Some simple formulae for Grounding in a Laboratory and the Respective Definition of "Strong Current": a gate into Electrical Safety

Emanuel Gluskin[1*], *Raul Rabinovici*[2]

[1] School of Engineering, Kinneret College in the Jordan Valley (on the Sea of Galilee), Tzemach 15132, Israel.
[2] Ben Gurion University of the Negev, Electrical Engineering Dept., Beer Sheva 84105, Israel.

* Communicating author: http://www.ee.bgu.ac.il/~gluskin/ gluskin@ee.bgu.ac.il

Abstract: The concepts of "high power" and/or "heavy current" are *defined* from the positions of electrical safety in a power laboratory. According to this criterion, for the nominal full power S_{nom} of the device under test (generator, motor, or transformer), we obtain that $R_{gr}S_{nom} \approx V_0 \Delta V$, where R_{gr} is the resistance of the grounding, $V_0 \approx 30V$ is the maximal voltage permitted for touching, and ΔV is the range of the output voltage of the power device, associated with its non-ideality as a voltage source. Limiting one of the values R_{gr}, or S_{nom}, for the other given, this formula *defines what is* "high power" for a given laboratory, and the concept of "heavy current" thus appears as a relative one, adjusted to the safety needs. This approach can be helpful in making the very important topic of electrical safety interesting for students and teachers.

keywords: Circuit Theory, Grounding, Nonideal Generator, Internal Impedance, Electrical Safety, Power Education.

1. Introduction

1.1. General

When speaking about typical values; it is common to say that microelectronics uses microamperes or smaller currents, electronics – from milliamperes to amperes, and the heavy current engineering – from amperes to mega-amperes or even more. These values are meaningful for one, however, only when they are associated with the currents of some known equipment.

In fact, the concept of "heavy current" (or high power) is relative for us just as, for instance, the concepts of "very heavy" or "very expensive" are. Developing a feasible definition of "heavy current", which is associated with *electrical safety* [1-4] -- a very important topic of modern electrical engineering, -- we introduce clear criterion for deciding what can be the power of the equipment to be examined (studied) in a *certain* laboratory.

We thus show that the criterion for decision whether or not a current used in a laboratory is heavy (i.e. the equipment is critically powerful) is first of all defined by the grounding resistance of the laboratory. From the pedagogical point of view, the given argument also demonstrates the extreme importance of the concept of *the non-ideal voltage source*, -- one of the main concepts of electrical engineering, associated, in particular, with Thevenin circuit equivalent [4]. The non-idealness of the generator appears to be instructive for the requirements to state the value of the grounding resistance.

As regards electrical safety *per se* (and not the circuit theory arguments), we can expect that a specifically experienced in this field engineer knows the main formal (final) results that we obtain. However, even for such a specialist, the basic circuit point of view will be useful.

1.2. The rational

We derive some simple formulae, from which we find that for the 0.1 ohm of the grounding resistance, measured in the Kinneret College, it is impossible to use in the new student-laboratory power equipment of the power higher than 20 kW. For higher power, in the faulty conditions, the voltage on the metallic body of the motor exceeds the allowed by the safety regulation 30 volt, and a student can be dangerously shocked by the voltage. For any laboratory, it is important to simply obtain such safety estimations before the grounding arrangements are planned in their details.

Usually, for grounding a laboratory, the grounding of the whole building in which the laboratory is placed, is used. As a rule, for a large building such grounding is sufficiently low-ohmic, but for a small new college in an agriculture area, it may be necessary to make separate grounding for the laboratory. The resistance of the grounding defines the maximal power of the equipment to be tested by the students, or, alternatively, one can find the upper bound for the grounding resistance according to the desirable nominal power of the equipment. Since the power of a device is increased when its internal (output) resistance/impedance is decreased, -- if we use a *too powerful* generator, i.e. a one whose internal resistance is *too small, smaller than the grounding resistance of the laboratory*, then the voltage on the body of the motor in fault will be *too high*, too dangerous for a human. As a methodological point, the sense of the (always relative) terms "high power" or "heavy current" thus appear via the ratio of the resistances (impedances).

