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Indirect Contacts Protection for Multi-Frequency Currents Ground Faults

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***Abstract*—In recent decades, most electrical appliances have been deeply transformed with the addition of power electronics. In case of failures, the fault current is no longer sinusoidal and the effects on human beings are, up to now, not well known. Non sinusoidal currents can be decomposed in a series of sinusoidal currents: for this purpose, the IEC Standard 62423 defines a test waveform for F type residual circuit breakers, which is composed of different frequencies weighted sinusoidal currents. In this paper, the human body response to multi frequency currents has been investigated considering the perception threshold for the test waveform defined in the IEC 62423.**

Keywords—indirect contacts; ground fault; multi-frequency currents; perception threshold; residual current protective devices

I. INTRODUCTION

Since the last century, with the increasing spread of electrical devices, the aspects concerning the effects of current on human body have been investigated [1]. Immobilization, stopping breathing, ventricular fibrillation and burns are the main effects of current on human beings [2].

Perception threshold is the smallest current that could just be felt. In particular, the first sensation with direct current and with alternating current at high frequencies is warmth, in contrast to the tingling sensation, which appears when alternating current at low frequencies is used.

First tests dedicated to know perception threshold values have been made by Dalziel [3]–[5]. Most studies on perception threshold have considered 50 Hz or 60 Hz sinusoidal currents, few studies regard higher frequencies and different waveforms [6], [7].

Based on the first ones, the conventional prospective touch voltage limit (U_L) has been defined with respect to the 50 Hz ÷ 100 Hz frequencies, which is the basis of the automatic disconnection of supply method to protect people from indirect contacts [8]–[15].

Nevertheless, practical cases, which may occur every day, are not only limited to the 50 Hz sinusoidal currents or other simple waveforms. In fact, in recent decades the household electrical appliances have been deeply transformed, with the addition of power electronics.

Today, even the simplest household appliances, such as washing machines, dishwashers, conditioners, etc., have internal electronic circuits: this allows the creation of very light and less bulky devices with high energy efficiency standards. In case of failures, the fault current is no longer sinusoidal and can be decomposed in currents with different frequencies. For this purpose, the IEC Standard 62423 [16] defines a test waveform for F type residual circuit breakers, which is composed by different frequencies weighted sinusoidal currents.

The knowledge about the effects of this type of currents on human body is still limited and not fully acquired. Therefore, it is very important to understand the human body's response to "multi-frequency" currents, because it covers possible practical situations that can occur with the modern household appliances.

The aim of this paper is to determine the perception threshold and the body impedance for the "multi-frequency" transient currents applied to the fingertip. As it is not possible to directly perform tests on the ventricular fibrillation threshold for human beings, in this paper the measurements have been carried out referring to the perception threshold.

Moreover, physiological characteristics of the individuals, such as sex, age, height, weight and skin hardness of fingers, are taken into account, because they influence the sensitivity to the current.

The next sections of this paper are organized as follows. Section II describes different types of residual current circuit breakers, with particular attention to the waveforms for which they are designed to trip. Section III presents an analysis of the effect of different types of currents on human body, in order to examine the possible correlation between perception and fibrillation thresholds. Section IV introduces the design of the experimental setup for the study of the perception threshold and of the body impedance for the "multi-frequency" currents applied to the fingertip of a sampling of volunteers, considered as representative of the Italian population. Finally, Section V contains the conclusions.

II. RESIDUAL CURRENT PROTECTIVE DEVICES

Generally, in TT systems, residual current protective devices (RCDs) are used for faults protection (protection against indirect contacts).

