IEC 60479-2

Edition 1.0 2019-05

INTERNATIONAL STANDARD

colour inside

BASIC SAFETY PUBLICATION

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

IEC 60479-2:2019-05(en)

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

About the IEC
The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications
The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigendum or an amendment might have been published.

IEC publications search - webstore.iec.ch/advsearchform
The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee,…). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished
Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and once a month by email.

IEC Customer Service Centre - webstore.iec.ch/csc
If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: sales@iec.ch.

Electropedia - www.electropedia.org
The world's leading online dictionary on electrotechnology, containing more than 22 000 terminological entries in English and French, with equivalent terms in 16 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

IEC Glossary - std.iec.ch/glossary
67 000 electrotechnical terminology entries in English and French extracted from the Terms and Definitions clause of IEC publications issued since 2002. Some entries have been collected from earlier publications of IEC TC 37, 77, 86 and CISPR.

IEC 60479-2

Edition 1.0 2019-05

INTERNATIONAL STANDARD

colour inside

BASIC SAFETY PUBLICATION

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

INTERNATIONAL ELECTROTECHNICAL COMMISSION

ICS 13.200; 29.020

ISBN 978-2-8322-6689-2

Warning! Make sure that you obtained this publication from an authorized distributor.

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

____

EFFECTS OF CURRENT ON HUMAN BEINGS AND LIVESTOCK –

Part 2: Special aspects

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

International Standard IEC 60479-2 has been prepared by IEC technical committee 64: Electrical installations and protection against electric shock.

This first edition cancels and replaces IEC TS 60479-2:2017. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to IEC TS 60479-2:2017:

a) change in status from Technical Specification to International Standard.

It has the status of a basic safety publication in accordance with IEC Guide 104.

The text of this International Standard is based on the following documents:

CDV	Report on voting
64/2300/CDV	64/2362/RVC

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

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 document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- 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 publication using a colour printer.

INTRODUCTION

In order to avoid errors in the interpretation of this document, it should be emphasized that the data given herein is mainly based on experiments with animals as well as on information available from clinical observations. Only a few experiments with shock currents of short duration have been carried out on living human beings.

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,
– equivalent current threshold for mixed frequencies,
– current pulse bursts and random complex irregular waveforms,
– electric current through the immersed human body, and
– unidirectional single impulse currents of short duration

are described.

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, and
– 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 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 60479-1. 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.

IEC 60479-1:2018, *Effects of current on human beings and livestock – Part 1: General aspects*

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

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

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

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 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]

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

$$\frac{1}{e} = 0,367\ 9$$

times an initial amplitude

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

3.9
shock duration
t_i
<of a capacitor discharge> 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
t_i
<for complex asymptotic waveform> 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 the burn of a cigarette.

4 Effects of alternating currents with frequencies above 100 Hz

NOTE Values for 50/60 Hz are given in IEC 60479-1. For frequencies up to 100 Hz the provisions of IEC 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 government-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 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 60479-1:2018, 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 independently 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 currents producing the same peak values by this measurement method.

A representative network can be found in IEC 60990 and in [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.

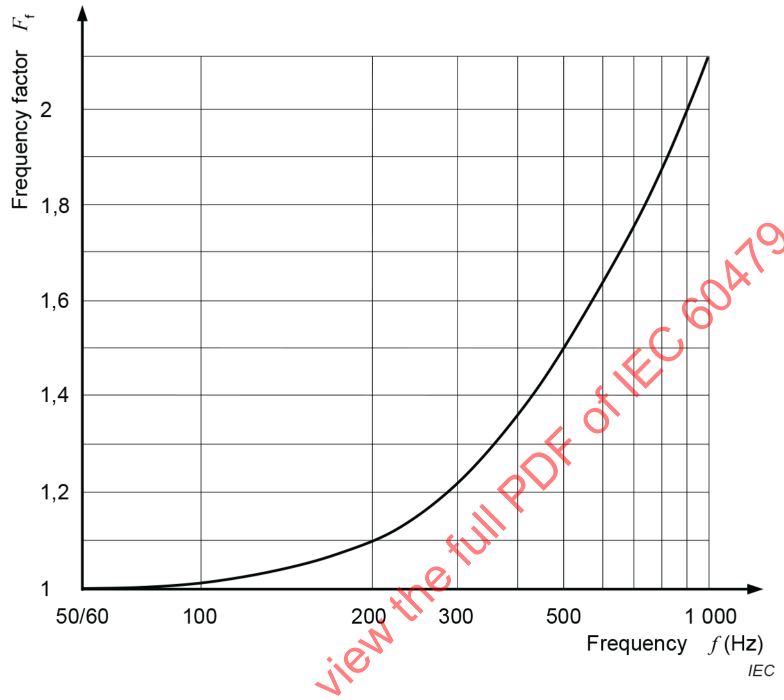


Figure 1 – Variation of the threshold of perception within the frequency range 50/60 Hz to 1 000 Hz

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.

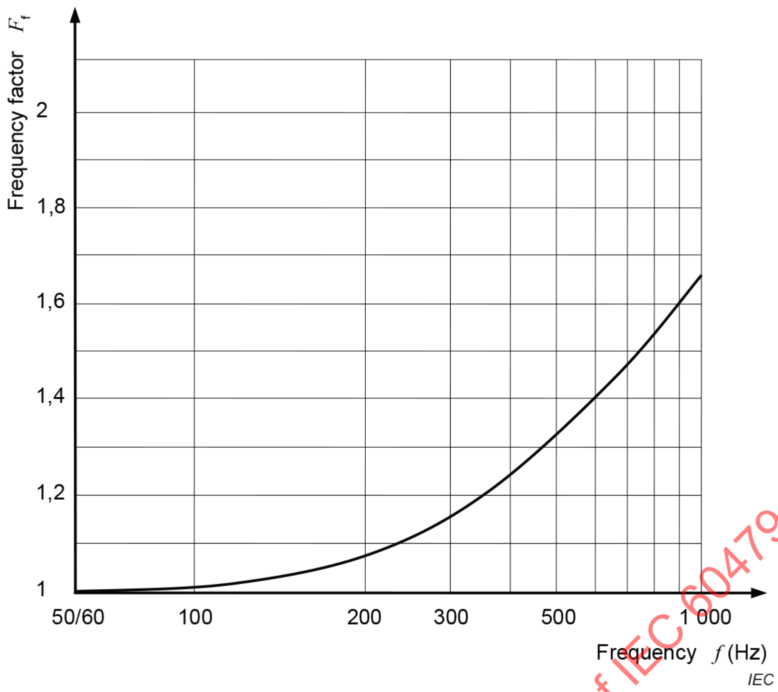


Figure 2 – Variation of the threshold of let-go within the frequency range 50/60 Hz to 1 000 Hz

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.