The electrical safety problem presents a remarkable situation regarding the concept of non-ideal voltage source. Indeed, usually, the non-ideality of a practical source is its disadvantage, and in order to keep the needed output voltage when a significant load is connected, we have to use a larger, more massive source (see Section 1.3 for a simple example), however, the non-ideality of the generator (motor) to be tested in the laboratory, is the advantage in the sense that it allows us to solve the safety problem by using a grounding resistance that simply has to be much smaller than the internal resistance of the source.

Not using any half-empirical models that can be important only for some specific cases, we obtain the estimations using only the basic Kirchhoff's equations and the simplest scheme.

Since the concept of non-ideal source (closely associated with the Thevenin Theorem) is one of the main concepts of basic circuit theory, the specific circuittheoretic and engineering positions of the present work give it some pedagogical slant, and the importance of the safety situation makes the work really timely.

1.3. A simple example of non-ideal source, which has to be known to everyone

For understanding the following example, it is sufficient for the reader to know Kirchhoff's circuit-equations and the fact that any real source, considered as one-port (i.e. having two "terminals") has some internal resistance (impedance), quite in the spirit of the famous Helmholtz-Thevenin-Norton theorem that equivalently (i.e. for the external circuitry) presents a linear one-port as an ideal voltage source with a resistance in series. If one is not sure in this electrical reality, -- he can be advised to try to "become a millionaire" by putting forward the idea of replacing the big, heavy and expensive car's 12V accumulator, by 8 single-cell torch batteries of 1.5V each, connected in series, and thus to start the engine. He will be disappointed to discover that at the start operation, the total voltage, given by the physically small (and *thus* having significant internal resistance) batteries, which is applied to the car's starter, is reduced to some milli-volts, because the internal resistance of such an absolutely improper *ad hoc* voltage source is much higher than the starter's resistance. Such a source is *very far from being ideal here*. Incidentally, by inserting two wires of different chemical origin (made, say, from zinc and copper) into a raw potato, one obtains (for this "source" unloaded) several tenths of a volt, but it would be naïve, of course, to seek promising applications of such a source.

When wishing to twice increase the *energy* accumulated in a battery, one can connect one more such battery in parallel. This obviously means parallel connection of the internal resistances of the batteries, and thus the internal resistance of the total battery is half of the resistance of the initially given battery. Thus, the extended source necessarily becomes more ideal both from the simple physical and circuit points of view. The physically natural fact that the US's powerful sources, e.g. Hoover Dam (previously, "Boulder Dam"), providing hydroelectric power in the USA, are physically (dimensionally) large, and thus very massive, can be explained just by the fact that the internal resistance of a voltage source is reduced as it is enlarging. Indeed, take a resister in form of a cube, and consider that $R \approx \rho \frac{l}{l^2} \sim l^{-1}$, in the usual notations. It is thus very reasonable to be careful with "good" voltage sources, i.e. with sources that well maintain their voltage when the current taken from them (which can pass via one's body) is increased. Such sources necessarily are very powerful! Of course, we mean, first of all, that one has to be careful with the usual line voltage, existing in the usual electrical socket.

1.4. The main notations and the conceptual frame

Considering steady-state sinusoidal processes, we use the usual "phasors" [4,5], denoted in *italic capitals* with the "hat", e.g., $\hat{I}, \hat{V}, \hat{E}$, and in a figure in *bold capitals*, e.g. **E**. (It is important to notice when we transfer from the phasors to their absolute values!)

Symbol S denotes the absolute value of the (total) complex power $\hat{S}$ [4], measured in volt-amperes (VA). $\hat{S} \equiv \hat{V}\hat{I}^* = P + iQ$ ('*' means complex conjunction), where P is the active, i.e. the usual nonnegative physical power, and Q is the "imaginary power", i.e. a *real value*, positive for inductance and negative for capacitance. Contrary to *P* that is well known also for non-sinusoidal processes, *Q* is usually (naturally) used only for sinusoidal processes, when phasors and impedances [5] are involved in the analysis. Since $S = |\hat{S}| = VI = \sqrt{P^2 + Q^2}$, $P \leq S$ and $|Q| \leq S$. *Q* is very often used in power systems description and analysis, since the load of a power device need not be purely resistive. Below, we use only *S*.

If (as here) in the expression for *any* power (*P*, *Q* or *S*) there is no factor 1/2, then, the included voltage and current are given in the r.m.s. values (V_{rms}, and A_{rms}) [4,5]. Somewhat incorrectly, the power specialists dealing only with the sinusoidal processes, often forget the notation "r.m.s", speaking about "volt" and "ampere"

Our "generator" to be under laboratory study, can be also a motor, or a transformer; it is just for certainty that we speak (only) about a generator.

