



G. PULLAIAH COLLEGE OF ENGINEERING AND TECHNOLOGY

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Department of Electrical and Electronics Engineering

***Bridge Course
On
Electrical Circuits***

Basic Definitions & Circuit Elements:

- Familiarity with and understanding of the basic elements encountered in electric networks.
- To learn the fundamental differences between linear and nonlinear circuits.
- To understand the Kirchhoff's voltage and current laws and their applications to Circuits.
- Meaning of circuit ground and the voltages referenced to ground.
- Understanding the basic principles of voltage dividers and current dividers. Potentiometer and loading effects.
- To understand the fundamental differences between ideal and practical voltage
- and current sources and their mathematical models to represent these source models in electric circuits.
- Distinguish between independent and dependent sources those encountered in electric circuits.
- Meaning of delivering and absorbing power by the source.

1. Introduction:

The inter connection of various electric elements in a prescribed manner comprises as an electric circuit in order to perform a desired function. The electric elements include controlled and uncontrolled source of energy, resistors, capacitors, inductors, etc. Analysis of electric circuits refers to computations required to determine the unknown quantities such as voltage, current and power associated with one or more elements in the circuit. To contribute to the solution of engineering problems one must acquire the basic knowledge of electric circuit analysis and laws. Many other systems, like mechanical, hydraulic, thermal, magnetic and power system are easy to analyze and model by a circuit. To learn how to analyze the models of these systems, first one needs to learn the techniques of circuit analysis. We shall discuss briefly some of the basic circuit elements and the laws that will help us to develop the background of subject.

1.1 Basic Elements & Introductory Concepts:

Charge:

- Is the quantity of electricity responsible for electric phenomena can be either positive or negative.
- The fundamental (smallest) quantity of charge is that of a single electron or proton. Its magnitude usually is denoted by the letter "e".
- According to the law of conservation of charge, the (net) charge in a closed region can neither be created nor destroyed.
- Two like charges repel one another, whereas two charges of opposite polarity attract.
- The unit of charge is coulomb (C) and the magnitude of "e" is :
$$e = 1.6 \times 10^{-19} \text{ C}$$
- The symbol is "q"
- The charge of a single proton is $q_p = e$
- The charge of a single electron is $q_e = e^-$

- Note that the term “charge” implies “net charge”: combined charge of protons. Present any given region of space **MINUS** combined charge of all electrons in that region. This is why *charge* is always an integral multiple of ‘e’.

Current:

- The current through a specified area is defined by the electric charge passing through the area per unit time.
- Current is the time rate of flow of electric charge past a given point

$$i = \frac{dq}{dt}$$

- The unit is ampere (A), an ampere is 1 coulomb per second.

Voltage:

- The voltage across an element is the work (energy) required to move a unit Positive charge from the – terminal to the + terminal.
- The unit of voltage is the volt (V).
- Voltage is also called **potential difference**.
- Current is associated with the movement of electric charge and voltage is Associated with the **polarity** of the charge

Electrical Network:

A combination of various electric elements (Resistor, Inductor, Capacitor, Voltage source, Current source) connected in any manner what so ever is called an electrical network. We may classify circuit elements in two categories, passive and active elements.

Passive Element:

The element which receives energy (or absorbs energy) and then either converts it into heat (R) or stored it in an electric (C) or magnetic (L) field is called passive element.

Active Element:

The elements that supply energy to the circuit is called active element. Examples of active elements include voltage and current sources, generators, and electronic devices that require power supplies. A transistor is an active circuit element, meaning that it can amplify power of a signal. On the other hand, transformer is not an active element because it does not amplify the power level and power remains same both in primary and secondary sides. Transformer is an example of passive element.

Bilateral Element:

Conduction of current in both directions in an element (example: Resistance; Inductance; Capacitance) with same magnitude is termed as bilateral element.

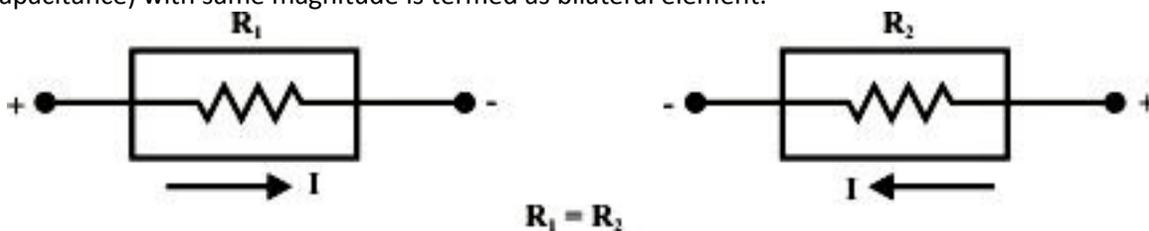


Fig 1(a): Bilateral Element

Unilateral Element:

Conduction of current in one direction is termed as unilateral (example: Diode, Transistor) element.

