THEORY ON DC ELECTRIC CIRCUITS

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To the woman who gave me the only reason to live: She
I love you, mom!

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Introduction

This book contain 15 chapters with the concepts and analysis techniques of direct current (DC) electric circuits and their related measurement systems. Their main contribution is providing a step-by-step explanation and detailed illustrations, as well as the technical analysis and solution of electrical circuits.

This document is intended as a major support for DC electric circuits courses from the Electrical Engineering program and the Automation Engineering program at Universidad de La Salle. The order of topics is listed as follows:

Chapters 1 to 4 include a review of basic operations, including significant figures, system of units and scientific notation. There is also an introduction to electric safety concepts.

Chapters 5 to 14 present the basic concepts, analysis techniques and theorems of DC electric circuits.

Chapter 15 introduces the concepts and techniques of measurement of basic DC electrical quantities.

1. Electric Risk

In Colombia, electric risk regulations are provided in the *Reglamento Técnico de Instalaciones Eléctricas* (RETIE) (Minminas, 2013). The RETIE is supported by the NTC 4120 standard *Efectos de la corriente sobre los seres humanos y los animales domésticos* (Icontec, 1997).

This chapter reviews a few basic concepts about the effects of electric current in human beings.

1.1. Common electric risk factors

The RETIE lists 11 common electric risks (Figure 1).

1. *Electric arc*. Is a permanent flow of electric current caused by the breaking of the electrical insulation between two points with different potential.
2. *Lack of electricity*. Is an electrical hazard, because there are several situations in which electricity is required, such as hospital facilities, or in case of risk of lighting resins, etc.
3. *Direct contact*. Is the risk of a person who directly touches one or several points with different potentials, causing the current to flow through the human body.
4. *Indirect contact*. Is the risk of a person who is not directly touching energized points, but who touches zones that are directly in contact with energized points. It also causes the current to flow through different paths of the human body.

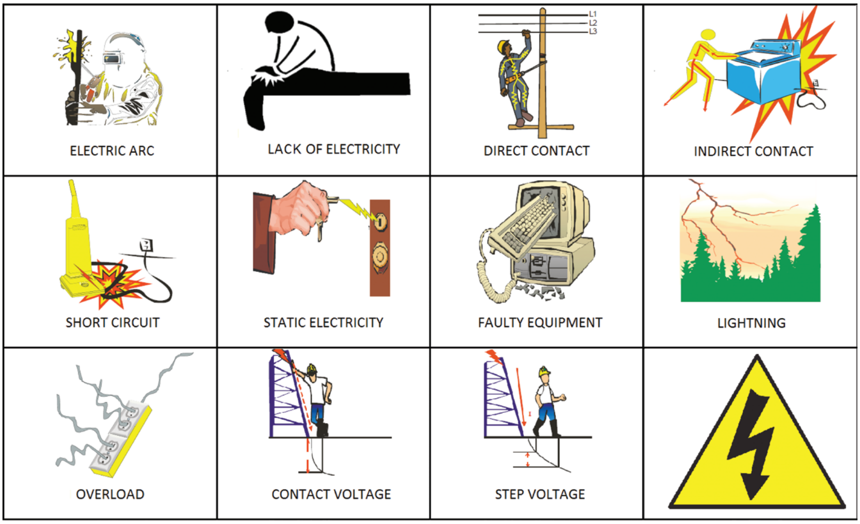


Figure 1. Electrical risk factors

Source: Minminas (2013).

5. *Short-circuit*. Is the equalization of the potential of two points with different potential by joining them with a conductive medium. The result is an electric current of high value.
6. *Static electricity*. Static electricity is a short-term electric discharge due to a body part approaching another object with a different potential. The current is low and it is usually not associated with serious health risks.
7. *Faulty equipment*. Is an electrical risk because it can involve one or all the of following electric risks: Direct contact, short-circuit, overload or static electricity.
8. *Lightning*. Is an electrical risk that can occur in two ways: direct impact of lightning on a person or impact of lightning on a grounded object, thus producing step voltage.
9. *Overload*. Is the electrical risk associated with several appliances being connected to the same installation, producing a current higher than the maximum current supported by the installation.

