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MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH

M'HAMED BOUGARA UNIVERSITY– BOUMERDES

Faculty of Technology

Electrical Systems Engineering Department

Course Handout

For L2 students: License LMD & Engineering

Major: Electrical Engineering groups-ST

Fundamental Electronic 1

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Course description

Electronics can be classified into two primary categories according to their functions: analogue and digital. They employ several techniques for signal processing and transmission, in addition to measurement and control. In contrast to digital circuits, which operate with discrete values that alternate between two states (often 0 and 1), analogue circuits utilize continuous or alternative currents and voltages that vary over time.

The course handout "Fundamental Electronic 1" includes the analogue electronics component and reflects the culmination of sixteen years of presenting analogue electronics program at Boumerdes University's Faculty of Technology.

This course material is developed in accordance with the course outline established by the National Pedagogical Committee of the Science and Technology Domain (CPND-ST) and is designed for second-year students in the LMD license and engineering program for the electrical engineering group, domain Sciences and Technology (ST). This program aims to familiarize students with the field of electronics, providing to both beginners and those seeking to enhance their comprehension of electronic principles.

Upon completion of the handout, you will possess a solid understanding of fundamental electrical principles and be equipped to explore more difficult topics in subsequent educational years. Furthermore, it is essential to remember that the analysis of electronic circuits demands extensive study and extra practice.

The course is structured into five chapters. In this handout, we will explore key concepts such as fundamental theorems for electronic circuit analysis and two-port networks. We will also introduce the essential electronic components like diode, transistor, and operational amplifier.

The **first chapter** examines the fundamental theorem for electronic circuit analysis, beginning with the Kirchhoff law. Moreover, profound theorems such as Superposition, Thevenin, Millman, and Norton are thoroughly examined using pertinent application examples.

The **second chapter** focuses on two-port networks and passive filters, discussing their properties, parameters, and representations and providing mathematical expressions for these representations. The second part explores passive filters, including high-pass and low-pass filters, their properties, frequency responses, and connection configurations.

The **third chapter** will delve into the operation mechanisms, characteristic curves, and applications of the diode.

In the **fourth chapter**, we will describe the bipolar transistor, studying its properties and operating modes, and then we will analyze its usage and applications.

In the **final chapter**, we will examine operational amplifiers (OAs), beginning with their schematic symbol, analyzing their principal characteristics, and investigating their diverse applications.

The handout includes an appendix at the end, representing the module content according to the CPND-ST framework proposed in 2018/2019.

Chapter 1: Fundamental circuit theorems

1. Introduction

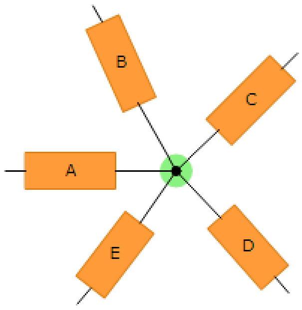
In this chapter, the concept of the most common circuit elements, either active or passive, is introduced, including their associations. The fundamental theorem for electronic circuit analysis is explored, starting with the Kirchhoff law. Furthermore, crucial theorems such as Superposition, Thevenin, Millman, and Norton's will be thoroughly examined using practical applications.

1. Circuit terminology

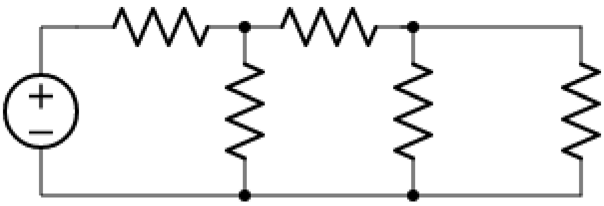
Some basic terminologies in the field of electronics will be given in this section:

- Circuit: An electrical current flows through a closed loop conducting path that is known as a circuit.
    - Closed circuit: A circuit is considered closed when all currents have a path back to their original source and the circle is complete.
    - Open circuit: A circuit is considered open when there is a path gap or opening, indicating that the circle is not entirely complete.
    - Short circuit: A short circuit occurs when a component is unintentionally linked to a low- resistance.
- **Elements:** Sources and components are considered elements.
    - Sources deliver energy to a circuit. There are two fundamental categories.
        - Voltage sources
        - Current sources
    - Components: two fundamental categories of components exist (active and passive components), and each has a unique voltage-current relationship.
        - Passive components: Resistor, Capacitor, and Inductor
        - Active components: Transistor, Operational amplifier, …
- **Path**: A path is a single line that joins sources with other elements.

- **Node:** A node is a junction, connector, or terminal that serves as a connection point between two or more branches of a circuit when two or more circuit elements are brought together. Dots are used to represent nodes.

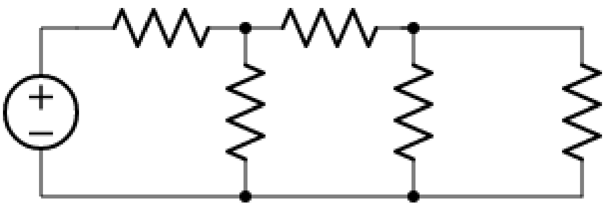


Question: How many nodes are in this circuit? (4)



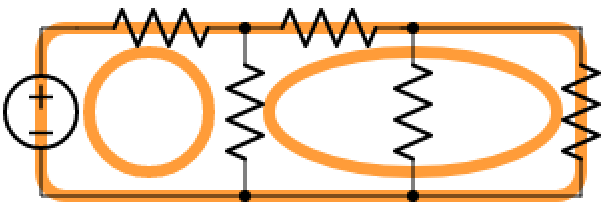
- **Branch :** A branch refers to a single or a collection of parts, like resistors or sources, that are connected between two nodes.

Question: How many branches are in this circuit? (6)



- **Loop**: In a circuit, a loop is a closed path where no node or circuit part is met more than once. Any node can be used as the starting point for a loop; then, draw a path through other nodes and elements until it returns to the original node.

Question: How many loops are in this schematic? (6)



- **Mesh**: A mesh consists of a single path that has a closed loop and no other paths. In addition, a mesh does not contain any loops. Kirchhoff's voltage law, on the other hand, controls mesh analysis.

- **Reference Node** : During circuit analysis, we normally designate one of the nodes in the circuit to be the reference node. Measurements of voltage at other nodes are made in relation to the reference node. Although any node can serve as the reference, two popular options that make circuit analysis easier are,
  - ✓ the negative terminal of the voltage or current source powering the circuit or
  - ✓ the node connected to the greatest number of branches.
- **Ground** : It is common to refer to the reference node as "ground." You'll encounter a variety of symbols for ground as depicted in the figure below:

Figure 1. 1: Ground symbol

- **DC and AC sources:** AC sources exhibit time-varying voltage or current supply, denoted by lowercase letters and usually containing indications of time dependency. Voltage or current supplied by DC sources remains constant and is denoted by excluding any explicit temporal dependence and using uppercase letters.

2. Basic circuits elements

In electrical circuits, there are two kinds of elements: active and passive. In contrast to a passive element, an active element can produce energy.

2.1. Passive elements

A passive element dissipates energy only. Resistors, capacitors, and inductors are the three fundamental passive circuit elements used in electric circuits.

2.1.1. Resistor

A resistor is a passive electrical component with two terminals that is used to implement electrical resistance in circuits. Within circuits, resistors lower voltage levels and minimize current flow. Several resistors are frequently used in circuits to restrict the flow of charges within them.

The symbol of this element is depicted in the Figure below:

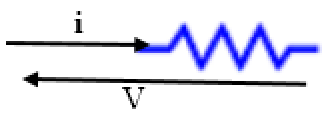


Figure 1. 2: Resistor symbol

Conductance, denoted by the symbol G and measured in Siemens [S], is the reciprocal of resistance. Conductance represents the degree of allowed flow of electric current through a specific component.

$$G = \frac{1}{R}[S] \tag{1.1}$$

2.1.2. Capacitor

A capacitor is an electrical circuit element that can store electrical energy in the form of an electric field. The property of the capacitor by virtue of which it stores electrical energy is known as **capacitance**. The symbol of this element is depicted in the Figure below:

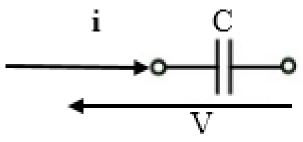


Figure 1. 3: Capacitor symbol

The current in a capacitor can be expressed as follows:

$$i = C\frac{dV}{dt} \tag{1.2}$$

2.1.3. Inductor

A finite-length wire coiled into a coil is the basic form of an inductor. Another fundamental circuit component that adds inductance to an electrical or electronic circuit is an inductor. The inductor possesses an attribute called inductance. That is used in most power electronic circuits to store energy in the form of magnetic energy when electricity is applied to it.

The circuit symbol of a typical inductor is depicted in the following illustration.

