**FUNDAMENTALS OF INDUSTRIAL HYGIENE, 6TH ED.**

**HOMEWORK #7**

**INDIVIDUAL MEASUREMENT OF ELECTRICITY**

**Objective:** Students will become familiar with the fundamentals of nonionizing radiation and its measurement, including common electrical and magnetic units and the transmission of electric power.

**Background:** Electrical phenomena have long been studied, although progress in theoretical understanding remained slow until the 17th and 18th centuries. Even then, practical applications for electricity were few, and it would not be until the late 19th century that engineers were able to put it to industrial and residential use. The rapid expansion in electrical technology at this time transformed industry and society. Electricity’s extraordinary versatility means that it can be put to an almost limitless set of applications, including transportation, heating, lighting, communications, and computation.

In 1791, Luigi Galvani published his discovery of bioelectricity, demonstrating that electricity was the medium by which nerve cells passed signals to the muscles. Alessandro Volta developed the battery for storing electrical energy in 1800, providing scientists with a more reliable source of electrical energy. The recognition of electromagnetism, the unity of electric and magnetic phenomena, is due to Hans Christian Orsted (1819) and Andre-Marie Ampere (1820); Michael Faraday invented the electric motor in 1821, and George Ohm mathematically analyzed the electrical circuit in 1827. Electricity and magnetism (and light) were definitively linked by James Clerk Maxwell in 1861 and 1862.

The presence of a *charge* gives rise to an electrostatic force, and these charges exert a force on each other. These phenomenon were investigated in the late 18th century by Charles-Augustin de Coulomb, who deduced that charge manifests itself in two opposing forms [attractive (positive) and repulsive (negative)]. This discovery lead to the well-known axiom: like-charged objects repel each other, while opposite-charged objects attract each other. The magnitude of the electromagnetic force, whether attractive or repulsive, is given by *Coulomb’s Law*, which relates the force to the product of the charges and has an inverse-square relationship to the distance between them.

Electric charge gives rise to, and interacts with, the *electromagnetic force*, one of four fundamental forces of nature. The most familiar carriers of electrical charge are the electron (-) and the proton (+), and each carries the same, although opposite, charge. Charge is a conserved quantity, meaning that the net charge within an isolated system will always remain constant; however, within the system, charge may be transferred between bodies, either by direct contact of by passing along a conducting material (e.g., wire).

The movement of electric charge is known as an *electric current*, the intensity of which is usually measured in amperes (*I*). While current can consist of any moving charged particle, most commonly these are electrons. The process by which electric current passes through a material is known as *electrical conduction*, and it varies depending on the nature of the charged particles and the material through which they are flowing. For example, current through a material with high resistance causes localized heating. While the particles themselves can move quite slowly (sometimes only fractions of a millimeter per second), the electric field that drives them propagates at close to the *speed of light* (186,000 *mi/s*, 299,792,458 *m/s*).

One of the most important discoveries relating to current was made accidently by Hans Christian Orsted in 1820, when he observed the current in a wire disturbing the needle of a magnetic compass. This marks the discovery of *electromagnetism*, a fundamental interaction between electricity and magnetics.

In engineering or household applications, current is often described as being either direct current or alternating current. These terms refer to how the current varies in time. *Direct current (DC)*, as produced from a battery, is a unidirectional flow from the negative part of the circuit to the positive. *Alternating current (AC)* is any current that reverses direction repeatedly, pulsing back-and-forth within a conductor without the charge moving any net distance over time.

An *electric field* (introduced by Michael Faraday) is created by a charged body in the space that surrounds it, and results in a force exerted on any other charges placed within the field. Like gravity, it extends towards infinity and exhibits an inverse-square relationship with distance. Unlike gravity, which always acts in attraction, an electric field can result in either attraction or repulsion. The electromagnetic force pushing two electrons apart is 1042 times that of the gravitational attraction pulling them together.