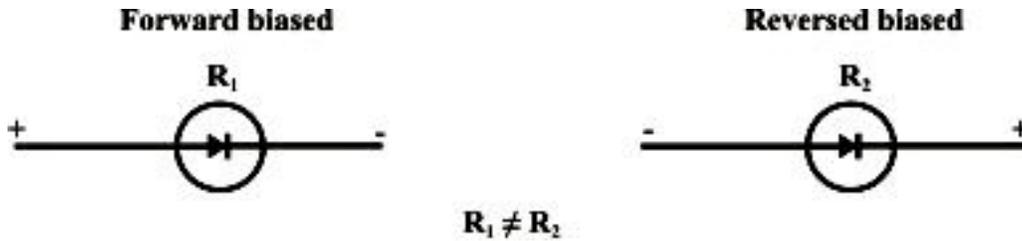


Fig 1(b): Unilateral element

Meaning of Response:

An application of input signal to the system will produce an output signal, the behavior of output signal with time is known as the response of the system.

1.2 Linear and Nonlinear Circuits:

Linear Circuit:

Roughly speaking, a linear circuit is one whose parameters do not change with voltage or current. More specifically, a linear system is one that satisfies

(i) homogeneity property [response of $\alpha u(t)$ equals α times the response of $u(t)$, $S(\alpha u(t)) = \alpha S(u(t))$ for all α ; and $u(t)$]

(ii) Additive property [that is the response of system due to an input $(\alpha_1 u_1(t) + \alpha_2 u_2(t))$ equals the sum of the response of input $\alpha_1 u_1(t)$ and the response of input $\alpha_2 u_2(t)$, $S(\alpha_1 u_1(t) + \alpha_2 u_2(t)) = \alpha_1 S(u_1(t)) + \alpha_2 S(u_2(t))$.

When an input $u_1(t)$ or $u_2(t)$ is applied to a system " S ", the corresponding output response of the system is observed as

$S(u_1(t)) = y_1(t)$ or $S(u_2(t)) = y_2(t)$ respectively. Fig. 1(c) explains

The meaning of homogeneity and additive properties of a system

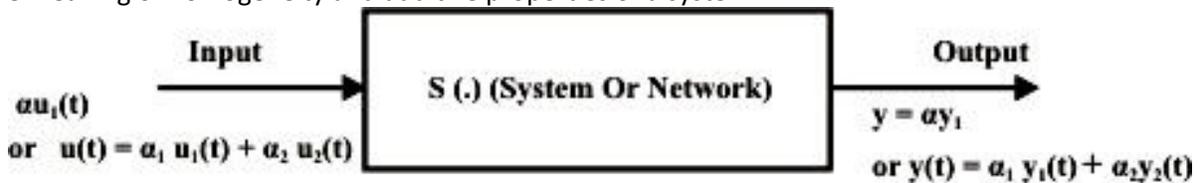


Fig .1(c): Input Output behavior of a system

Non-Linear Circuit:

Roughly speaking, a non-linear system is that whose parameters change with voltage or current. More specifically, non-linear circuit does not obey the homogeneity and additive properties. Volt-ampere characteristics of linear and non-linear elements are shown in Figs 2 - 3. In fact, a circuit is linear if and only if its input and output can be related by a straight line

passing through the origin as shown in Fig 3. Otherwise, it is a nonlinear system.

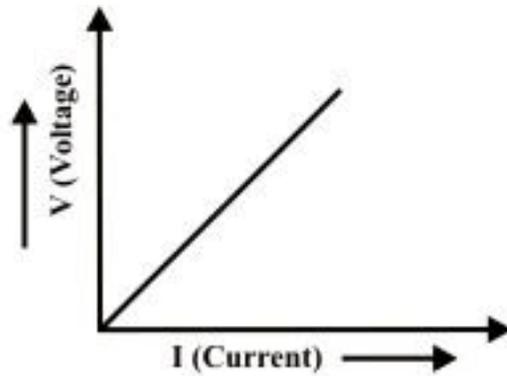


Fig 2: V-I characteristics of linear element

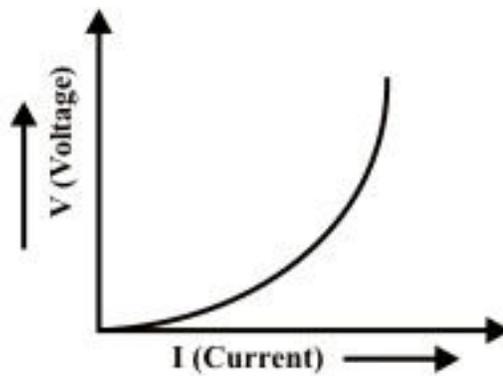


Fig 3: V-I characteristics of non - linear element

Potential Energy Difference:

The voltage or potential energy difference between two points in an electric circuit is the amount of energy required to move a unit charge between the two points.

1.3 Kirchhoff's Laws:

Kirchhoff's laws are basic analytical tools in order to obtain the solutions of currents and voltages for any electric circuit; whether it is supplied from a direct-current system or an alternating current system. But with complex circuits the equations connecting the currents and voltages may become so numerous that much tedious algebraic work is involve in their solutions.

Elements that generally encounter in an electric circuit can be interconnected in various possible ways. Before discussing the basic analytical tools that determine the currents and voltages at different parts of the circuit, some basic definition of the following terms are considered.