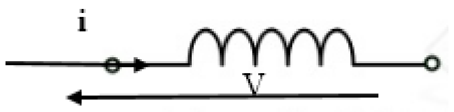


Figure 1. 4: Inductor symbol

Given an inductor “L”, the voltage across it is equal to:

$$v = L\frac{di}{dt} \tag{1.3}$$

2.2. Active elements

Such as voltage source and current source.

2.2.1. Voltage sources

A voltage source is an active component of a circuit that, generates a constant voltage. However, the required voltage between the terminals of real or practical voltage sources decreases as the load current it supplies increases.

The two popular symbols for constant voltage sources are depicted in the figure below:

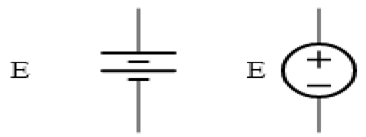


Figure 1. 5: Voltage source symbol

2.2.2. Current sources

A current source can provide a circuit with a constant supply of current independent of the voltage that evolves across its terminals.

A current source is represented by these two typical symbols, in which the direction of positive current flow is shown by the arrow.

Figure 1. 6: Current sources symbol

3. Circuit elements association

Equivalent circuit components can be coupled for easier and more efficient circuit analysis. Element associations can be in series or in parallel. We can group the elements to simplify the analysis of circuits:

3.1. Serial Association

When two circuit elements are arranged in a sequential manner meaning both components are linked in series and share one common terminal that is not shared with any other circuit component.

The same current flows through both parts when they are connected in series, even though the voltage in each will often vary.

In the series circuits, we have:

1) The same current flows through each resistance :$I_1 = I_2 = \cdots = I_N = I$

2) The supply voltage **V** is the sum of the individual voltage drops across the resistances:$V = V_1 + V_2 + \cdots + V_N$

3.1.1. Resistors in series

Consider the resistances shown in the figure below.

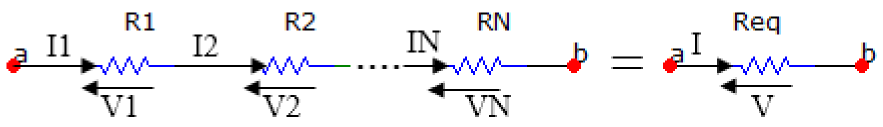


Figure 1. 7: Resistors in series

The total or equivalent resistance of the series circuit is the arithmetic sum of the resistances connected in series.

The equivalent resistor of N resistances connected in series is given by the following equation:

$$R_{eq} = R_1 + R_2 + R_3 + \cdots + R_N = \sum_{n=1}^{N} R_n \tag{1.4}$$

3.1.2. Capacitor in series

Capacitances in series combine like resistors in parallel.

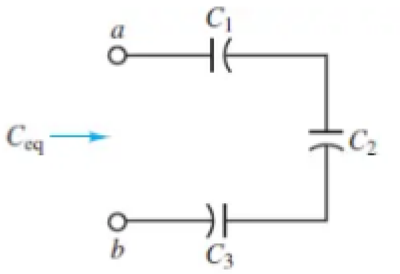


Figure 1. 8: Capacitance in circuit with series capacitors

The equivalent capacitance of capacitors connected in series is given by :

$$C_{eq} = \frac{1}{\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}} \quad (1.5)$$

3.1.3. Inductor in series

Consider the connection below:

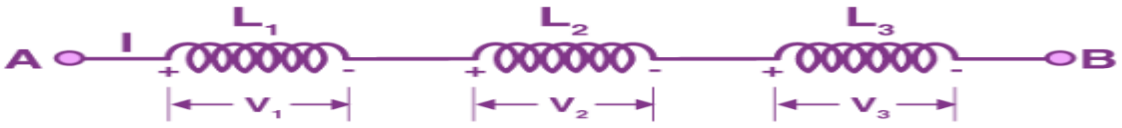


Figure 1. 9: Inductors in series

The following formula yields the equivalent inductance of inductors connected in series:

$$L_s = L_1 + L_2 + L_3 + \cdots + L_n \quad (1.6)$$

3.1.4. Voltage sources in series

It is always possible to associate two voltage sources in series, without considering their values. Their connection is comparable to a single source whose voltage is the algebraic sum of each of the voltage.

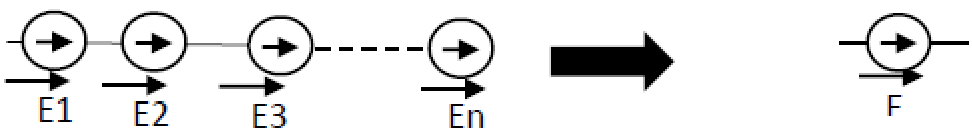


Figure 1. 10: Voltage sources in series

$$E = E_1 + E_2 + E_3 + \cdots + E_n \quad (1.7)$$

3.2. Parallel Association

When two components of a circuit share two terminals, they are linked in parallel. Then the current passing through each of them will generally be different. While the voltage in each element is the same.

3.2.1. Resistor in parallel

Examine the parallel circuit depicted in the opposite figure.

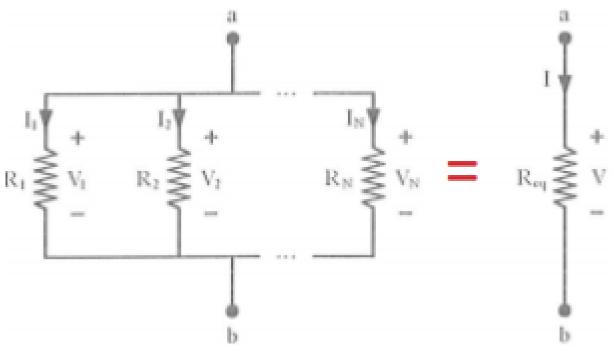


Figure 1. 11: resistors in parallel

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots + \frac{1}{R_N} = \sum_{n=1}^{N} \frac{1}{R_N} \tag{1.8}$$

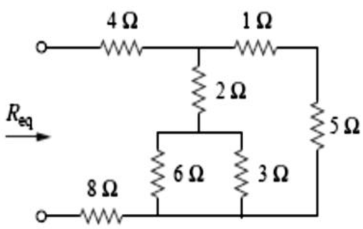
Keep in mind that **Req** is always less than the smallest resistors in the parallel combination.

$$\begin{cases} V_1 = V_2 = \cdots = V_N \\ I_1 + I_2 + \cdots + I_N = I \end{cases}$$

3.2.1.1. Example

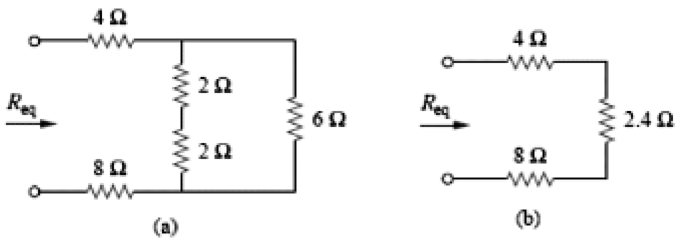
We consider the circuit in the figure opposite:

- Calculate the equivalent resistance **Req**.



3.2.1.2. Solution

The value of Req= ?



$Req = (4 + 2.4 + 8) = 14.4\Omega$

3.2.2. Capacitor in parallel

Capacitances in parallel combine like resistors in series.

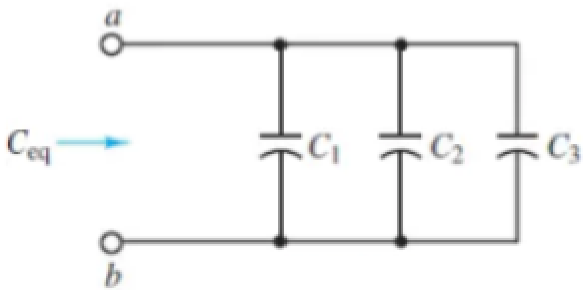


Figure 1. 12: Equivalent capacitances in circuit with parallel capacitors

When capacitors are connected in parallel, their equivalent capacitance is determined by:

$$C_P = C_1 + C_2 + C_3 + \cdots C_N \quad (1.9)$$

3.2.3. Inductor in parallel

Consider the example below:

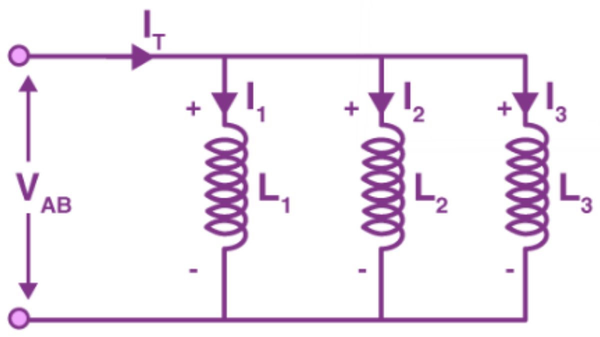


Figure 1. 13: Inductors in parallel

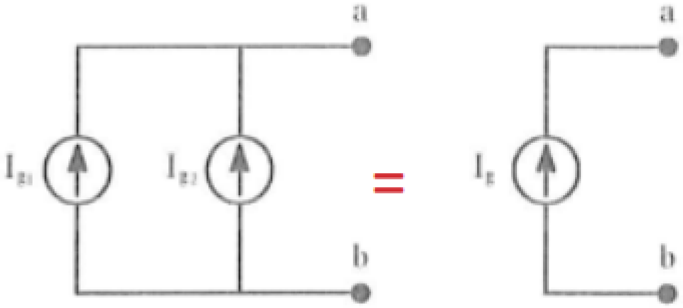
The following formula yields the equivalent inductance of inductors connected in parallel:

$$\frac{1}{L_P} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \cdots + \frac{1}{L_N} \quad (1.10)$$

If inductors are joined in parallel form, their effective inductance drops. Inductors in parallel are almost identical to the capacitors in series.

