Determining Voltage Levels of Concern for Human and Animal Response to AC Current

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***Abstract*—Whenever a voltage potential is present between two points – in close enough proximity – for a human or an animal to bridge the gap between them, there is the possibility for current to flow through the body. For the purposes of this paper, the contact scenarios of interest are limited to publicly or privately accessible locations such as swimming pools, hot tubs, pipe lines, street lights, electric service boxes and other areas where electric shock complaints are reported. This paper supplies a review of the literature on human and animal response to ac current along with a review of the standards and documents that presently have published values for voltage, current, or resistance. These documents prove useful in understanding the establishment of published limits and levels of concern. A methodology is described whereby new levels of interest for contact scenarios may be developed using a systematic process that follows the basic methodology applied in establishment of prior limits.**

***Index Terms*—Contact voltage, neutral-to-earth voltage, conductive-object-to-earth voltage, stray voltage**

I. Introduction

Voltage potential between a conductive object and a ground reference, or between a neutral conductor and the earth—often referred to by terms such as contact voltage, stray voltage, or elevated neutral-to-earth voltage (NEV)—can be a concern for electric utilities and the public. Such concerns range from perceptible voltage levels at animal water troughs to shock complaints from streetlamps, manhole covers, gas lines, water pipes, swimming pools, and hot tubs. Complaints about humans or animals getting shocked are not new. In fact, these issues have been around since the inception of electric power. Although measurement protocols and mitigation techniques are available, it can sometimes be difficult to correlate measured voltage levels to complaints about shocking sensations. In fact, sometimes during a shock complaint investigation the measured voltage levels are not large enough to correlate to the levels known to impact humans. This can be attributable to the variation in NEV levels that occur at different times during the day and during the year. Such measurement issues present an opportunity within the IEEE to assist with development of methods to better evaluate concerns associated with perceptible voltages.

To date, very few states or provinces have considered establishing limits on voltage levels for human-contact areas. Some states such as Wisconsin have adopted very specific methods for assessing perceptible voltages at animal contact points and have defined thresholds above which remedial actions must be taken. Other states and provinces have considered or are in the process of passing regulations aimed at performing periodic measurements or at limiting the level of voltage to which animals and humans may be exposed.

II. Areas of Interest and Summary standards Development Needs

To understand which current or voltage limits may be appropriate, it necessary to understand the various responses of the body to electric currents along with the other physiological aspects that impact current flow in the body paths. It is also important to have consistent and repeatable measurement protocols for the specific investigation types where a protocol will be useful. While there are a number of additional topical areas related to electric shock and perception issues, the most common complaints stem from:

- Farm Animal Contact Areas
- Urban Street Level Energized Conductive Objects
- Swimming Pools
- Metallic Pipelines

Given the previous discussion there is an opportunity for the IEEE standards development process to assist in both improvement and enhancement of the protocols and equipment requirements necessary for comprehensive and accurate shock complaint assessments and a further opportunity to assist in development of a process whereby application specific limits may be considered. The measurement protocols and equipment issues were discussed in detail in [1], while the limit consideration process is expanded on in this paper.

III. Effects of Body Current on Humans and Animals

Any time that a sufficient voltage is present across two conductive points, current will flow if the points are bridged by an external impedance. Because animals and humans, in the electrical sense, represent such external impedances, the current flow through the body when contacting the two points, can range from little or no perceptible effect, to shocking sensation, to the possibility of electrocution.

The effect on any given body depends upon:
a) the path impedance
b) the applied frequency
c) the current magnitude, and
d) the duration of the current flow

Generally speaking, the longer the contact duration, the higher the voltage and the lower the impedance of the body, the greater the chances that the electric current will exceed the level necessary for human or animal perception. With this in mind, several important questions must be answered in order to support a process useful in limit establishment or level of concern determination. The important questions include:

1. What are the significant variables that define human and animal body impedance?
2. What impedance ranges are useful for characterization of humans?
3. What impedance ranges are useful for characterization of different animals?
4. Based on the impedance ranges, what 50/60-Hz contact voltage levels may be considered acceptable or unacceptable?
5. What are the voltage and/or current levels that an investigator may be most interested in?

All five of these questions can be answered based on the substantial body of research available on human and animal physiology as follows:

What are the important variables related to defining human and animal body impedance? The contact impedance of the skin of humans and the hoofs (or paws) of animals tends to be at least 30 times greater than the internal tissue impedance. Therefore, the *contact impedance* and the *environment* (wet, salty sweat, or dry) become the dominant variables. Other current path impedances such as the external contact medium, (earth, cement, metal, liquids, etc.) and the source impedance are wide ranging variables but do not impact the selection of a body impedance value.

