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SAFETY LIMITS FOR SINUSOIDAL WAVES WITH PHASE CONTROL

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ABSTRACT

To define the safety limits against flashing danger, the reference document is the IEC Report 60479, where the results of numerous studies and experiments on the effects of electric current on the human body have been assembled and surveyed. The IEC 60479-2 also describes the effects of special waveforms of current, since the increasing diffusion of equipment supplied by static converters, that generate non-sinusoidal waveforms, leads to verify them. In this work a few special waveforms, of which the effects are yet not clear, have been considered.
An experimental study has been carried out for determining the safety limits of sinusoidal waveforms with phase control, with low control angles and for different frequencies.

KEY WORDS:

Power systems
Electrical safety
Effects of current passing through the human body

1. INTRODUCTION

Aim of this work is the experimental evaluation of threshold of ventricular fibrillation for special sinusoidal waves with phase control (fig.4), changing the control angle and the frequency; it would be necessary to individuate and to compare the safety limits for the special waveforms with the curve of ventricular fibrillation in the graphic time/current, related with the alternating currents effects (15 Hz – 100 Hz) on the body (fig.1). The perception threshold (the minimum value of current which causes any sensation for the person through which it is flowing) has been dealt, considering the relation between threshold of perception and fibrillation. The trend of current perception for sinusoidal waves changing the frequency is reported in fig.2, in fig.3 the corresponding current fibrillation for different frequencies is shown. The reference document for considering the effects on the human body of electrical currents of various magnitudes and duration flowing through the body is the IEC Report 60479. The IEC Publication 60479-2 considers sinusoidal and special waveforms. Between the special waveforms, the IEC 60479 considers the sinusoidal waveforms with phase control, with a regulation angle greater than 60° till 100Hz. So the purposes have been:

- to evaluate the effects of current induced from alternating voltage waves, for regulation angle less than 60°;
- to evaluate the effects of current passing through the human body, if stimulated from phase control waves, increasing the frequency beyond 100Hz;
- to evaluate the trend of threshold of perception, changing body structure, sex and age;
- to evaluate current waveforms passing through the body, changing voltage waveforms applied to electrodes, because of the presence of internal impedance and impedance of the skin.

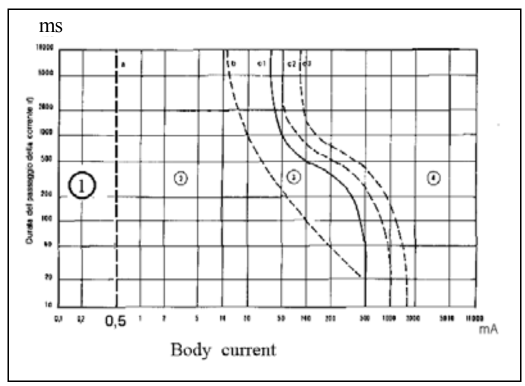

Fig.1: effect zones. The zone 1 is the zone where usually there are no reaction effects.

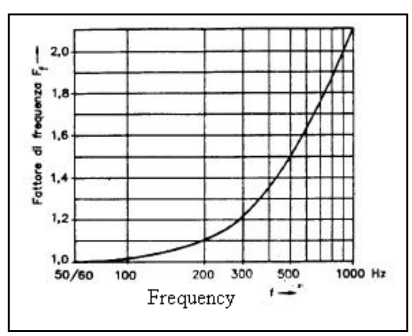

Fig.2

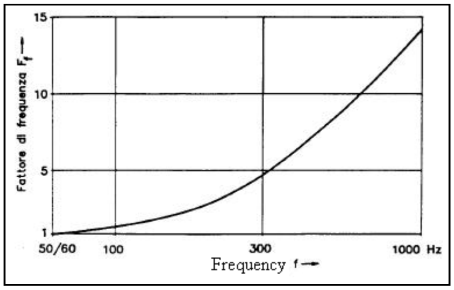

Fig.3

Since the waveforms have very short conduction time in comparison with the non-conduction time and anyway shorter than 10 ms, analogies with effects of unidirectional single impulse currents of short duration have been looked for, trying to determine if specific energy I^2t and specific charge could be important for evaluation of threshold of perception.

2. MEASURING APPARATUS

To analyze effects of currents on human body, similarly to fault of electric systems, the voltage waveforms have been imposed to electrodes and then the current waveforms have been studied.