Symbol '$(v.r.)$' means "voltage regulation", which is a relative difference between the nominal and the actual output voltage appearing when a load is connected. That the load changes the output voltage is associated with non-ideality of any real generator, *i.e. with its nonzero internal impedance*. That any real generator is non-ideal, is very important; for an ideal generator no grounding would be helpful.

Students in the power laboratory can study one-phase and three-phase devices. We speak only about the parameters of one phase. This simplification does not much alter the discussion, because the theory of 3-phase transformers and motors or generators is always reduced to a 1-phase analysis.

"Nominal" *means "maximal for a long period of work"*, that is, maximal in the steady state. In the equations below, V_{Load} always means $(V_{Load})_{nom}$.

Of course, a current heavier than the nominal does not immediately burn up a generator. It needs to be remembered, however, that excessive currents through the human body may be prohibited even for very short periods.

It should be stressed that the present work is written in the spirit of basic general courses, and not as a part of any special electrical safety course, though Section 4 somewhat improves this situation adding some "urgent" information related to electrical safety per se. The main purpose is to let one observe that in a situation unusual for him, knowledge of the basic physical *limitations* of electrical equipment, and some simple circuit equations, can give one a solid background for seeing the scientific problematicity (and beauty!) of the situation, here that of the grounding. Since the very important, and interesting in its physics foundations, topic of Electrical Safety, traditionally composed of two parts, -- for humans and equipment, -- cannot be taught here in any serious detail, the reader should complete his knowledge using the references that will now be found more interesting.

In a general view of the professional literature, the topic of grounding, -- this most classical subtopic of electrical safety, -- is being developed in various scientific directions. For instance, works [6-16] include many interesting specific points for future research.

The final terminological comment is that in power-systems' literature the term "power capability" (say, of a laboratory), is often met. This term is obviously relevant to the general situation we deal with, but for the concrete analysis we shall use only the physical terms of "power" and "current".

2. The criterion of safety

2.1. The argument

Considering the simplest one-phase model (See Fig. 1), let us start from the current $\hat{I}$ of the generator's load that is denoted as Z_L (Z_{Load} in the figure).

$$\hat{I} = \frac{\hat{E}}{z + Z_L}, \tag{1}$$

where $\hat{E}$ (**E** in the figure) is the phasor representing the output electromagnetic force ("EMF"), and z is the equivalent output impedance of the generator.

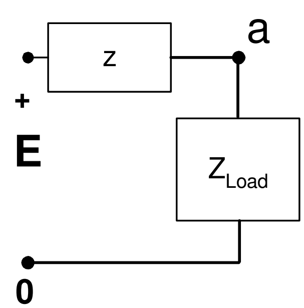

Fig. 1: The scheme of the generator (one phase) *in the usual case*. 'z' is the internal impedance of the generator, which makes the generator a non-ideal voltage source. Point '***a***' relates to the output of the generator. In Fig. 2, related to *the fault situation* in which the output conductor touches the metallic body of the generator, the load is not shown, because Z_L is large compared to the grounding resistance connected to the body.

For the load to receive a significant part of the voltage (i.e. the generator to be proper for the load), it obviously must be that

$$Z_L >> z, \tag{2}$$

i.e., $\hat{I} \approx \hat{E}/Z_L$.

For a nominal load, we have nominal current, $I = I_{nom}$.

We are interested also in the *fault-current* I_{gr} to the ground, which appears when an internal conductor with faulty isolation touches the grounded body of the device, and some voltage appears on the body of the generator. For this situation (Fig. 2) the relatively large Z_L is irrelevant (even if it remains connected to '**a**'), but the resistance of the grounding, R_{gr}, connected to the body of the device, becomes involved:

$$\hat{I}_{gr(foult)} = \frac{\hat{E}}{z + R_{gr}}. \tag{3}$$

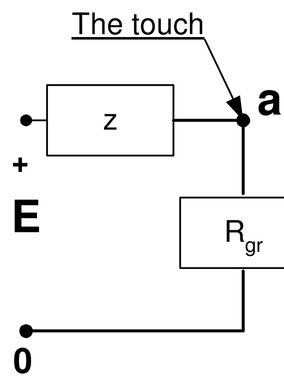

Fig. 2: The situation of the fault. R_{gr} "replaces" Z_{Load}. Since the resistance of human body, usually estimated as 1000 ohm [4], i.e. is always *much* larger than R_{gr}, it is ignored here. Obviously, the ratio $R_{gr}/|z|$ is very important. It defines voltage $\hat{V}_a$, appearing at ***a***, which may be of a dangerous for human value, for a usual value of *E*.

