concentrate” through the body. The presence of the body distorts the electric field and paths of current flow in the water. The least distortion of the electric fields and current paths will occur when the resistivity of the water is nearly the same as the resistivity of the body parts displacing the water. However, since the body is not homogeneous, the presence of a body in the water will always distort the electric field and current paths to some extent.

The strength of the electric field (in V/cm) is equal to the resistivity (in Ω·cm) times the current density (in A/cm^2). Therefore, for two parallel paths with the same electric field across them, the path with the lower resistivity will carry a proportionately higher current density.

Table 3 shows approximate values of resistivity for examples of various human body parts at normal body temperature [22], [23]. The values apply for low-frequency alternating current or direct current.

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