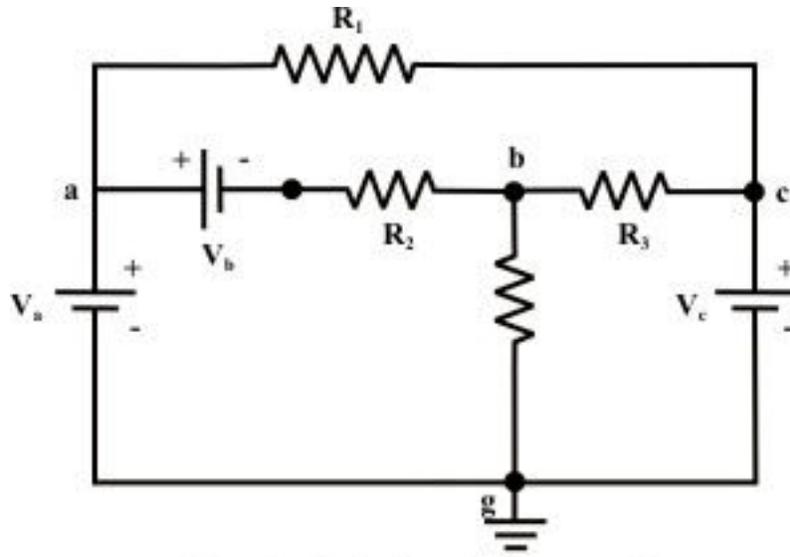


Fig 4: A sample Resistive circuit

- Node- A node in an electric circuit is a point where two or more components are connected together. This point is usually marked with dark circle or dot. The circuit in Fig 4 has nodes a, b, c, and g. Generally, a point, or a node in a circuit specifies a certain voltage level with respect to a reference point or node.
- Branch- A branch is a conducting path between two nodes in a circuit containing the electric elements. These elements could be sources, resistances, or other elements. Fig 5(a) shows that the circuit has six branches: three resistive branches (a-c, b-c, and b-g) and three branches containing voltage and current sources (a-, a-, and c-g).
- Loop- A loop is any closed path in an electric circuit i.e., a closed path or loop in a circuit is a contiguous sequence of branches which starting and end points for tracing the path are, in effect, the same node and touches no other node more than once. Fig. 5(b) shows three loops or closed paths namely, a-b-g-a; b-c-g-b; and a-c- b-a. Further, it may be noted that the outside closed paths a-c-g-a and a-b-c-g-a are also form two loops.
- Mesh- a mesh is a special case of loop that does not have any other loops within it or in its interior. Fig. 5(b) indicates that the first three loops (a-b-g-a; b-c-g-b; and a-c-b-a) just identified are also 'meshes' but other two loops (a-c-g-a and a-b-c-g) are not. With the introduction of the Kirchhoff's laws, a various types of electric circuits can be analyzed.

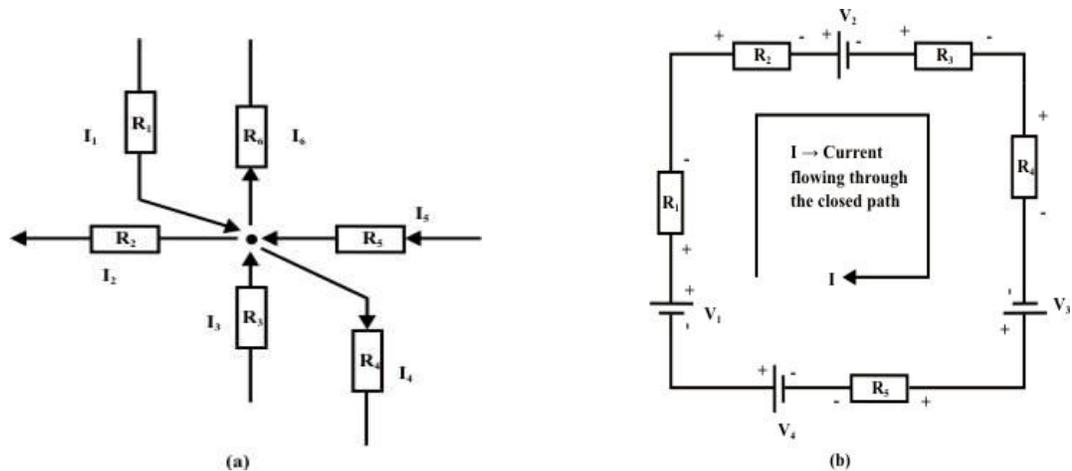


Fig. 5: Illustration of Kirchhoff's laws

Kirchhoff's Current Law (KCL):

KCL states that at any node (junction) in a circuit the algebraic sum of currents entering and leaving a node at any instant of time must be equal to zero. Here currents entering (+ve sign) and currents leaving (-ve sign) the node must be assigned opposite algebraic signs (see Fig 5 (a), $I_1 - I_2 + I_3 - I_4 + I_5 - I_6 = 0$).

Kirchhoff's Voltage Law (KVL):

It states that in a closed circuit, the algebraic sum of all source voltages must be equal to the algebraic sum of all the voltage drops. Voltage drop is encountered when current flows in an element (resistance or load) from the higher-potential terminal toward the lower potential terminal. Voltage rise is encountered when current flows in an element (voltage source) from lower potential terminal (or negative terminal of voltage source) toward the higher potential terminal (or positive terminal of voltage source). Kirchhoff's voltage law is explained with the help of fig. 3.5(b).