From (1) and (3)

$$\frac{\hat{I}}{\hat{I}_{gr(foult)}} = \frac{z + R_{gr}}{z + Z_L} \ . \qquad (4)$$

Since, the voltage $\hat{V}_a$ on the body of the faulty generator is

$$\hat{V}_a = \frac{R_{gr}}{z + R_{gr}} \hat{E} \ ,$$

and since $\hat{E}$ is, generally, not a small value (e.g. in Europe is usually 220 Vrms which can be lethal), it is necessary that

$$R_{gr} << |z| ,$$

otherwise the grounding is not effective.

Using the latter inequality and (2), we have from (4)

$$\frac{I}{I_{gr(fault)}} = \frac{|z + R_{gr}|}{|z + Z_L|} \approx \frac{|z|}{|Z_L|} = \frac{|z| I_{nom}}{|Z_L| I_{nom}} = \frac{\Delta V}{V_{Load}} \ . \qquad (5)$$

where $\Delta V = |z| I_{nom}$ is the relatively small voltage fall on *z*, while $V_{Load} = |Z_L| I_{nom}$ is the nominal output voltage that for our precision can be replaced by E (see Fig.1 again).

The internal voltage drop ΔV reflects (represents) the non-idealness of the generator, which means that a more powerful generator (i.e. one that can give more current without an essential reduction of the output voltage) has a smaller *z*.

Using the concept of *voltage regulation* (*v.r.*) [17],

$$v.r. = \frac{\Delta V}{V_{Load}} = \Delta V_{p.u.} \qquad (6)$$

(where *p.u.* means "per unit", i.e. relative to the nominal voltage), we can rewrite (5) as

$$I = \Delta V_{p.u.} I_{gr(fault)} = (v.r.) I_{gr(fault)} .$$

Remark: Precise definition of "voltage regulation" ΔV is somewhat different (see [17] for details); the *phases* of the complex numbers Z_L and *z* (see again Fig.1) are also involved in it. However, it is sufficient for our estimations to assume that these phases/angles are equal, i.e. $z / Z_L \approx |z| / |Z_L|$, and then we have the voltage division between Z_L and *z* just as for real values of usual restances. One can avoid the concept of "voltage regulation" in the analysis, if in each case, *z* is given, or measured, but for power systems, usually not *z* but $v.r. = \Delta V_{p.u.}$ is given; thus it is worthwhile to involve this concept.

Considering that *v.r.* is usually given in the range of 0.05-0.1, we shall use for an estimation, the value 0.08. Thus,

$$I_{\max(permitted)} \approx 0.08 I_{gr(fault)} . \qquad (7)$$

2.2. Watch the importance of the non-ideality of the voltage source!

In order to better see the role of *z*, let us note that the following seemingly different formulations are equivalent:

The rated power (below, S_{nom}) of a generator is small (then the generator is also physically/dimensionally small), i.e. the generator is weak.

The internal impedance z of the generator is large.

The generator is a strongly non-ideal voltage source, i.e. it cannot provide the desirable specified voltage for many loads.

The relative voltage regulation of the generator is significant.

The equivalence of these formulations shows the importance of the concept of the non-ideal source, -- the concept without which one cannot correctly understand the role of R_{gr}.

Since it has to be that $R_{gr} << |z|$, the larger is $|z|$ (i.e. the smaller and weaker is the generator), the easier it is to satisfy inequality (8) given below, providing the safety, by the actually obtainable R_{gr}.

3. The 'fault" situation

3.1 The criterion in terms of the maximal permitted nominal current

Requiring that the voltage V_a on the body of the generator in the "fault" situation be limited to the *permitted* voltage $V_o \approx 30V$ [4], we obtain (see Fig. 2) that

$$V_a \approx E\frac{R_{gr}}{|R_{gr}+z|} \approx \frac{ER_{gr}}{|z|} \leq V_o \approx 30V\,, \qquad (8)$$

from which

$$R_{gr} \leq \frac{V_0}{E}|z| \approx \frac{30V}{E}|z|. \qquad (9)$$

For the realistic $E = 220V_{rms}$ we have from (9) that $R_{gr} \leq 0.15|z|$.