An electric field generally varies in space, and its strength at any one point is defined as the force (per unit charge) that would be felt by a stationary, negligible charged if placed at that point. As the electric field is defined in terms of force, and force is a vector, so it follows that an electric field is also a vector, having both magnitude and direction. There is a finite limit to the electric field strength that can be withstood by any medium. Beyond this point, electrical breakdown occurs and an electric arc causes flashover between the charged parts. Air, for example, tends to arc across small gaps at electrical field strengths in excess of 30 *kV* per centimeter. The most visible natural occurrence of electric breakdown is lightning, caused when charge becomes separated by rising columns of air, raising the electric field in the air to greater than it can withstand. A typical lightning discharge may be as great as several hundred million volts, with currents ranging between 5,000 and 20,000 amps.

The concept of *electrical potential* is closely linked to that of the electric field. A small charge placed within an electric field experiences a force, and to have brought that charge to that point against the force requires work. The electrical potential is usually measured in volts, and one volt is the potential for which one joule of work must be expended. A more useful concept is that of *electric potential difference*, which is the energy required to move a unit charge between two points. The Earth is assumed to be at the same potential everywhere, and this reference point takes the name *earth* or *ground*. Earth is assumed to be an infinite source of equal amounts of positive and negative charge, and is therefore electrically uncharged.

Electricity and magnetism are fundamentally interlinked, mixed into a single, inseparable phenomenon called *electromagnetism*. Although there is some evidence of the use of magnetic materials dating earlier than 1000BC, in western civilizations, it was not until the late 1100s that Alexander Neckam first described the compass and its use in Europe. In 1600, William Gilbert described his experiments with a model earth, concluding that the Earth was itself magnetic and that this was the reason compasses always pointed north. As previously mentioned, in 1819, Orsted identified a link between electricity and magnetism, and shortly thereafter Andre-Marie Ampere discovered that the magnetic field circulating in an electrical circuit was related to the current flowing though the circuit. In 1831, Michael Faraday found that a time-varying magnetic flux through a loop of wire induced a voltage.

Magnetism is a class of physical phenomenon that includes forces exerted by magnets. It has its origin in electric currents and the fundamental magnetic moments of elementary particles. These give rise to a magnetic field that acts on other currents and moments. All materials are influenced to some extent by a magnetic field. Most materials do not have permanent moments, some are attracted to a magnetic field, others are repulsed by a magnetic field, and yet others have a much more complex relationship with an applied magnetic field. Substances that are negligibly affected by magnetic fields are known as non-magnetic substances (non-permeable), and include copper, aluminum, gases, and plastic.

The phenomena of magnetism is mediated by the magnetic field. An electric current or magnetic dipole creates a magnetic field, and that field, in turn, imparts magnetic forces on other particles that are in the fields. Magnetism is seen whenever electrically charged particles are in motion (e.g., from movement of electrons in an electric circuit).

**Part I: Basic Electrical Units**

Electrons [negative (-)] and protons [positive (+)] are charged particles, each having the same amount of charge. Like-charged particles repel each other and opposite-charged particles attract each other. When combined, opposite-charged particles cancel each other out; however, a piece of material with more protons than electrons will have a positive charge, while a piece of material with more electrons than protons will have a negative charge.

**Pressure**

Each charged particle that is out of balance (not cancelled out) exerts some electrical force (pressure) as it tries to get back into balance. Electrons push as they try to get away from each other, and protons pull as they try to attract electrons towards them. If an excess of electrons accumulate, their mutual repulsion will create a “pressure”, which is measured in *volts (V)*, named after Alessandro Volta. The greater the pressure (i.e., more accumulated charges), the higher the voltage. If there is no pathway for the electrons to escape, the pressure will remain the same or, if more electrons are added, increase. Therefore, voltage is the *potential* to cause an electrical current.

**Current**

Given a path (conductor), electrons will flow away from a negative charge and towards a positive charge. This flow is known as a current, and is measured in *amperes (I)*, named after Andre-Marie Ampere. The more electrons moving down the conductor, the greater the current. Note that ampere (*amp*) refers to a rate . . . the number of electrons passing a given point per unit of time. The amp is technically defined as 62,420,000,000 (6.242  1010) electrons per second.

**Resistance**

The electrons flowing through a conductor will encounter resistance, which is measured in *ohms (R)*, named after Georg Simon Ohm. The ohm is defined as a resistance between two points on a conductor under a constant potential difference of 1.0 *volt* that produces a current of 1.0 *amp*. *Ohms* and *amps* are inversely related, that is, (for a given voltage and conductor) as *ohms* (resistance) increases, *amps* decrease and as *ohms* decrease, *amps* increase.