KVL equation for the circuit shown in Fig 5(b) is expressed as (we walk in clockwise direction starting from the voltage source V_1 and return to the same point)

$$V_1 - IR_1 - IR_2 - V_2 - IR_3 - IR_4 + V_3 - IR_5 - V_4 = 0$$

$$V_1 - V_2 + V_3 - V_4 = IR_1 + IR_2 + IR_3 + IR_4 + IR_5$$

Example: L-3.1 For the circuit shown in Fig 6, calculate the potential of points A, B, C, and E with respect to point D. Find also the value of voltage source V_1 .

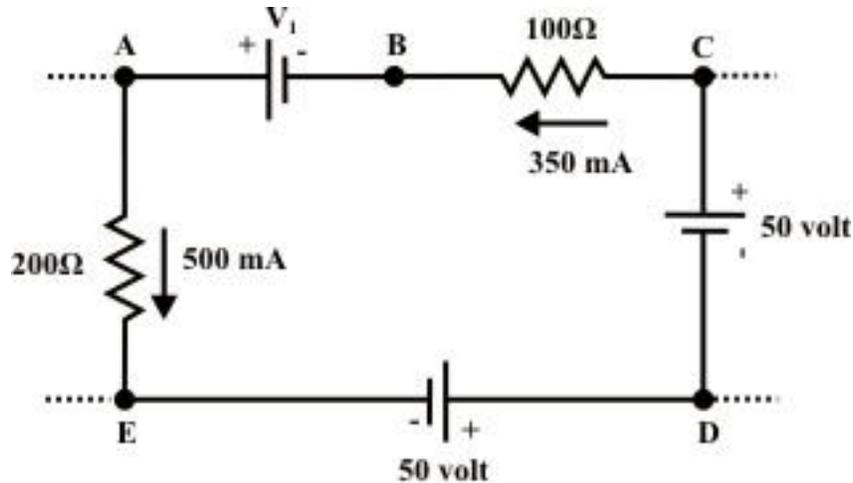


Fig 6: A part of DC resistive Circuit is presented

Solution:

Let us assume we move in clockwise direction around the close path D-E- A-B-C-D and stated the following points.

- 50 volt source is connected between the terminals D & E and this indicates that the point E is lower potential than D. So, V_{ED}

(i.e., it means potential of E with respect to D) is -50 volt and similarly $V_{CD} = 50$ volt or $V_{DC} = -50$ volt .

- 500 mA current is flowing through 200 Ω resistor from A to E and this implies that point A is higher potential than E . If we move from lower potential (E) to higher potential (A), this shows there is a rise in potential. Naturally, V_{AE}

$$= 500 \times 10^{-3} \times 200 = 100 \text{ volt}$$

$$\text{and } V_{AD} = -50 + 100 = 50 \text{ volt .}$$

$$\text{Similarly, } V_{CB} = 350 \times 10^{-3} \times 100 = 35 \text{ volt}$$

- V_1 voltage source is connected between A & B and this indicates that the terminal B is lower potential than A i.e., $V_{AB} = V_1$ volt or $V_{BA} = -V_1$ volt. . One can write the voltage of point B with respect to D is $V_{BD} = 50 - V_1$ volt.

- One can write KVL law around the closed-loop D-E-A-B-C-D as $V_{ED} + V_{AE} + V_{BA} + V_{CB} + V_{DC} = 0$
 $-50 + 100 - V_1 + 35 - 50 = 0 \Rightarrow V_1 = 35$ volt. Now we have $V_{ED} = -50$ volt, $V_{AD} = -50 + 100 = 50$ volt,
 $V_{BD} = 50 - 35 = 15$ volt, $V_{CD} = 15 + 35 = 50$ volt.

1.4 Meaning of Circuit Ground and the Voltage referenced to Ground:

In electric or electronic circuits, usually maintain a reference voltage that is named “ground voltage” to which all voltages are referred. This reference voltage is thus at ground potential or zero potential and each other terminal voltage is measured with respect to ground potential, some terminals in the circuit will have voltages above it (positive) and some terminals in the circuit will have voltages below it (negative) or in other words, some potential above or below ground potential or zero

potential.

Consider the circuit as shown in Fig 7 and the common point of connection of elements V_1 & V_3 is selected as ground (or reference) node. When the voltages at different nodes are referred to this ground (or reference) point, we denote them with double subscripted voltages V_{ED} , V_{AD} , V_{BD} , and V_{CD} . Since the point D is selected as ground potential or zero potential, we can write V_{ED} as V_E , V_{AD} as V_A and so on.

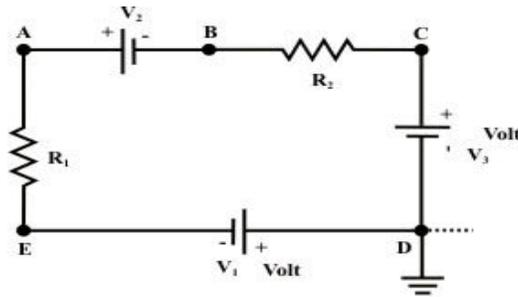


Fig 7: A sample dc resistive circuit

In many cases, such as in electronic circuits, the chassis is shorted to the earth itself for safety reasons.

1.5 Understanding the Basic Principles of Voltage Dividers and Current dividers:

1.5.1 Voltage Divider:

Very often, it is useful to think of a series circuit as a voltage divider. The basic idea behind the voltage divider is to assign a portion of the total voltage to each resistor. In Fig 8 (a), suppose that the source voltage is E . By the circuit configuration shown one can divide off any voltage desired (V_{out}), less than the supply voltage E , by adjusting R_1 , R_2 and R_3 .

