On Electrical Safety in Academic Laboratories

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Abstract—Academic laboratories should be a safe environment in which one can teach, learn, and conduct research. Sharing a common principle, the prevention of potential accidents and imminent injuries is a fundamental goal in the laboratory environments. In addition, academic laboratories are attributed exceptional responsibility to instill in students the culture of the safety. In this paper, the authors discuss the challenges to electrical safety in modern academic laboratories, where users may be exposed to harmful touch voltages.

I. INTRODUCTION

A. Electricity and Human Vulnerabilities

Electricity is in constant use by academic personnel (i.e., researchers and students) in engineering disciplines both within and outside the laboratory environments, the misuse or careless use of which may potentially result in significant physical harms or death. Injuries engendered by electricity include electrical shocks, burns, and falls. Electrical shocks occur when the electric current passes through the human body, the severity of which depends on (i) amount of current flowing through the body, (ii) path of the current through the body, (iii) duration of time the body is in contact with the electricity,—so called “being in the circuit”, i.e., the body becomes part of an electrical path,—and (iv) the wet/dry status of the exposed body. With the direct current (DC) of 1 mA, a human can detect a “tingling” feeling, while the “let-go” median threshold for such currents is 76 mA, under which one cannot release the energized conductor. In the case of 60 Hz alternating current (AC), the values are 0.4 mA and 16 mA, respectively. Women are particularly more sensitive to the effects of electrical current, where approximately 70% of the current is sufficient to result in the same effect as it has on men [1], [2]. Higher currents harvest a respiratory inhibition, then ventricular fibrillation, and ultimately a cardiac arrest. Table I summarizes the electric current levels and the corresponding human body reactions [2].

<table>
<thead>
<tr>
<th>Electrical Current</th>
<th>Human Body Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mA</td>
<td>Just a faint tingle. Threshold of sensation.</td>
</tr>
<tr>
<td>5 mA</td>
<td>Mild shock felt. Disturbing, but not painful. Most people can “let it go”. However, strong involuntary movements can cause injuries.</td>
</tr>
<tr>
<td>6-25 mA (females)</td>
<td>Painful shock. Muscular control is lost. This is the range where “freezing currents” start. It may not be possible to “let go”.</td>
</tr>
<tr>
<td>9-30 mA (males)</td>
<td>Extremely painful shock, respiratory arrest (breathing stops), some severe muscle contractions. Flexor muscles may cause holding on; extensor muscles may cause intense pushing away. Heart fibrillation possible. Death is possible.</td>
</tr>
<tr>
<td>1000-4300 mA (1-4.3 A)</td>
<td>Rhythmic pumping action of the heart ceases. Muscular contraction and nerve damage occur; death likely.</td>
</tr>
<tr>
<td>10000 mA (10 A)</td>
<td>Cardiac arrest and severe burns occur. Death is probable.</td>
</tr>
<tr>
<td>15000 mA (15 A)</td>
<td>Lowest overcurrent at which a typical fuse or circuit breaker opens a circuit.</td>
</tr>
</tbody>
</table>

* Effects are described for voltages less than ~600 volts.
* Higher voltages cause severe burns.

B. Electrical Hazards in Academic Laboratories

Students enrolled in undergraduate programs in colleges and universities must be introduced to the culture of laboratory safety. Students in academic laboratories may, in fact, be required to work on electrical installations and electrical equipment with no safety background. Such experiments are precisely supervised by an instructor who establishes “Do’s” and “Don’ts” of the procedures for students. In these laboratories, work may normally be based upon the repetition of established experiments and procedures, which are typically executed at low voltages (i.e., not exceeding 1kV). Undergraduate students in the laboratory should never be allowed to mount circuits or equipment live, but only when
benches are de-energized. Dead working will call for at least two safety barriers to be put in place to protect users [3]:

1. De-energization of equipment and verification that the installation is dead;
2. Securing against re-energization of the equipment.