3.2.4. Current sources in parallel

Regardless of their current values, two current sources can be connected in parallel. The parallel of two current sources results in a single current source whose current value is equal to the algebraic sum of each of the currents.



$$I_g = I_{g1} + I_{g2}$$

Figure 1. 14: Current sources in parallel

3.3. Series-parallel circuits

A configuration that consists of both series and parallel parts is called a series-parallel configuration. When elements are not arranged in series or parallel, the configuration is considered complicated.

3.4. Kennelly theorem

Kennelly theorem is a situation that frequently raised in circuit analysis when the resistors are neither in parallel nor in series.

The delta (Δ) interconnection is also referred to as Pi interconnection & the wye (Y) interconnection is also referred to as Tee (T) interconnection.

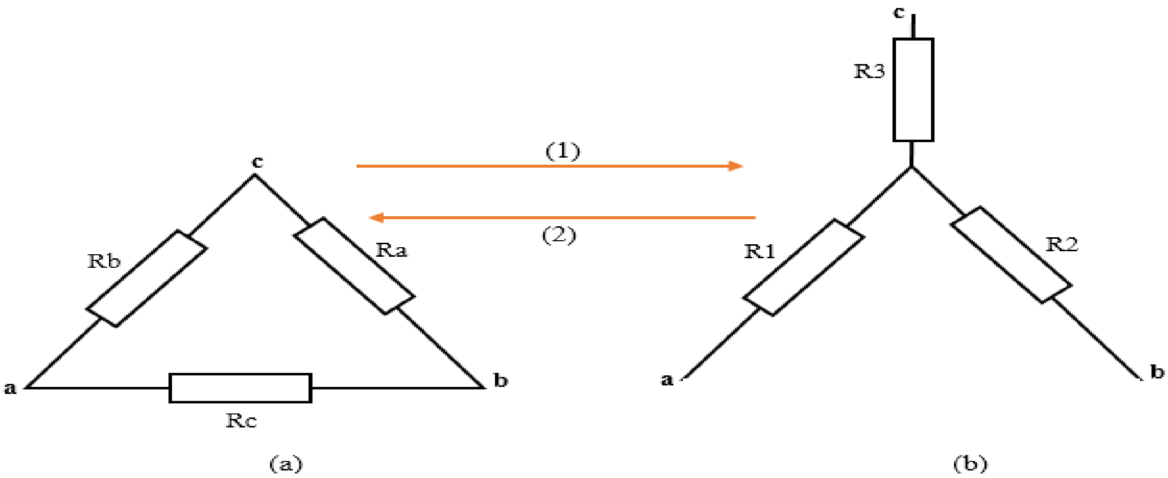


Figure 1. 15: Kennelly representation : a) Δ representation ; b) Y representation

The relationship between the resistances in **Y** and Δ configurations are given by the following formulas:

Case 1: Convert Delta (Δ) to Wye (Y-network) interconnection, we can get:

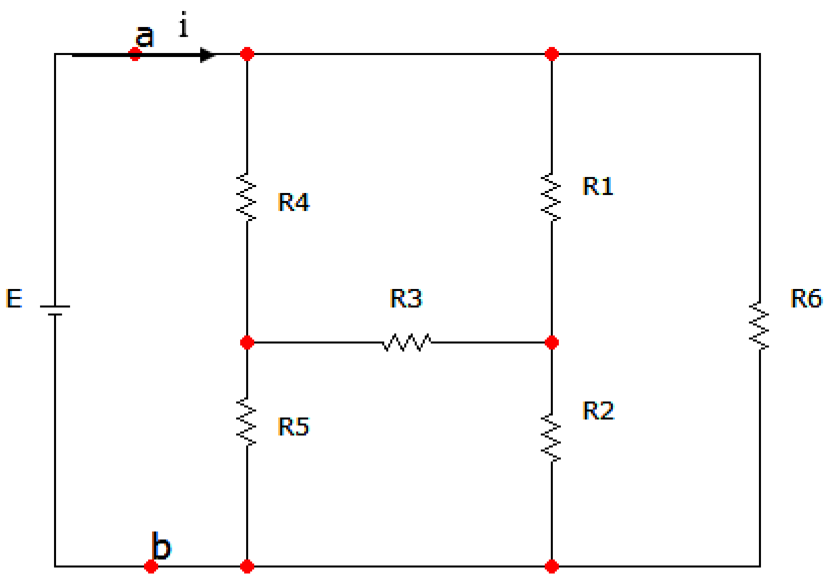
$$\begin{cases} R_1 = \frac{R_b R_c}{R_a + R_b + R_c} \\ R_2 = \frac{R_a R_c}{R_a + R_b + R_c} \\ R_3 = \frac{R_b R_a}{R_a + R_b + R_c} \end{cases} \tag{1.11}$$

Case 2: Convert Wye (Y-network) to Delta (Δ) interconnection, we can get:

$$\begin{cases} R_a = \frac{R_1 R_2 + R_2 R_3 + R_3 R_1}{R_1} \\ R_b = \frac{R_1 R_2 + R_2 R_3 + R_3 R_1}{R_2} \\ R_c = \frac{R_1 R_2 + R_2 R_3 + R_3 R_1}{R_3} \end{cases} \tag{1.12}$$

3.4.1. Example

Consider the following circuit:



Given: E=120V; R1=10Ω;R2=20Ω;R3=5 Ω; R4=12.5Ω;R5=15Ω;R6=30Ω .

1) Using Kennelly theorem, find the equivalent resistance **Rab**.
2) Calculate the current **i.**

3.4.2. Solution

1) The resistance Rab=?

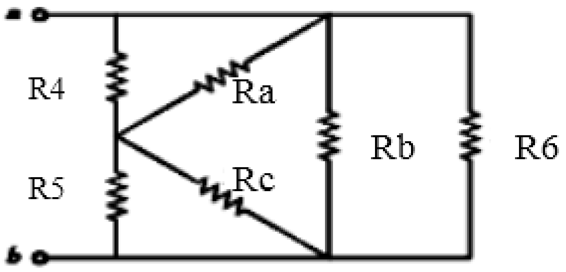
Using Kennelly theorem, we can convert the Y-network defined by R1, R2, and R3 with using equation (1.12), we can get:

$$R_a = \frac{R_1R_2 + R_2R_3 + R_3R_1}{R_1}$$
$$R_b = \frac{R_1R_2 + R_2R_3 + R_3R_1}{R_2}$$
$$R_c = \frac{R_1R_2 + R_2R_3 + R_3R_1}{R_3}$$

N.A:

$$R_a = \frac{10 \times 20 + 20 \times 5 + 5 \times 10}{10} = 35\Omega$$
$$R_b = \frac{10 \times 20 + 20 \times 5 + 5 \times 10}{20} = 17.5\Omega$$
$$R_c = \frac{10 \times 20 + 20 \times 5 + 5 \times 10}{5} = 70\Omega$$

The equivalent circuit is depicted in the figure below:



hence, we find :

$Rab \; = \; [R4//Ra + R5//R6]//[Rc//R6]$

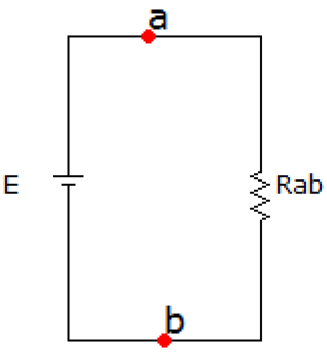
N.A:

$Rab \; = \; [12.5//17.5 + 15//35]//[70//30] =$

$Rab = 6.632\Omega$

2) The current i=?

The equivalent circuit is depicted in the opposite figure:



By applying Ohm's law, we can get:

$$i = \frac{vs}{Rab} = \frac{120}{9.632} = 12.458A$$

4. Ideal and real sources

An ideal source is a theoretical concept that represents an idealized behavior of a source. An ideal source has no internal resistance or impedance and can provide infinite power to the circuit.