To increase electrical current (i.e., *amps*, the flow of electrons), three things can be done. First, voltage can be increased. The higher the pressure, the more electrons can be forced down the conductor. Second, the size of the conductor can be increased. The greater the size, the more electrons can be accommodated. Third, a conductor with less resistance can be used. The lower the resistance, the greater the amps. Note that if you were to increase two or even all three, far more electrons can be moved.

This provides us with several electrical relationships, all of which can be summarized through the use of a simple triangle diagram.

**Figure 1:** The electric voltage triangle.

 

*V = I  R*

 voltage equals amperage times resistance

*I = V ÷ R*

 amperage equals voltage divided by resistance

*R = V ÷ I*

 resistance equals voltage divided by amperage

Example: Consider a typical home in which most appliances operate at 120 *volts* and the remaining fixtures (e.g., water heater, clothes drier, range, baseboard heaters) operate at 240 *volts*.

A toaster operates under a resistance of 18 *ohms* and draws a current of 6.7 *amps*. Is the toaster a 120-*volt* or 240-*volt* model?

*V = I  R* *V* *=* 6.7 *amps*  18 *ohms*  *V* *=* 120 *volts*

A 120-*volt* countertop microwave oven draws a current of 8.3 *amps*. What is the resistance?

*R = V ÷ I* *R* *=* 120 *volts* ÷ 8.3 *amps* *R =* 14.5 *ohms*

The filament of a standard 120-*volt* light bulb has a resistance of 10 *ohms*. What current does it draw?

*I = V ÷ R* *I =* 120 *volts* ÷ 10 *ohms* *I =* 1.2 *amps*

**Part II: Units of Electrical Power and Energy**

**Watts**

Power (*P*) is the rate at which energy is generated or consumed and is measured in *watts (W)*, named after James Watt, in units that represent ‘energy per unit time.’ The more working getting done or the more quickly the work is getting done, the more watts required. The unit is defined as the rate at which work is done when 1.0 amp of current flows through an electrical potential difference of 1.0 volt.

**Watt-hour**

Energy (*E*) refers to the electrical potential that is generated or consumed over a given amount of time and is measured in *watt-hour (Wh)*. If energy is being transmitted or used at a constant rate over a period of time, the total energy is the product of power and the time. Given the limited power of a single *watt*, most applications make use of the *kilowatt-hour* (thousand *watts/hour*). For example, the typical household is billed according to the thousands of *watts* consumed per hour (*kWh*) over the course of a month.

This provides us with several electrical relationships, all of which can be summarized through the use of another simple triangle diagram.

**Figure 2:** The electric power triangle.

 

*P = I  V*

 power equals amperage times voltage

*I = P ÷ V*

 amperage equals power divided by voltage

*V = P ÷ I*

 voltage equals power divided by amperage

The two triangles can be combined to illustrate a myriad of electrical relationships:

 **Figure 3:** Ohm’s and Watt’s Laws

 

Example: A 100-*watt* light bulb is turned on for one hour. How much energy is used?

*E* = *P  t*

*E* = 100 *W*  1 *h*

*E* = 100 *Wh* (0.1 *kWh*)

Example: A heater rated at 1000 *watts* is operated for 4 hours. What is the total power consumption?

*E* = *P  t*

*E* = 1000 *W*  1 *h*

*E* = 4000 *Wh* (4 *kWh*)

**Part III: Electric Power Transmission**

*Electric power transmission* is the bulk transfer of electrical energy from generating power plants to electrical substations located near demand centers. This is distinct from *electric power distribution*, which refers to the local wiring between substations and customers. Transmission lines, when interconnected to each other, become *transmission networks*. The combined transmission and distribution network is known as the *power grid*.

In the early days, electric power was transmitted at the same voltage as used by lighting and mechanical loads, which restricted the distance between generating plants and consumers. In 1882, generation was with *direct current (DC)*, which could not easily be increased in voltage for long distance transmission. Different classes of loads (e.g., lighting, fixed motors, traction (railway) systems) required different voltages, and so, used different generators and circuits. Altogether, early electric power transmission and distribution resulted in a myriad of interlaced conductors (see images below).