Reference [3] states that “equipment must be placed in an electrically safe work condition before working on or near it”, reinforcing the concept of the safety barriers. Safety barriers shall need to be set up by an electrically skilled person, i.e., “a person with relevant education, knowledge and experience to enable him or her to analyze risks and to avoid dangers which electricity could create” [3]; or by a competent person, defined as “who is capable of identifying existing and predictable hazards in the surroundings or working conditions, which are unsanitary, hazardous, or dangerous to employees, and who has authorization to take prompt corrective measures to eliminate them.” [3, 4]; or by a qualified person, i.e., “One who has demonstrated skills and knowledge related to the construction and operation of electrical equipment and installations and has received safety training to identify the hazards and reduce the associated risk.” [4, 5].

Laboratory technicians, faculty members, and teaching assistants (often in charge of undergraduate laboratories) must all receive the safety training required to be able to put in safety laboratory benches by properly de-energizing and securing the supply.

In particular, qualified personnel must receive specialized training in the following:

- The skills and techniques necessary to distinguish exposed live parts from other parts of the electrical equipment.
- The skills and techniques necessary to determine the nominal voltage of exposed live parts.
- The clearance distances specified for working on or near the exposed energized equipment and the corresponding voltages to which the person will be exposed.
- Appropriate safety equipment and tools necessary to safely perform work in accordance with the standards and guidelines.

Once circuits and equipment are then energized for measurements, they must be inaccessible to a person’s finger. Critical points that might allow direct contact with live parts are however the plugs, which make electrical connections among power supply and bench equipment. Standard plugs may offer a degree of protection IPXXB (i.e. protection against person’s access with finger) [5, 6], only if completely inserted into a receptacle, which may not always be the case in undergraduate laboratories. For this reason, safety laboratory cables should always be employed (Fig. 1).

Plugs of safety cables are finger safe, as they keep a degree of protection IPXXB in all conditions of insertion. Laboratory multimeters should also be equipped with test leads with protected tips, or with safety plugs.

In the above finger-safe conditions, no live parts are accessible during measurements, and students do not perform direct work on live parts (i.e. live work) [2, 3]. The finger-safe protective measure may however fail (e.g., due to aging of plugs), thus users should accordingly be made aware of the potential hazards of touch voltages.

If the laboratory is not in finger-safe conditions, measurements must be considered live working [3], and cannot be performed by students. Only skilled, competent, or qualified persons (e.g. faculty) should be allowed to perform measurements, with the aid of personal protective equipment (PPE), e.g. insulating gloves.

It is important to recall that all electrical equipment in academic laboratories must be listed by a nationally recognized testing laboratory (NRTLs), and used in accordance with the instructions on the listing. Safety is the primary directive in an academic laboratory also considering the fact that productivity in a research lab is strictly related to the level of safety.

II. ELECTRICAL SEPARATION

The risk of electric shock might be lowered by means of electrical protective separation. Electrical separation is carried out by means of isolation transformers, which provide galvanic separation between the electrical system and the loads (Fig. 2).

Isolation transformers used for safety have a unity turn ratio, and double or reinforced insulation between the primary and secondary coils.

Isolation transformers installed at each bench provide galvanic separation and would prevent ground-fault currents from flowing; thus, persons in contact with the faulty...
laboratory equipment cannot receive an electric shock. The galvanic isolation provides, in fact, an electrically separated system, which prevents current from reaching the ground through the person’s body [7].

In the absence of fault currents, the fault might however remain undetected and unresolved. For this reason, the bench should be equipped with an insulation monitoring device that would continuously monitor the impedance-to-ground of the system, and trip if such impedance would decrease below a certain threshold.

Isolation transformers would be beneficial as an additional protection against direct contact with live parts; they would also reduce short-circuit currents and the risk of electric arcs.

III. SAFETY IN ACADEMIC LABORATORIES WITH VARIABLE-FREQUENCY DRIVES

Protection against electric shock in the case of failure of basic insulation of equipment is generally carried out by automatic disconnection of supply. In TN systems in accordance with [8], and in the electrical systems adopted in the U.S. as per [9], such disconnection is guaranteed by overcurrent protective devices, i.e., circuit breakers and fuses; reference [8] would not require residual current devices (RCDs) in TN systems.

The disconnection of the supply is an effective protective measure, if the following condition at each bench in the laboratory is verified:

\[ I_a \leq \frac{U_0}{Z_s}, \tag{1} \]

where \( Z_s \) is the fault-loop impedance as seen by the fault-current (dotted line in Fig. 3); \( U_0 \) is the system nominal voltage to ground; \( I_a \) is the current causing the automatic operation of the over-current protective device within a maximum permissible disconnection time [9, 10].