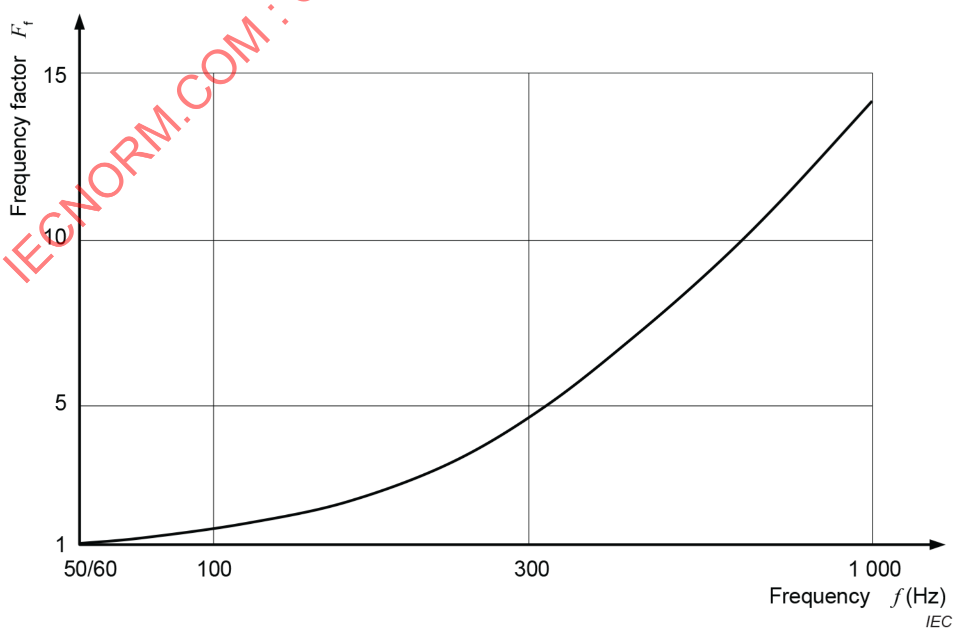


Figure 3 – Variation of the threshold of ventricular fibrillation within the frequency range 50/60 Hz to 1 000 Hz, shock durations longer than one heart period and longitudinal current paths through the trunk of the body

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.

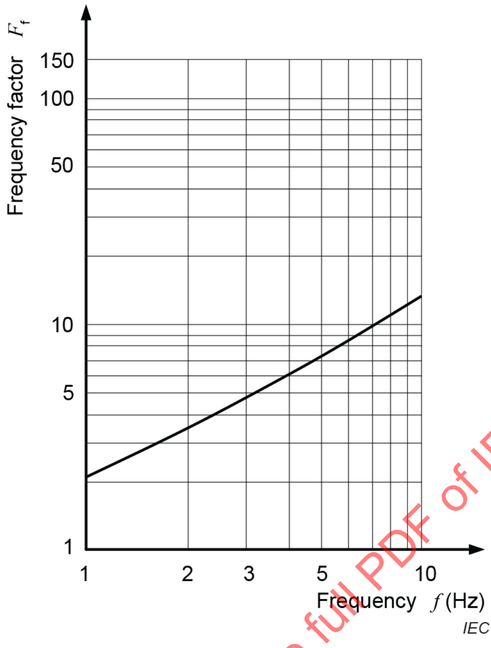


Figure 4 – Variation of the threshold of perception within the frequency range 1 000 Hz to 10 000 Hz

4.3.2 Threshold of let-go

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

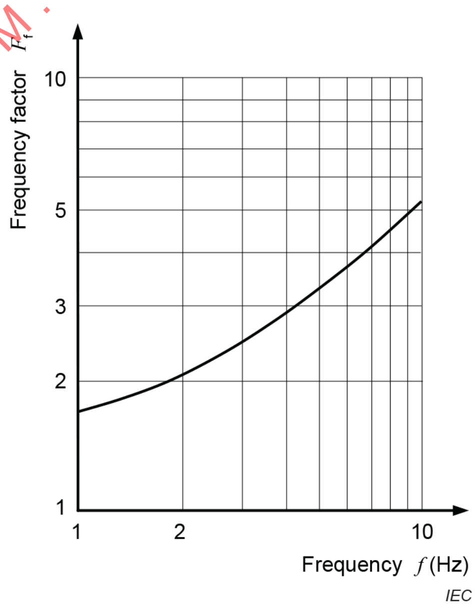


Figure 5 – Variation of the threshold of let-go within the frequency range 1 000 Hz to 10 000 Hz

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 values of 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 mill amperes.

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 1 000 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.

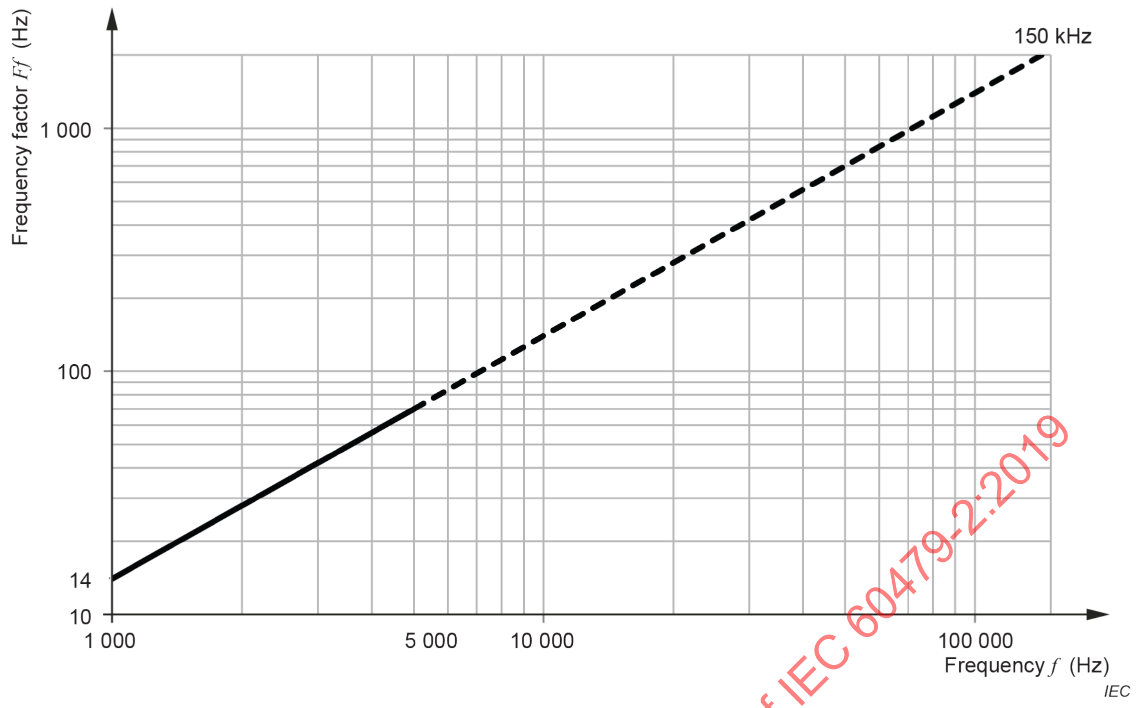


Figure 6 – Variation of the threshold of ventricular fibrillation for continuous sinusoidal current (1 000 Hz to 150 kHz)

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.