The voltage waveforms are: sinusoidal waves with control angle of 15,° 30°, 45°, 60°, 90° and sinusoidal wave (fig.4). All waves have been studied at 50 Hz, at 200 Hz and at 400 Hz.

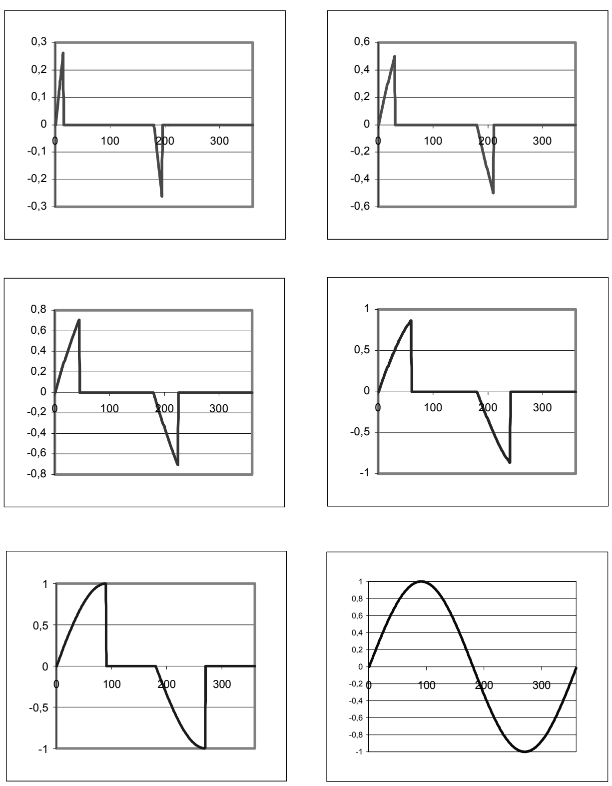

Fig.4

The measuring apparatus essentially consists in two flat electrodes (1×0.5cm) applied to the fleshy ends of the fore finger of the subject. The impedance of the skin is also very influenced by contact pressure; so, in order to obtain a constant pressure during the tests, a small spring has been placed under the electrodes. The electrodes were connected to the output of an analogic amplifier. The signal was synthesised with a personal computer and sent to the amplifier through a D/A converter. For every test, the condition for which the subject perceived the current (formication at the fleshy ends of the finger) was searched and next parameters were annotated: the rms value of current and voltage and the peak value of voltage. In some cases, the current and voltage waveforms were also researched. For each subject these personal data were noted: age, sex, height and weight.