If equation (1) is verified, touch voltages appearing on faulty laboratory equipment will not cause ventricular fibrillation. It is advisable to perform measurements of the fault-loop impedance to assess the electrical safety before opening laboratories to users [11].

In academic laboratories, variable-frequency drives (VFDs) may be used to control AC motor speed and torque for educational purposes. VFDs vary motor input frequency and voltage and may have AC-to-DC and DC-to-AC converters.

The first challenging concern in this scenario is that the determination of \( Z_s \) might not be possible, because the impedance introduced by the solid-state electronics present in the VFD may not be known.

Most importantly, at the occurrence of a ground-fault at the motor (Fig. 3), the VFD may limit its output current to about 1.5 or 1.8 times its current rating. Thus, the VFD contribution to the fault might not be detected by the upstream overcurrent protective device, and the fault might not be cleared within the maximum permissible time [10].

A possible solution to reduce the risk of electric shock in academic laboratories would be the use of residual current circuit breaker with overload protection (RCCB) type F or type B [10, 12, 13] at each bench. Such RCCBs are designed for use with drives and inverters supplying motors, and provide protection in case of alternating residual sinusoidal currents up to 1 kHz, pulsating direct residual currents, and smooth direct residual currents.

IV. ELECTRICAL SAFETY IN ACADEMIC LIGHTING LABORATORIES

Lighting laboratories are designed to allow students to experiment with light fixtures, perform electrical, but also photometric, measurements on fixtures, wire them, and code control strategies.

Trainers include light emitting diode (LED) fixtures, which have also become the dominant choice in all laboratories for general and task illumination, due to their longer operating life, and low energy consumption. LED lamps also allow a high color rendering, and color tuning, which has become an important feature in educational institutions.

The installation of double capped LED tubes (e.g. to replace linear fluorescent lamps) raises safety concerns, due to the risk of electric shock. In LED double capped lamps, the electrical continuity between the two ends of the fixture may be permanent. This is not true for linear fluorescent lamps, where the electrical continuity between the two caps only occurs during the discharge through the ionized gas.

For instance, G5 type and G13 type linear fluorescents do not provide for the simultaneously insertion of both ends of LED lamps [12, 14]. If the replacement is performed when the circuit is energized, when one set of pins is inserted into the lamp holder, the contact with the uninserted pins may cause electric shock (Fig. 4).

Reference [13, 15] clearly lists the steps necessary for mounting tubular LED lamps: the first instruction is “Switch off electricity”. This crucial step may be overlooked by users and maintenance personnel in laboratories, who may be used to replacing fluorescent fixtures, whose pins are never
energized during replacement. Clearly, the risk of electric shock due to accidental contact with the energized pins can only be lowered through a specific training of laboratory users.

Fig. 4. Simplified circuit diagram of double capped LED linear lamp

V. ACADEMIC RESEARCH LABORATORIES

Electrical safety in research and development (R&D) laboratories share the same common-ground rules and guidelines mentioned earlier for the undergraduate laboratories. However, additional cautions and careful considerations should be taken into account as student researchers at times are working individually on experiments directly dealing with the electrically-powered equipment. This poses a potential risk of danger concerning electric safety (e.g., shocks, fires, sparks, etc.). Academic research laboratories may involve new methodologies and/or highly specialized equipment, which may not be covered by safety product standards. Thus, hazards in such laboratories may not be completely known to faculty and researchers.

The management of the safety in research laboratories may be further challenged by the irregular presence of faculty principal investigators, if they no longer perform bench research. Thus, principal investigators may not be able to supervise on a daily basis laboratory safety practices [14, 16].

Already in 1951, Prof. Dalziel indicated the difficulty, if not the impossibility, to apply standard electrical safety criteria to experimental electrical laboratories, due to their unique hazards [15, 17]. The electrical safety challenges in research laboratories have been recognized by [16, 18], which in the 2018 edition broadened article 350 to include amendments to the safety-related work requirements for ordinary workplace, to be applied to research and development laboratories.