5.2 Equivalent magnitude, frequency and threshold

In 5.2, the hazard may be taken as having 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 given in IEC 60479-1:2018, Figure 20 and Figure 22 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

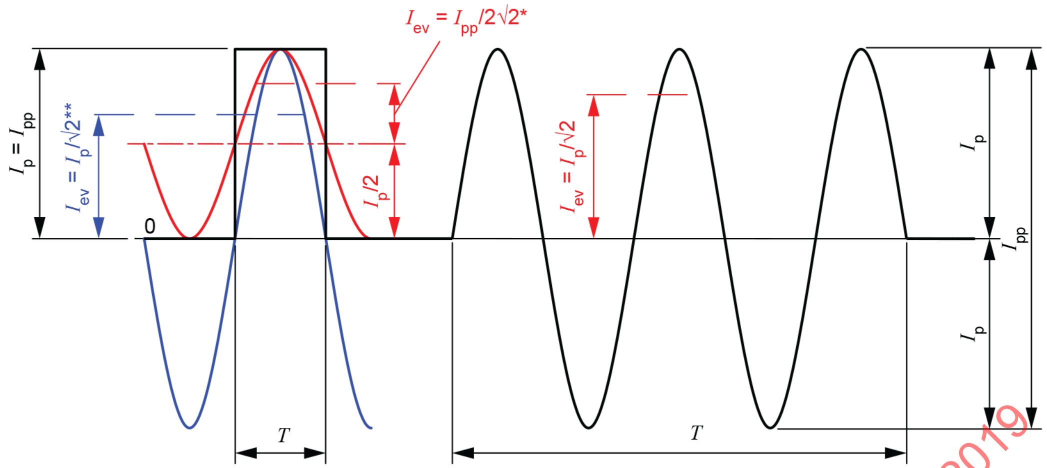
The different current thresholds (perception, inability of let-go and ventricular fibrillation) for waveforms consisting of specific ratios of alternating to direct current are equivalent to a pure sinusoidal alternating current with a current having the characteristic equal to I_{ev}.

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

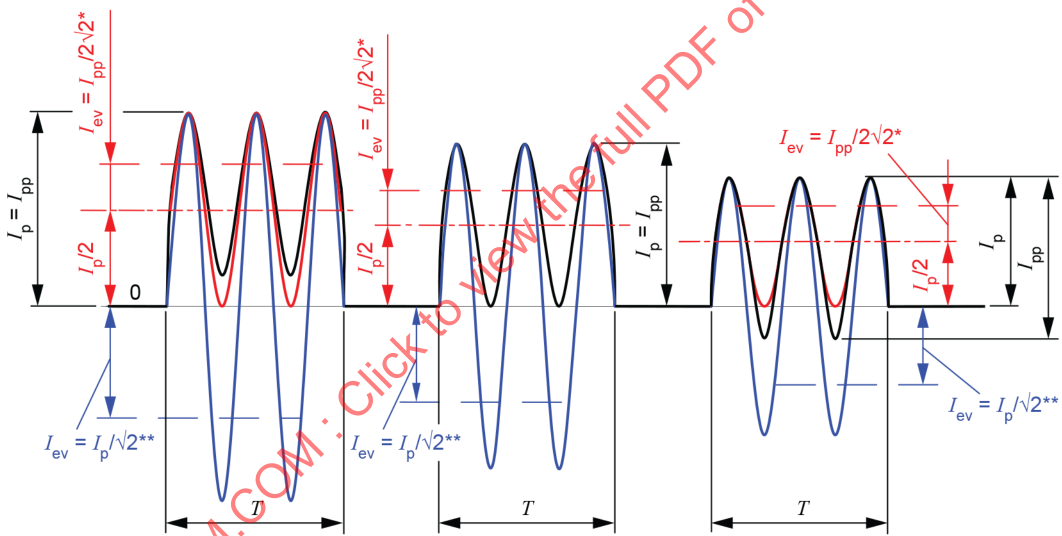
Figure 7 shows typical waveforms, which are dealt with in 5.3.1. Pure DC and pure AC are represented as well as combined waveforms of various AC to DC ratios.



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

IEC

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



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

IEC

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

Figure 7 – Waveforms of currents

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. A value of 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, $I_{\text{AC peak}} = 7{,}176 \times \exp(-0{,}143\,4 \times \text{DC}) - 0{,}106\,1$, 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 information given by Dalziel.

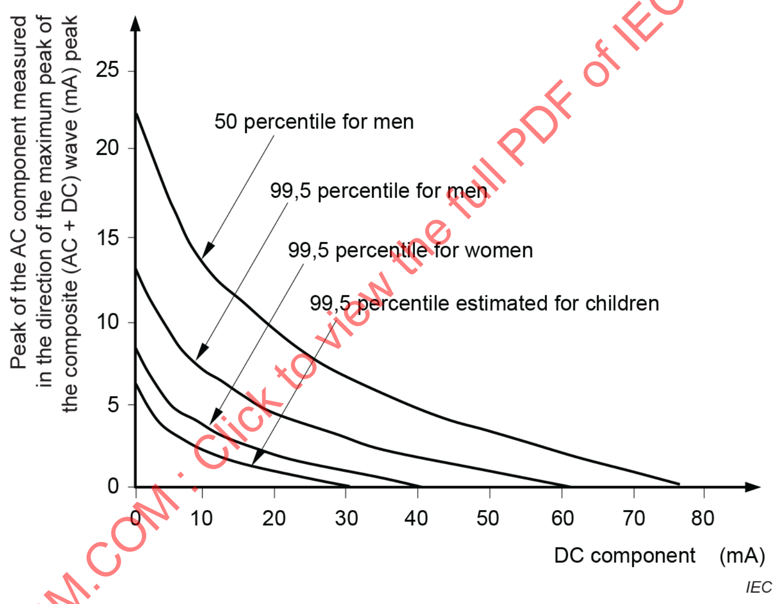


Figure 8 – Let-go thresholds for men, women and children

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

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

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

The equation, $I_{\text{AC peak}} = 6{,}394\,5 \times \exp(-0{,}138\,8 \times \text{DC}) - 0{,}094\,5$, 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 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:

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

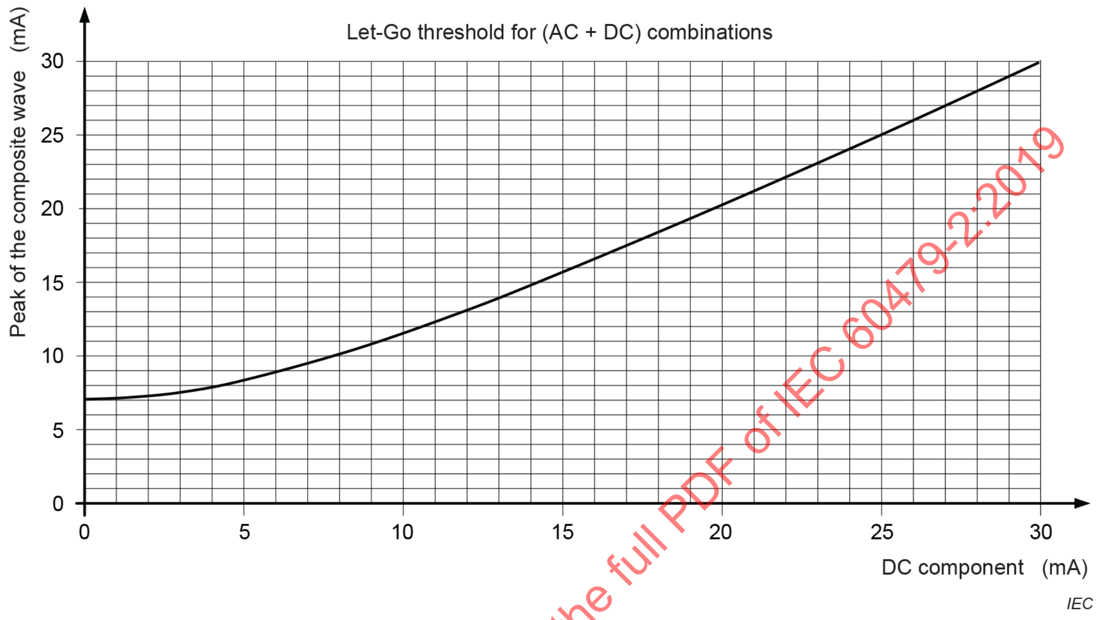


Figure 9 – 99,5-percentile let-go threshold for combinations of 50/60 Hz sinusoidal alternating current and direct current

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 less applicable the smaller the ratio AC to DC becomes. For pure DC shocks of a duration of less than 0,1 s, the threshold is equal to the corresponding RMS value of the alternating current (see IEC 60479-1:2018, Figure 20 or Figure 22).

