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Elements of Electrical Safety for Physics Students

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Abstract

Starting from J.D. Jackson's definition [1] of the topic of grounding, we present some knowledge of electrical safety, essential for every physics student.

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1. Introduction

Importance of the topic of Electrical Safety for students working in a laboratory or for future engineers, empirical scientists, and even simple householders, is obvious. We widely use electrical supply, generated by very powerful power plants with furnace burning natural gas, oil, coal, nuclear reactors, or with hydro, solar, wind and other renewable energy sources. Through the supply of the electricity via the wires, the power sources offer us numerous possibilities of having very serious injuries if we do not use the advantage of having the power supply with reasonable care. Here, we shall focus on the topic of grounding – one of the central and educationally interesting topics of Electrical Safety.

Wishing to avoid the very unsuccessful term "general resistance of the earth mass" found, e.g., in Israeli official instructive book "Electrical Law" [2], let us start from the definition of grounding found in the classical text [1]:

"When a conducting object is said to be *grounded*, it is assumed to be connected by a very fine conducting filament to a remote reservoir of charge that serves as a common zero of potential. Objects held at fixed potentials are similarly connected to one side of a voltage source, such as a battery, the other side of which is connected to the common 'ground'. Then, when initially electrified objects are moved relative to one another in such a way that their distributions of electricity are altered, but their potentials remain fixed, the appropriate amount of charge flow from or to the remote reservoir, assumed to have an inexhaustible supply. The idea of grounding something is a well-defined concept in electrostatics where time is not a factor, but for oscillating fields the finite speed of propagation blurs the concept. In other words, stray inductive and capacitive effects can enter significantly. Great care is then necessary to ensure a 'good ground'."

The concept "remote reservoir of charge" of [1], is definitely much better than the concept of "general resistance of the earth mass" of [2]. The latter concept is even misleading, because the very concept of resistance [3] is associated with the way of the measurement, for which the geometrical presentation of the relevant piece (sample) of material must be given. Just assume that you measure the resistance of a material ball, while the electrodes are connected to the North's and the South's poles of the ball. Then, move one of the contacts towards the other; the measured resistance is obviously reduced, with the limiting value of zero, obtained when the contacts touch each other.

However, the words "very fine conducting filament" of [1] are generally wrong. No realistic grounding can be "very fine" -- a mistake that has to be pinpointed just because of the wide use of [1]. Presumably, Jackson would like to have the "very fine" filament exclusively because of the field problem, that is, for suitability in the calculation of the fields, not considering the main purpose of the grounding. In order to see the mentioned suitability, consider a spherical capacitor (two concentric conducting spheres), with the internal sphere having its potential zero. The theory of such capacitor is quite simple, and one easily obtains, via the radiuses of the spheres, r_1 and r_2 the formula for the capacitance [3]

$$C = \frac{4\pi\varepsilon}{\frac{1}{r_1} - \frac{1}{r_2}}, \quad r_1 < r_2 \qquad (1)$$

However, in order to ground the internal sphere, one has to make a hole in the external sphere for the grounding wire *with a possible current in it* to pass via the hole. Obviously, the simple picture of the field, which led to (1), will be less disturbed, if the diameter of the grounding wire (the "conducting filament" in [1]) is much smaller than the diameter of the hole. Indeed, the magnetic field of the current in the wire is stronger *near* the wire. Since the grounding wire *has* to supply the charge, we cannot ignore the current, whose pulses cause time varying magnetic field, resulting in some electrical field.

Nevertheless, the thinness of the grounding wire represents a problem from the positions of the electrical safety -- one should not forget an important reason why grounding is really needed!

According to the formula for resistance of a piece of wire of length *l*, and cross-section S, [3]

$$R = \frac{\rho l}{S} \qquad (2)$$

as the diameter of the wire tends to zero (and so S does), *R* becomes large.

Let us give an example showing how the latter is dangerous for the grounding. This example is taken from [4], where we also dealt with finding a relation between the internal resistance of the generator and its power, here we assume that the internal resistance R_{int} *is given*.