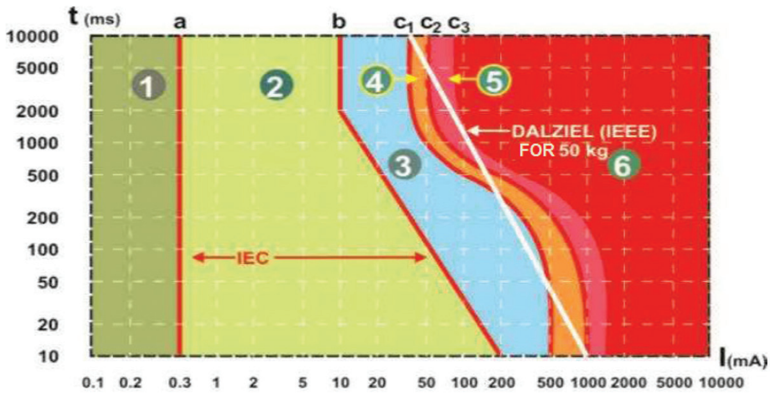
10. *Contact voltage*. Is the electrical risk due to the difference of potential between the hand and the foot of a person who touches a structure with a different potential to the ground potential, causing the current to flow through the human body.
11. *Step voltage*. Is the electrical risk due to the difference of potential between both feet of a person, causing the current to flow through the human body.

1.2. Effects of current in human beings

The RETIE (Minminas, 2013) states that, in a given current path through the human body, danger of a current flow to people depends on both its magnitude and duration. Figure 2 shows the effects of the alternating current (AC) in the interval from 15 Hz to 100 Hz.

The threshold for ventricular fibrillation depends on physiological and electrical parameters. The C1 curve is taken as a limit to design protective equipment. The threshold values in less than 0.2 s are applied only during the vulnerable period of the cardiac cycle. When the electric current flows into the body, the three following effects will occur: a nervous effect, a chemical effect, and a caloric effect. The following are the common consequences of an electric current flowing into the body:

- Electrification: Is a term used for not mortal accidents.
- Electrocution: Occurs when the current flows into the body. The consequence is death.
- Tetanization: Muscle tetanization is the annulment of the ability of muscle control or uncontrolled muscle stiffness due to passage of an electric current.
- Choking: Occurs when the current flow affects the nervous center that controls respiratory function, causing respiratory arrest.



ZONE 1	Usually no reaction
ZONE 2	Usually no dangerous pathophysiological effects
ZONE 3	Usually no risk of fibrillation
ZONE 4	Risk of fibrillation (up to about 5%)
ZONE 5	Risk of fibrillation (up to about 50%)
ZONE 6	Cardiac arrest, respiratory arrest and severe burns. Fibrillation risk (above 50%)

Figure 2. Effects of AC in the range of 15 Hz to 100 Hz on the human body

Source: Minminas (2013).

- Necrosis: Is the burn produced by the energy released in the electric current flow (Joule heating) or by heat radiation from an electric arc.
- Renal blockage: Is the interruption of metabolic kidney action. It is produced by the toxic effects of burns.

1.3. Electric impedance of the human body

The NTC 4120 standard (Icontec, 1997) provides the human body circuit model, in order to analyze the potential risk effects of electric current.

- *Internal impedance of the human body.* Can be considered as purely resistive and its value depends on the current path and the contact surface area.
- *Impedance of skin.* Can be considered as a resistive-capacitive network and its value depends on voltage, current flow duration, contact surface area, contact pressure, skin humidity, temperature, and type of skin. Figure 3 shows a representation of the impedance percentage for each area of the human body.

