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# Electrical Shock Hazards and Safety Standards

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***Abstract*—The experimenter in the laboratory encounters all types of electrical equipment. Some pieces of test equipment are battery operated or operate at low voltage so that any hazard is minimal. Other types of equipment are isolated from electrical ground so that there is no problem if a grounded object makes contact with the circuit. There are, however, pieces of test equipment that are supplied by voltages that can be hazardous or that can have dangerous voltage outputs. The standard power supply used in the United States for power and lighting in laboratories is the 120/240 V, grounded, 60 Hz sinusoidal supply. This supply provides power for much of the laboratory equipment so an understanding of its operation is essential in its safe use. Higher voltage, sometime three phase, supplies equipment or motors with large power requirements. Nonsinusoidal or high-voltage type outputs from laboratory power supplies are also encountered in the laboratory. It is important to appreciate the effect of these various voltages on the human body to understand the potential hazard.**

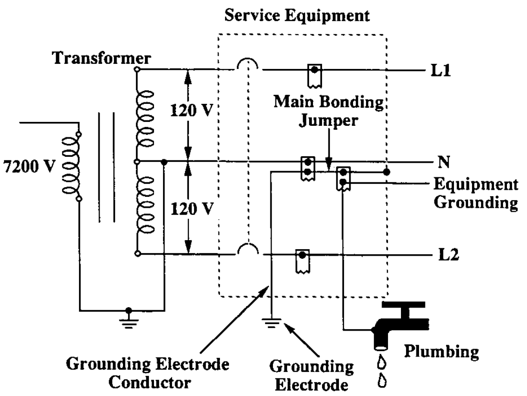

Fig. 1. Transformer and service entrance equipment for a 120/240 V secondary system.

## I. THE 60 HZ 120/240 V ELECTRICAL SYSTEM

THE standard supply used for laboratory power to energize test equipment in the United States is the 120/240 V, grounded, 60 Hz sinusoidal system. Safety in the laboratory depends on understanding the operation of such systems and possible hazards.

The National Electrical Code details the generally accepted U.S. requirements for the installation of all electrical systems and equipment not owned and under the exclusive control of the electric utility [1]. Fig. 1 shows the service entrance for a building where the power company's typical distribution voltage of 7200 V, single phase, is converted to the 120/240 V secondary voltage for use in the building. The transformer is often outside the building and only the three secondary conductors, called the service conductors, enter the building. One of these three conductors, called the grounded or neutral conductor, is grounded to earth at the transformer and at the service equipment grounding electrode. This grounding is accomplished by connecting to a grounding electrode such as a metallic water main system, other forms of extensive buried metal with good contact to the earth, or a ground rod. The voltage between the two ungrounded lines is a nominal 240 V, while the voltage from either ungrounded conductor to the grounded neutral conductor is a nominal 120 V. These nominal voltages are sometimes referred to as 110 or 115 V for the line-to-neutral voltage or 220 or 230 V for the line-to-line voltage. The grounded conductor carries normal load current and is called the "grounded conductor" or the "neutral conductor." This conductor must always have a white color insulation for identification when routed inside a building or on the load side of the service equipment. The grounded conductor is insulated and is only grounded at one point, at the service equipment, except for a few permitted exceptions, such as for grounding clothes dryers or electric ranges. The National Electrical Code does not permit an insulation color of white or green for ungrounded conductors, since white is reserved for the grounded conductor while green is reserved for the equipment grounding conductor.

The equipment grounding conductor, called the "grounding conductor" to differentiate it from the grounded or neutral conductor, is also a conductor which is grounded. This is shown in Fig. 1. The grounding conductor is bonded to the grounded conductor and to the service equipment cabinet at the service entrance. Unlike the grounded conductor, the equipment grounding conductor can be grounded at many places as long as there is the required effective metallic path for fault current back to the neutral at the service equipment. The grounding conductor, either bare or with a green colored insulation, is used for grounding all exposed metal parts of the equipment that might become energized in the event of an electrical fault in the equipment. The multiple grounded equipment grounding conductor normally carries current only in the event of a ground fault to the equipment grounding. The grounded conductor, on the other hand, is always insulated, is grounded at only one point at the