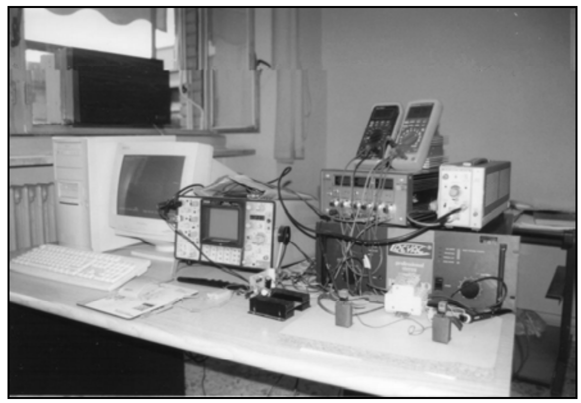

Fig.5: experimental set-up

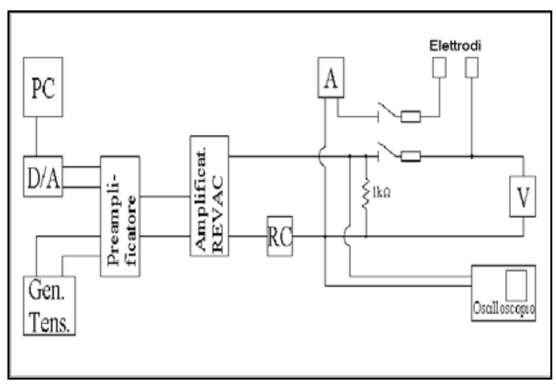

Fig.6: circuit plan of measure system

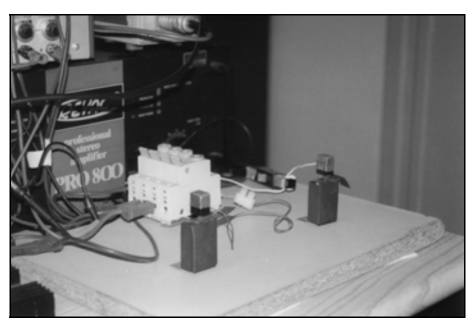

Fig.7: electrodes

3. RESULTS INVESTIGATION

More than one hundred tests on voluntary persons have been carried out, equally distributed between men and women.
The collected data, which follow a normal distribution, have been analysed calculating the main value, the main quadratic discard and applying the Chauvenet's criterion to eliminate anomalous data.
The experimental data have been compared with those reported on the Publication IEC 60479-2, to validate the tests and remark differences between them.
There is a very satisfactory reciprocity with the IEC data, considering the per-cent variation of threshold of perception increasing the frequency, in reference to own current perception at 50 Hz.

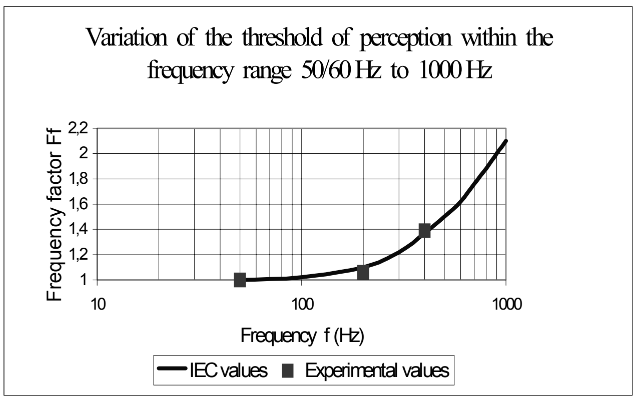

Fig.8

The main rms value of perception for sinusoidal wave at 50 Hz is lower than the IEC value (0.303 mA against 1 mA).
In fig.9, the results of experiments and IEC Publication are reported for sinusoidal waveforms at three frequencies: 50, 200, 400Hz with a probability of perception of 50%. It's evident the difference.

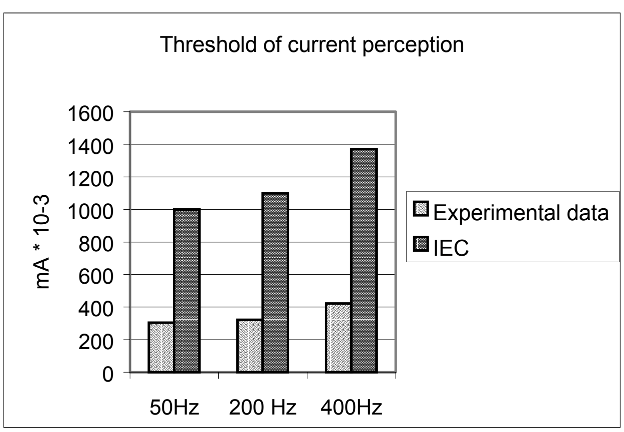

Fig.9

The influence of body structure on the trend of threshold of perception have been analysed, particularly have been studied the correlation between current perception and the weight (kg), the weight/height ratio (kg/m) and the corporal mass index (kg/m^2). The most evident relation is between the current perception and the weight (fig 10); the height appears on the contrary very little influent. This effect can be explained: the taller is the person the longer are the limbs (arms and legs), so it's very important to determine the internal impedance of human body (Z_i). For the threshold of current perception, the internal impedance has the only effect to modify the value of voltage to have the perception.

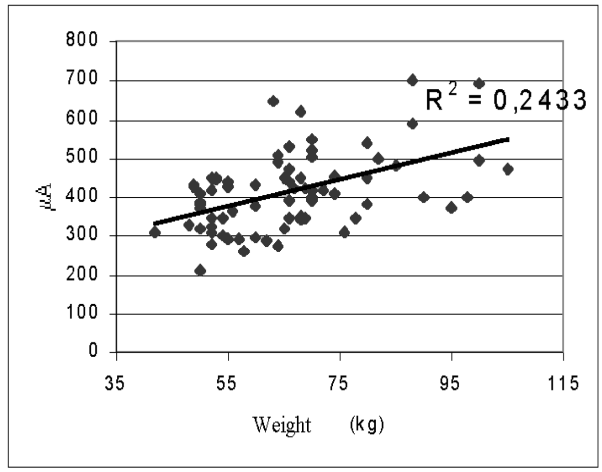

Fig 10

There are differences for the current perception between men and women: women are more sensitive to current than men (about the 20%).
In fig.11 for example, the thresholds of the perception current have been reported for sinusoidal waveforms, at three difference frequencies; also for the other waveforms women result to be more sensitive.