4.1. Ideal voltage and current sources

Ideal sources have no internal resistance or impedance and can provide infinite power to the circuit.

4.1.1. Ideal voltage sources

An ideal voltage source maintains a constant voltage across its terminals regardless of the load impedance or current.

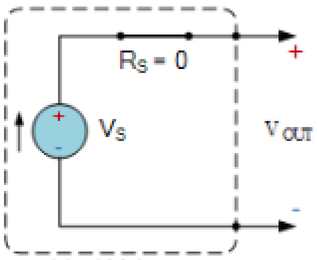


Figure 1. 16: Ideal Voltage source

4.1.2. Ideal current sources

An ideal current source keeps the current flowing through its terminals constant, independent of the voltage or load impedance.

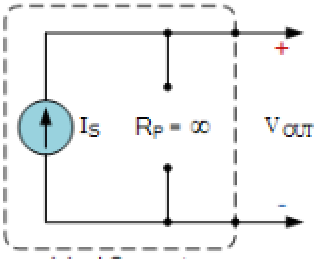


Figure 1. 17: Ideal current source

4.2. Real voltage and current sources

Real sources have some internal resistance or impedance and can provide limited power to the circuit.

4.2.1. Real voltage sources

It is composed of a current generator in series with an internal resistance r.

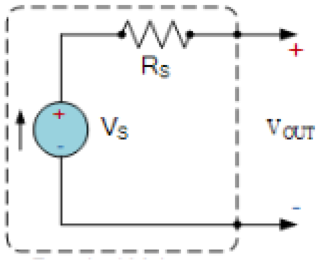


Figure 1. 18: Real voltage source

4.2.2. Real current sources

It is composed of a current generator in parallel with an internal resistance r.

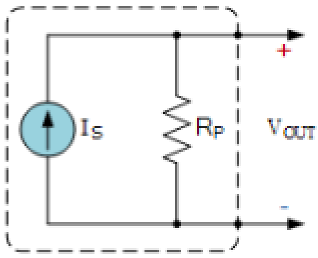


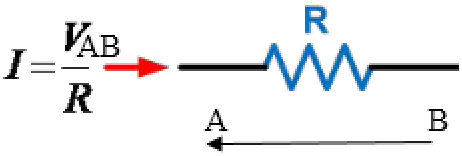
Figure 1. 19: Real current source

5. Basic laws

The basic laws consist of several distinct laws, concepts, and definitions. These involve Ohm's law and Kirchhoff's law, which specify how current, voltage, and resistance are related.

5.1. Ohm's law

The principle of Ohm's law declares: that the electrical current flowing through any conductor is proportional to the potential difference (voltage) at its ends, given the physical conditions of the conductor do not vary.



$$Current\ (I) = \frac{Voltage\ (V)}{Resistance\ (R)}\ in\ Amperes\ [A] \qquad (1.13)$$

Where I refers to electrical current flowing through the resistor R, and V represents Voltage drop of the resistor, and R is the value of the resistance measured in Ohms (Ω).

5.2. Kirchhoff’s laws

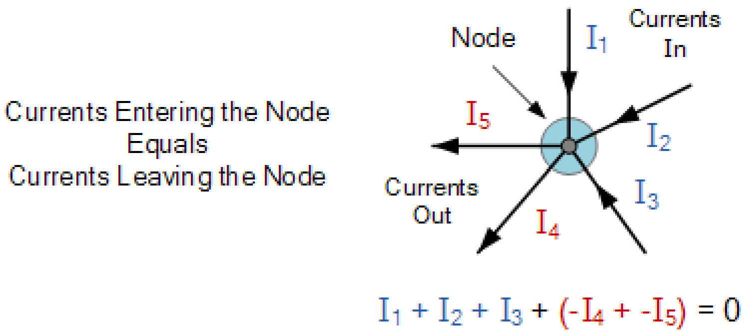
One of the simplest methods to analyze a r circuit is to apply Kirchhoff's laws to the circuit. Kirchhoff's laws are two rules:

5.2.1. Kirchhoff’s current law (KCL)

The Kirchhoff current law (KCL) states that the algebraic total of the electrical current flowing through a circuit's common node is equal to zero. It can be given by the equation below:

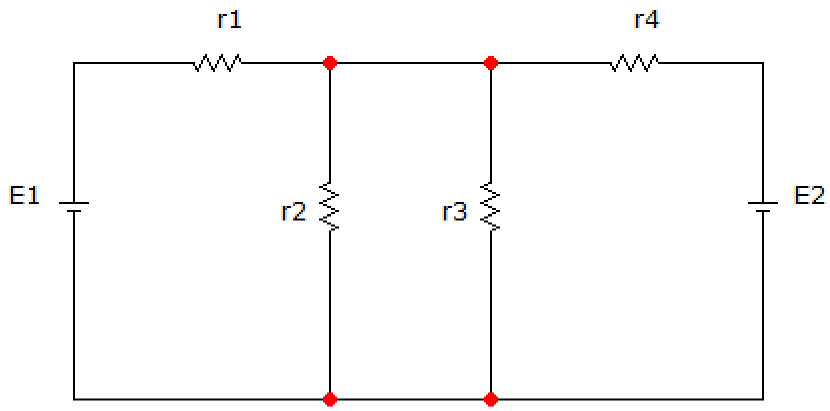
$$\sum I_{in} = \sum I_{out} \qquad (1.14)$$

Giving a positive sign to a current that enters a node necessitates that we provide a negative sign to one that gets out and the opposite is true.



5.2.1.1. Example

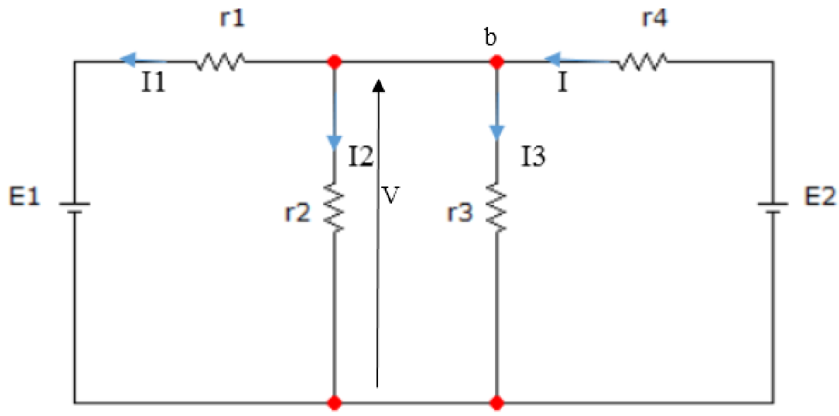
Using the Nodal KCL method, find the current through resistor R_2.



Given: E1=50V; E2=20V; r1=20Ω; r2=100Ω; r3=120Ω; r4=30Ω.

5.2.1.2. Solution

Let us redraw the circuit with naming nodes and branch currents as shown in the figure below:



At node "b", $I = I1 + I2 + I3$

From the aforementioned figure, we derive

$$\frac{E2 - v}{r4} = \frac{v - E1}{r1} + \frac{v}{r2} + \frac{v}{r3}$$

Or

$$\frac{E2 - 20}{30} + \frac{v - 50}{20} + \frac{v}{100} + \frac{v}{120} = 0$$

$v = 31.18V$

The current through $I2 = \frac{V}{r2} = \frac{31.18}{100} = 311.8mA$.

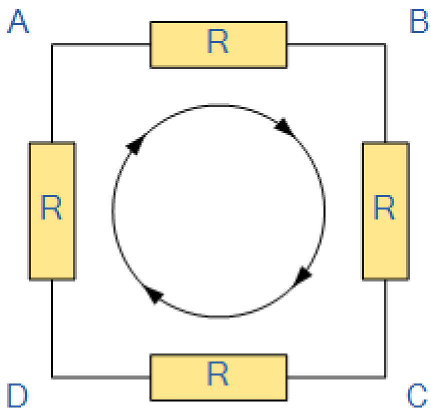
5.2.2. Kirchhoff's voltage law (KVL)

KVL Rule: The sum of voltages around a closed loop circuit is equal to zero.

$$\sum_{k=1}^{n} V_k = 0 \qquad (1.15)$$

Kirchhoff's law of tensions requires that each loop have an algebraic sign or reference direction. As we follow a closed path, every tension will manifest in the loop as either an increase or a decrease in the direction of the loop's displacement.