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service entrance, and is part of the normal load current-carrying circuit. Without the equipment grounding conductor, an ungrounded 120 V conductor might contact a metal enclosure and not operate any circuit protection because the enclosure was not well grounded and there would be only a high resistance path to ground from the enclosure. A metal enclosure resting on a table, floor, or on the earth would not be well grounded electrically. The metal enclosure would be at 120 V with respect to ground. A person simultaneously contacting the enclosure and a grounded object, such as a grounded electrical device or plumbing, could then provide a path for current through his or her body from the faulted equipment to ground. This typical type of accident, where there is no equipment grounding, is shown in Fig. 2.

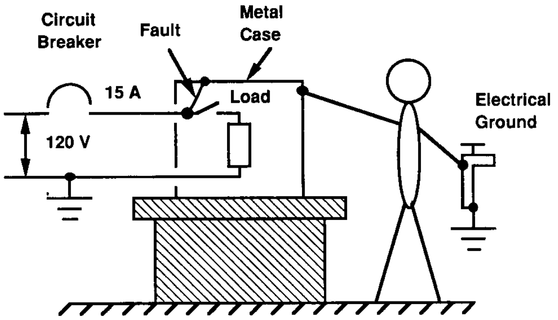

Fig. 2. Typical electric shock accident where a fault to the ungrounded metal case will not operate overcurrent protection but can lead to a severe shock.

Fig. 3 shows typical interior wiring in a building. The double pole circuit breaker shown is the main disconnect for the system. A 150 A service would have a 150 A main circuit breaker. The circuit breakers are selected to match the conductor size while the conductor size is determined by the maximum current to be supplied and the allowable voltage drop in the conductor. The smallest size conductor used for any power wiring in a building is AWG 14. The lamp shown is supplied with 120 V; one terminal being connected to the white insulated grounded conductor, while the other terminal receives its power through the switch from the 15 A circuit breaker. The heater is supplied from a 20 A circuit breaker while the heater's metallic case is grounded by the bare or green colored equipment grounding conductor. The clothes dryer heating element, being a large electrical load, is operated at 240 V to reduce current requirements. The dryer also has a 120 V supply from the ungrounded line to the grounded conductor for the drum motor, timer, and light. The dryer chassis, by special exception, uses the grounded conductor for equipment grounding [2].

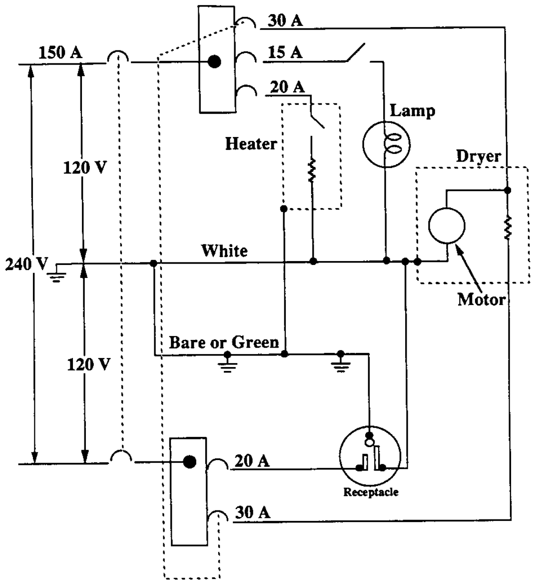

Fig. 3. Interior wiring for 120/240 V loads in a home or laboratory.

The grounding-type receptacle shown in Fig. 3 is wired with the ungrounded conductor connected with a brass or copper colored screw to the receptable socket with the shorter slot. The grounded conductor is connected with a white or silver colored screw to the socket with a longer slot. The circular socket for the plug's third prong is connected to the bare or green insulated equipment grounding conductor or to a conduit system that provides an effective equipment grounding path back to the service entrance. This connection to the equipment grounding conductor is made at the green colored screw. When a three-prong grounding-type plug is inserted into the receptacle, the equipment supplied by the power cord has 120 V for operation through the two parallel blades while the equipment grounding is provided by the equipment grounding pin. A two-blade polarized plug, used for equipment that does not require equipment grounding, can only be inserted into the receptacle one way because one of the blades is wider than the other. This wider blade can only be inserted into the longer receptacle socket slot connected to the grounded conductor. With a polarized plug, all of the circuitry on the load side of the switch in the device which is powered through the plug will be at ground potential when the switch is off. With a nonpolarized plug where the plug blades are the same size, the plug could be reversed on insertion so that the switch in the device would be in the grounded lead. In this case, the switch would still turn power on and off but when turned off there would be 120 V on an interior wiring on the load side of the switch, which could be a shock hazard for anyone probing in the equipment. The three-pong grounding-type plug is inherently polarized since it can only be inserted one way, so it will also ensure that any switch in the equipment will open the ungrounded conductor.