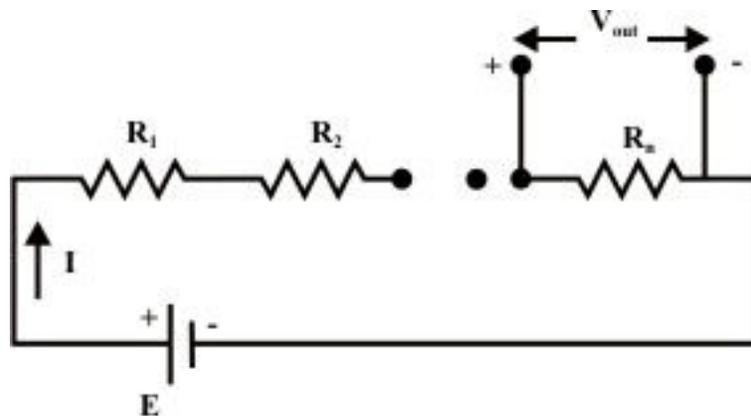


Fig 8(a): Voltage Divider

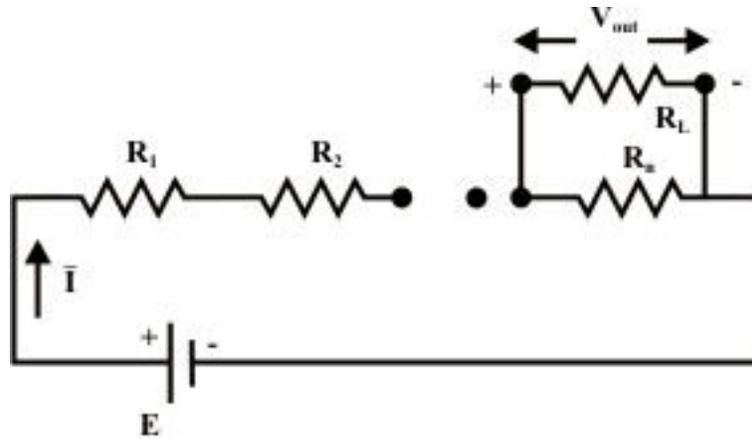


Fig 8(b): Voltage divider with load

From Fig 8(b) the output of the voltage divider V_{out} is computed by the relation:

$$V_{out} = IR_n = \frac{E}{R_1 + R_2 + \dots + R_n} R_n \quad (1)$$

Equation (1) indicates that the voltage across any resistor R_i ($i = 1, 2, \dots, n$) in a series circuit is equal to the applied voltage (E) across the circuit multiplied by a factor

$$R = \frac{R_i}{\sum_{j=1}^n R_j} \quad (2)$$

It should be noted that this expression is only valid if the same current I flows through all the resistors. If a load resistor R_L is connected to the voltage divider (see figure 3.8(b)), one can easily modify the expression (1) by simply combining R_L & R_n in parallel to find a new R_{n-n}^- and replacing R_n by R_{n-n}^- in equation (2).

Example:

For the circuit shown in Figure 9,

(i) Calculate V_{out} , ignoring the internal resistance R_s division. of the source E . Use voltage

(ii) Re calculate V_{out} taking into account the internal resistance R_s of the source.

What percent error was introduced by ignoring R_s in part (i)?

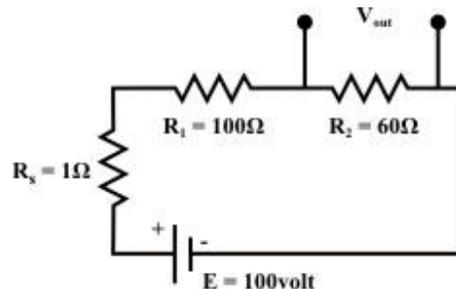


Fig 9: original circuit

Part (i):

From equation (1) the output voltage V_{out} across the resistor R_2

$$R_2 = \frac{E}{R_1 + R_2} \times R_2 = \frac{100}{100 + 60} \times 60 = 37.9V \text{ (when the internal resistance } R_s \text{ of the source is considered zero.)}$$

Similarly, $V_{out} = 37.27$ volt

When R_s is taken into account for calculation

$$\text{Percentage error is computed as } \frac{37.9 - 37.27}{37.27} \times 100 = 1.69\%$$

1.5.2 Current divider:

Another frequently encountered in electric circuit is the current divider. Fig 10 shows that the current divider divides the source current I_s between the two resistors

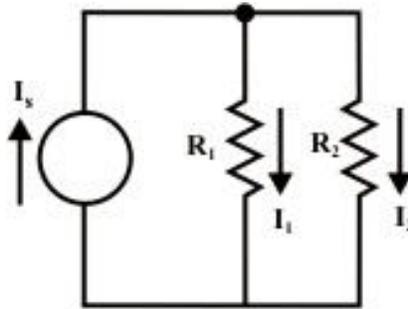


Fig 10: Current divider

The parallel combination of two resistors is sometimes termed as current divider, because the supply current is distributed between the two branches of the circuit. For the circuit, assume that the voltage across the branch is V and the current expression in can be written as:

$$\frac{I_1}{I_S} = \frac{\frac{V}{R_1}}{V\left(\frac{1}{R_1} + \frac{1}{R_2}\right)} = \frac{R_2}{R_1 + R_2} \quad \text{Or } I_1 = \frac{R_2}{R_1 + R_2} \times I_S$$

Similarly, the current flowing through the R_2 can be obtained as

$$I_2 = \frac{R_1}{R_1 + R_2} \times I_S$$

It can be noted that the expression for I_1 has R_2 on its top line, that for I_2 has R_1 on its top line.