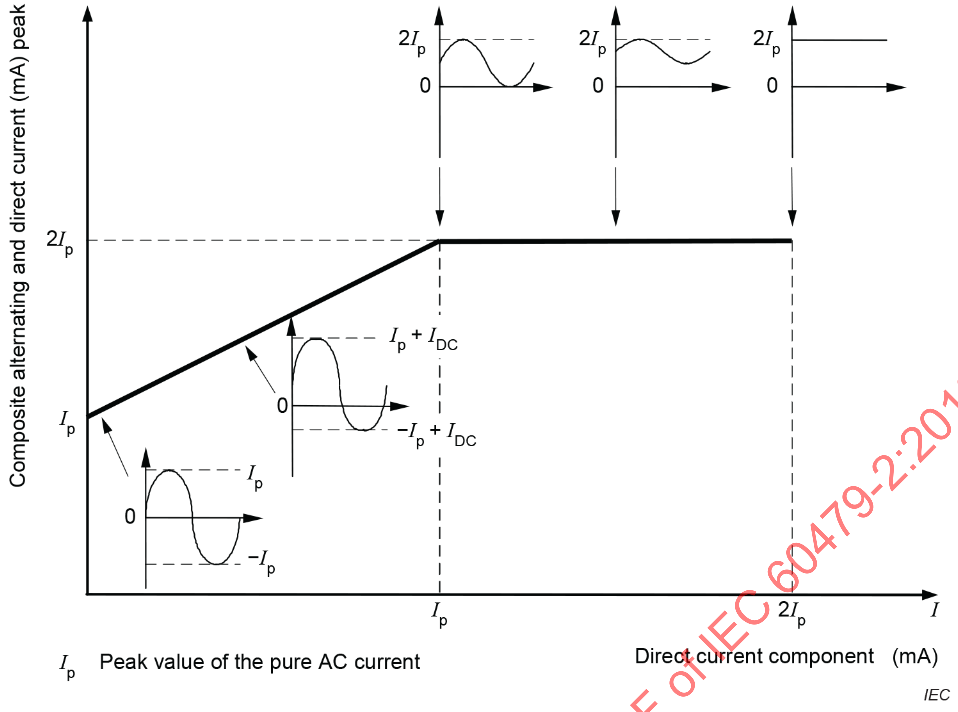
c) In the duration range from 0,75 to 1,5 times the period of the cardiac cycle, the amplitude parameter changes from peak value to peak-to-peak value.

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 $\left(2 \cdot I_{\text{p}}\right)$ (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.

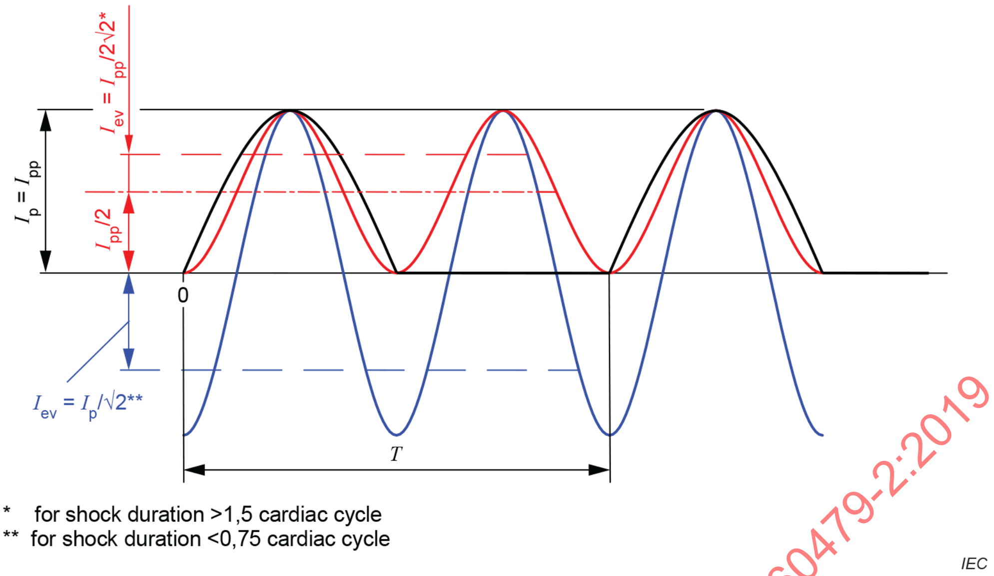


NOTE The peak-to-peak value I_{pp} remains constant up until the I_p value and then the peak value of the composite remains constant at a value of two times the peak of the AC with no DC component.

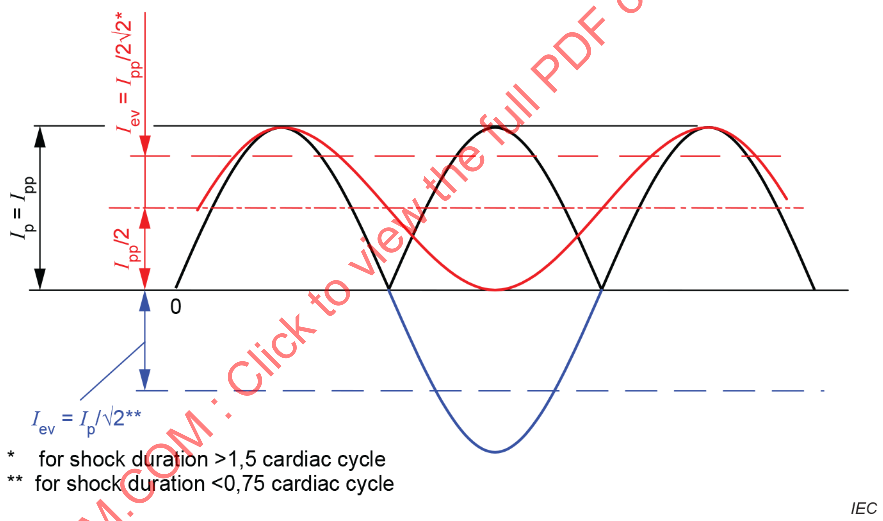
Figure 10 – Composite alternating and direct current with equivalent likelihood of ventricular fibrillation

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:

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

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:

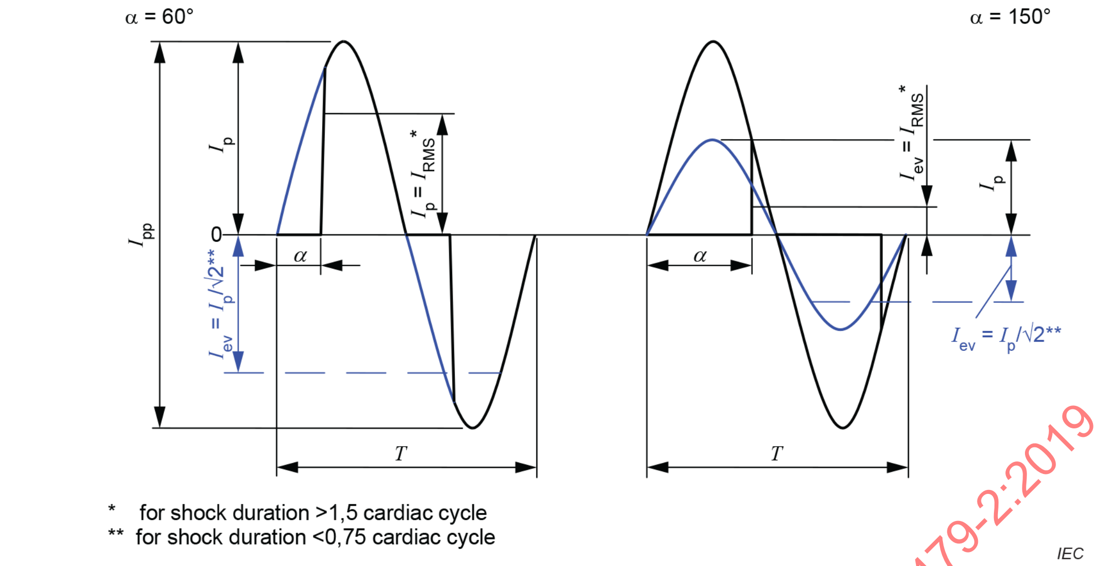
$$I_{ev} = I_{RMS}$$

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.

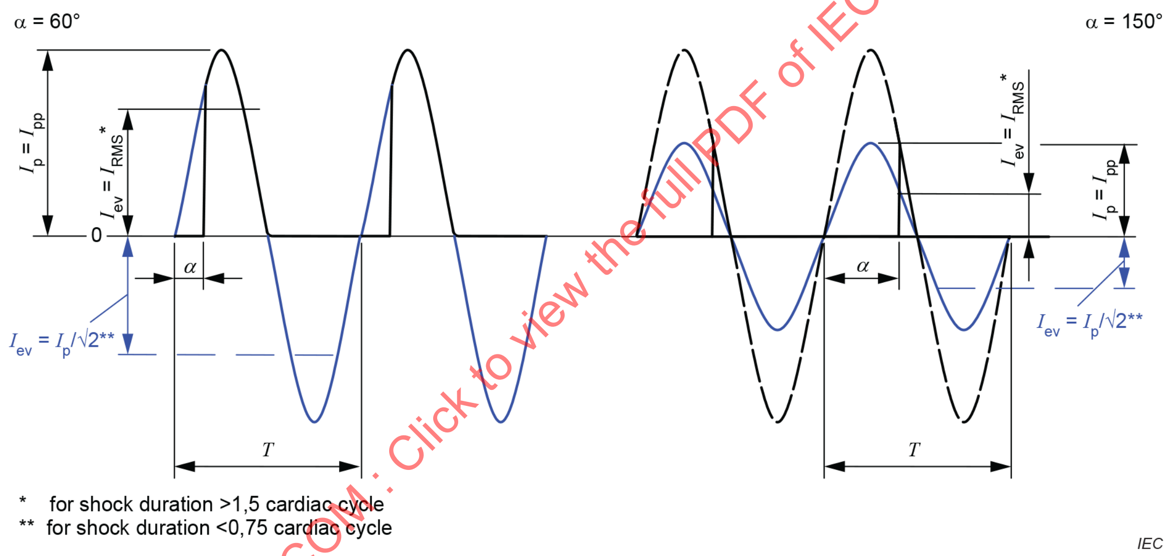
6 Effects of alternating current with phase control

6.1 Waveforms and frequencies and current thresholds

Figure 12 shows the waveforms for symmetrical and asymmetrical control.



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.

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.

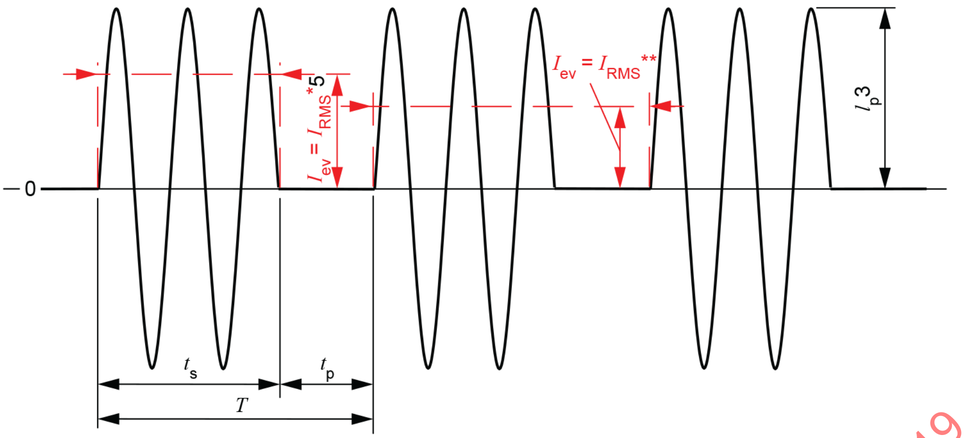
NOTE 1 For phase control angles above 120°, a rise of the threshold of fibrillation is to be expected.

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.



* 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 $p \approx 17$

IEC

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.

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 calculated with multicycle control factor

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.

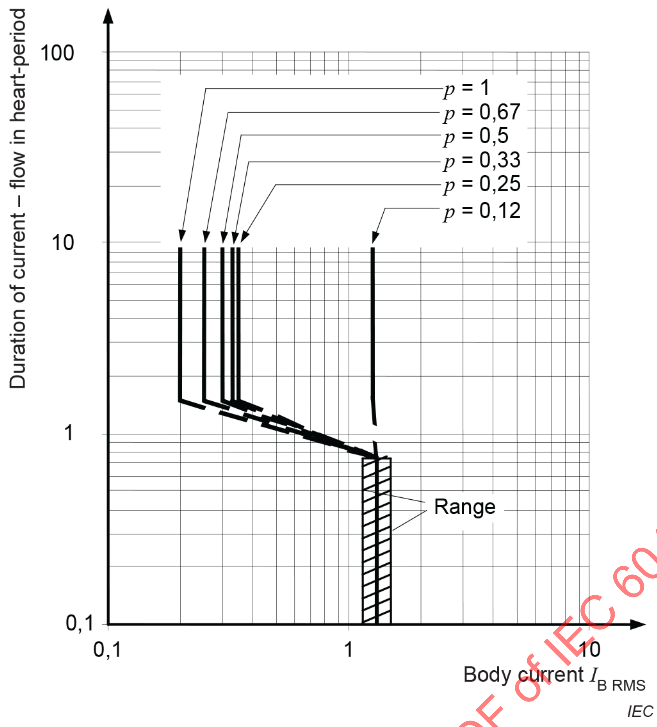
These effects are related to the peak value of the current [13] and the currents have to be combined frequency by frequency to estimate the total effect.

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].



NOTE Body current $I_{B\ RMS}$ 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 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 IEC 60479-1:2018, Figure 20 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 in 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:

- 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:

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

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 IEC 60479-1:2018, Figure 22. 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

Two or more pulses of current through the heart that are separated by less than 300 ms have an increased likelihood of creating disturbances in the heart with cumulative effects [41], [45]. 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, provided that each of the pulses excites the heart tissue in such a manner as to elicit a ventricular response [45], [46].