## II. GROUNDING

There are many misconceptions relating to electrical ground. Faults to a grounded conductor or object in the laboratory will conduct through metal conductive material, such as electrical conductors, conduit, or plumbing pipes. There will be little current in the earth. There are currents in the earth when power lines fall on the ground or the line is contacted by something on the ground such as a crane, tree, or person. Merely contacting the earth does not mean that the electrical resistance into the earth is low because this resistance depends on the type of earth contact, area of the contact, and the earth resistivity.

The reasons for grounding are well stated in Article 250-01 of the National Electrical Code:

> "Systems and circuit conductors are grounded to limit voltages due to lightning, line surges, or unintentional contact with higher voltage lines, and to stabilize the voltage to ground during normal operations. Systems and circuit conductors are solidly grounded to facilitate overcurrent device operation in case of ground faults.
>
> Conductive materials enclosing electrical conductors or equipment, or forming part of such equipment, are grounded to limit the voltage to ground on these materials and to facilitate overcurrent device operation in case of ground faults."

## III. PROTECTIVE EQUIPMENT AND DEVICES

### A. Equipment Grounding

Many electrocutions occur when a grounded cord-connected 120 V tool or appliance is used with ineffective equipment grounding. The equipment grounding is defeated by breaking off the grounding pin of the attachment plug or by using an adapter for converting a grounding-type plug to a two-blade plug without properly grounding the adapter to the grounded face plate screw on the receptacle. These modifications are often made because the grounding-type plug with its three prongs will not fit in a two-socket receptacle. A defective tool or appliance with a short circuit to its metal case or chassis can function without an intact grounding pin. Without effective equipment grounding, however, someone contacting the energized case while also contacting electrical ground could receive a severe shock.

### B. Double Insulation

Referring to tools or appliances as double insulated implies that the insulation system between internal energized conductors and any possible point of external contact consists of both a functional and protecting insulation, with the two physically separated [3]. The protecting insulation must survive failure of the functional insulation and protect against electric shock. The functional insulation is insulation necessary for the proper functioning of the equipment, such as the winding insulation of a motor. The protecting insulation is an independent insulation that provides protection if the functional insulation fails. An enclosure of insulating material is an example of protecting insulation. Double insulated equipment does not require or use equipment grounding so that only a two-blade plug is used. There are always two levels of insulation between any exposed external metal parts subject to possible contact and any energized internal parts. Fig. 4 shows the difference in wiring between an electric drill, which utilizes equipment grounding, and a double insulated drill.

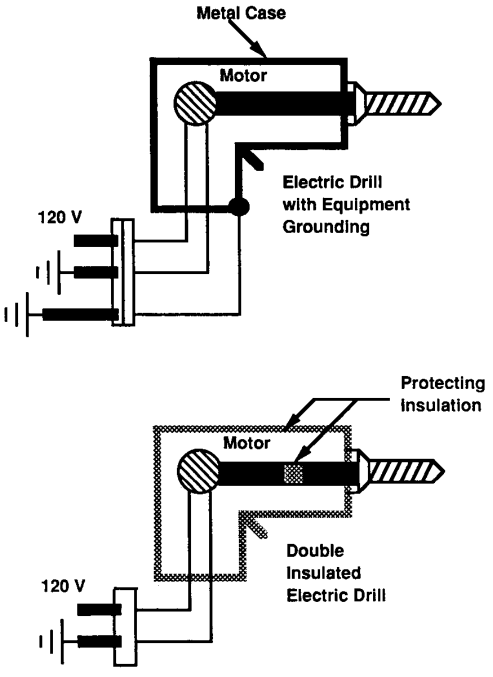

Fig. 4. Comparison of construction between electric drill with equipment grounding and one which is double insulated.