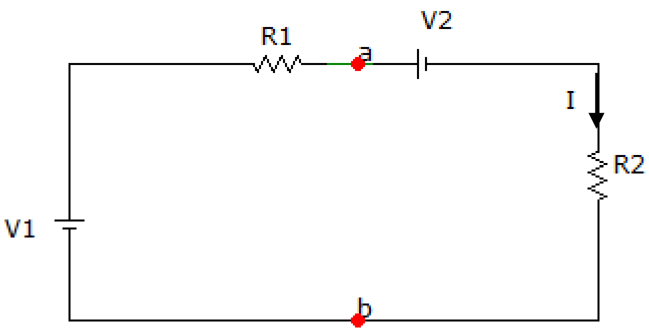
Within a circuit, you can write as many distinct equations as there are loops in the circuit. However, only some of them will be independent (defined by the number of loops).



Using KVL we obtain: $V_{AB} + V_{BC} + V_{CD} + V_{DA} = 0$

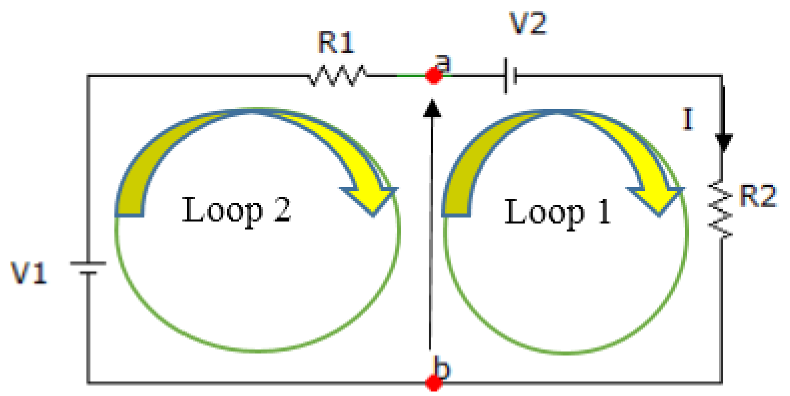
5.2.2.1. Example

Using KVL, find the current I and the voltage Vab in the following circuit.



Given: R1=80KΩ; R2=40KΩ; V1=6V; V2=12V.

5.2.2.2. Solution



1)The current I=?

Using KVL, we find: $V1 - V2 = (R1 + R2)I \qquad \Rightarrow I = \frac{V1-V2}{(R1+R2)}$

NA: $I = \frac{6-12}{40+80}$**= -0.05mA**

2) the voltage Vab=?

Using KVL, we find:

Loop 1: $Vab = V2 + R2.I$

Loop 2: $Vab = V1 - R1.I$

NA:

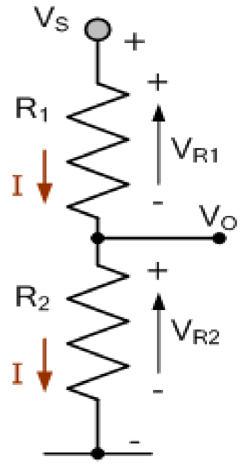
Vab=12+40×(-0.05)=10V

Vab=6-80×(-0.05)=10v

6. Voltage and current circuit dividers

A connected series circuit functions as a voltage divider as it divides the entire supply voltage into distinct voltages across the circuit elements. As the whole circuit current is divided among all of its branches, a parallel circuit serves as a current divider.

6.1. Voltage dividers



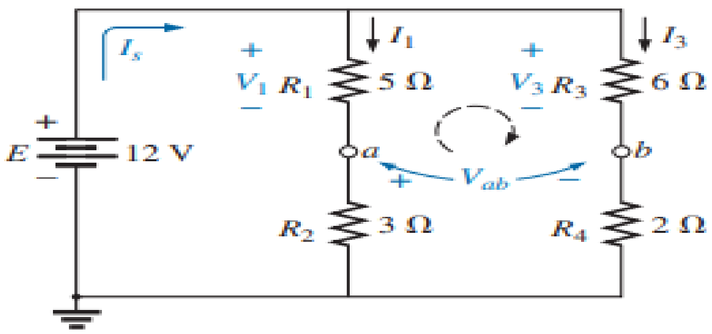
While the current flowing through every component in a series circuit is the same, voltage divider circuits are used to generate various voltage levels from a single voltage source.

$$V_{R1} = V_S(\frac{R_1}{R_1+R_2}) \quad (1.16)$$

$$V_{R2} = V_S(\frac{R_2}{R_1+R_2}) \quad (1.17)$$

6.1.1. Example

Consider the network presented in the figure below.



1) Using Kirchhoff voltage law (KVL), find the voltages V1, V3, and Vab.

6.1.2. Solution

1) The voltage V1, V3, and Vab.

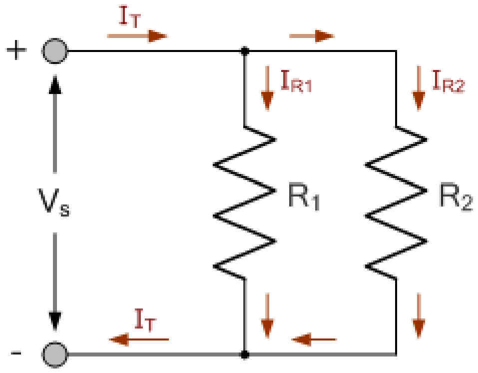
Using voltage divider:

$$\begin{cases} V1 = \dfrac{R1}{R1+R2} \times E = \dfrac{2}{5+3} \times 12 = 7.5V \\ V3 = \dfrac{R3}{R3+R4} \times E = \dfrac{6}{6+2} \times 12 = 9V \end{cases}$$

By using Kirchhoff voltage law, we obtain

$$vab + v1 - v3 = 0 \Rightarrow vab = v3 - v1 = 9 - 7.5 = 1.5V$$

6.2. Current dividers



Current Divider circuits allow currents to pass across two or more parallel branches, but each component in the parallel circuit has the same voltage.

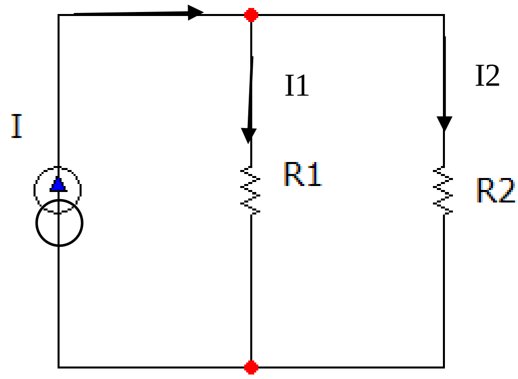
$$I_{R1} = I_T(\frac{R_2}{R_1+R_2}) \quad (1.18)$$

$$I_{R2} = I_T(\frac{R_1}{R_1+R_2}) \quad (1.19)$$

6.2.1. Example

Consider the following circuit:

- Calculate the currents I1 and I2.



Given: I= 20A; R1=5Ω; R2=10Ω.

6.2.2. Solution

The current flowing through resistor R1 is, according to the current divider rule:

$$I_1 = I \times (\frac{R_2}{R_1 + R_2})$$

N.A:

$$I_1 = 20 \times \left(\frac{10}{10 + 5}\right) = 13.33A$$

The current through a resistor R2, will be calculated as follow:

$$I_2 = I \times (\frac{R_1}{R_1 + R_2})$$

N.A:

$$I_2 = 20 \times \left(\frac{5}{10 + 5}\right) = 6.67A$$

7. Fundamental theorem’s

Electric circuit theorems are usually important to finding voltage and currents in multi-loop circuits. These theorems investigate basic electrical or electronic parameters, such as voltages, currents, resistance, and so forth, using fundamental mathematical laws, formulas, and equations. These foundational theorems comprise the standard theorems such as the Millman, Norton, Thevenin, and Superposition theorems.

7.1. Superposition theorem

Among the theorems that apply to both DC and AC networks, the most basic one is superposition. The theorem is suitable for networks that consist of numerous sources dispersed among several nodes.

Superposition is the mathematical equation that expresses the voltage across an element in a linear circuit as the total of the voltages across that element resulting from each of the independent sources operating separately.

Superposition enables the analysis of a linear circuit with many independent sources by determining the individual contributions of each source.

In the following, we will explore how to put the superposition principle into practice:

1) Shut down all independent sources except one source. Determine the output (voltage or current) resulting from the active source.

2) Repeat the step one for each of the remaining independent sources.

3) Determine the overall contribution by summing all contributions from independent sources.

Note:

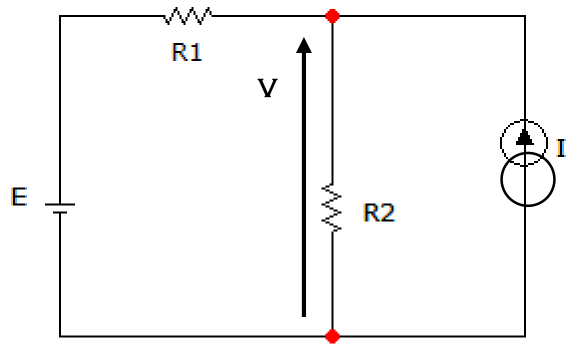
- In Step 1, it is necessary to substitute each voltage source with 0 V (indicating a short circuit) and each current source with 0 A (indicating an open circuit).