Example: L-3.3 Determine $I_1, I_2, I_3,$ & I_5 using only current divider formula when $I_4 = 4A$.

Solution:

When $I_4 = 4A$

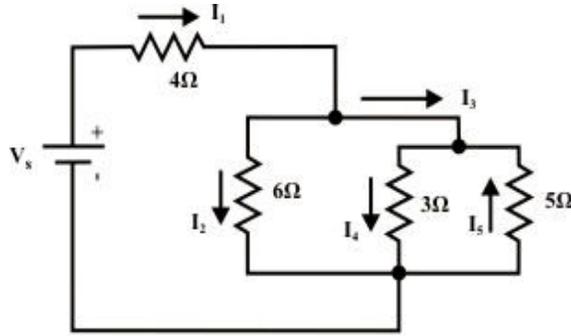


Fig 11: Circuit diagram

Solution:

Using the current division formula we can write

$$I_4 = \frac{5}{5+3} I_3 = \frac{5}{8} I_3 \rightarrow I_3 = \frac{4 \times 8}{5} = 6.4 \text{ A}$$

$$\text{Similarly } -I_5 = \frac{3}{8} I_3 = \frac{3}{8} \times 6.4 = 2.4 \text{ A}$$

$$\text{And we can write } I_3 = \frac{6}{6+(3||5)} I_1 = \frac{6}{6+1.879} I_1 = \frac{6}{7.879} I_1 \rightarrow I_1 = \frac{7.879}{6} \times I_3 = \frac{7.879}{6} \times 6.4 = 8.404 \text{ A}$$

$$\text{Then } I_2 = \frac{1.879}{6+1.879} \times I_1 = \frac{1.879}{7.879} \times 8.404 = 2.004 \text{ A}$$

1.6 Potentiometer and its function:

The potentiometer has a resistance R_p and its wiper can move from top position $x = x_{max}$ to bottom position such that $x = 0$. The resistance R_x corresponds to the position x of the wiper. Potentiometer is same throughout its length. Fig 12 represents a potentiometer whose output is connected to a voltmeter. In true sense, the measurement of the output

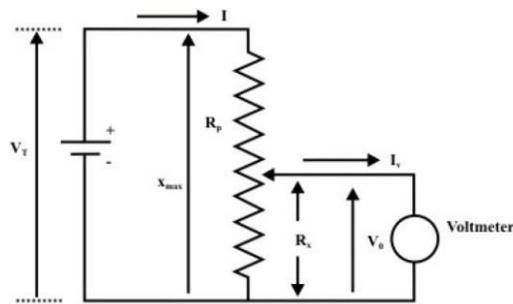


Fig 12: A voltmeter connected across the output terminals of potentiometer

$$\frac{R_x}{x} = \frac{R_p}{x_{max}} \Rightarrow R_x = \left(\frac{R_p}{x_{max}} \right) x$$

voltage V_o with a voltmeter is affected by the voltmeter resistance R_v and the relationship between V_o and x (x = wiper distance from the bottom position) can easily be established. We know that the voltmeter resistance is very high in $M \Omega$ range and practically negligible current is flowing

through the voltmeter. Under this condition, one can write the expression for voltage between the wiper and the bottom end terminal of the potentiometer as

$$V_{out} = (IR_x) = \frac{V_T(= IR_p)}{x_{max}} \times x = V_T \times \frac{x}{x_{max}} = V_{out} = V_T \times \frac{R_x}{R_p}$$

It may be noted that depending on the position of movable tap terminal the output voltage (V_{out}) can be controlled. By adjusting the wiper toward the top terminal, we can increase V_{out} . The opposite effect can be observed while the movable tap moves toward the bottom terminal. A simple application of potentiometer in real practice is the volume control of a radio receiver by adjusting the applied voltage to the input of audio amplifier of a radio set. This audio amplifier boosts this voltage by a certain fixed factor and this voltage is capable of driving the loudspeaker.

Example- L-3.4 A potentiometer has 110 V applied across it. Adjust the position of $500k-R_{bot} \Omega$ such that 47.5 V appears between the movable tap and the bottom end terminal (refer Fig. 12).

Solution-

Since the output voltage (V_{bot}) is not connected to any load, in turn, we can write the following expression

$$V_{out} = V_T \times \frac{x}{x_{max}} \frac{V_{bot}}{V_T} = \frac{R_{bot}}{R_T} \rightarrow R_{bot} = \frac{V_{bot}}{V_T} R_T = \frac{47.5}{110} \times 500000 = 216K\Omega$$

1.7 Practical Voltage and Current Sources

1.7.1 Ideal and Practical Voltage Sources:

- An ideal voltage source, which is represented by a model in Fig. 13, is a device that produces a constant voltage across its terminals ($V = E$) no matter what current is drawn from it (terminal voltage is independent of load (resistance) connected across the terminals)