### C. Fuses and Circuit Breakers

The ungrounded and grounded conductors are protected against overload by overcurrent devices such as a fuses or circuit breakers in the ungrounded conductor. This circuit protection primarily protects the wire insulation from overheating because of excess current. The rating of the fuse or circuit breaker used depends on the size of the conductor being protected and the conductor's "ampacity." The ampacity of a conductor is the current that can be continuously carried without exceeding the insulation temperature rating for a given ambient temperature. Circuit protection devices have an inverse current-time operating characteristic to match the heating characteristics of the conductor insulation. As an example, a 15 or 20 A circuit breaker will operate in less than one hour at 120% of rating, in less than 2 minutes at 200% of rating, and in 5-35 seconds at 300% of rating [4], [5]. Fuses have similar characteristics. Thus, fuses and circuit breakers offer no protection against electrocution where the lethal current is about 0.1 A. They also offer only limited protection against equipment damage in the event of a fault where arcing can cause considerable damage at relatively low currents.

### D. Ground Fault Circuit Interrupter (GFCI)

Under normal operating conditions, the current supplying a device should be the same in both the ungrounded and grounded conductors. There should be no current in the grounding conductor. When there is a ground fault

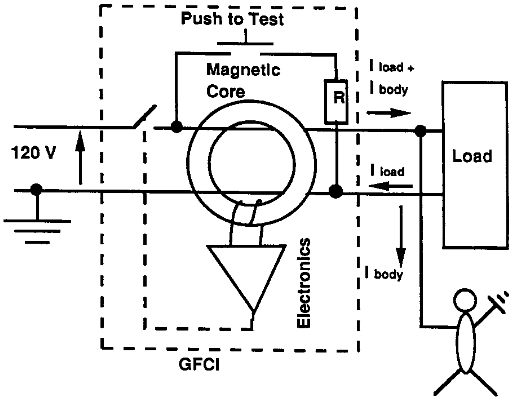

Fig. 5. Schematic diagram for the basic ground fault circuit interrupter operation.

involving the equipment, there will be another current path from the ungrounded conductor to ground other than the intended path through the device to the grounded conductor. A person would provide such a path for ground fault current through his or her body by contacting the energized ungrounded conductor or an accidentally energized metal enclosure while also contacting a grounded object. The current in the ungrounded conductor would consist of two components: the regular load current, which would also be in the grounded conductor, and the ground fault current that was in the person's body. The difference in current between the ungrounded and grounded conductors would be the ground fault current.

The ground fault circuit interrupter (GFCI) operates by routing the ungrounded and grounded conductors through a magnetic core, as shown in Fig. 5. A voltage is developed in a coil on the core proportional to the current unbalance in the conductors. Normally, there will be no voltage induced in the coil because there is no current unbalance between the equal but opposite currents in the ungrounded and grounded conductors passing through the core. The ground fault circuit interrupter control circuitry uses the indication of current unbalance produced when there is a ground fault and there is more current in the ungrounded than in the grounded conductor. This signal is used to control circuitry which opens the power circuit to prevent dangerous shocks. The GFCI is set to trip when there is a current unbalance of 6 mA, which is much lower than the usual branch circuit overcurrent protection level of 15 or 20 A. It is important to note that the GFCI does not limit the current in the ground fault—the body resistance limits the current. The push-to-test button produces a test current through the magnetic core to test the circuit and cause the GFCI to trip [6].

## IV. CODES AND STANDARDS

The generally accepted code for electrical systems, not owned by and under the exclusive control of an electric utility, is the National Electrical Code.

The National Electrical Code, revised every three years, is produced by a private nonprofit organization, the National Fire Protection Association. This code has no force of law unless it is adopted by individual jurisdictions. Since many jurisdictions do adopt the Code, it is a widely accepted standard for good practice. Installations must meet the code requirements in effect when the installation work was done but do not have to be reworked to meet later code requirements. The National Electrical Code does not cover systems and installations exclusively under the control of utilities which are covered by the National Electrical Safety Code.