In particular, [16, 18] introduces the figure of the Competent Person, that in addition to all the requirements of the aforementioned qualified person, is also “responsible for all work activities or safety procedures related to custom or special equipment and has detailed knowledge regarding the exposure to electrical hazards, the appropriate control methods to reduce the risk associated with those hazards, and the implementation of those methods.” The competent person will enforce the use of the appropriate laboratory safety practices.

Custom or special equipment for research may have exposed high-voltage terminals and/or conductors. Reference [18] permits the use of insulating blankets, covers, or barriers (i.e. physical obstructions) to prevent users from being in inadvertent contact with parts that are or may become energized. Such protective measures may provide protection against contact only from likely directions of access, and not from all directions; intentional contact by deliberate circumvention of the barriers is not prevented [6, 19]. Users performing tasks involving such special equipment must be qualified and specifically trained: training must be provided or paid by the owner of the special equipment (i.e. the school); students must be considered for all intent and purposes as regular workers.

A. Basic Rules of Engagement

When working in a research laboratory that involves experimental designs and operations, researcher should be familiar with the equipment in the workspace, even if he/she is not directly using it. It is also very crucial to be cautious of what other researchers, co-workers, and peers are doing and/or using in the laboratory. Working and experimenting alone with the electrical equipment should be limited in such laboratory settings.

Skilled, competent, and qualified persons should be made aware of the following basic rules:

- Wiring inspection of the equipment before each use.
- Immediate replacement of all frayed or damaged electrical cords.
- Limiting the use of extension cords to only temporary operations. Otherwise, installation of new electrical outlets should be requested.
- Minimizing the potential for water or chemical spills on or near electrical equipment.
- Knowing the location and how to operate the shut-off switches and/or circuit breakers.
- Changing the experimental setup when ensuring the turned-off status of power sources, if applicable.

Qualified personnel whose work on energized equipment involves either direct contact with or contact by means of tools or materials, must be trained on how to work safely on energized circuits. This includes getting familiar with the proper precautionary work practices, personal protective equipment, insulating, shielding materials, and the use of insulated tools.

Again, the class of electrical work and the level of safety requirements vary depending on the field of research. A chemist or biologist will typically work with low-energy, plug-controlled equipment. A plasma physicist, high-voltage electrical researcher, or accelerator engineer will typically work with high-voltage, high-current, and high-power electrical equipment, mandating more detailed and well-thought safety considerations and hazard controls.
Furthermore, depending on the usage and level of electricity requirement in the research laboratory settings, facilities operation and maintenance personnel must periodically verify the safety designs and, if needed, perform the design changes to the laboratory’s electrical infrastructure. Specific changes may be required when converting from dry- to wet-laboratory environment, or when a change in the electrical load exceeds the capacity in a given area. For the latter issue, a professional engineer should be employed for the assessment of the new electrical load.

### B. Unidirectional Impulse Currents

Electrical equipment typically found in research laboratories may include energy storage devices, such as high-voltage capacitors and inductors [18, 20], which may cause electric shock due to their discharge.

Reference [18, 21] defines the unidirectional impulse currents of short duration, such as those due to a capacitor discharge, have a duration up to 10 ms. References [17, 21] also indicate that the principal factor for the initiation of ventricular fibrillation due to such currents is the specific fibrillating energy $F_E$ (2).

$$F_E = \frac{E^2}{2R} \text{ (A}^2\text{s)}$$  \hspace{1cm} (2)

Where $V$ is the charging voltage, $C$ is the capacitance, $t_i$ is the shock duration, and $R$ is the resistance of the discharging circuit, of which the person’s body forms part.

The capacitor energy decays exponentially, therefore, theoretically an infinite time is required to completely discharge the capacitor. However, the duration $t_i$ of the capacitor discharge, which is the shock duration, is assumed to be $3RC$, where RC is the time constant of the discharge circuit [18, 21].