RCDs are classified, as follows, into different categories, according to their ability to ensure protection against various types of earth fault currents:

- AC types are only suitable for the detection of sinusoidal fault currents. The tripping is then ensured for residual sinusoidal current applied suddenly or slowly rising.
- A types ensure uncoupling for residual unidirectional pulsating with or without phase angle control currents and for residual unidirectional pulsating superimposed to a direct current of 6 mA with no undulations; all cases are polarity independent, with current applied suddenly or slowly rising. They allow to control any fault current that could be generated with the use of electronic devices.
- F types were specifically developed to protect people against indirect contacts when using devices powered by inverters. In addition to type A requirements, they are tested with a multi-frequency current composed of different frequencies weighted sinusoidal currents (10 Hz, 50 Hz and 1 kHz). The purpose is to simulate the composite current flowing to earth in case of a ground fault that occurs downstream of the inverter.
- B types, in addition to the detection of the fault currents of the F types, can trip with: residual sinusoidal currents superimposed on a direct current without undulations; residual sinusoidal currents up to 1000 Hz; unidirectional pulsating residual currents superimposed on a direct current without undulations. B types are recommended for use with drives and inverters for the power supply of motors of pumps, lifts, textile machinery, machine tools, etc.

The currents associated with the different types of RCDs are shown in Fig. 1.

In order to study, for indirect contacts protection, the effect of multi-frequency currents on human beings in case of ground fault, the current waveform proposed by the IEC Standard 62423 [16] is taken as reference for the testing of F type RCDs.

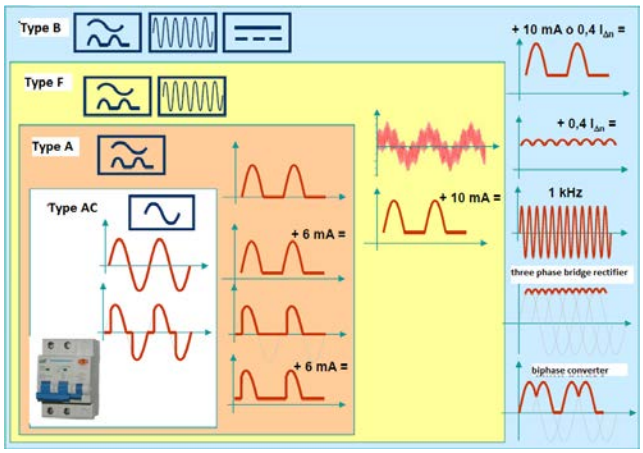


Fig. 1. Types of different switches.

III. Effects Of Multi-Frequency Currents Flowing Through The Human Body

The effects of mixed frequencies currents passing through the human body have not been deeply studied. On this argument, the IEC Standard 60479-2 [17] and Dalziel [18] suggest that the effects of perception thresholds and let-go currents are related to the peak value of the current and they have to be combined frequency per frequency to estimate the total effect. Moreover, 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 at the fundamental frequency with an amplitude equivalent to the quadratic summation of all components amplitudes corrected by the appropriate frequency factor. The perception thresholds and let-go currents are related to very different biophysical mechanisms and cannot be directly compared. However, they both depend upon the crest value of the current (not on the r.m.s. value) and they increase as the frequency increases.

Fig. 2 shows the variation of the thresholds within the frequency range 50Hz ÷ 1000Hz, where the *Frequency factor* F_f is the ratio of the threshold current for the relevant physiological effects at the frequency f to the threshold current at 50/60 Hz [17].

In this paper, a qualitative evaluation of the human body response to multi-frequency currents is investigated considering the threshold of perception for multi-frequency current normalized by the IEC Standard 62423 [16] for F type RCDs.

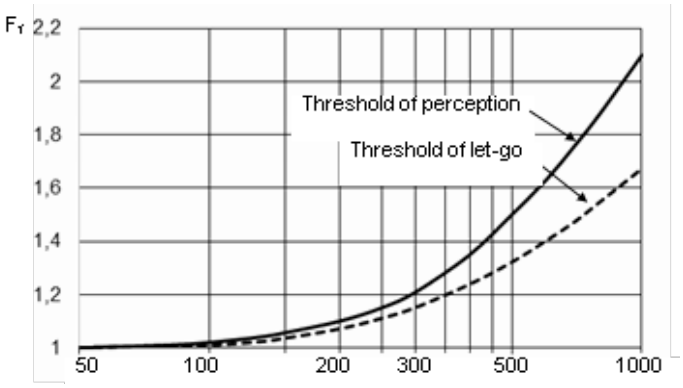


Fig. 2 Variation of the thresholds within frequency range 50Hz – 1000Hz.