Electrical engineers in the early 20th century faced a problem figuring out how to transmit electric power to distance points. The power losses became prohibitive when large direct currents were transmitted over long wires. The solution to the problem was to transmit electric power over the wires using a high voltage and a small current so that the power losses were smaller. This approach required that the high voltage be converted back down to a lower voltage (and corresponding higher current) at the place where the electric power was being used. The answer to this problem was to keep changing the polarity of the voltage and current and use the resulting changes in magnetic fields to induce another current.

The transformer and Nikola Tesla’s *alternating current (AC)* were essential for a combined AC distribution system for both lighting and machinery. Regarded as one of the most influential electrical innovations, the universal system used transformers to step-up voltage from generators to high-voltage transmission lines, and then to step-down voltage to local distribution circuits or industrial customers. By using common generating plants for every type of load, important economies of scale were achieved, resulting in reduced cost for consumer and increased overall use of electric power.

**Transformers**

A *transformer* is a device that swaps current for voltage and *vice versa*, while maintaining an approximate constant power flow across the device. A transformer couples two circuits; a primary circuit that feed in power and a secondary circuit where a load consumes the power. A transformer consists of two separated coils of wire wrapped around a core.



**Induction**

When a fluctuating electric current (AC) flows through a wire, it generates a magnetic field around the wire. Conversely, when a magnetic field fluctuates around a piece of wire, it generates an electric current in the wire. The strength of the magnetism is directly related to the size of the electric current.

The coil that is energized is known as the *primary coil*. If a second coil of wire (*secondary coil*) is placed near the first one (but not touching), and a fluctuating current is sent through the first, an electrical current will be induced (*induction*) to flow in the secondary circuit.

Note: Transformers do not work with DC, where a steady current constantly flows in the same direction.

** step-up transformers**

Boost low voltage to a higher one:

If the secondary coil has twice the number of turns as the first coil, the secondary voltage will be twice the size of the primary voltage.



To calculate the change between the current in the secondary circuit vs. the primary circuit:

II° voltage ÷ I° voltage = # turns in II° coil ÷ # turns in I° coil

and

I° current ÷ II° current = # turns in II° coil ÷ # turns in I° coil

** step-down transformers**

Reduces high voltage to a lower one:



**Transmission Lines**

Transmission line conductors are made of aluminum wire wrapped around a steel cable core (aluminum-conductor steel-reinforced – ACSR). Aluminum is used because it has about half the weight of a comparable resistance copper cable, as well as being cheaper, while the inner, steel cables are included for strength. Since the length of the conductor cable will change depending on air temperature, the weight of additional load such as ice cover, and heating resulting from resistance to the electrical current being carried, a minimum overhead clearance must be maintained for safety.

**Conductor Size**

**Pouillet’s Law**

The resistance of a given material will increase with the length, but decrease with increasing cross-sectional area.

$$R= \frac{pL}{A}$$

where: *p* = resistivity of material current is flowing through (in *ohmm*)

 *L* = length of conductor (in *m*)

 *A* = cross-sectional area of conductor (in *m*2)

Example: Assume transmission of a current over a distance of 402 *km* (250 *mi*) through a 7.62 *cm* (3-*in*) and a 1.27 *cm* (½-*in*) aluminum conductor. Calculate the total resistance encountered by the electric current.

First, calculate the cross-sectional area of both conductors: ($A\_{circle}= π  r^{2}$)

7.62-*cm* conductor: $A= 3.14  \left(3.81 cm\right)^{2} $ $A= 3.14  14.52 cm^{2}$ $A=45.59 cm^{2}$

1.27-*cm* conductor: $A= 3.14  \left(0.64 cm\right)^{2} $ $A= 3.14  0.41cm^{2}$ $A=1.29 cm^{2}$

To keep units the same, convert these values to *m*2 (divide by 10,000):

7.62-*cm* conductor: $A= 45.59 cm^{2}  \frac{1 m^{2}}{10000 cm^{2}} $ $A=0.004559 m^{2} $

1.27-*cm* conductor: $A= 1.29 cm^{2}  \frac{1 m^{2}}{10000 cm^{2}} $ $A=0.000129 m^{2} $

Next, look up the resistivity of the conductor (see table on following page):

$$p\_{aluminum}=2.82  10^{-8} ohm m$$

Note: Resistivity is generally given in units of *ohmm*, although other units, such as *ohmin* are sometimes used.