What impedance ranges are useful for characterization of humans? The answer depends upon the specific situation and whether or not immersion in water is involved. For dry conditions, 1,000 ohms [2, 3] and 2,000 ohms [4] are cited as conservative values for a bare foot to hand contact and a range of voltage from 220 Vac down to 50 Vac. For immersion conditions values below 200 ohms might apply in the case of a swimming pool or a hot tub [5].

What impedance ranges are useful for characterization of different animals? The literature is not specific on impedance values other than for dairy cows (500 ohms is a value frequently used there), but the wet and dry values cited for humans (200 to 2,000 ohms) can be considered a useful range of impedances for dogs and other animals as well. Since some of the human data was based upon tests using dogs.

Based on the impedance ranges, what 50/60-Hz contact voltage levels may be considered acceptable or unacceptable? No single value for voltage can be considered acceptable or unacceptable because each contact situation may be different. For example, Table 1. provides a list of standards suggesting that for humans, voltages below 15 Vac are relatively safe for wet contact areas and voltages below about 50 Vac are relatively safe for dry contact situations. These levels come from established standards and take into consideration the wide range of body impedance values and the various effects of current flows through the body.

What are the voltage and/or current levels that an investigator may be most interested in? As previously stated, it is the current level though the body that determines whether or not there will be an adverse reaction. The literature identifies a number of current thresholds, and arguably the most important are *perception*, *startle*, and *fibrillation*.

In terms of perception levels, humans are reported to be slightly more sensitive than animals. However, that may be partially related to the fact they can more easily communicate that perception. The literature indicates that 0.1 milliamps can be perceived by some humans and as little as 1.5 volts may create that perception [6]. Because a human in a swimming pool with an arm sticking out of the water and contacting a metal railing or ladder may represent just a few hundred ohms of impedance, 1.5 volts may be perceptible to some humans at pools and spas.

In terms of startle reaction levels, the UL leakage current limits [4] provide the basis where 0.5 milliamps has been selected as the level where more than 99 percent of the population will not have a startle reaction to that level of current. These values were determined by way of substantial testing and have some inherent factors of safety built in. It is difficult to translate this to a precise voltage, but the most conservative 15 volt level found in Table 1. provides a level that may be useful for initial discussion for a startle reaction threshold.

In terms of fibrillation levels, test data for dogs have been applied to humans based on the inferences that dog fibrillation currents are about 80% of that for humans [6]. The minimum threshold (through the heart path) is approximately 67 milliamperes for adults and 30 milliamperes for children. The literature does note that the surface area of a child's hand or foot being less than that of an adult means that it is more difficult to achieve an equivalent current level – given an identical voltage. It is not easy to calculate current through the heart for the various contact scenarios, therefore one will not be estimated here. It may be noteworthy to mention that according to [7] no fibrillation deaths are known to have been documented with voltages of 50 Vac or less. This emphasizes the difficulty in using a body impedance values to attempt to calculate a safe voltage. Further, the contact mode foot-to-foot, hand-to-foot, etc defines the portion of the current through the heart path and a foot-to-foot contact – for example – would produce very little heart current.

IV. Established and New Levels of Concern

Levels of concern for contact voltages have been established for animal contact, for skilled trade industries, and by various safety and standards organizations. It is important to understand how these levels have been derived in order to ensure that appropriate methods are employed—if and when new levels of concern are established. With this in mind, the objectives here are to:

- Summarize the effects of current flow through the body for situations where a proposed new level of concern may be of interest
- Summarize "established" levels for human and "non-farm animal" contact scenarios
- Discuss historical aspects of the established levels of concern
- Discuss some issues to be considered when establishing new levels for contact scenarios where a level does not presently exist

Effects of Current Flow Through the Body

As detailed previously, there are a number of defined effects due to current flow through the body, ranging from perception to tissue damage. Thus, situations where limits may be considered are notably different. For example, when there is an aversion concern for farm animals, the "equivalent voltage" level of concern at 1 to 2 Vac is very low compared to the levels established by OSHA (>50 Vac) for worker safety. Because of the different objectives, there will be differing levels of concern. Objectives, based on the effects of current flow through the body, can be categorized into three areas for short-term 50/60-Hz ac contact scenarios:

1. Aversion – Examples include animals avoiding a metal grate, animals not wanting to drink water, and humans not wanting to enter a pool or hot tub.
2. Injury – The actual level of concern here is referred to as "startle reaction" where the result is a possible injury (such as falling from a ladder or spilling a pan of boiling water).
3. Fatalities – The level of concern here is "heart fibrillation" or "respiratory paralysis."