IV. Experimental Setup

In order to evaluate the perception threshold for non-sinusoidal currents, an experimental setup was assembled. Moreover, the measurement protocol and the choice of the sample were defined. Details can be found in the following paragraphs.

A. *Measurement device*

A block diagram of the electrical circuit is shown in Fig. 3.

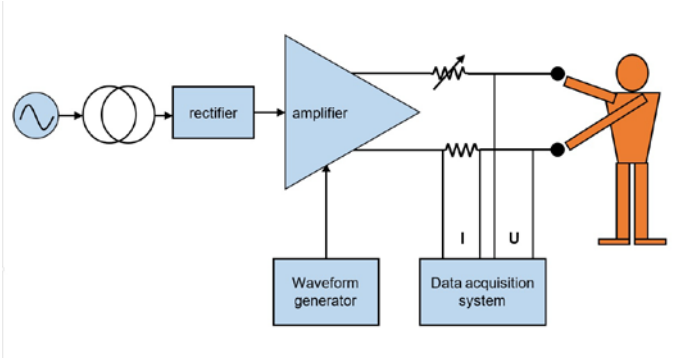
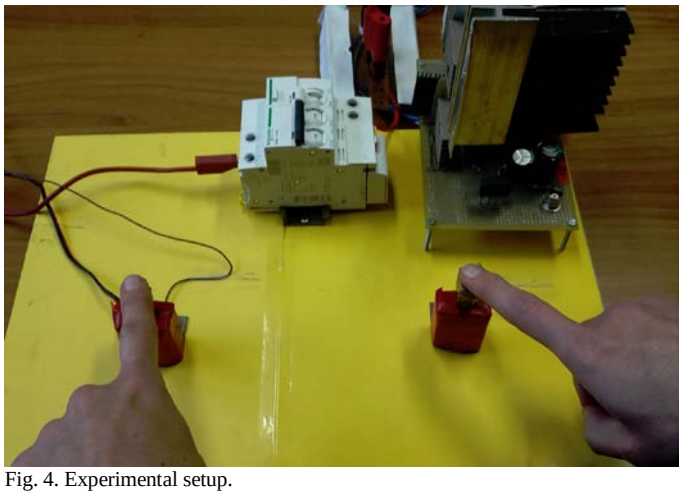


Fig. 3. Experimental electrical circuit.

The power is supplied through an isolation transformer, which provides additional protection against direct contacts. The waveform is provided by a function generator (with sampling rate of 50 MegaSample/s and 14-bit resolution), which can provide a well-defined output voltage or a used-defined waveform, previously set on a PC.

The output waveform is then amplified to the desired level of voltage by means of a power operational amplifier.

As shown in Fig. 4, the voltage applied to the person's fingertips is set through a voltage divider: a potentiometer is connected in series with the total body impedance (Z_T). Changing the potentiometer resistance, the touch voltage and the current through the human body are modified. Notice that their increment rate is a function of the volunteer's Z_T.


Fig. 4. Experimental setup.

As the current slope shall be sufficiently low in order to define the perception threshold with a sufficient accuracy for all the possible volunteers (that could potentially have a very low or high Z_T), the variation range of the potentiometer was chosen in the range from 0 to 500 kΩ.

To check that the voltage divider appropriately works, the touch voltage and the current through the human body are computed with reference to two values of Z_T: 1 kΩ and 320 kΩ. These values are chosen according to the Z_T values given by the IEC Standard 60479-1 for a current path hand to hand for small surface areas of contacts in dry conditions at touch voltages equal to 25 V to 200 V a.c. 50/60 Hz [2].

The current and voltage profiles for these two different values of Z_T are reported in Fig. 5. To improve safety, the circuit is equipped with a high sensitivity one-pole RCD (10 mA).

The monitoring and recording of the touch voltage and current waveform are carried out with a 4-channel device. The main specifications and settings of this instrument are reported in Table I.