Lastly, plug in the values from above and perform the final calculations: $R= \frac{pL}{A}$

7.62-*cm* conductor: $R= 2.82  10^{-8} ohm m  \frac{402000 m }{0.001559 m^{2}}$ $R= 7.27 ohm$

1.27-*cm* conductor: $R= 2.82  10^{-8} ohm m  \frac{402000 m }{0.000129 m^{2}}$ $R= 87.88 ohm$

 **Resistivity of Common Materials**

 **Material Resistivity (*Ωm*) Resistivity (*Ωin*)**

Silver (Ag) 1.59  10-8 6.26  10-7

Copper (Cu) 1.68  10-8 6.61  10-7

Gold (Au) 2.44  10-8 9.61  10-7

Aluminum (Al) 2.82  10-8 1.11  10-6

Iron (Fe) 1.00  10-7 3.94  10-6

Carbon Steel 1.43  10-7 5.63  10-6

Stainless Steel 6.90  10-7 2.72  10-5

Sea Water 2.00  10-1 7.87

Drinking Water 2.00  102 7.87  103

Wood (damp) 1.00  103 3.94  104

Glass 1.00  1013 3.93  1014

Hard Rubber 1.00  1013 3.93  1014

Wood (dry) 1.00  1015 3.93  1016

 Air 2.30  1016 9.06  1017

**Load (line) Loss**

**Joule’s Law**

The energy losses incurred in power transmission are proportional to the square of the current.

*P*(loss) = *I*2  *R*

where: *I* = current (in *amps*)

 *R* = resistance (in *ohms*)

Example: Assume a line voltage of 400 *kV* (400,000 *volts*) from a 750 *MW* supply. These values can be used to determine the current (*amps*) at the source (*I = P / V* . . . = 750,000,000 *watts* ÷ 400,000 *volts* . . . = 1875 *amps*). Calculate the line loss from power transmitted 402 *km* (250 *mi*) over the 7.62-*cm* and 0.5-*cm* conductors.

First, the current must be determined:

$I=P ÷V$ $I=750,000,000 watts ÷400,000 volts$ $I=1875 amps$

Next, calculate the line loss for each size conductor:

7.62-*cm* conductor: $P\_{loss}= \left(1875 amps\right)^{2} 7.27 ohms$

$$P\_{loss}= 3,515,625 amps  7.27 ohms$$

$$P\_{loss}= 25,558,594 watts (25559 kW)$$

3.4% of the power produced!

1.27-*cm* conductor: $P\_{loss}= \left(1875 amps\right)^{2} 87.88 ohms$

$P\_{loss}= 3,515,625 amps  87.88 ohms$

$$P\_{loss}= 308,953,125 watts (308953 kW)$$

41% of the power produced!

Example: Now, make a comparison of line loss assuming a line voltage of 100,000 volts.

First, determine the current given the 100,000 volt scenario:

$I=P ÷V$ $I=750,000,000 watts ÷100,000 volts$ $I=7500 amps$

7.62-*cm* conductor: $P\_{loss}= \left(7500 amps\right)^{2} 7.27 ohms$

 *(100,000 volt)* $P\_{loss}= 56250000 amps  7.27 ohms$

$$P\_{loss}= 408937500 watts (408938 kW)$$

54.5% of the power produced!

Note: From the above calculations using Joule’s Law, it is clear that transmitting power at high voltage (low current) and through a large conductor is far more efficient.

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**HOMEWORK #7**

**INDIVIDUAL MEASUREMENT OF ELECTRICITY**

**Name:**

**EXERCISES:** Perform the calculations identified below. Show your work neatly and clearly in a manner similar to the examples provided above (i.e., write the formula and show steps of your calculations).