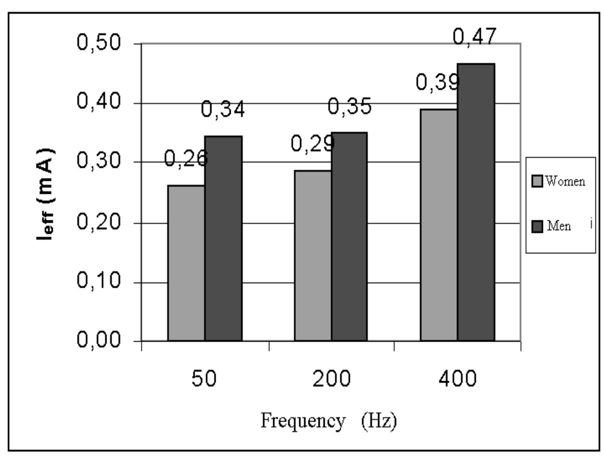

Fig.11

With regard to the effect of the age, the study has verified that there is a probable relation between the age and the threshold of perception (lower sensibility increasing the age), but it's important to say that the experimental data have not a good correlation probably due to the high distortion of the tested pattern (the 80% of the pattern has an age between 20 and 30 years).

4 CURRENT WAVEFORMS

The human body is a network of capacitances and resistances; so the current waveforms are different from the voltage waveforms. In fig.12, Zt is the total impedance of the human body, it's composed by the impedance of the skin, Zp1 and Zp2, and by the internal impedance Zi. The analysis with the oscilloscope allowed to study simultaneously the waveforms of applied voltage and flowing current, to see phase shift and deformation of current.

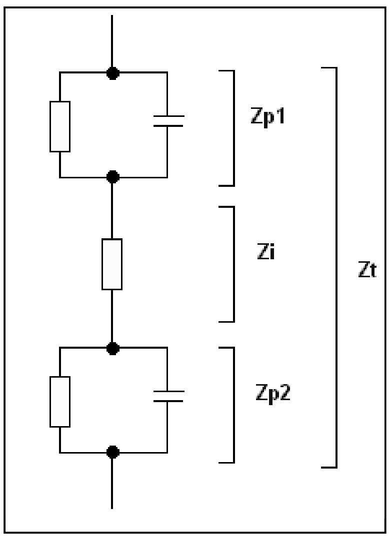

Fig.12

In fig.13, the case of the application of an alternating voltage at 200Hz has been shown, it's possible to see the phase shift between the voltage on the electrodes and the current flowing through the body.

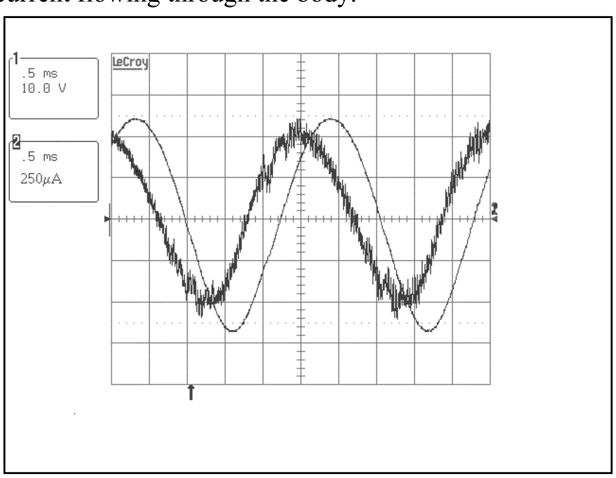

Fig.13

The phase shift φ is due particularly to the impedance of the skin (the internal impedance can be considered as mostly resistive). Knowing the applied voltage, the flowing current and the phase shift, it's possible to calculate the capacitive component of the skin. ($Z_{pC}=(V/I)\cos\varphi$).

The peak current values are two for every single voltage wave: the first current wave follows the imposed voltage and has one peak, more or less clear; the second one appears when the voltage impulse finishes, by the capacitance discharge.