- Dependent sources remain intact as they are under the control of others.

7.1.1. Example

We consider the following circuit,

Find the voltage V across R2 by using the superposition theorem.

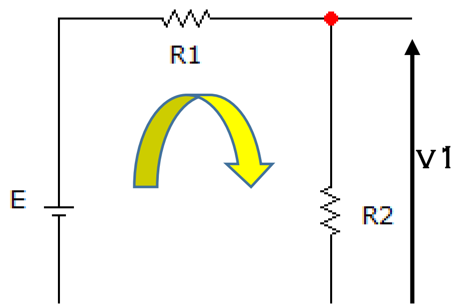


Given: E=6V; I= 3A; R1=8Ω; R2=4Ω.

7.1.2. Solution

The voltage V =? by using the superposition theorem

Case 1: Current source is discarded (open circuit)



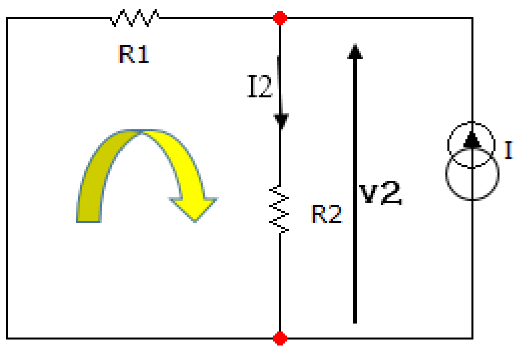
Using the voltage divider:

$$v1 = \frac{R2}{R2 + R1} \times E$$

N.A:

$$v1 = \frac{4}{4+8} \times 6 = 2V$$

Case 2: Voltage source is discarded (short circuit)



by applying the current divider:

$$I2 = \frac{R1}{R2 + R1} \times I$$

N.A:

$$i2 = \frac{8}{4+8} \times 3 = 2A$$

Then, $v2 = R2 \times I2 = 4 \times 2 = 8V$

At the end: $v = v1 + v2$

NA: $V = 2 + 8 = 10V$

7.2. Thevenin's theorem

The statement indicates that an equivalent circuit with a voltage source VTh connected in series with a resistor RTh can take the place of a linear two-terminal circuit.

- VTh: The voltage at terminal “**ab**” for an open circuit is called VTh. (disconnect RL)
- RTh: The input or equivalent resistance at the terminal “**ab**” when the independent sources are turned off.

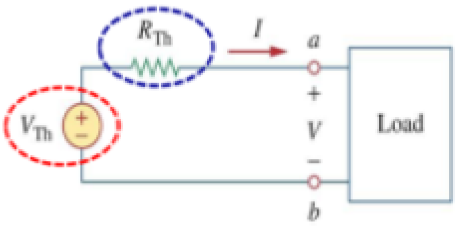


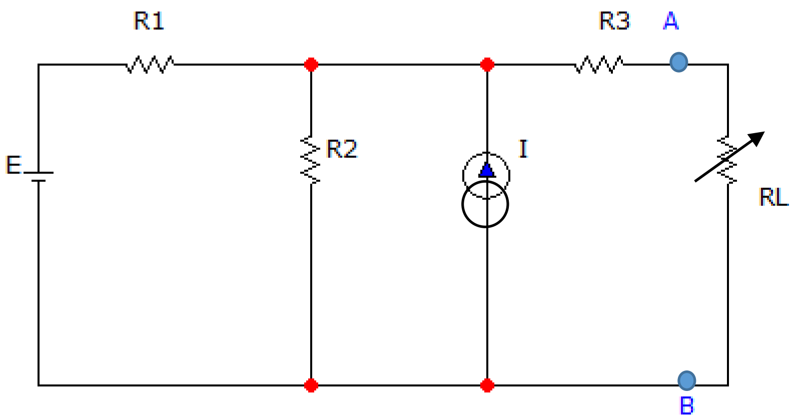
Figure 1. 20: Thevenin equivalent circuit

To find the equivalent resistance RTh:

- Case 1: All independent sources are turned off if there are no dependent sources on the network. The network's input resistance measured between terminals **“a”** and **“b”** is denoted by RTh.
- Case 2: If there are dependent sources on the network. Dependent sources are not to be shut off since they are regulated by circuit variables.

7.2.1. Example

Consider the following circuit:



Given: E=32V; I=2A; R1=4Ω;R2=12 Ω;R3=1 Ω.

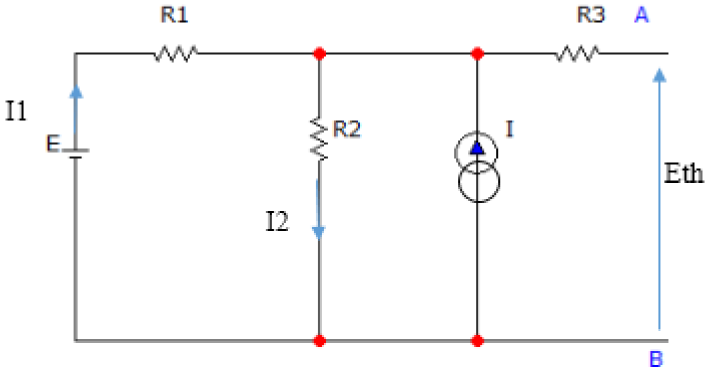
- Find the Thevenin equivalent circuit at a & b for the following circuit:

7.2.2. Solution

The Thevenin equivalent circuit: Eth=? And Rth=?

Step 1: Remove the RL from the circuit, then calculate Eth=?

Eth is the open circuit voltage at the terminal A and B:



$E - R1I1 - R2(I1 + I) = 0 \Rightarrow I1 = \frac{E - R2 \times I}{R1 + R2}$

N.A: $I1 = \frac{32 - 12 \times 2}{4 + 12} = 0.5A$

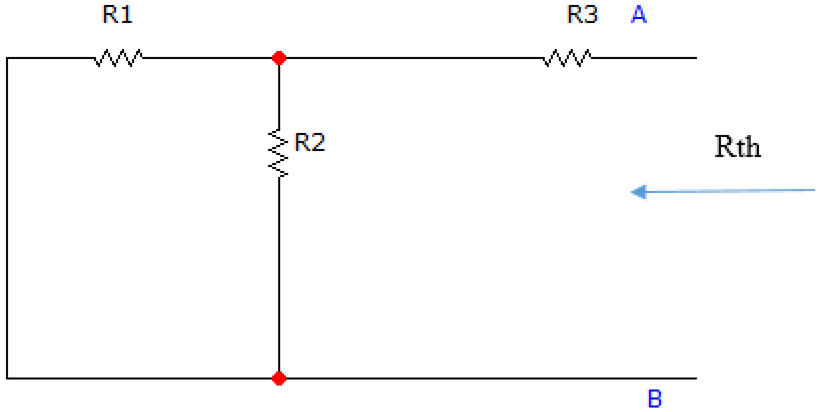
Thus,

$Eth = R2(I1 + I)$

N.A: $Eth = 12(2 + 0.5) = 30V$

2) Find the equivalent resistance Rth

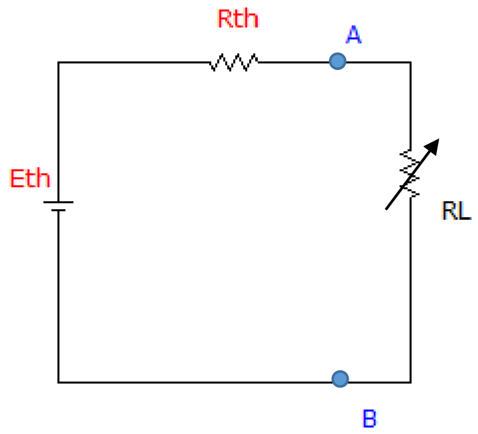
Consider voltage source as a short circuit, and the current source as an open circuit.



$Rth = (R1 // R2)$+R3

N.A: $Rth = 4//12 + 1 = 4\Omega$

Then, the equivalent circuit will be:



7.3. Millman's theorem

Millman's theorem applied to any circuit drawn as a set of parallel-connected branches, where each branch consists of a resistor or a series combination of a battery and a resistor. It asserts that every circuit including several voltage sources, each one in series with its resistance, may be substituted by one voltage source (VEQ) in series with a resistance (REQ).