There are no official government standards for privately procured electrical equipment. Some of the most widely used standards are those produced by Underwriters Laboratories Inc. Underwriters Laboratories (UL) is also a private nonprofit organization. When the National Electrical Code specifies "Listed" equipment to be used, this usually means equipment that has been manufactured and tested to meet certain recognized standards such as those produced by Underwriters Laboratories or similar organizations.

## V. EFFECTS OF ELECTRICITY ON THE HUMAN BODY

There has been considerable study in the area of effects of 60 Hz sinusoidal alternating current on the human body because of its widespread use in the United States and in other parts of the world. Sinusoidal alternating currents at a frequency of 50 Hz are used in some other countries. The effects of 50 or 60 Hz currents are substantially the same. From these investigations, current levels have been determined which cover the range of effects from the threshold of perception, let-go current, ventricular fibrillation, and cardiac asystole or standstill. The condition where the heart no longer pumps blood, such as in ventricular fibrillation or cardiac asystole, is called cardiac arrest. When dealing with electrocution (death caused by electricity), the discussion will primarily be concerned with the shock effects on the cardiovascular system as lethal electrical shocks usually cause death because of the effect on the heart. It is generally agreed that it is the magnitude and time duration of a continuous current which passes through the body which causes a given effect. The voltage in a circuit is only important insofar as it will produce a given current depending on the impedance in the circuit path. Higher voltages can cause serious burn injury because of the heat of an arc and the tissue damage caused by the large currents. The higher currents associated with high voltage shocks tend to produce cardiac asystole rather than ventricular fibrillation [7], [8].

Death at lower voltages, such as 120/240 V, can usually be attributed to ventricular fibrillation. Depending on the type of electrical contact made and the current level produced by the voltage, death can occur at these voltages with no electrical burn marks on the body and with no definitive autopsy findings that could prove electrocution had been the cause of death. Ventricular fibrillation is an uncoordinated, asynchronous contraction of the ventricular muscle fibers of the heart in contrast to their normal coordinated and rhythmic contraction. The heart seems to quiver rather than beat. This condition is usually caused by an electrical shock where the path for the current is through the chest, such as between two arms or between an arm and a leg. Once a person's heart goes into ventricular fibrillation, blood circulation ceases, unconsciousness occurs in less than 10 seconds, and irreversible brain damage starts in 4–6 minutes. Cardiopulmonary resuscitation is used as a temporary measure to provide some oxygenated blood circulation for the heart and brain until a defibrillator can be used to terminate the fibrillation with a pulse shock to the chest that may restore the normal heart rhythm. It is rare for a fibrillating heart to revert to a normal rhythm without using a defibrillator.

Shocks with a current path through the respiratory center can cause respiratory arrest. The respiratory center is in the medulla of the brain, at the base of the skull slightly above a horizontal line from the back of the throat. Shocks from the head to points below the neck or between two arms could lead to respiratory arrest [9].

## VI. ELECTRICAL PARAMETERS FOR 60 HZ SHOCKS

### A. *Electrical Resistance of the Human Body*

The electrical resistance between the limbs of an individual can vary over a wide range when the skin is intact. It depends on the contact conditions such as dry skin versus moist skin, the rough skin of a laborer versus a baby's tender skin, and so on. Tests indicate that a good approximation for the lowest possible resistance between any two limbs, excluding the skin resistance, is 500–1000 Ω. This is the resistance measured with a good contact under the skin. The skin has a variable resistance which is quite high for dry intact skin and quite low for moist or torn skin. Using the value of 500 Ω and applying Ohm's law, a person across 120 V might have a current as high as 240 mA through his or her body when the contact points are any two limbs. The current through the chest could be higher if the current path were across the chest where the lowest body resistance is on the order of 100 Ω. Such a current path is found in the case of a man lying on the ground with a defective tool resting on his chest. Studies indicate that the body resistance may not be constant but is a function of time and voltage [10], [11].