Since (see again Fig. 2)

$$(I_{gr})_{fault} = \frac{V_a}{R_{gr}} \quad , \qquad (10)$$

for the critically *safe* case of $V_a = V_o$ we have (10) as

$$(I_{gr})_{fault} = \frac{V_o}{R_{gr}} \approx \frac{30V}{R_{gr}} \quad . \qquad (11)$$

The use of (11) in (7) yields

$$(I)_{\max(permitted)} = \frac{2.4V}{R_{gr}} \quad . \qquad (12)$$

In a rough, easily remembered form, (12) is $I_{nom} \sim 1/R_{gr}$ where R_{gr} is taken in ohms, and I_{nom} in amperes.

This is the criterion for "heavy current" that we wanted to suggest. It must be written now also in the terms of power.

3.2. The criterion in terms of the maximal permitted nominal power

The maximal permitted nominal power of the generator, i.e. the defined "high power",

$$S_{\max(permitted)} = V_{Load} \cdot I_{\max(permitted)}, \qquad (13)$$

can be estimated, using (12), as

$$S_{\max(permitted)} = \frac{(2.4V)\, V_{Load}}{R_{gr}},$$

from which the requirement for R_{gr} is

$$R_{gr} \le \frac{(2.4V)\, V_{Load}}{S_{nom}} \; .$$

For $V_{Load} = 220V_{rms}$, and $S_{nom} = 20\,kVA$, we have the maximal permitted R_{gr} as

$$(R_{gr})_{\max} = 0.0264\ \Omega,$$

and for $S = 500VA$, $(R_{gr})_{\max} \approx 1\Omega$.

Of course, for the usual buildings without any power laboratories, such small (very good) R_{gr} is never met. The large values of $R_{gr} \sim 10\Omega$ that are often met for usual civil houses, prohibit one from creating a laboratory for close working with "open" electrical power devices in such a house.

If it is given (as in Kinneret College) that $R_{gr} \approx 0.1\Omega$, then we must limit S_{nom} to about 4kVA. However, small table generators and motors for students' experiments, produced by special firms for educational equipment, can have S_{nom} of only about 100VA. Such generator or motor can be studied in the usual electronics laboratory.

4. A discussion and some completions

Thus, according to the safety criteria, the smaller the grounding resistance, the higher is the current to be defined as "heavy current". Obviously, for $R_{gr} \sim 10\Omega$ of a usual building, and for $R_{\text{gr}} \sim 0.01\ \Omega$ of a power transformer station, the laboratory safety criterion gives very different values for the permitted current, i.e. for the power of the equipment to be tested. For the very typical for a building, $R_{gr} \approx 3\Omega$, work current of 10A is already strong. For a transformer station, the "heavy current" starts from 300A.

Considering these limitations, one has to remember that we speak about laboratory experiments with working power devices, and in the same building, some much more powerful equipment (for instance air-condition compressors), *not investigated in the* *working state*, can be present. If the latter equipment has to be repaired or reinstalled, the technician disconnects it from power supply, and the situation is safe. However, if the building includes power laboratory, then the value of the grounding is defined by the laboratory power equipment.

Even if one remembers such medical facts that a current of 50-60 mA causes muscle cramping, and 10 microampere flowing directly via the heart (e.g., in a medical laboratory) can be lethal [1-4], some conclusions may be unexpected. Thus, for instance, though the path of the current in the body (from leg to leg, i.e. far from the heart), taking place when one walks on electrified soil, does not seem to be dangerous, since the sufficiently high "step's voltage" can cause cramps and falling on the soil with an unpredictable, probably very dangerous, change of the situation.

Also somewhat unexpectedly, the generally very important grounding of equipment is not always useful. If lightning is common around the building, then it can insert many dangerous voltage pulses into the grounded equipment just via the grounding system [1].