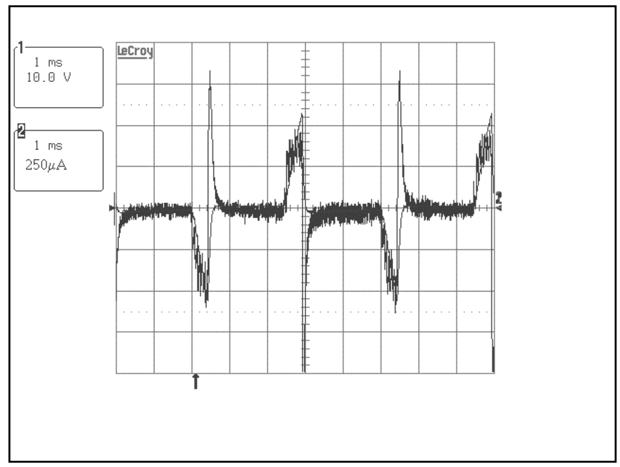

Fig.14

With reference to the fig.14, the electric charges, represented from the areas in the current/time graphic, during the time of the voltage conduction and the time of the absence of the signal, are not the same, because of a charge share flows through the body, while the other one is warehoused from the capacitances and causes the second peak.

The current waveforms have been studied to value the electric parameters of the human body at low level of applied voltage, to varying voltage waveforms and frequencies; the aim of collecting these experimental results is to have the data to validate next numerical simulations.

Using PSpice and Ansys Software, it's possible to simulate the human body circuit,but it's necessary to know the parameters (Zi, Zp..) and how these change by the boundary conditions.

If the human body circuit at the low level of voltage runs well and gives good results, so that current waveforms are similar to the reported data, higher levels of voltage can be studied, knowing its influence on parameters from literature.

5. DISCUSSION OF RESULTS

For this study, the peaks have not been considered since the conduction time is very short, so the peak values of the threshold of perception are the greatest current values, measured during the voltage application and when also the impedances of the skin are present.

The rms values consider on the contrary the whole waveform, including the peaks.

In the fig.14, the peak values of current perception for the waves with phase control and for the sinusoidal waves have been compared, at the three frequencies.

If the conduction time lessens, that is the phase control lessens, the peak value must increase ($I_p = kt^{-0.5}$), so that the impulse can be caught. The peak values for waveforms with phase control of 60° and 90° are very near to the results of the sinusoidal wave, according the IEC 60479-2: also for frequencies higher than 100Hz, the peak values for phase angle >60° are similar to those of a.c..

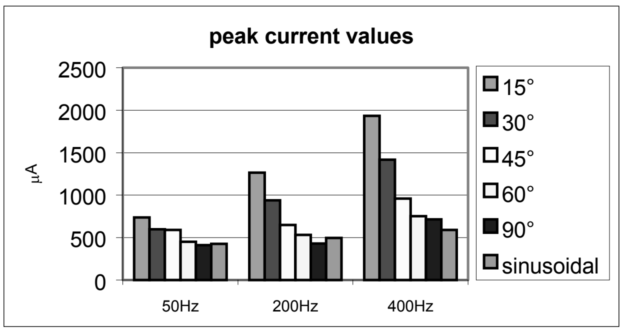

Fig 14

In the fig.15, the rms values have been reported; it's important to note the different trend between the frequency of 50 Hz, where the a.c. pure has the highest threshold of perception and the frequencies of 200 and 400Hz, where the a.c. pure has the lowest threshold of perception.

In IEC 60479-2, for the sinusoidal waveforms with phase control at 50Hz and for long shock-duration, the equivalent alternating current Iev (r.m.s value of a sinusoidal current presenting the same risk as regards ventricular fibrillation as the waveform concerned) has the same rms value of the current: that means that, increasing the frequency, the safety level becomes higher.

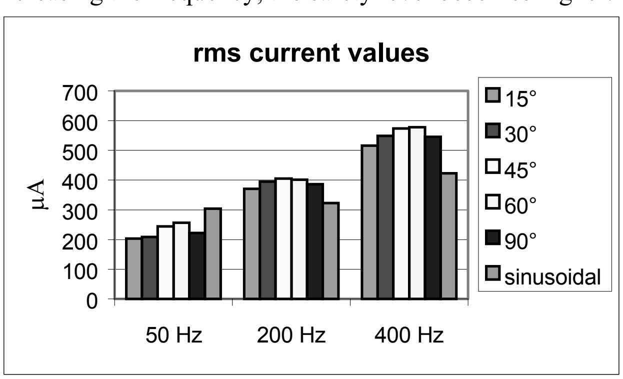

Fig 15

In the fig.16, the rms values of applied voltage to have the current perception have been reported, the voltage measured for the waveforms with phase control are very lower than those of sinusoidal waves. The corresponding peak values don't have a clear trend, but all the results, for the waveforms with phase control, are between 20V and 30 V, very near to the a.c peak voltages.