2. A case from students' power laboratory

Thus, we speak about a teaching laboratory where a student studies a generator, and it may occur that a defective 220 volts generator might electrify its metal body that the student touches. Since the metal body is grounded, there is a "competition" between the source of 220 volt and the source (the ground) of 0 volt – which one will define the body's potential? Electrical safety requires that the potential of the metal body that can be touched by the student to be less than 30 volts. The actual potential obviously (see Fig.1) depends on the ratio

$$\frac{R_{gr}}{R_{\text{int}}} \qquad (3)$$

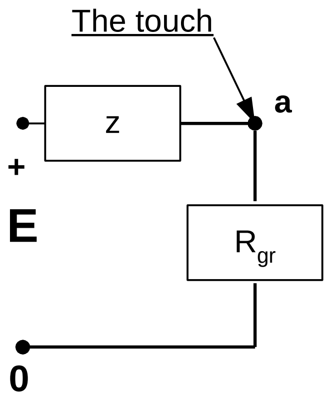

Fig. 1: Our equivalent scheme. "Z" is our "R_{int}". The generator is thus {**E**,Z}. **E** here is 220V. Point **a** denotes the metal body of the generator, which can be touched by the student, and where, in the case of the fault, a dangerous voltage arises.

Since the resistance of the human body is much larger than R_{gr}, in the parallel connection of the two, the resistance of the body can be ignored, and the voltage divider, seen in Fig. 1, defines the voltage on the generator's body as

$$V = 220\frac{R_{gr}}{R_{\text{int}} + R_{gr}} \approx 220\frac{R_{gr}}{R_{\text{int}}} \text{ volt.} \qquad (4)$$

(As we shall immediately see, the assumption of $R_{gr} << R_{\text{int}}$ is justified). In order to have this be less than 30 volts, we require that

$$\frac{R_{gr}}{R_{\text{int}}} < \frac{30}{220}, \qquad (5)$$

that is, approximately,

$$R_{gr} < \frac{R_{\text{int}}}{7}. \quad (6)$$

Since the more powerful the generator, the smaller R_{int} is (i.e. the generator is "more ideal"), and since we are interested, in the laboratory, to study generators that are as powerful as possible -- R_{int} actually is rather small (say, a half ohm). Obviously, R_{gr} *must be very small*. The latter excludes using a "very fine filament" and if one also considers that it is necessary to have *very firm* mechanical connections of all the pieces of the grounding path (for the reliability of the grounding) – then one sees that the grounding connections are actually made of a wide (massive) pieces of wire.

Works [5-31] are advised for more conceptual (and history, e.g. [31]) reading.

Some questions for additional consideration

The following questions show how multifold and complicated is the topic of electrical safety, and how easily we can meet the associated hazards. Though some of the questions are simple, their list outlines the scope of the topics one should keep in mind when considering electrical safety, and this gives a correct orientation.

Does the reader know (and for what reason) that*:*

1. powder, e.g. flour, can be explosive,

2. when a liquid flows in a plastic pipe, an electrostatic charge is accumulated on the pipe walls, and this is the static charge which can cause a dangerous spark,

3. the water that is pouring from a faucet to a bucket may be positively charged, and the fact that the bucket may be metal and then left for some time on the ground does not eliminate the charge in the water quickly enough; because of the charge, the water may lead (see [17] for an interesting example) to a spark,

4. it is prohibited to turn on or off a light if the switch is located in an area (say the kitchen) where a strong smell of gas is detected,

5. in order to cause ignition or explosion of a certain gas, powder or liquid, the spark has to possess some minimal energy; which is somewhat similar to the medical fact that in order to be infected by a virus and became ill, a certain amount (dose) of the virus is necessary.

6. regarding the possibly of causing explosions, a corona-type discharge is less dangerous, than a spark-type discharge.

7. by saying that a flammable liquid is ignited, we mean that the *vapor* (*gas*) of the liquid, over its surface, is ignited,

8. a flammable gas may be ignited only at a certain concentration, and at a higher concentration it becomes explosive; the explosive concentration is usually about twice the flammable concentration,

9. the dangerous "step" voltage caused by lightning can be distributed both in the horizontal and the vertical direction (on buildings),

10. there have been cases of injury by lightning through a telephone cable,

11. if a car is staying on a junction during a storm, and an electrical wire falls on the car, no passenger should emerge from the car, but rather wait for an electrician to remove the wire,

12. kite-flying by children near voltage lines is dangerous,

13. static charge is dangerous not only in the chemical industry but also in the integrated circuit industry, where the discharge can cause damage to the thin layers of the microcircuits,