Both the instantaneous and the r.m.s. values of voltage and current are measured and recorded. In this way, the complete waveforms are available for future analysis and, at the same time, the r.m.s. electrical quantities can be constantly monitored during the test.

A shunt resistance (100 Ω) is used to measure the current through the human body. This value is chosen in order to fulfill two opposite requirements: the resistance should as smallest as possible, in order to not offer any significant opposition to the flowing current, but, at the same time, high enough to ensure the voltage measurement. To reduce the measurement error, the value of the resistance is measured. A sampling time of 5 µs is set, as the maximum frequency of the considered waveform is 1 kHz.

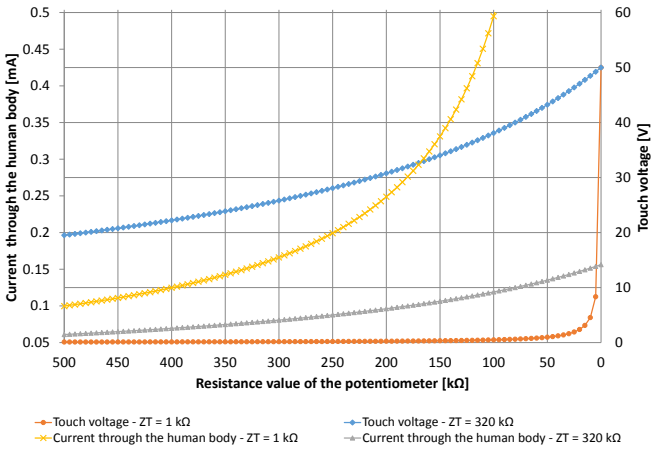


Fig. 5. Touch voltage and current through the human body profiles as a fuction of the potentiometer resistance set.

TABLE I
MAIN SPECIFICATION AND SETTING OF THE HIGH-SPEED DEVICE

Quantity	Value
Voltage measurement range	100 V
Current measurement range	1 mA
Measurement resolution	1/640 of measurement range

Another important point is the definition of the condition to start the measurement (trigger setting). Totally, the high speed record is set to save the measured values for an interval time of 3 s. This short time is entirely sufficient to fulfill the measurement task. In fact, the waveform portion of interest runs over a particular event, i.e. when the person subjected to the test perceives the passage of the current and, as a reaction, raises the fingers from the contacts.

Considering this as the trigger event, the high speed records save the 60% of the measured values before the trigger event occurs, and the remaining 40 % after.

B. *Measurement protocol*

Besides designing and assembling the measurement setup, also the measurement protocol is defined as follows. Before the measurements, the volunteers are briefed on the testing procedure and, in a trial run, they are familiarized with the tingling sensation that would be felt.

At the beginning of the test, the volunteer pushes down his/her fingers on two electrodes until he/she gets halfway of the spring connected to the contacts. In this way, the resultant force depends on the intrinsic characteristics of the spring itself and not by the contact pressure applied by each person (which could influence the impedance of the human body and therefore also the threshold of perception).

During the test, the current flows from the first contact, through the person, to the second contact. In particular, for each subject, four different types of tests are carried out, with three separate currents at nominal frequency of 10 Hz, 50Hz, 1000 Hz and with the composite current normalized by the IEC Standard 62423 [15] for F type RCDs.

In particular, the latter current (Fig. 6) is the sum of three sinusoidal components with frequency 10 Hz, 50 Hz and 1000 Hz weighted as indicated in Table II.

In order to reduce sampling errors, and in particular the subjective side in volunteer response [19], each test is repeated three times and the sequence of tests on each subject is randomized.

For each test, the resistance of the potentiometer is set at the maximum value, which corresponds to the minimum voltage on the electrodes.

Gradually, the value of the resistance is decreased intervening manually on a potentiometer. The decrease of resistance is interrupted when the volunteer perceives the passage of the current and, as a reaction, raises the fingers from the contacts, automatically activating the trigger of the data acquisition system.