The most challenging aspect of defining thresholds for these three areas is that:

- There are differences in the body-part impedances for animals versus humans.
- There are differences for the various current paths and the amount of associated "heart current" flow.
- There are differences in the actual point-to-point contact mechanisms (hand-to-foot, chest-to-foot, and so on) for both wet and dry conditions.

These differences present the challenge of requiring multiple limits for the same scenario or going with the most conservative value for all combinations. To illustrate the point, an energized street-level service box may cause a serious injury to an animal while that same voltage level may cause no impact to a human that is wearing rubber-soled shoes.

Published Levels of Concern for Human and Animal Contact Scenarios

Table 1. provides a selection of established values for human contact situations. This table is useful for comparison purposes and provides a frame of reference for some of the parameters that are used to establish contact scenario limits.

Table 1. Summary of Published Contact Voltage Levels of Concern for Humans

Reference Document	Published Level	Concern Category
UL-101 [4]	0.75 milliamps reaction current 2,000-ohm human body impedance.	Reaction Current
UL-60950-1 [8]	42.4 Vac and 60 Vdc is the stated limit under dry conditions and human hand path.	Shock Hazard
IEC 479-1 [9]	25 Vac clearly safe, 50 Vac marginally safe (duration dependent). 1000 ohm body impedance cited	Shock Hazard
OSHA Rule (29 CFR Part 1910) [10]	Circuits operating above 50 Vac or 50 Vdc.	Shock Hazard
NFPA 70E [11]	30 Vrms or 60 Vdc. 500-ohm wet human body resistance.	Shock Hazard
IEEE Yellow Book – Std. 902-1998 [5]	Currents as low as (10) milliamps and voltages above 50 V can cause fibrillation. 500-ohm minimum body resistance for wet conditions or cuts. 100-500 ohms for immersion (Table 7-2)	Heart Fibrillation
NACE [12]	15 volts.	Shock Hazard
NESC [13]	51 volts.	Shock Hazard
NEC® [14]	Circuits operating above 50 Vac or 50 Vdc or 15 V for wet areas.	Shock Hazard
IEEE Std 80 [2]	60 Vac for 4 sec. 1000 ohm human body impedance	Shock Hazard

Historical Aspects of Established Levels of Concern

It is important to understand from a historical standpoint how existing limits and levels of concern were established. Whether or not the established limit includes built-in "factors of safety" can ensure that the researchers do not make erroneous assumptions relative to establishment of any new limits. The actual text in the reference documents (found in Table 1.) indicate that at least a few of the established levels of concern have "factors of safety" already built in.

As an example, [6] explains that if we look at the testing and sampling methodology utilized by Underwriters Laboratories (UL) to help define the ANSI leakage current limits, we find that the UL conducted experiments with human volunteers holding cups of rice and applied a series of random currents. First, tests were performed for a contact from one (hand or wrist) to the other arm (where the other arm was immersed in saltwater). This provides a "wet-versus-dry" impedance factor of safety that is "built in" relative to the ultimate limit.

Next, the test team established that women were more sensitive than men, and so all of the follow-on tests were conducted with a sample of 20 women (in essence this cuts out 50% of the population) and provides a second "built in" factor of the safety.

Finally, the average reaction considered borderline hazardous was 2.2 mA, and a limit of 0.5 mA was ultimately adopted. Now by recombining the male and female population, the limit of 0.5 mA minimizes the chance of a startle reaction to less than 1% of the total human population.

Parameters to Consider for Development of Levels of Concern

For discussion purposes, we can summarize the previous sections and the relevant parameters that might be considered in the establishment of limits. These include:

1. Current threshold – A current threshold must be established based on the intended avoidance objective. (aversion? injury? fatality?)

2. Body Path Resistance – For conversion of a current threshold to a voltage level (or vice versa), the defined body-path resistance is necessary. The type of contact defines the path as hand-to-foot, foot-to-foot, hand-to-hand, front-paw-to-rear-paw, and so on.