14. today there are instruments in the chemical and electronic industries, made from special plastic materials that have a low *triboelectric ability* (i.e. the ability to absorb static charge) allowing to reduce the risk of a spark; the development of such materials is a challenging field of material science,

15. one can be shocked while holding a well-grounded frame of a drill if the floor is electrified by a motor with faulty isolation, and *because* one holds a grounded object,

16. one can be shocked by the line voltage when connecting one of the wires of an unlit bulb to the zero-potential wire of the line, while not directly touching the phase-wire of the line, which is because the wires in the switch are inter-placed, and the switch does not interrupt the hot wire -- thus the voltage can come to one's hands via the lamp,

17. the large metallic foundation of a high-voltage line column (post, tower) has to be grounded at each of its corners (think about one lying on the ground, touching the electrified foundation by **his** shoulder),

18. new buildings have their grounding electrode systems organically included in the building's foundations,

19. in the conditions when even a short-time overvoltage of power equipment is dangerous, the grounding of the equipment may be unwanted or even prohibited, because of the possibility of the electrification of the soil around the grounding electrodes, caused by a lightning stroke (a high voltage can come to the equipment via the grounding); this is relevant to the regions where lightnings are usual,

20. in order to improve the quality of grounding, in some cases special salts are introduced into the soil – this reduces ρ in (2),

21. there have been cases where plumbers working near old houses received electric shocks when disconnecting a water pipe from the underground water system,

22. when starting to work, electricians sometimes first touch an open electric wire *with the back of a hand.*

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References

[1] J.D. Jackson, "Classical Electrodynamics," John Wiley, New York, 1975. (See p. 23)

[2] Hok ve Takanot be Nose Hashmal ("The Law and Rules Regarding Electricity," *in Hebrew*) The Office of Safety and Health, 1919

[3] R.P. Feynman, R. Leighton, M. Sands, "*Feynman Lectures of Physics*," **Addison Wesley**, vol. 2, New York, 1965.

[4] E. Gluskin, "The parameter of order for estimation of the needed grounding resistor," FJEC (Far East Journal of Electronics and Communications), Volume 22 No. 1-2 (2019).

[5] R. Artdej, "Investigating undergraduate student's scientific understanding of laboratory safety", **Procedia Social and behavioral sciences**, Vol. 46, pp. 5058-5062, New York, 2012.

[6] C.O. Ponferrada, J.G. Daque, D.C.L. Buadlart, E.J.L. Cabigon, V.R.K.R. Galarpe, "Laboratory Safety Awareness Among General Physics Undergraduate Students", **Engineering Technology & Applied Science research**, vol. 7, no 6 (2017)

[7] Ashley R. Carter, "On building a research Laboratory, not starting one", **American Journal of Physics**, **87**, 413 (2019)

[8] Beryl Lieff Benderly, "Danger in School Labs: Accident count Experimental Science", **Scientific American**, August 1, 2010.

[9] E. Leonard Jossem, "The education of physics graduate assistants", **American Journal of Physics**, vol. 68, no 6, June 2000

[10] Science lab safety – http//www.youtube.com/watch?v=5g

[11] Todd Campbell, Drew Nelson, and Phil Seak Oh, "Grounding instruction around scientifically rich, often complex phenomena", **Science Teacher** (Normal III), September 2013, pp. 35-41.

[12] "Grounding – the removal of charge", **The physics classroom**, http//www.physicsclassroom/class;

[13] I.A. Jamieson, S.S. Jamieson, H.M. ApSimon, and J.N.B. Bell, "Grounding and Human Health – a Review", **Journal of Physics**, Conference Series, volume 301, number 1.

[14] G. Chevalier, R. Mori, and Oschman, "The effect of earthing (grounding) on human physiology", **European Biology Bioelectromagnetic**, 2007, **1**, 600-621.

[15] G. Chevalier, S.N. Sinatra, J.L. Oschman, K. Sokol and P. Sokol, J. Environ, Public Health 2012, 291541; doi: 101155/2012/291541

[16] K. Sokol and P. Sokol, "Earthing the human body influences physiological processes", **Journal of Alternative and Complementary Medicine**, 2011; 17(4):301-308.

[17] W. F. Cooper, "*Electrical Safety Engineering*," Newnes-Butterworth, London, 1982. (In particular, Section 10.21)

[18] L. B. Gordon, "Electrical hazards in the high energy laboratory," **IEEE Transactions on Education**, Vol. 34, No. 8 (Aug. 1991), pp. 231-242.