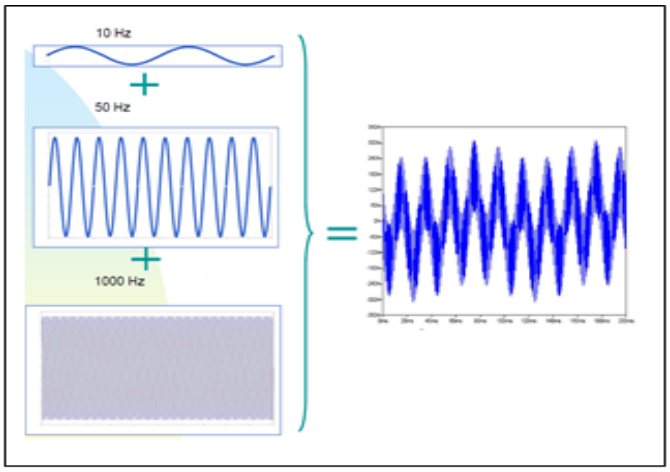


Fig. 6. Experimental multi-frequency current.

TABLE II
DIFFERENT WEIGHTED COMPONENTS OF MULTI-FREQUENCY CURRENT

I_1 Main frequency (50-60 Hz)	I_2 Clock (1 kHz)	I_3 Motor (10 Hz)
0,138 $I_{\Delta n}$	0,138 $I_{\Delta n}$	0,035 $I_{\Delta n}$

During the test, both the current flowing through the human body and the voltage applied are measured the human body impedance of the volunteer at different frequencies can be therefore calculated.

Moreover, before each test, the characteristics of the person under test (sex, age, height, weight and skin hardness of fingers) are recorded. In this way, the influence of the physiological characteristics on human impedance and, thus, on the perception threshold values can be statistically evaluated.

C. *Choice of the sample*

The sampling of volunteers is created in order to be representative of the Italian population distributions, as it concern sex and age, in the following way.

First, the adequate sample size is estimated by means of the following formula (1):

$$N = \left(\frac{Z_{\frac{\alpha}{2}} \cdot s}{d} \right)^2 \cong 62 \qquad (1)$$

where:

- N is the total number of subjects required in the study for estimating the perception threshold of population;
- $Z\alpha/2$ is the value of the normal distribution function for an alpha level of 0.05. It refers to the probability that the measurements actually reflect the characteristics of the population and are statistically significant with a confidence level of 95 %. Its value is 1.96;
- s is the sample standard deviation, considered equal to 0.4 mA, as it results from the preliminary tests carried out on about 20 volunteers;
- d refers to the measurement accuracy; an error estimation less than 0.1 mA of the true mean is established.

For the sake of caution, in order to consider also eventually unusable measurements, the sample size is chosen equal to 70.

Secondly, a “Stratified Sampling” is performed considering the sex and age distribution of the Italian population [20].

The first stratum refers to the sex: since male and female are practically equal in number, the total number of volunteers N is divided into two groups.

The second stratum concerns the age distribution: the Italian population is divided into four age classes; therefore, the volunteers are selected proportionally to the frequencies of each age class. Thus, it is chosen a sample of volunteers distributed as shown in Table III.

TABLE III
SAMPLE AGE DISTRIBUTION

Age	n. of volunteers
20-30	14
30-40	17
40-50	21
50-60	18

V. CONCLUSIONS

In this paper, the perception threshold for "multi-frequency" transient currents applied to the fingertip has been discussed. Starting from the past literature knowledge about electrical safety, the effects of the current on human body have been analyzed with particular attention to the perception threshold. In order to analyze the protection against electric contacts, different types of residual current protective devices (RCDs) have been introduced. An experimental set up with an electrical circuit has been assembled to define the perception threshold for non-sinusoidal currents. At the moment, the measurements described above are in progress on a group of volunteers, in order to determine the perception threshold and the body impedance for capacitive discharge stimuli to the fingertip. In particular, for each subject, four different types of tests are carried out, with three separate currents at nominal frequency of 10 Hz, 50Hz, 1000 Hz and with the composite current normalized by the IEC Standard 62423 for F type RCDs.

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