3. Body Weight – The literature suggests that body weight may be useful in approximation of current sensitivity, but Reilly [6] points out that the researchers are not in consensus agreement on whether body weight is useful for safety criteria.

4. Wet versus Dry Threshold – For most contact voltage scenarios, wet conditions represent a worst case because the skin, the paw, or the hoof contact resistance is at a minimum when wet. According to IEC 479-1 [9], for levels up to 50 Vac and under wet conditions, the impedance decrease can be as much as 25%.

5 Factor of Safety – Unlike the factor of safety considerations for voltage insulation or for bridge construction, human and animal sensitivity to current thresholds present a wide range of values. Therefore, there is no simple way to select a single multiplier that can be considered a safe value for the entire population. Past methods for developing conservative limits and levels of concern include:

- Conservative Levels Based on Species and Subspecies – In order to be conservative, the most sensitive species (dogs) are used to define most heart fibrillation safety criteria since they are slightly more sensitive to the same heart current as compared to humans. Further for humans, females are typically more sensitive than males and are used in establishment of more conservative levels.
- Percentage of Population – Similar to what is used for the ANSI leakage current limits and the Wisconsin dairy cow perception thresholds, researchers may opt to use a percentage of the population likely to not be effected by a given current threshold.
- Injury Threshold – Injuries to body tissue caused by electric current flow is different from injuries due to a startle reaction, this may need to be considered when evaluating any new limits or levels of concern. The documents referenced in Table 1. should be consulted as well. For example, Annex B of [9], indicates that in real testing, 100 living humans were subjected to 25 Vac under dry conditions and no serious injuries were observed.

Proposed Process for Development of New Levels of Concern

What we can derive from the historical limits and the rationale behind those limits is that a scientific methodology does apply to the establishment of the established limits, and we can benefit from past research to articulate that process. The literature provides a large and diverse selection of both voltage and current limits already. Therefore, taking advantage of the rationale behind those published limits yields the following approach or procedure for development of new limits:

1. State the condition where the limit will be proposed (street-level conductive objects, pools, and spas, and so on).
2. Refer to existing standards (such as Table 1.) to find any "similar reference scenario" to ensure that an appropriate limit cannot be pulled directly from existing material.
3. If nothing in the existing standards is applicable, define the level of concern objective (aversion, injury, fatality).
4. Define the species where the limit will apply (humans, dogs, or other species).
5. Define the contact mode(s) such as hand-to-hand, foot-to-hand, and so on.
6. Based on the condition (from 1) where the limit will be proposed, define a worst case voltage expectation
7. Estimate a minimum body impedance value based on the contact mode(s) and the worst case voltage expectation
8. Consider how wet or dry conditions might warrant either raising or lowering the impedance value.
9. Estimate the complete circuit current path impedance value
10. Define the current threshold(s) based on the objective and taking into consideration the contact scenario(s) as well as the full current path impedance value.
11. Where practical, reduce the current threshold(s) to a single worst case and articulate/document the factors of safety that have been considered in that limit.
12. Calculate the voltage limit(s) that apply to the contact scenario and the species based on the current threshold(s) and the impedance value(s).
13. Define the appropriate measurement protocol for the limit(s).

An Application Example

The following section provides an example utilizing the previously described step-by-step procedure to identify a potential level of concern for "wet contact" locations such as swimming pools and hot tubs.

1. State the condition where the limit will be proposed – The condition where the limit applies is the area immediately surrounding the pool or spa water, within touch or step distance.

2. Refer to existing standards to find any "similar reference scenario" – Reviewing Table 1., there are no similar pool or spa limits, but there is some information related to NEC® Article 680 and a 15-V shock hazard reference that should be researched further. Also, there are references to application of "minimal" resistance values for immersion conditions of 100 to 500 ohms in IEEE 902 that should be researched further to understand the context related to the applicable voltage levels.

3. If nothing in existing standards apply, then define the level of concern objective – In this example NEC® 680 and IEEE std. 902 are useful for understanding the contact scenario but don't really address the particular objective for this scenario (which is '*aversion*' due to tingling perception or nuisance shocking where persons may be afraid to get back into the pool).

4. Define the species where the limit applies – The species where the limit applies for this example is *humans*.

5. Define the contact mode(s) such as hand-to-hand, foot-to-hand, and so on. – The contact mode(s) can be "upper arm to hand," "torso to lower leg," or other combinations where the affected person is either in the water, is sitting at the waters edge or is in the process of exiting the water via a non-immersed metallic handrail.