The topic of Electrical Safety, related, in general, to human safety and safety of equipment, includes many other interesting subtopics, as, for instance, accumulation of static charge on surfaces and bodies, which can cause sparks, conditions for ignition of flammable liquids, explosions of gases and dusts [1,3], human physiology and finding a good equivalent electrical scheme of the human body [18]. Even evaluation of the resistance of the grounding electrode [1] is an interesting problem associated with the theory of electrical fields. (Prove that R_{gr} is directly proportional to the specific resistance of the soil, -- this explains why sometimes salt is added to the ground, and why the quality of the grounding can be different in the different seasons of the year.)

Thus, the present discussion of the grounding problem is only one of the possible routes into the field where many interesting physics problems can be found. Monograph [1] and the relevant sections of the textbook [4] can be especially recommended for the first reading. Reference [19] is very complete in analyzing usual construction and numerical details, and in [20] includes a good collections of grounding schemes.

Hopefully, the discussion can also motivate one to complete his knowledge regarding the basic circuitry. Thus, for instance, for describing the transfer of the real average power *P* in a power distribution line, in terms of the Thevenin scheme for the source, some nice curves, named "nose curves", are used (e.g. [21]) in the *P-V* plane. As well, as [22,23] show, the Thevenin theorem still includes some points for study, which can be interesting even for a circuit specialist.

Focusing on the main circuit-theory point, we cannot consider here the engineering arrangements in detail, but there are some additional aspects that cannot be completely ignored from the positions of one's general education. These are, first of all, a remarkable protecting device that already received a wide use (but *insufficient*, since some severe electrical traumas that actually occurred *in water pools*, could be avoided by use of this device). The *physical aspects* of creating the circuit connections are also very important, because *for heavy currents* the connections have to satisfy special requirements

4.1 The magnetic- electronic protection device

An acquaintance with the very simple but remarkable device named "Ground Fault Circuit Interrupter" (GFCI, see also [24]) that interrupts the current (voltage) supply when there is a leakage of even a small current to the ground which can pass via a human body is absolutely necessary. The basic scheme of the device, involving a magnetic core, is shown in Fig. 3.

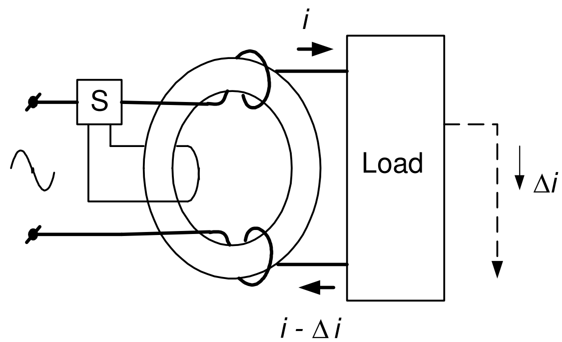

Fig. 3: The principle scheme of GFCI. Because of the same number of turns in the main windings, the current of the load, flowing forward and back should create zero magnetic flux in the core, but when there is a leakage fault, it is not the same current forward and back, and the appearing non-zero magnetic flux generates the control voltage in the additional winding that opens switch *S*, interrupting the power supply. Observe that if the system is sufficiently sensitive, then the input wires of the load can directly pass inside the core (without the turns), and it is also interesting to consider the loop made by the leakage current Δi *per se*, in order to see this current as *directly* defining the nonzero magnetic flux in the core.

According to the Kirchhoff's current law, the leakage of the current in the load causes inequality of the coming and returning terminals' currents, which pass via the transformer's windings. (In terms of rigorous circuit theory [25], this means that the faulty load is not a one-port.) Then, because of Ampere's law, the magnetic flux in the core becomes nonzero, and because of Faraday's law and the alternating nature of the currents, on the additional (control) winding some voltage appears, opening the switch.

4.2 The problem of physical connections, which is not always seen via electrical scheme

Since today, GFCI has become mandatory in any dwelling place, the question arises that, maybe, having this remarkable protecting device, we should not worry about the quality of the grounding, considered in the main text? In order to see the absolute non-seriousness of this idea, we have to somewhat rethink the role of the physical foundation of the electrical safety arrangements, which is relevant, in fact, to the foundation of the whole of electrical engineering.

The general point is that not only the idealized elements that represent a real circuit via its "electrical scheme" are based on physics (e.g., the action of the inductor, given by the Ampere and Faraday laws), but also every application of the elements (as in any technical theory) has some limits that are defined by physics. In the present case, the latter aspect, -- not quite usual in the reality of student's education, -- is that the *reliability* of the circuit has unusual importance here. In this case, *the very connections* of the wires (in a scheme, just the lines and the not always shown geometrical points of their connections!), *which also are elements of the circuit*, become the main focus.