The capacitor discharge can cause ventricular fibrillation, the likelihood of which depends on the current path in the human body, but also whether the impulse occurs within the vulnerable period of the cardiac cycle (i.e. T cycle). It is important to note that high energy impulses falling outside the heart vulnerable period can cause fibrillation even minutes after the original event [21]. Reference [18, 21] indicates that a value of $F_E$ of $0.5 \times 10^{-3}$ A$^2$s is painful1, and a value of $F_E$ of $50 \times 10^{-3}$ A$^2$s is likely to cause ventricular fibrillation, for a current-pathway hand-to-foot, and a body resistance $R = 1$ kQ.

Reference [22] recommends the use of automatic, mechanical discharging devices for equipment with stored energy greater than 10 J. Such limit is well below the ventricular fibrillation threshold and is therefore conservative. The discharging devices, contained within protective barriers, will bleed dangerous residual charge after the equipment has been de-energized.

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1 Pain is defined in [18] as an “unpleasant experience such that it is not readily accepted a second time by the subject submitted to it.”

### VI. Hazards in Laboratories Due to Electromagnetic Field Exposure

In the past years, there has been an increasing concern for potential health risks due to extremely-low frequency electromagnetic fields (ELF) at power frequency (50-60 Hz) and from radio frequency emissions (RF) radiated from several communication equipment; typical radiators may include wireless devices, such as cell phones and cordless phones, cellular antennas and towers, and broadcast transmission towers, particle accelerators. Research laboratories are no exception, due to the presence of power frequency equipment, but also possibly due to full wireless coverage for, at least, voice and data transmission.

The problem of the exposure to ELF and RF electromagnetic fields is relevant, as faculty and graduate students may spend several hours a day in academic laboratories.

In 2002, the International Agency for Research on Cancer (IARC) of the World Health Organization (WHO) classified the ELF magnetic fields from power lines as “possibly carcinogenic to humans (Group 2B)” [20, 23]; in 2013, IARC also placed non-ionizing electromagnetic fields (EMF), ranging from 30 kHz to 300 GHz, in Group 2B [21, 24].
Distinguishing between non-thermal (low-intensity) biological effects in the ELF range, and thermal effects (high-intensity) for microwave exposure in the RF range, ICNIRP defined appropriate basic restrictions to avoid potentially disturbing effects on both central nervous system (CNS), i.e., the head, and the peripheral nervous system (PNS), i.e., the rest of the body. At each frequency, ICNIRP derived a reference level as a guidance figure deliberately set below the field required to produce the basic restriction. Unperturbed electric (V/m) and magnetic (A/m) fields or magnetic flux density \( B \) (T) strengths are used in the ELF range, while the equivalent plane wave power density (W/m\(^2\)) is used for RF (usually above 10 MHz). Fig. 5 shows the reference levels for public exposure. Above 100 kHz the RF specific reference level must be considered additionally, limiting the equivalent power density below 2 W/m\(^2\) up to 400 MHz.

Fig. 6 pictures an actual research and educational laboratory; the switchboard supplying power to the laboratory was installed immediately above point P2. Tests consisting of magnetic flux density measurements at different locations within the laboratory were carried out. The measuring equipment was a Narda PMM 8053 with ELF probe EHP-50-C and the RF probe EP-300. Table 1 shows the distribution of measured values at the floor and the table level \((h=0.75\, \text{m})\). In P2 and P3 the highest magnitudes of magnetic flux were measured. Although these measurements were below the ICNIRP reference level of 100 mT, they were well above the Italian attention value equal to 10 \( \mu \text{T} \) applicable for exposure greater than 4 hours per day.

Because countries in the world may have more or less stringent quantitative limits than the ICNIRP reference level, it is not possible to generalize the results of measurements to all laboratories. The practice of the prudent avoidance of the electromagnetic fields must however be followed and measurements should be performed.

<table>
<thead>
<tr>
<th>Point</th>
<th>Magnetic Flux Density ( B ) (( \mu \text{T} ))</th>
<th>X [%]</th>
<th>Y [%]</th>
<th>Z [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.75</td>
<td>2</td>
<td>87</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>0</td>
<td>14</td>
<td>86</td>
</tr>
<tr>
<td>3</td>
<td>43</td>
<td>6</td>
<td>3</td>
<td>91</td>
</tr>
<tr>
<td>4</td>
<td>3.73</td>
<td>1</td>
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<td>6</td>
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<td>5</td>
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<tr>
<td>6</td>
<td>1.25</td>
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</tr>
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<td>7</td>
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</tr>
<tr>
<td>11</td>
<td>7.53</td>
<td>3</td>
<td>2</td>
<td>95</td>
</tr>
</tbody>
</table>

VII. WARNING SIGNS AND PSYCHOLOGICAL PERCEPTION OF DANGER

Warning signs in academic laboratories caution students and faculty of electrical hazards, and instruct on the proper precautions to take to avoid accidents. Equipment with operating voltage greater than 50 V, should be labeled with appropriate warning signs. Switches to turn off all electrical power to the equipment in case of emergency should be prominently labeled.