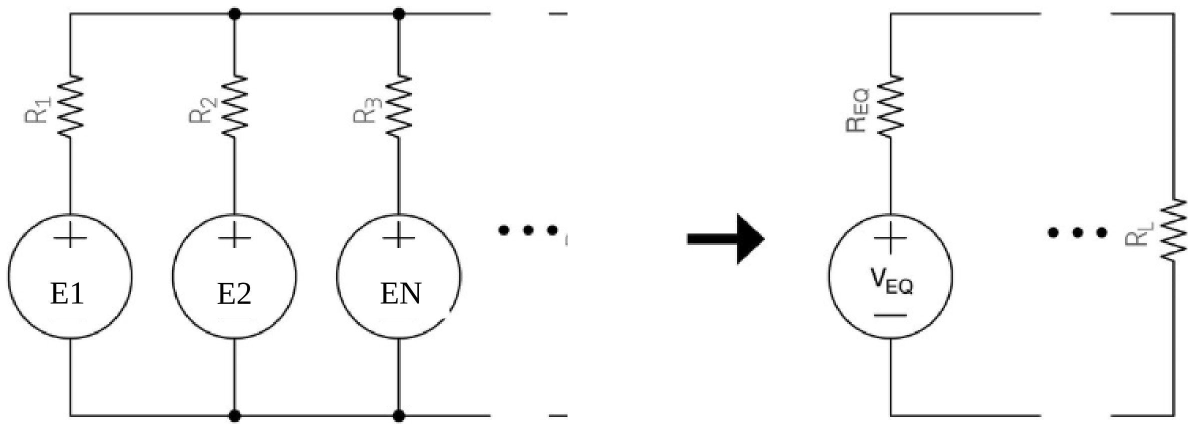


Figure 1. 21: Milman equivalent circuit

As per Millman's Theorem

If the N number of sources is given, the.

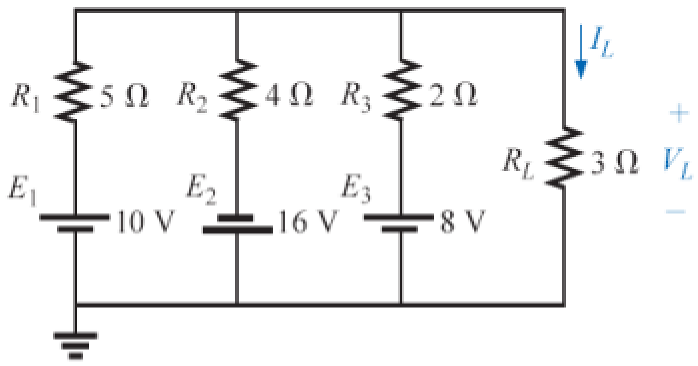
$$Veq = \frac{\frac{E_1}{R_1}+\frac{E_2}{R_2}+\frac{E_3}{R_3}+\cdots+\frac{E_N}{R_N}}{\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}+\cdots+\frac{1}{R_N}} \tag{1.20}$$

Req will be

$$Req = \frac{1}{\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}+\cdots+\frac{1}{R_N}} \qquad (1.21)$$

7.3.1. Example

Consider the circuit in the opposite figure.



Using Millman's theorem, find

1) The Millman equivalent circuit
2) The current through the resistor RL, and the voltage across the resistor RL

7.3.2. Solution

1) The Millman equivalent circuit: Veq=? & Req=?

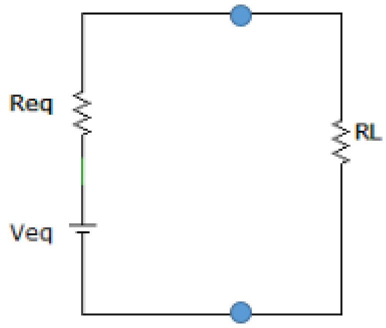
We can apply the equations (1.20) & (1.21) directly we obtain

$$\begin{cases} Veq = \dfrac{\dfrac{E_1}{R_1}+\dfrac{E_2}{R_2}+\dfrac{E_3}{R_3}}{\dfrac{1}{R_1}+\dfrac{1}{R_2}+\dfrac{1}{R_3}} \\ Req = \dfrac{1}{\dfrac{1}{R_1}+\dfrac{1}{R_2}+\dfrac{1}{R_3}} \end{cases}$$

N.A:

$$\begin{cases} Veq = \dfrac{\dfrac{10}{5}-\dfrac{16}{4}+\dfrac{8}{2}}{\dfrac{1}{5}+\dfrac{1}{4}+\dfrac{1}{2}} = 2.105V \\ Req = \dfrac{1}{\dfrac{1}{R_1}+\dfrac{1}{R_2}+\dfrac{1}{R_3}} = 1.053\Omega \end{cases}$$

The resultant circuit is depicted in the opposite figure.



2) The current through the resistor RL:

$$\begin{cases} IL = \dfrac{Veq}{Req + RL} = \dfrac{2.105}{1.053 + 3} = 0.519A \\ VL = IL \times RL = 0.519 \times \ 3 = 1.557V \end{cases}$$

7.4. Norton's theorem

Norton's theorem simplifies an electric circuit down to a single resistance (R_N) in parallel with a constant current source (I_N). The statement indicates that an equivalent circuit with a current source I_N connected in parallel to a resistor R_N can take the place of a linear two-terminal circuit.

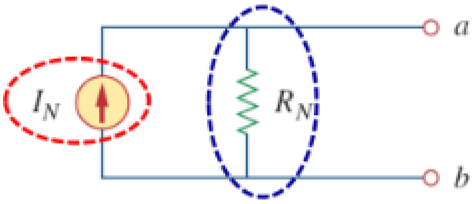


Figure 1. 22: Norton equivalent circuit

where

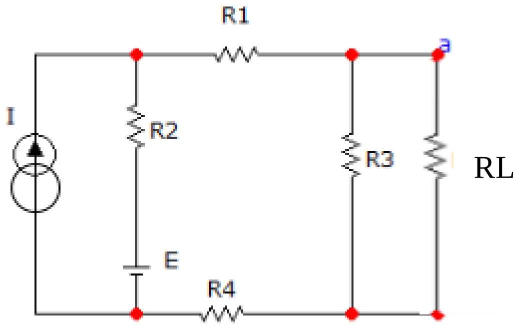
- IN is the short-circuit current through the terminals.
- RN is the input or equivalent resistance at the terminals when the independent sources are turned off.

Note: The Thevenin and Norton equivalent circuits are related by a source transformation.

7.4.1. Example

Consider the following circuit:

- Find the Norton equivalent circuit at the terminals a & b.



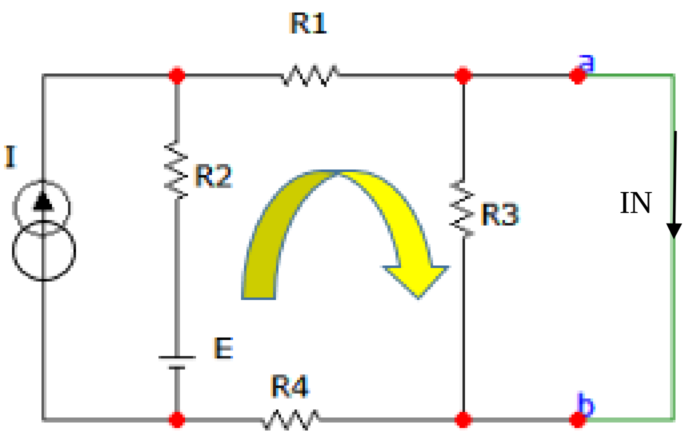
Given: I=2A; E=12V; R1=8Ω; R2=4Ω; R3=5Ω; R4=8Ω.

7.4.2. Solution

The Norton equivalent circuit IN=? And RN=?

1) IN=?

Short circuit the load, and then calculate the short circuit current (IN). the obtained circuit is given below:



By using KCL: $IN = I + I1$

By using KVL: $E - R2 \times I1 - (R1 + R4)IN = 0$

We replace equation (1) in equation (2), we get:

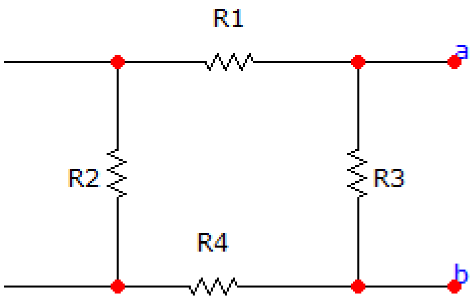
$$IN = \frac{E + R2 \times I}{R1 + R2 + R4}$$

N.A:

$$IN = \frac{12 + 4 \times 2}{8 + 4 + 8} = 1A$$

2) RN=?

- Disconnect RL
- Open current sources, and open load resistor
- Short circuit voltage sources



$RN = (R1 + R2 + R4) \,//\, R3$

N.A: $RN = (8 + 4 + 8)//5 = \mathbf{4\Omega}$

8. Norton and Thevenin equivalent circuits

Both Thevenin's and Norton's theorems being similarly useful approaches for simplifying the analysis of a complicated network, it follows that a means must exist for converting a Thevenin-equivalent circuit into a Norton-equivalent circuit and conversely.