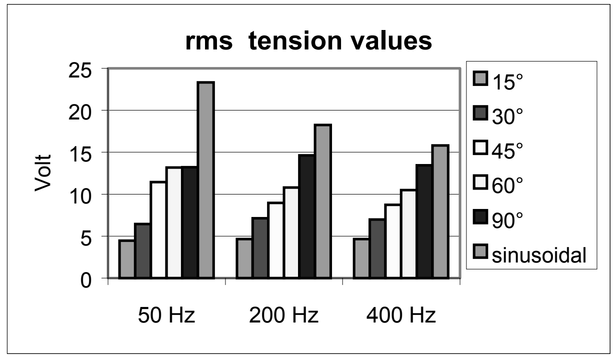

Fig.16

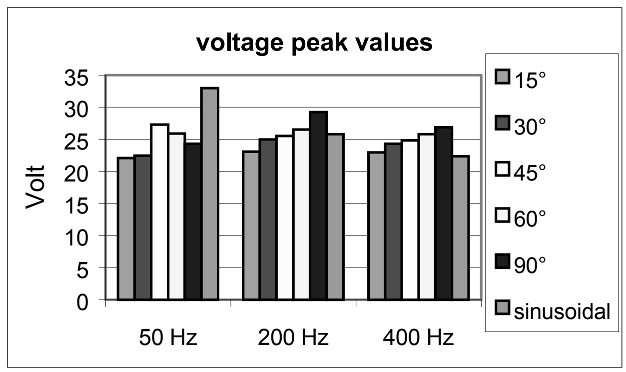

Fig.17

The impedance of the human body (rms voltage value/rms current value) is reported in fig.18; the impedance lessens to increasing the frequency and to lessening the phase control angle.

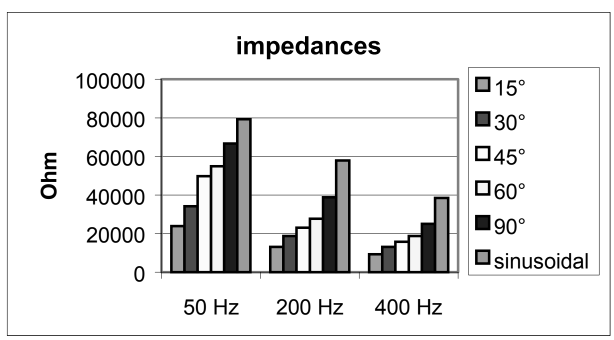

Fig.18

The analysis on the specific energy $\mathbf{I^2t}$ brings to conclude that it's not particularly significative for the determination of the threshold of perception.

6. CONCLUSION

The research has shown that, for these particular waveforms, the parameter, that more influences the threshold of perception, is the peak current value.
The peak values for waveforms with phase control of 60° and 90° are very similar to the results of the sinusoidal wave, according the IEC 60479-2: also for frequencies higher than 100Hz, the peak values for phase angle ≥60° are similar to those of a.c.. For phase angle<60°, the peak values increase, lessening the time conduction.
The peak value is difficulty valuable a priori because it's depending from the voltage waveforms and from the impedance of human body.
Every voltage waveforms, changing the time of conduction of the signal and the way of application, induce in the body particular current waveforms, some ones can be very tiresome for the persons, although the voltage is lower than the data reported in the Publication IEC60479-2. So when it's possible, it would be better to carry out a specific experimental investigation.
For the ventricular fibrillation, the safety levels seem to become higher than those reported in IEC 60479-2 for 15-100Hz, increasing the frequency.
The threshold of perception (and also the threshold of ventricular fibrillation) changes from person to person, also remarkably; particularly women are more sensitive to the current than men; weight and age can influence the threshold of perception.
The collection of the data and the imagines of the voltages and the currents have allowed to understand the trend of the impedance of human body and the corresponding deformations of current waveforms: by this way, the basis for numerical simulations and its validation have been placed. The human body circuit could help to know the current trend and evaluate, for a time conduction, the highest peak current value.

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