The installation of signs and warning labels in the workplace is part of the “administrative controls” per [22, 25]. Figure 7 demonstrates an example list of rules enforced in the electrical laboratories at the George Washington University (GWU), Washington DC, USA. Safety conveyed by signs is, however, highly dependent on person awareness, knowledge, and actions, and ultimately depends on the way the danger is perceived by students and faculty members. Two processes may cause students and faculty to ignore signs in laboratories: habituation and interference. Habitation is the diminishing of a physiological and emotional response to a frequently repeated stimulus; the continuous exposition to a sign “desensitizes” our response to it. Interference is when one memory causes us to have trouble remembering another; we might repeatedly see the warning signs, but we may not remember which area of the laboratory poses danger, because we are unable of making a new memory of it. Warning signs “translate” the danger with text and images, which may however weaken our perception, and our emotional connection to the hazard. Reference [26] indicates that text size matters more than picture size in attracting and focusing attention. However, the picture does matter in the initial attraction of intelligence.

The authors believe that warning signs suitable for post-millennial students may require a different strategy to improve
Before inspections, turn its power off. Turn off the circuit breakers or unplug the equipment.

In order To turn off a safety switch, use your left hand (wear insulating gloves made of leather or heavy cotton or rubber), turn your face away from the box, and pull the handle down. Circuits may discharge violently when being turned on or off and the cover to the junction box may be blown open.

- Use only tools and equipment with non-conducting handles when working with electrical devices.
- All current transmitting parts of any electrical devices must be enclosed.
- When checking an operating circuit, keep one hand either in a pocket or behind your back to avoid making a closed circuit through the body.
- Maintain a work space clear of extraneous material such as books, papers, and clothes.
- Never change wiring with circuit plugged into power sources.
- Never plug leads into power source unless they are connected to an established circuit.
- Avoid contacting circuits with wet hands or wet materials.
- Wet cells should be placed on a piece of non-conducting material.
- Check circuits for proper grounding with respect to the power source.
- Do not insert another fuse of larger capacity if an instrument keeps blowing fuses: this is a symptom requiring expert repairs. If a fuse blows, find the cause of the problem before putting in another one.
- Extension cords must be connected to a power strip equipped with a fuse.
- Do not use or store highly flammable solvents near electrical equipment.
- Multi-socket outlets (cube taps) should not be used in place of permanently installed receptacles.
- If additional outlets are required have them installed by an electrician.
- Keep access to electrical panels and disconnect switches clear and unobstructed.

![Fig. 7. Example set of general rules and checklist in electrical laboratories](image)

VIII. CONCLUSION

This paper, based on [27], has discussed some of the major electrical safety issues concerning the academic laboratories. In undergraduate laboratories, the safety of users may be challenged by the lack of safety background, which will therefore require proper supervision and a list of “Do’s” and “Don’ts” detailing the lab procedures.

In academic research (R&D) laboratories, specialized equipment may not yet be covered by safety standards. In this case, the proper training of users becomes an integral part of the electrical safety measures, and should be emphasized.

Energy storage devices in academic laboratories may cause electric shock due to their unexpected discharge and electronic components may render inapplicable the disconnection of the supply as a protective measure.

This paper has analyzed the above issues, with the purpose of raising the electrical safety awareness of users, and possibly establishing a common reference. Possible solutions on how to shape a culture of electric safety and increase it in academic laboratories were herein also proposed.

REFERENCES

electrodynamics, the development of numerical and analytical techniques for piezotronics based on piezoelectric ZnO nanostructures, and graphene research interests include electromagnetic compatibility, energy harvesting

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Biography