[19] E. Gluskin, "*Betichut Hashmalit*," (Lecture Notes on Electrical Safety, in Hebrew), **The British Library**, Shelfmark HEC 1998 a 508.

[20] J.D. Irwin & R. M. Nelms, "*Basic Engineering Circuit Analysis*", **Wiley**, New York, 2008.

[21] G. McPherson & R.D, Laramore, "*An introduction to Electrical Machines and Transformers*", **Wiley**, New York, 1990.

[22] http://www.hit.ac.il/staff/gluskin/full.pdf

[23] E. Gluskin, "On the human body's inductive features: A comment on 'Bioelectrical parameters…' by A.L. Lafargue et al., "**Bioelectromagnetics**, 24(4), 2003 (292-293)

[24] *National Electrical Code*, NFPA (National Power Protection Association) Quincy, Mass., 2010.

[25] S. Corsi, G.N. Taranto, "Voltage instability, -- the different shapes of the nose", from Bulk Power System Dynamics and Control - VII. Revitalizing Operational Reliability, 2007 iREP Symposium (19-24 Aug. 2007, Charleston, SC), DOI: 10.1109/IREP.2007.4410582.

[26] E. Gluskin, "An Extended Frame for Thevenin (Norton) Theorem", **IEEE CASS Newsletter**, vol. 5, issue 6 (the "Forum" section), Dec. 2011.

[27] E. Gluskin, "An Extended Frame for applications of Helmholtz-Thevenin-Norton Theorem", J Electr Eng Electron Technol (JEEET), 2013, 2:2. http://www.scitechnol.com/extended-frame-for-applications-of-the-helmholtztheveninnorton-theorem-8nCB.php?article_id=1419.

[28] http://hyperphysics.phy-astr.gsu.edu/hbase/electric/gfi.html

[29] Ch.A. Desoer, E.S. Kuh, "*Basic Circuit Theory*", **McGraw Hill**, New York, 1969.

[30] W.H.J. Childs, "Physical Constants", London, Methuen & Co. LTD; (also New York. John Wiley& Sons).

[31] "*A Short History of Circuits and Systems*" IEEE CAS book (Editors: Franco Maloberti and Anthony C. Davies), River Publishers, Danmark, 2016: https://ieee-cas.org/sites/default/files/a_short_history_of_circuits_and_systems-_ebook-_web.pdf

Appendix: Some historical background

The lightning-rod for lightning protection was proposed by Benjamin Franklin approximately in 1750.

The use of a "Faraday cage" for lightning protection of buildings was introduced by James Clerk Maxwell in 1876.

Luigi Galvani conducted the first experiments on the influence of an electrical current on a live (animal's) body in 1791. Galvani could have answered question 22 of Section 3.

Approximately one hundred years after Galvani's experiments, the pioneer of heavy-current and high-frequency current engineering, Nikola Tesla, started a systematic study of the influence of electrical current on the human body, which was necessary for the safe application of his inventions. It was Tesla who discovered that at very high frequencies one can touch a very high voltage, and in his lecture in Philadelphia in 1893 Tesla personally demonstrated touching the terminals of a 200 kV source. Tesla had proved that the 50 - 60 Hz line is the most dangerous among the alternating current supplies, and that contrary to Edison's opinion, up to about 500 volts, the constant-voltage current is more dangerous for people than alternating current of 50 or 60 Hz. The proofs were experimental and demonstrated on very few individuals, often Tesla himself. Even today we do not know enough about the electrical parameters of the human body that allow to calculate precisely the distribution of the density of electrical current, which is passing through it, and this is a subject of biophysical investigations. Tesla's experiments, motivated by his interests in electrical safety, also led to the medical applications which are called today electrotherapy.

The "Fire Protection Handbook", which included important rules of electrical safety, named the National Electrical Code (NEC) appeared in the USA in 1897. It is now published by the American National Fire Protection Association (NFPA) with many improvements.

NEC is a very extended and complete list of instructions for electrical safety arrangements. This document has influenced electrical safety rules in many countries outside the USA, though in England, Germany, Switzerland, Russia and some other countries there are their own detailed and also very useful regulations.

The NEC is readily available today (including a CDROM version). Even just a study of the *classification of hazardous areas* given in the NEC provides an understanding of some basic electrical safety problems.