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], provided that each of the pulses excites the heart tissue in such a manner as to elicit a ventricular response [45], [46].

The first pulse of current in a series can be evaluated using IEC 60479-1:2018, Figure 20 or Figure 22, whichever is appropriate [14], [18], [19], [20]. If the second pulse of current triggers a ventricular response and if it is separated by less than 300 ms from the first pulse, then 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, separated by less than 300 ms, each of which having triggered ventricular responses. Under such conditions, the minimum threshold may only be approximately 10 % or less of the threshold applicable to the first current pulse [14], [18], [19], [20], [41], [45].

Table 1 provides an estimate of the threshold of ventricular fibrillation that is applicable to current pulse in a series as a worst case, assuming that they are separated by less than 300 ms and that each of them triggered a ventricular response. 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.

Each pulse of current is sufficient in magnitude and duration to excite the heart tissue and to trigger a ventricular response, 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 – Estimate for ventricular fibrillation threshold after each pulse of current in a series of pulses each of which excited the heart tissue in such a manner as to trigger ventricular responses

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 IEC 60479-1:2018, Figure 20 or Figure 22	Estimate of the ventricular fibrillation threshold after each pulse of current in a series of pulses each of which having excited the heart tissue such as to trigger a ventricular response [41], [45] %
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.

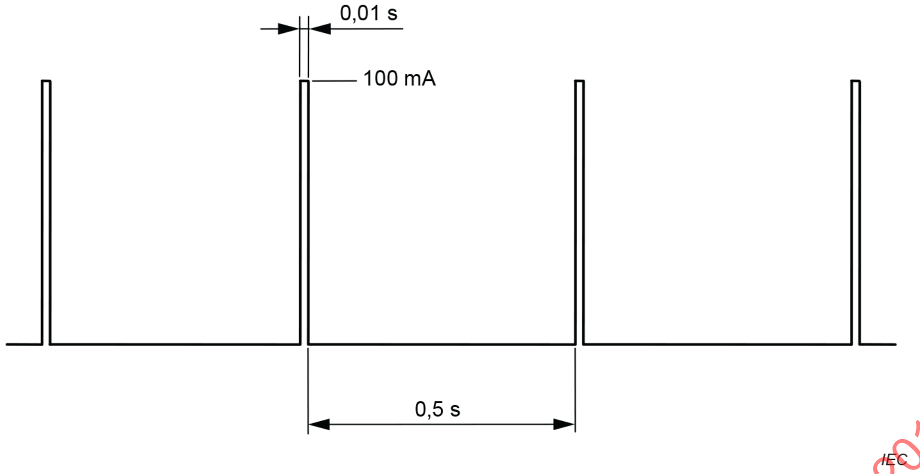


Figure 15 – Series of four rectangular pulses of unidirectional current

According to IEC 60479-1:2018, Figure 22, 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

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.

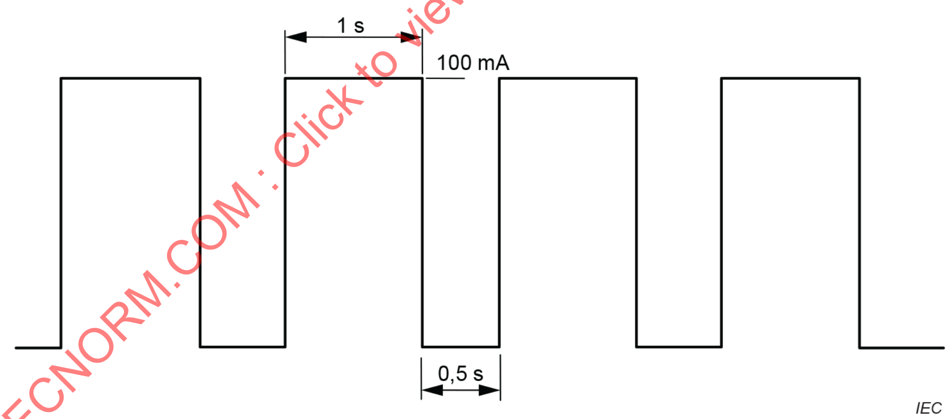


Figure 16 – Series of four rectangular pulses of unidirectional current

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 IEC 60479-1:2018, Figure 22, 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.

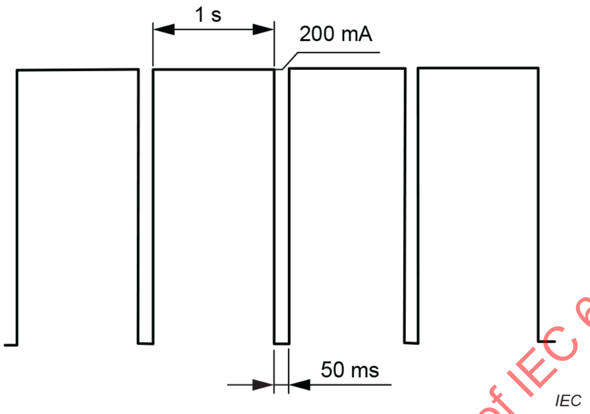


Figure 17 – Series of four rectangular pulses of unidirectional current

According to IEC 60479-1:2018, Figure 22, each of the pulses by itself is capable of inducing reversible disturbances in the heart (DC-3 region). It is assumed that each such pulse triggers a ventricular response, and the 50 ms quiet interval between the pulses does not allow the disturbances to subside before the onset of the next pulse occurs in the series. Therefore, under the assumptions that ventricular responses have been triggered, there may be 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. Therefore a simple, reliable and conservative method is presented below. The method can be used to transform results delivered from waveforms such as that in Figure 18 into results which can be entered into IEC 60479-1:2018, Figure 20. The method is that proposed by Pratt [29].

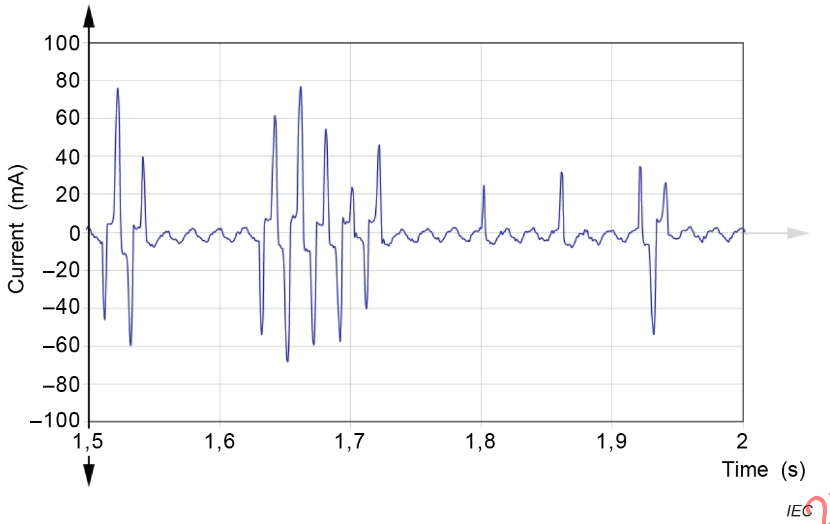


Figure 18 – Example of current versus elapsed time over a contaminated insulator

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.

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 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 in accordance with 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 IEC 60479-1:2018, Figure 20. It may therefore be considered that this method is a transform method to map a random complex waveform onto the RMS curve satisfying IEC 60479-1:2018, 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 IEC 60479-1:2018, Figure 20 is considered valid to 100 Hz.