### B. *Threshold of Perception*

The threshold of perception for a finger-tapping contact at 60 Hz is approximately 0.2 mA. A current of 0.36 mA can be perceived by 50% of a group of men while 50% of a group of women can perceive 0.24 mA [12]. A shock of such low level, in itself, is not dangerous, but it could be dangerous if it startles an individual so that he or she falls from a ladder or has some other involuntary action that could lead to harm. The maximum allowable leakage for appliances is 0.5 mA. [13] Tests conducted by Underwriters Laboratories indicate that leakage currents of this magnitude, even though they may be perceived by some people, should not cause individuals to have a possibly dangerous startle reaction.

### C. *Let-Go Current*

A somewhat higher current than the threhold of perception level is the let-go current level. The let-go current is important because with a current of this magnitude in an individual's hand and arm, the victim can be involuntarily held by his or her own muscles to the energized conductor he or she is grasping and cannot let go. Contact resistance may then descrease because of perspiration, tearing of the skin, or a tighter grasp so that lethal currents can pass through his or her body. The let-go current for women is lower than that for men. That is, at 60 Hz, 1/2% of the women (1 out of 200) could not let go at 6 mA while 1/2% of the men could not let go at 9 mA. Half of the women could not let go at 10.5 mA while half the men could not let go at 16 mA [14]. The nominal trip level of 6 mA for the ground fault circuit interrupter was determined from the let-go threshold for women. The let-go current threshold can be considered as a "go–no go" situation. If a person is once frozen to a circuit, either he or she will get off and live, or he or she will not get off. If he or she does not get off, then the contact resistance may decrease to increase the body current to the lethal level and ultimately lead to death. To let go of the circuit, the individual must fight against his or her own muscles while enduring a painful shock. Several electricians have told the author of being on a ladder when they became frozen to the circuit. They freed themselves by kicking the ladder out from under themselves to allow their body weight to pull them free. This is an example of how the mind is functioning, but the arm muscles cannot be controlled voluntarily. Others have stated that when frozen to the circuit, they shouted for help, while bystanders reported that they only heard a sound more like a whisper.

### D. *Ventricular Fibrillation and Cardiac Asystole*

Ventricular fibrillation is truly life threatening since the only possible relief requires the use of a defibrillator. From experiments with animals extrapolated to possible human application, the 60 Hz current value for shocks with the current path through the chest which will produce ventricular fibrillation is given by the expression

$$I = 100/T \text{ mA rms}$$

where the shock duration $T$ is in seconds and $0.2 \text{ s} < T < 2 \text{ s}$ [15].

For short duration shocks, shorter than the cardiac cycle period of approximately one second, the electrical current to cause fibrillation must be large and occur during the portion of the heart cycle called the vulnerable period. This vulnerable period is during the $T$ wave of the electrocardiogram cycle. Shocks longer than a cardiac cycle can cause premature ventricular contractions that lower the shock threshold current to minimum after four or five premature ventricular contractions. Using these concepts, a safe current limit is considered as 500 mA for shocks less than 0.2 seconds in duration and 50 mA for shocks longer than 2 seconds [10].

High voltage shocks may lead to cardiac asystole rather than ventricular fibrillation. Asystole can occur with electrical shocks where the current is greater than 1 A. A fall or blow on the chest may cause the heart to revert to a normal rhythm from cardiac asystole without requiring the use of a defibrillator.

### E. *Effect of Waveshape and Frequency*

There has not been as much study concerning the hazard of pulse or impulse shocks compared to 60 Hz shocks. From animal experiments used to develop the defibrillator and from study of electrical accidents involving capacitor discharge type shocks, it has been found that with pulse-type shocks the hazard is related to the electrical energy in the discharge. Pulse shocks with an energy content above 50 J are probably hazardous. Shocks with an energy content of about 0.25 J are harmless but objectionable [16]. As an example of effect, the annoying electrostatic shock caused by walking on a carpet and then touching a grounded object has an energy of about 10 mJ.

The current level to produce ventricular fibrillation for shocks longer than 2 seconds depends on the frequency. The fibrillation current level of 150 mA for direct current is three times higher than that for 60 Hz sinusoidal currents. Sinusoidal currents from 15 to 100 Hz have about the same fibrillation level of 50 mA as at 60 Hz. The current level required for fibrillation rises rapidly with frequencies above 100 Hz; the value is about five times higher at 300 Hz and about 15 times higher at 1 kHz than at 60 Hz. These results can be used to evaluate the hazard of nonsinusoidal current shocks where the reduced effects of the higher frequency harmonics have to be considered in the study [17], [18].