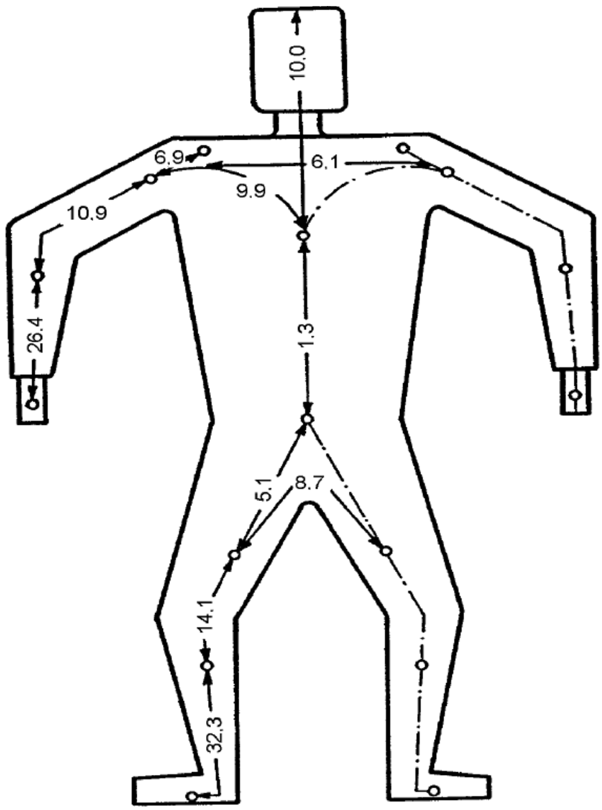


Figure 3. Representation of the impedance percentage for each human body area

Source: Icontec (1997).

Exercises

1. A person is replacing a house's power outlet (V_n = 100 V) and accidentally touches the wires. Figure 4 shows a representation of the risk situation.

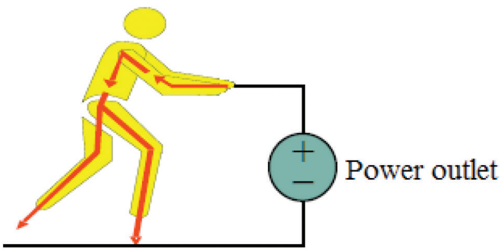


Figure 4. Representation of the risk situation (Exercise 1-1)

   Based on the human body resistance value stated in the RETIE, determine:

   a. The maximum breaking time of current in order to avoid fibrillation risk.
   b. The electric risk if the person stays connected to the power outlet by 1 s.

2. The workers in a power substation are subject to risk of contact voltage. There are two options of breaking devices to design the required protection system. Figure 5 shows a representation of the risk situation, and the operation curves of available breaking devices.

   Based on the resistance value of the human body stated in the RETIE, the effects on the human body shown in Figure 2 and the breaking device curves determine:

   a. The electric circuit model of the risk situation.
   b. The best breaking device between A and B to avoid cardiac arrest.

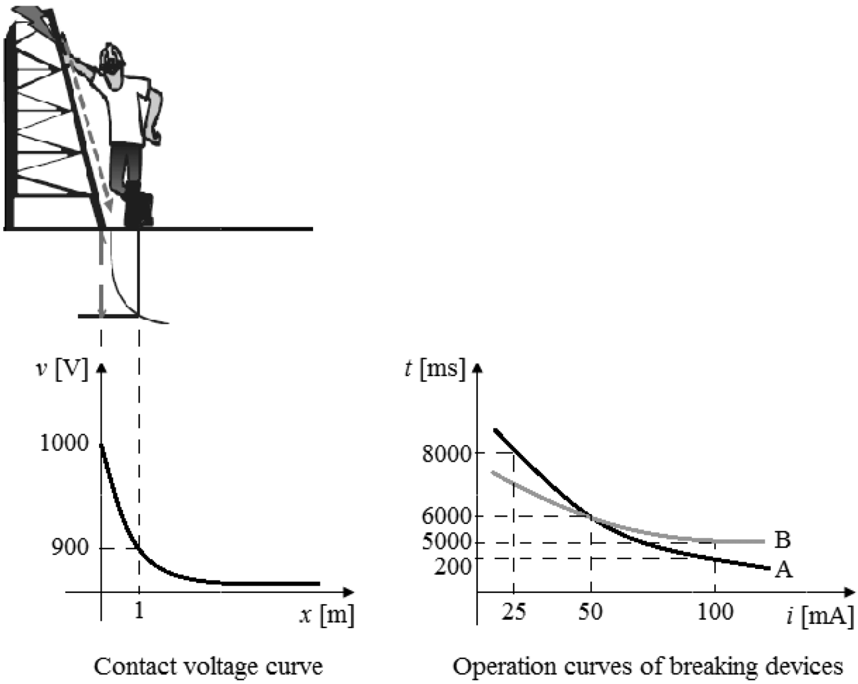


Figure 5. Representation of the risk situation and operation curves of available breaking devices (Exercise 1-2)

Source: Minminas (2013).

3. A worker is subject to risk of step voltage because he is walking near a metallic structure impinged by a lightning bolt. The risk situation and the lightning bolt curve are shown as follows:

If the energy absorbed by the worker is higher than 1 J, there could be risk of cardiac arrest.

Based on the resistance value of the human body stated in the RETIE, determine:

a. The electric circuit model of the risk situation.
b. The step voltage between the worker's feet.
c. If the worker could experience cardiac arrest.