**Part I: Basic Electrical Units**

1a) Consider a short piece of insulated wire. Is there a current flowing in this wire? *(1 point)*

1b) The two ends of the wire are connected together to form a complete circuit. Now is there a current flowing in the wire? *(1 point)*

1c) Given a 50-*amp* load and a conductor having 4.4-*ohm* resistance, what is the voltage? *(2 points)*

1d) Given 440 *volts* and a conductor with 3.2-*ohm* resistance, what is the amperage? *(2 points)*

1e) Given 120 *volts* and a 10-*amp* load, what is the resistance of the conductor? *(2 points)*

1f) A filament of a flashlight bulb has a resistance of 50 *ohms* and should be used with a current of 0.03 *amps*. What volt battery is needed? *(2 points)*

1g) A 3-*volt* battery is used with a flashlight bulb having a resistance of 100 *ohms*. How much current is flowing when the bulb is lit? *(2 points)*

1h) A 4.5-*volt* battery is used to produce a 0.3-*amp* current in a flashlight bulb. What is the resistance of the light bulb filament? *(2 points)*

**Part II: Units of Electrical Power and Energy**

Electric heaters are designed around high resistance conductors that convert electric energy into heat energy. If a 120-*volt* portable heater with a 10-*ohm* resistance is plugged in and turned on the highest setting.

2a) What is the current flowing through it? *(2 points)*

2b) What is the power rating of this heater? *(2 points)*

2c) How much energy is consumed if this heater is left on for 8 hours? *(2 points)*

A toaster operates at 120 *volts* and is rated at 800 *watts*.

2d) What is the resistance of the toaster element? *(2 points)*

2e) What is the current flowing through it? *(2 points)*

Consider the following bathroom on a 120-*volt*, 20-*amp* circuit (i.e., the bathroom circuit is protected by a 20-*amp* breaker to prevent overheating of the wires and damage to fixtures). The homeowner enters the bathroom and turns on the 100-*watt* light, an 850-*watt* heater, and a 400-*watt* ventilation fan. After showering, the person plugs in an 1100-*watt* blow-dryer.

2f) Calculate the individual current (amperage) drawn by each item *(4 points)*

2g) Is the bathroom circuit overloaded? *(2 points)*

**Part III: Electric Power Transmission**

Wanapum Dam on the Columbia River generates 1100 *MW* (1,100,000,000 watts) of power consisting of a current of 40,741 *amps* at 27,000 *volts*. As was seen in previous calculations, electric power is transmitted more efficiently (i.e., with less loss) if the size of the conductor is increased and if the voltage is higher. To transmit its load more efficiently, the power generated at Wanapum Dam is stepped-up to 230 *kV* (230,000 *volts*) before being sent down a 7.62-*cm* (3-*in*) ACSR overhead power line to Seattle 225 *km* (140 *mi*) away.

3a) What is the current (in *amps*) in the transmission lines? *(2 points)*

3b) What is the ratio of wraps between the primary coil and secondary coil in the step-up transformer?

 *(2 points)*

3c) When the electric power arrives near its destination, it is routed through a sub-station where the voltage is stepped-down to 14,400 *volts* for local distribution. What is the ratio of wraps between the primary coil and secondary coil in the step-down transformer? *(2 points)*

3d) Prior to being sent into a home, the electric power is again passed through a transformer (typically on a power pole adjacent to the home), where the voltage is stepped-down to 240 *volts*. What is the ratio of wraps between the primary coil and the secondary coil in the step-down transformer? *(2 points)*

During a winter power outage, a homeowner connects a 6,000 *watt* generator and feeds 240 *volts* into their breaker panel.

3e) How many *amps* of current are flowing into the breaker panel? *(2 points)*

In response to the power outage, linemen begin working to repair breaks in the power lines. Since the power is out in the neighborhood, the linemen assume there is no power in the lines they are handling. Unfortunately, the homeowner forgot to flip the main feed breaker when they hooked up the generator. As a result, power from the generator is back-feeding through the transformer outside the house and into these same power lines.

3f) What voltage are the workers exposed to? *(2 points)*

3g) What current are the workers exposed to? *(2 points)*

3h) Could this current be lethal to the linemen? Describe how. *(5 points)*