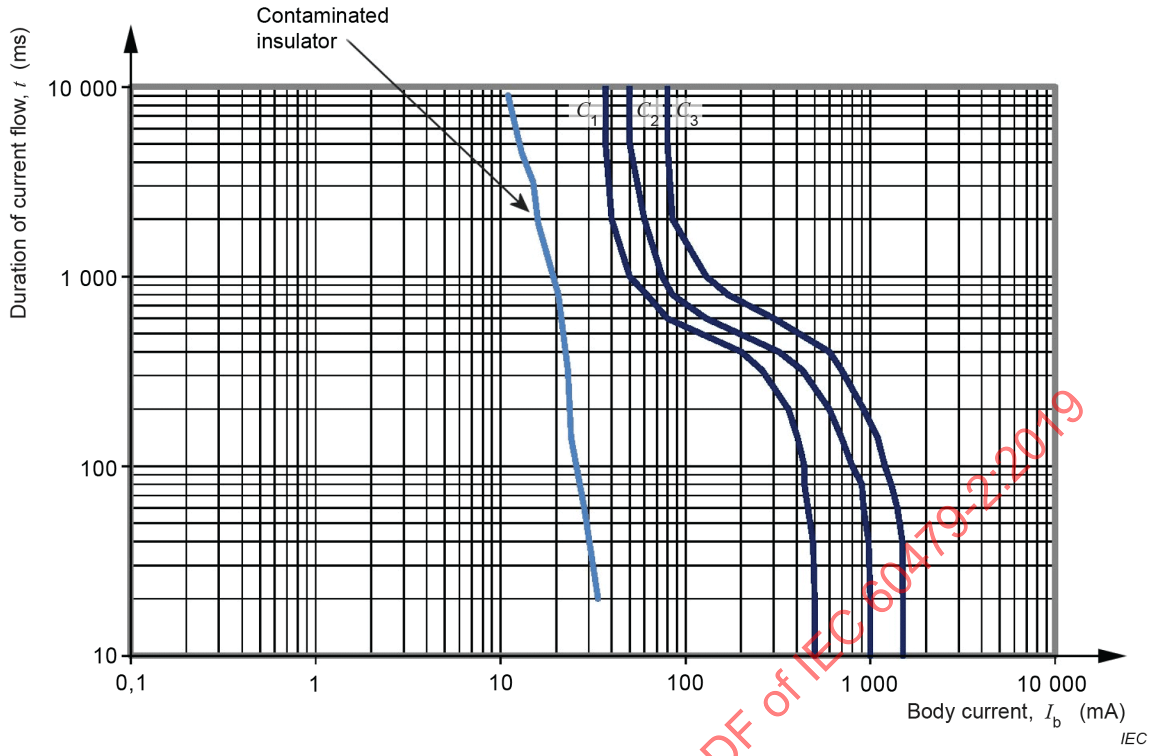


Figure 19 – PC plotted on the AC time current curves (IEC 60479-1:2018, Figure 20)

The waveform is unlikely to cause VF if the PC curve, plotted on Figure 20, as it 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.

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.

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

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).

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, 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 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.

(Mechanical pressure exerted on the closed eye can also produce phosphenes.) Although phosphenes themselves are not 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 IEC 60479-1:2018, Figure 20. 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 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 60479-1.

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,

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

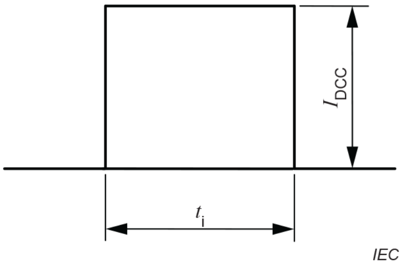
$I_{\text{AC(p)}}$ = peak value of the current of the sinusoidal impulse,

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

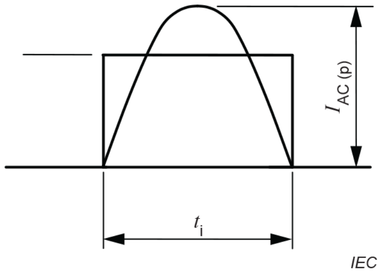
$I_{\text{C(p)}}$ = peak value of the capacitor discharge.

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, $I_{\text{C(p)}}$ is determined by:

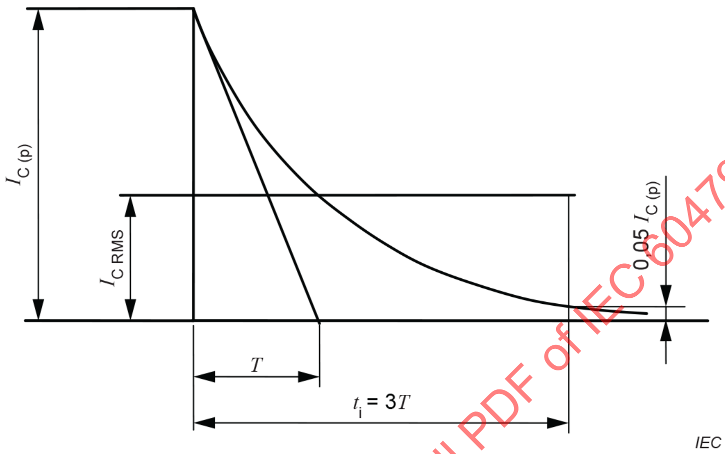
$$I_{\text{C(p)}} = \frac{U_{\text{e}}}{R_{\text{i}}}$$



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:

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

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

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

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

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

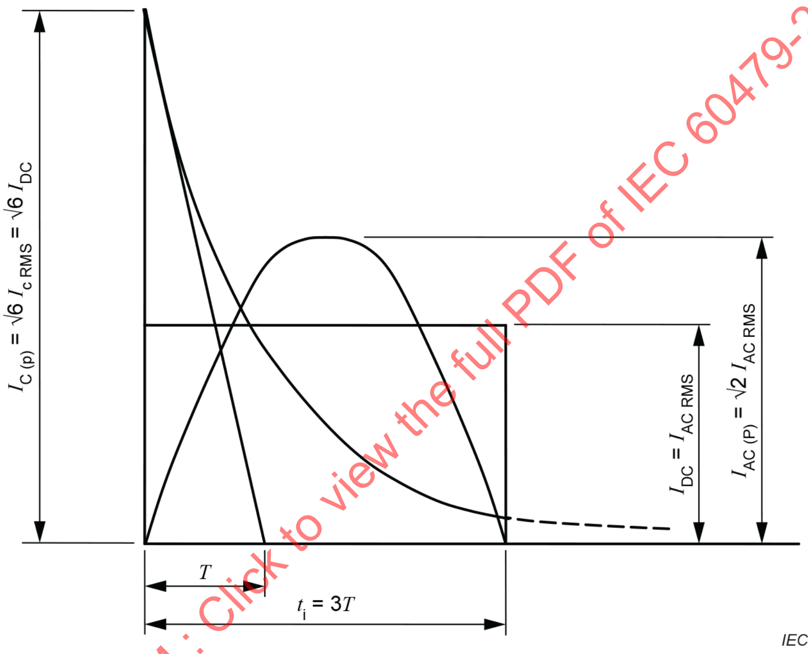
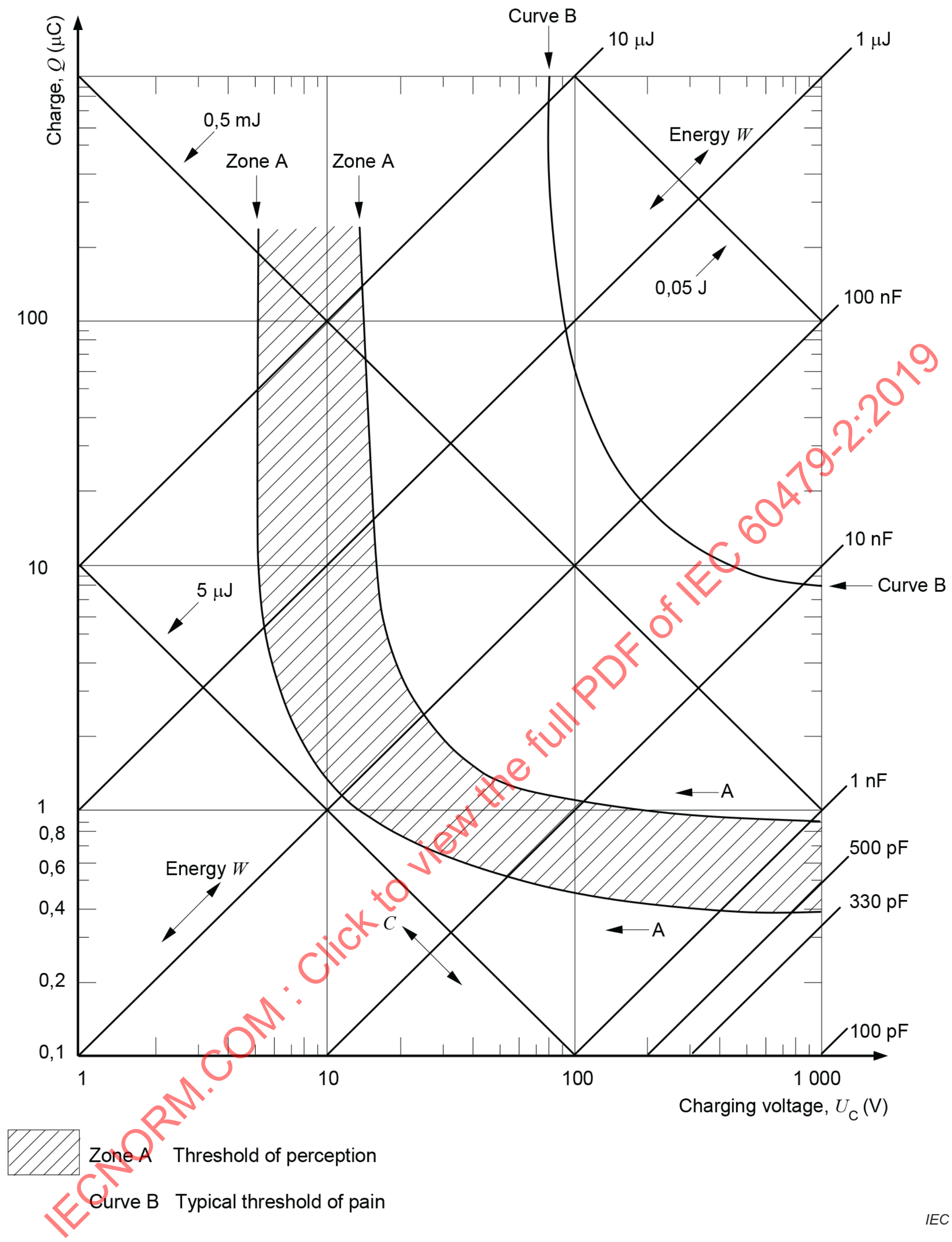


Figure 21 – Rectangular impulse, sinusoidal impulse and capacitor discharge having the same specific fibrillating energy and the same shock duration

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.



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.

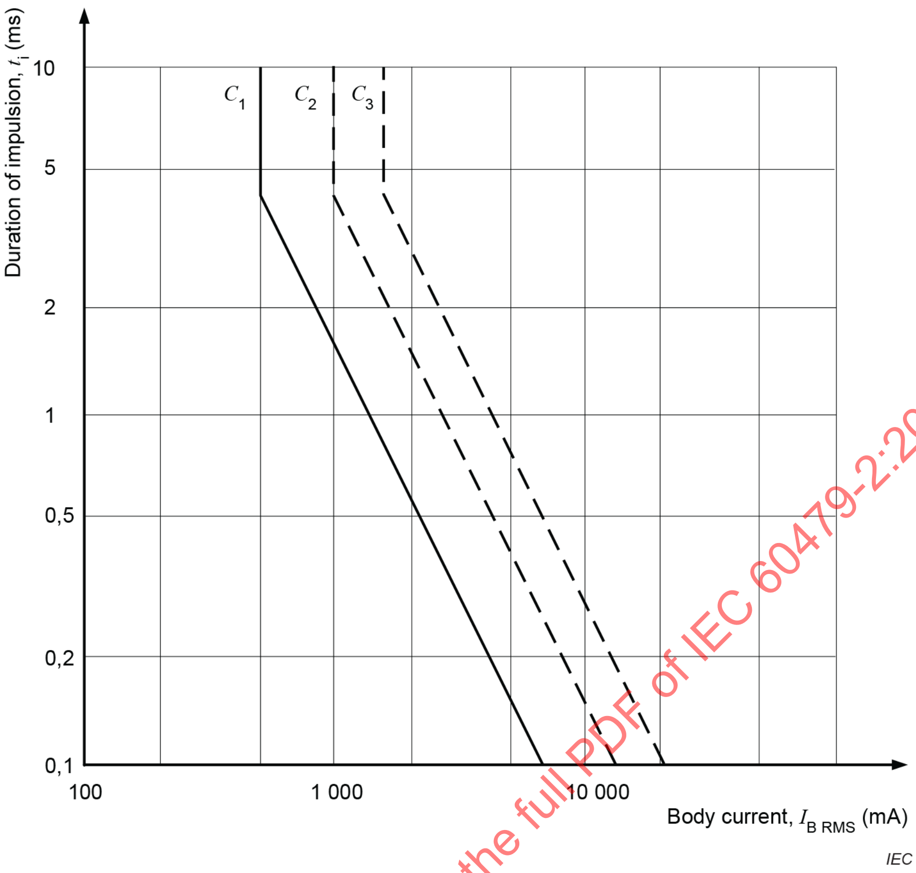
Experiments on animals show:

– 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.

– that the specific fibrillating charge F_q 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.



The curves indicate the probability of fibrillation risks for current flowing in the path left hand to feet. For other current paths, see IEC 60479-1:2018, 5.9.

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

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

11.4.2 Examples

In order to explain the practical application of the relationships described in 11.4.1, two examples are given and the respective effects of shocks are presented in Tables 5 and 6, respectively. 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 IEC 60479-1:2018, Figure 20.

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 (C)	$0{,}01 \cdot 10^{-3}$	$0{,}1 \cdot 10^{-3}$	10^{-3}	$10 \cdot 10^{-3}$
Discharge energy W_c (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 IEC 60479-1:2018, Clause 4.

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 (C)	$0{,}2 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	$20 \cdot 10^{-3}$	$200 \cdot 10^{-3}$
Discharge energy W_c (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 the 5 % percentile rank of IEC 60479:2018, Clause 4.

[b] As the shock duration t_i is longer than 10 ms, fibrillation thresholds are to be taken from IEC 60479-1:2018, Figure 20.