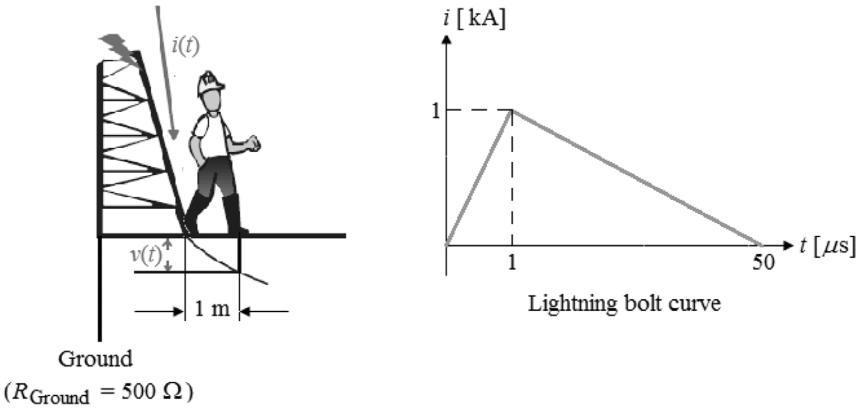


Figure 6. Representation of the risk situation and the lightning bolt curve (Exercise 1-3)

Source: Minminas (2013).

2. Significant Figures

The importance of significant figures is to avoid the answer of any mathematical operation from being more precise than the numbers in the operation (DeWitt, 2008). Usually, significant figures are used in numbers obtained from any physical measurement.

Example:

- *Take division:* $9 \div 7 = 1.285714286$. *The answer is more precise than the numbers in the mathematical operation.*
- *Using significant figures:* $9 \div 7 = 1$. *The answer has the same precision as the numbers in the mathematical operation.*

2.1. Rules of significant figures

The use of significant figures is based on the following rules:

First. All numbers different from zero are significant:

Example:
The number 5 has 1 significant figure
The number 94.656 has 5 significant figures

Second. All zeros located between non-zero numbers are significant:

Example:
The number 905 054 has 6 significant figures
The number 102 has 3 significant figures

Third. All zeros located between non-zero numbers and the decimal point are significant.

Example:
The number 40.1 has 3 significant figures
The number 1000.2 has 5 significant figures

Fourth. All zeros located to the right of the decimal point are significant.

Example:
The number 9.000 has 4 significant figures
The number 565.000065 has 9 significant figures

Fifth. All zeros located to the left of non-zero numbers are not significant.

Example:
The number 0.25 has 2 significant figures
The number 0.0000046 has 2 significant figures

Sixth. All zeros located to the right of non-zero numbers with no decimal point are not significant.

Example:
The number 10 has 1 significant figures
The number 45 940 has 4 significant figures

2.2. Mathematical operations with significant figures

2.2.1. Multiplying and dividing with significant figures

The result of multiplying or dividing 2 or more numbers must be expressed with the least quantity of significant figures of one of these numbers.

Example:
Take operation: 45.1 × 2.415 ÷ 1.2465= 87.377858. *Using three significant figures, the answer is* 87.4.

2.2.2. Adding and subtracting with significant figures

The result of adding or subtracting 2 or more numbers must be expressed with the least quantity of significant figures of one of these numbers.

Example:
Take operation: 45.1 × 2.415 ÷ 1.2465 = 87.377858. *Ordering the numbers:*

	4	5	.	1			
+		2	.	4	1	5	
−		1	.	2	4	6	5
	4	6	.	2	6	8	5

Round up

Using 3 significant figures, the answer is 46.3.

Exercises

1. How many significant figures are in the following numbers?

    a. 926.9
    b. 707
    c. 123.06
    d. 0.0402
    e. 0.82610
    f. 338.00

2. Perform the following operations with the right number of significant figures:

    a. 1.6204 – 1.593
    b. 15.6 + 29.4 + 215.83 + 98.1
    c. 52.5 + 44.99 – 125.957 – 331.22
    d. 3.68 ÷ 0.94
    e. 211.5 × 2.48
    f. 1.395 × 2.89 × 0.54
    g. 1.56 × 15.2 ÷ 3.7

3. Round the following numbers to 3 significant figures:

    a. 0.6824
    b. 12.84
    c. 0.00004162
    d. 3.3391
    e. 5.558