The direct current level for threshold of perception is about three times higher than the 0.5 mA, 60 Hz value. The threshold of perception and let-go levels for sinusoidal currents are about the same as for 60 Hz for frequencies from 15 to 300 Hz; the current levels are less than twice the 60 Hz level at 1 kHz. With direct current, there is a severe feeling of shock when the circuit is made or broken while there is little pain when the current is maintained. Because of this fact, there may be no true let-go phenomenon for direct current since let-go levels were defined as the current when the test subjects refused to let go because of the anticipated severe jolt [14].

## VII. HIGH VOLTAGE SAFETY

The laboratory investigator will often encounter voltages above the usual 120/240 V laboratory power source. Such voltages may be used to energize test equipment requiring high power or may be the output of high voltage supplies. Higher voltages usually present a greater shock hazard to a person because of the increased current or greater energy that could be delivered. High voltage supplies will not necessarily deliver greater currents or energies than lower voltage supplies if the high voltage supply has its output limited. The ability of a power supply to deliver high currents or energy depends on its output characteristics. Another consideration with higher voltages is that such voltages may cause insulation failure. Higher voltages may lead to dielectric breakdown and to subsequent arcing. Two types of dielectric breakdown must be considered—either through air or over or through a solid or liquid dielectric material.

The breakdown strength for air is approximately 30 kV/cm or 75 kV/in. This value depends on factors such as the shape of the electrodes, rate or rise of the voltage, and polarity of the voltage. Below approximately 350 V, there can be no breakdown through air no matter how small the air gap is made. Once an arc is initiated, only about 20 V/cm or 50 V/in is required to maintain the arc regardless of the magnitude of the arc current [19].

Arcing may be initiated through or over a solid material at voltages well below that required through air. Over or through a solid material, there may be dielectric breakdown or tracking which permits an arc to be initiated at voltages as low as 6 or 12 V if the resistance in the track is low enough to maintain the arc after it initiates over the carbon track. Arcs over or through solid dielectrics are not uncommon for the usual 120 V system when there is a dielectric failure caused by insulation failure or surface contamination.

## VIII. TYPICAL LABORATORY ACCIDENTS

Using equipment that is supposed to be energized by a grounding-type power cord has led to many accidents when the equipment grounding has been defeated either intentionally or by accident. The major problem is that the equipment will usually operate normally and not alert the experimenter if an internal fault develops that energizes the exposed metal on the case. The experimenter will probably discover the problem when he or she touches the case and receives a shock or the case is contacted by a grounded object and sparks fly.

A student helper miswired a grounding-type attachment plug on a power cord to some electrical equipment. The green equipment grounding conductor from the chassis was connected to one of the ungrounded energized blades in the attachment plug, while the black circuit conductor from the equipment was connected to the grounding pin in the plug. The equipment would not operate but, worse yet, the student's professor received a serious shock when he contacted the energized case. The professor was frozen to the equipment and was only saved when another student pulled him free. Similar accidents occur if the receptacle is miswired or the attachment plug is inserted into the receptacle with an improper orientation.

Test circuits are often operated directly from the 120 V line or through an auto-transformer. In either case, one of the lines is at ground potential and the other is energized with respect to ground. Great care must be taken to avoid a shock from the energized line to ground. Any test equipment with a gounded input must be connected to the circuit so that the grounded test lead does not contact the ungrounded energized conductor. Use of an isolation transformer will provide an ungrounded power source without these problems.

A laboratory worker was using an insulation tester with a sinusoidal output of 1500 V, 60 Hz, and an available current from the unit of 300 mA. She made contact across the test probes and was electrocuted. Great care must be exercised when using high voltages with sufficient current capacity to be lethal.

All capacitors should be considered charged unless the experimenter personally has discharged the unit. Capacitors can maintain their charge for long periods. Besides being possibly lethal, the shock from a capacitor can produce violent motions that can lead to physical injury or contact with energized equipment.

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