One must see that even in the electrical problem, the concept of "connection" is first of all *mechanical* (here, a mechanical-metallurgical) one. We cannot rely only on a smart electronic device here. The *simplicity* of the grounding circuit with its massive electrode(s) in the soil, and the *massive* (large) conductors that *it is possible to reliably* (*much more reliably than any electronic device*) *mechanically connect,* is something that will be never avoided!

Making correct connections in a grounding circuit is a well developed science, associated with good knowledge of the features of physical materials. Usually, the connections of the very massive copper conductors are made using big brass terminals, screws, and nuts. Brass has the advantage of corrosion resistance and it has some elastic features for a *good contact* to be created by forceful screwing. (Try to apply a very strong force to a small screw and you will find a good reason for the screws, and thus the conductors, to be reliably connected, be big/massive.) There are special metallic, not flat, washers eliminating any slot, etc.. The brass parts have to be well connected to the copper conductors, which should require some knowledge of chemistry. A visit to a power-equipment factory (say, a water plant) guided by a local electrical engineer is highly recommended for any technical students.

One sees that the connection of the grounding electrode relevant to Fig.2 is much more reliable than any connection in Fig.3. Take in Fig.2 a point on the wire, under '**a**', and consider it as a junction collecting only two wires, which perfectly agrees with application of Kirchhoff's current law. Formally, there is a continuum of such "junctions" to be chosen, without any profit for circuit analysis, but there may be the physically problematic connection of the brass and copper conductors just at the chosen point. That is, electric scheme not always shows the problems of the real circuit.

Another practical point is that however quick is the action of the GFCI, it may be insufficiently quick in a particular case (since the human in danger may be a physiologically weak), and it is desirable, of course, to have on the body of the faulty machine less than the permitted maximum touch voltage even during the short period of operation of GFCI.

One sees that *simplicity of a constructive solution is associated with reliability* and that in the war for good electrical safety we must have several lines of fortifications!

5. Conclusions and final remarks

The derived formulae formalizing the main point of the "strength" of the current, *seen against the quality of the grounding in the laboratory*, should be very useful, especially in the simplified form (15). For a generator having nominal output voltage V_L and nominal power S_{nom}, the required limitation on R_{gr} is

$$R_{gr} \leq \frac{V_o \, \Delta V}{S_{nom}} = (v.r.) \frac{V_o \, V_{Load}}{S_{nom}} \approx \frac{(2.4V) \, V_{Load}}{S_{nom}} \;, \qquad (14)$$

which is easily remembered when it is written as $R_{gr}S_{nom} < V_o\Delta V$. Since $S_{nom} = I_{nom}V_{Load}$, (14) can be rewritten as $I_{nom} \leq \frac{2.4V}{R_{gr}}$, or as $R_{gr}I_{nom} \approx 2.4V$. Wishing to be surer in the safety arrangements, one recommends

$$R_{gr}I_{nom} \leq 1V, \quad \text{and} \quad R_{gr}S_{nom} \leq (1V)\cdot V_{Load}. \qquad (15)$$

Voltage regulation is an important characteristic of a generator, associated with its non-ideality, i.e. with the internal impedance. The larger is the voltage regulation, the weaker is the generator, and then the requirement for R_{gr}, i.e. for obtaining electrical safety, becomes easier. We have to limit either R_{gr}, or the total VA power S_{nom} of the generator.

Though the observations of the present work and the suggested definition of heavy current are made solely in terms of the general circuit theory, they should contribute to one's interest to the topic of electrical safety. The discussion can be useful for electrical engineers of general profile, and, on the pedagogical regard, the relevant considerations should be given in a basic course that is taken by the students who will perform the laboratory study of power devices, or work in the future with such devices. These may be students of electrical engineering, physics, chemistry, or, e.g., the new popular Water Engineering track in the Kinneret College where elements of electrical safety are included into a basic circuit course, which causes noticeable interest of the students.

As a practical point, it is made clear that when a power laboratory for students is planned, measurement of the resistance of the grounding of the building is absolutely necessary, and it may appear necessary to create separate grounding for a laboratory. Obviously, to create power laboratory in one's hen-coop should be prohibited!

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