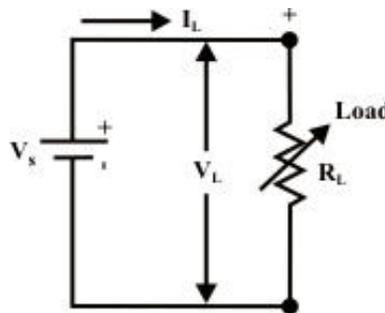


Fig 13: Ideal DC voltage source

For the circuit shown in Fig 13, the upper terminal of load is marked plus (+) and its lower terminal is marked minus (-). This indicates that electrical potential of upper terminal is V_L volts higher than that of lower terminal. The current flowing through the load R_L is given by the expression $V_s = V_L = I_L R_L$ and we

can represent the terminal V – I characteristic of an ideal dc voltage as a straight line parallel to the x-axis. This means that the terminal voltage V_L remains constant and equal to the source voltage V_s , irrespective of load current is small or large. The V – I source is presented in Fig 14.

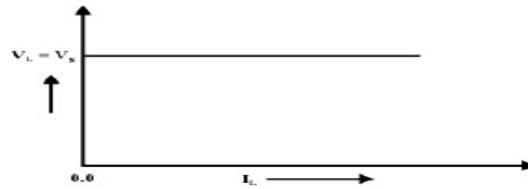


Fig14: VI characteristics if Ideal Voltage Source

However, real or practical dc voltage sources do not exhibit such characteristics (see Fig 14) in practice. We observed that as the load resistance R_L connected across the source is decreased, the corresponding load current I_L increases while the terminal voltage across the source decreases (see eq.1). We can realize such voltage drop across the terminals with increase in load current provided a resistance element (R_s) present inside the voltage source. Fig. 3.15 shows the model of practical or real voltage source of value V_s .

The terminal V – I Equation characteristics of the practical voltage source can be described by an

$$V_L = V_s - I_L R_s \tag{3.1}$$

and this equation is represented graphically as shown in Fig 15. In practice, when a load resistance R_L more than 100 times larger than the source resistance R_s , the source can be considered approximately ideal voltage source. In other words, the internal resistance of the source can be omitted. This statement can be verified using the relation $R_L = 100R_s$ in equation (3.1). The practical voltage source is characterized by two parameters namely known as (i) Open circuit voltage (V_s) (ii) Internal resistance in the source’s circuit model. In many practical situations, it is quite important to determine the source parameters experimentally. We shall discuss briefly a method in order to obtain source parameters.

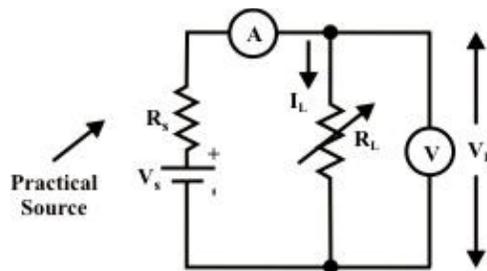


Fig 15: Practical DC voltage source

Method-:

Connect a variable load resistance across the source terminals (see fig. 3.15). A voltmeter is connected across the load and an ammeter is connected in series with the load resistance. Voltmeter and Ammeter readings for several choices of load resistances are presented on the graph paper (see fig.

3.16). The slope of the line is $-R_s$, while the curve intercepts with voltage axis (at $I_L = 0$) is the value of V_s . The $V - I$ characteristic of the source is also called the source's "**regulation curve**" or "**load line**". The open-circuit voltage is also called the "no-load" voltage, V_{oc} . The maximum allowable load current (rated current) is known as full-load current I_{FL} and the corresponding source or load terminal voltage is known as "full-load" voltage V_{FL} . We know that the source terminal voltage varies as the load is varied and this is due to internal voltage drop inside the source. The percentage change in source terminal voltage from no-load to full-load current is termed the "**voltage regulation**" of the source. It is defined as

$$\text{Voltage regulation (\%)} = \frac{V_{OC} - V_{FL}}{V_{FL}} \times 100$$

For ideal voltage source, there should be no change in terminal voltage from no-load to full-load and this corresponds to "zero voltage regulation". For best possible performance, the voltage source should have the lowest possible regulation and this indicates a smallest possible internal voltage drop and the smallest possible internal resistance.

1.7.2 Ideal and Practical Current Sources

- Another two-terminal element of common use in circuit modeling is 'current source' as depicted in Fig 16. An ideal current source, which is represented by a model in Fig 17(a), is a device that delivers a constant current to any load resistance connected across it, no matter what the terminal voltage is developed across the load (i.e., independent of the voltage across its terminals across the terminals).