6. Based on the condition (from 1) where the limit will be proposed, define a worst case voltage expectation – The contact scenario is the swimming pool where the voltage source is nearly always elevated NEV and worst case generally does not exceed 10 Vac. This voltage value will be important when considering the body path impedance because the outer layer skin resistance (and subsequent total body impedance) changes with the applied voltage [9].

7. Estimate a minimum body impedance value based on the contact mode(s) (from 5) and the worst case voltage expectation (from 6) – Under this scenario, Table 1. would suggest at least a 2,000 ohm hand to foot body resistance value for 5% of the population. Because the most likely contact mode(s) would be torso to lower leg or chest to hand, the 2,000 ohm value might be realistically reduced to 500 ohms or perhaps less!

8. Consider how wet or dry conditions might warrant either raising or lowering the impedance value – The impedance values need to be factored for wet conditions and very minimal body resistance and current paths such as hand to chest (when exiting the pool via a non-immersed handrail) or torso to foot (when sitting poolside with feet in the water). Fortunately, these are aversion and not fatality objectives! For this scenario, it is not unreasonable to use a body current path impedance as low as perhaps 200 ohms.

9. Estimate the complete circuit current path impedance value – This determination is not simple, but the full circuit source in this case is the energized pool water (very small resistance) through the body path (a few hundred ohms) back through the cement deck and the earth (a few thousand ohms skin to cement) and back through the grounding electrodes (20 to several hundred ohms). The minimum full circuit path impedance would be the sum of all of these and is most likely in the range of 2,000 to 2,500 ohms.

10. Define the current threshold(s) based on the objective (from 3) and taking into consideration the contact scenario(s) (from 5) as well as the full current path impedance value (from 9) – Based on the aversion objective and considering the contact scenario(s), the currents that cause perceptible complaints are most likely between 0.5 mA and 5.0 mA. Note that the actual perception threshold will be different for adult males, females and children, so any value selected does not imply perception for the majority of humans.

11. Where practical, reduce the current threshold(s) to a single worst case and articulate/document the factors of safety that have been considered in that limit – Reducing the current threshold(s) to a single worst-case 0.5 mA value would suggest that only a small percent of the population is able to perceive this value. Because the level of concern is pool use aversion, the factor of safety is not applicable for this case.

12. Calculate the voltage limit(s) that apply to the contact scenario and the species based on the current threshold(s) and the impedance value(s) (V = I x R) – The applicable voltage level that applies to the contact scenario and to the human species would yield a minimum voltage level of perception at 1.0 to 1.25 volts (where R is 2,000 to 2,500 ohms and I is 0.0005 amps). This calculated voltage may explain why some children and female adults have been known to perceive and complain about voltage levels in this very range, but it is a fairly small percentage of the complaints that result from voltages this low.

13. Define the appropriate measurement protocol for the limit(s) – The appropriate measurement protocol for the applicable voltage level is a typical residential shocking complaint investigation procedure where a high impedance true rms meter is used to measure the ac voltage between the pool water and various contact points within step and reach distance of the water. The investigator may also consider using a load resistor of 200 ohms to evaluate the currents that may be flowing through the body path.

Note: the preceding is simply an application example and should not be construed as a recommended level of concern. To develop a level of concern or a limit, the process would require industry expert consensus and field validation.

Because this methodology incorporates the basic process used to establish some of the limits found in existing standards, variations may be readily applied to the other areas of interest where no existing limit is available. The possible areas where future levels or limits may be useful include:

- Wet contact locations (swimming pools, hot tubs, and so on)
- Non-wet area residential contact locations
- Above-ground pedestrian-level contact locations (light poles, bus shelters, and so on – with applicability mainly to humans)
- Street-level contact locations (manhole covers, grates, service boxes, and so on – with applicability to pets and to humans)

As a note of caution, while the process provides a way to evaluate situations where there may be an interest in understanding the various levels of concern, the intent is not to define or represent levels where no action is required. For example, if an object such as a manhole, a service box, or a light pole becomes energized due to either direct or indirect contact (through gravel, soil, etc.) with the ac voltage source, it does not matter what voltage level is measured on the object. The most important consideration would be to secure the area with warning or caution barriers such that humans and animals are unlikely to contact the energized object(s) until the source can be de-energized and appropriate repairs made. On the other hand the process provides very useful methodology for understanding the voltage levels that may present perception and other shock complaints.

V. References

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