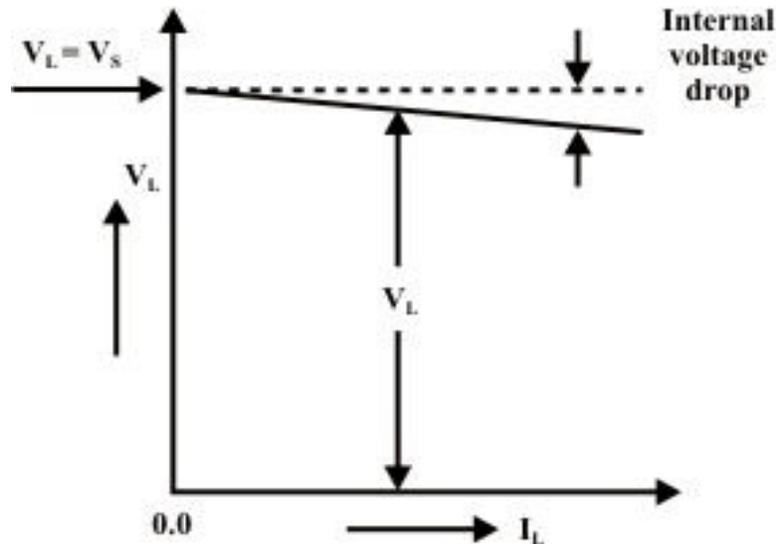


Fig 16: VI characteristic of practical voltage source

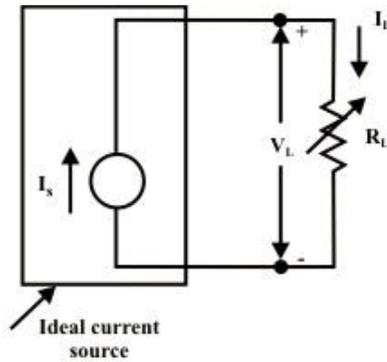


Fig 17(a): Ideal Current source with Variable load

It can be noted from model of the current source that the current flowing from the source to the load is always constant for any load resistance (see Fig 17(a)) i.e. whether R_L is small (V_L is small) or R_L is large (V_L is large). The vertical dashed line in fig. 3.18 represents the $V - I$ characteristic of ideal current source. In practice, when a load R_L is connected across a practical current source, one can observe that the current flowing in load resistance is reduced as the voltage across the current source's terminal is increased, by increasing the load resistance R_L . Since the distribution of source current in two parallel paths entirely depends on the value of external resistance that connected across the source (current source) terminals. This fact can be realized by introducing a parallel resistance R_s in parallel with the practical current source I_s , as shown in fig. 3.17(b). The dark lines in fig. 18 show the $V-I$ characteristic (load-line) of practical current source. The slope of the curve represents the internal resistance of the source. One can apply KCL at the top terminal of the current source in fig. 17(b) to obtain the following expression.

$$I_L = I_s - \frac{V_L}{R_s} \text{ or } V_L = I_s R_s - I_L R_s = V_{OC} - I_L R_s$$

The open circuit voltage and the short-circuit current of the practical current source are given by

$$V_{oc} = I_s R_s \text{ and } I_{short} = I_s$$

Respectively. It can be noted from the Fig 17(b) that source 1 has a larger internal resistance than source 2 and the slope the curve indicates the internal resistance R_s of the current source. Thus, source 1 is closer to the ideal source. More specifically, if the source internal resistance $R_s \geq 100 R_L$ then source acts nearly as an ideal current source.

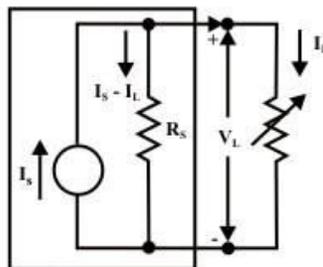


Fig 17(b): Practical Current source with Variable load

1.7.3 Conversion of a Practical Voltage Source to a Practical Current source and vice-versa:

Voltage Source to Current Source

For the practical voltage source in fig. 19(a), the load current is calculated as

$$I_L = V_s / (R_s + R_L) \quad (3)$$

Note that the maximum current delivered by the source when circuit condition is given by $I = V/R$ expression for load current as

$$I_L = \frac{I_s * R_s}{R_s + R_L}$$

1.8 Independent and Dependent Sources that encountered in electric circuits:

➤ Independent Sources

So far the voltage and current sources (whether ideal or practical) that have been discussed are known as independent sources and these sources play an important role to drive the circuit in order to perform a specific job. The internal values of these sources (either voltage source or current source) – that is, the generated voltage V_s or the generated current I_s (see Fig 15 & 17) are not affected by the load connected across the source terminals or across any other element that exists elsewhere in the circuit or external to the source.

➤ Dependent sources

Another class of electrical sources is characterized by dependent source or controlled source. In fact the source voltage or current depends on a voltage across or a current through some other element elsewhere in the circuit. Sources, which exhibit this dependency, are called dependent sources. Both voltage and current types of sources may be dependent, and either may be controlled by a voltage or a current.

In general, dependent source is represented by a diamond (\diamond)-shaped symbol as not to confuse it with an independent source. One can classify dependent voltage and current sources into four types of sources as shown in fig.21. These are listed below:

- (i) Voltage-controlled voltage source (VCVS)
- (ii) Current-controlled voltage source (ICVS)
- (iii) Voltage-controlled current source (VCIS)
- (iv) Current- controlled current source (ICIS)

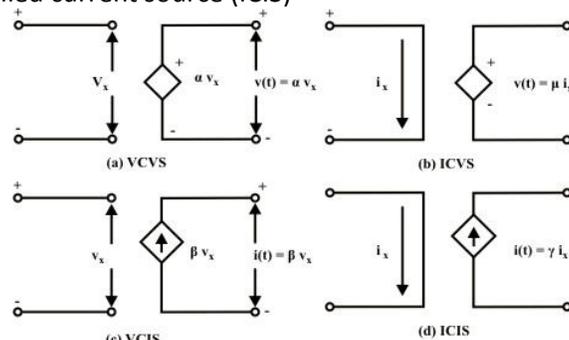


Fig 21: Ideal dependent (controlled) Source