The procedure for calculating the Thevenin equivalent resistance is identical to that for calculating the Norton equivalent resistance.

To transform a Norton Current Source into a Thevenin Voltage Source, it is important to note that Thevenin and Norton equivalent circuits should produce the same voltage across the load terminals when no load resistor is connected.

Therefore, we can infer that the Thevenin voltage is equal to the product of Norton's current and the Norton resistance.

Chapter 2: Two port Networks - Quadrupoles

1. Introduction

This chapter breaks down the general topic into two parts: The first part is dedicated to studying two-port networks, and the second part is interested in passive filters. In the first part, we will discuss in detail two port networks, their properties, important parameters, and representations. In addition, the mathematical expressions that describe the several representations of two-port networks are provided. The second part will cover passive filters, including the high-pass filter and the low-pass filter, as well as those derived from them, along with a study of their properties and frequency responses. We will also explore various connection configurations for passive filters.

2. A two-port networks

A two port network is one of the most fundamental concepts in network theory and circuit analysis. It refers to a network that comprises of two connection points known as ports through which input and output signals can pass. Understanding two port networks is essential for analyzing more complex signal processing and electronic systems.

2.1. Two-port networks representation

A two port network can be simply represented as a "pair of two-terminal electrical networks in which, the current enters through one terminal and leaves through another terminal of each port." In other words, it is a network that has two ports for input/output with each port consisting of two terminals.

The figure below shows a basic representation of a two port network:

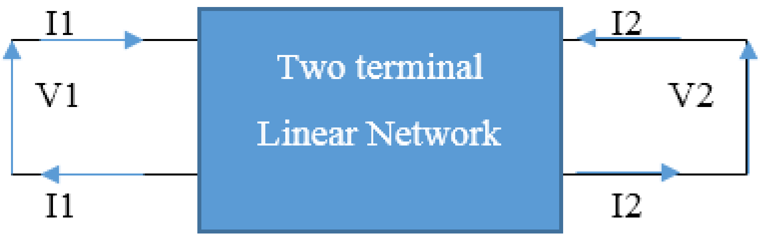


Figure 2. 1: Basic Representation of Two Port Network

As seen, a two port network contains four terminals divided into two ports. Port 1 comprises terminals 1 and 1' while port 2 contains terminals 2 and 2'. Here, current I1 flows into terminal 1 and exits from terminal 1'. Similarly, for port 2, current I2 enters through terminal 2 and leaves through terminal 2'.

The two port network allows modeling relationships between input and output quantities like voltages (V1, V2) and currents (I1, I2).

2.2. Two-Port Network Parameters

The input-output relationships in a two port network can be described through various parameter sets. Based on which variables are considered dependent/independent, different parameter representations are possible.

Some common two-port network parameters include:

2.2.1. Z parameters of two-port network

Z parameters of two-port network: The Z parameters, also known as impedance parameters, represent the relationship between the voltage and current at each port of the network. They are defined by the voltage and current ratios at the input and output ports.

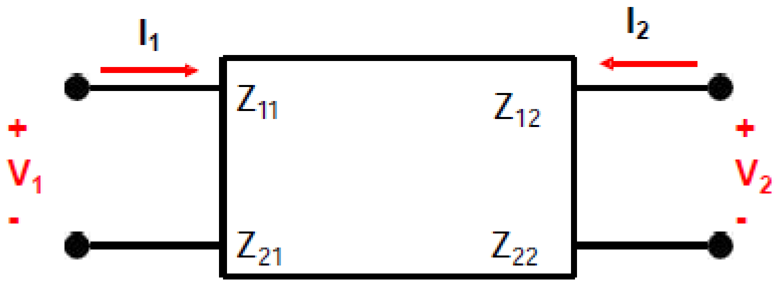


Figure 2. 2: Z parameters model

With voltages dependent and currents independent, this gives impedance parameters Z_{11}, Z_{12}, Z_{21}, and Z_{22}.

$$V_1 = Z_{11} I_1 + Z_{12} I_2$$
$$V_2 = Z_{21} I_1 + Z_{22} I_2 \quad (2.1)$$

The Z parameters are :

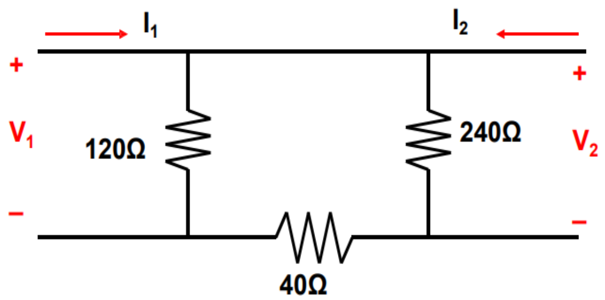
$$Z_{11} = \frac{V1}{I1}, when\ I2 = 0$$
$$Z_{12} = \frac{V1}{I2}, when\ I1 = 0$$
$$Z_{21} = \frac{V2}{I1}, when\ I2 = 0$$
$$Z_{22} = \frac{V2}{I2}, when\ I1 = 0$$

o Since Z parameters are just the voltage-to-current ratios, they are also known as impedance parameters. The units of Z parameters are Ohm (Ω).

o By performing an open circuit of port two, we may compute two Z parameters, Z11 and Z21. Similarly, we can determine the other two Z values, Z12 and Z22 by doing an open circuit of port1. Therefore, the Z parameters are occasionally referred to as open-circuit impedance parameters.

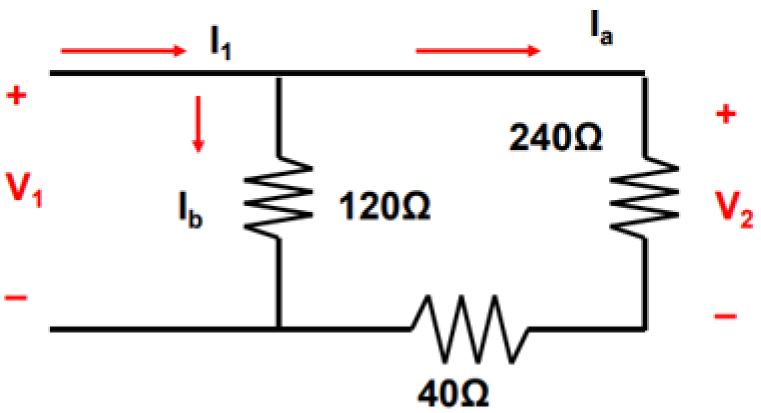
2.2.1.1. Example

Find the Z – parameter of the circuit below.



2.2.1.2. Solution

I2=0 (open circuit). Redraw the circuit



$$V1 = 120\ Ib \qquad (1)$$

$$Ib = \frac{280}{400} I1 \qquad (2)$$

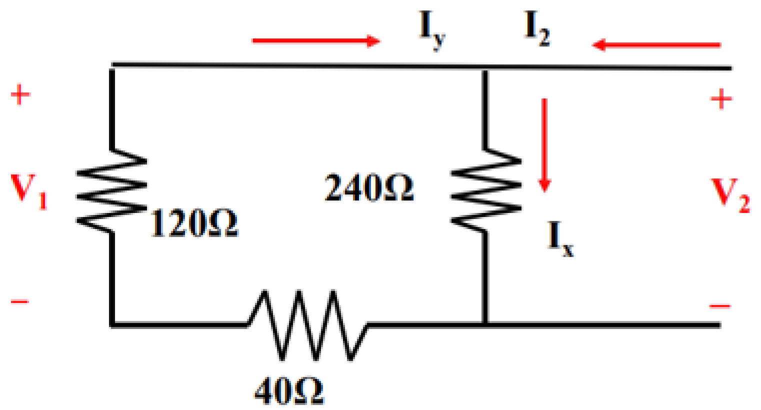
$V2 = 240Ia$ (3)

$Ia = \frac{120}{400} I1$ (4)

Replace (2) into (1) , we obtain $Z_{11} = \frac{V1}{I1} = 84\Omega$

Replace (4) into (3) , we obtain $Z_{21} = \frac{V2}{I1} = 72\Omega$

2) I1=0 (open circuit port 1). Redraw the circuit



$V2 = 240\ Ix$ (1)

$Ix = \frac{160}{400} I2$ (2)

$V1 = 120Iy$ (3)

$Iy = \frac{240}{400} I2$ (4)

Replace (2) into (1) , we obtain $Z_{22} = \frac{V2}{I2} = 96\Omega$

Replace (4) into (3) , we obtain $Z_{12} = \frac{V1}{I2} = 72\Omega$

In matrix form : $[Z] = \begin{bmatrix} 84 & 72 \\ 72 & 96 \end{bmatrix} \Omega$

2.2.2. Y parameters of two-port network

The Y parameters, or admittance parameters, describe the conductance and susceptance of the network at each port. They are the reciprocal of Z parameters and are useful for analyzing networks in terms of current rather than voltage.

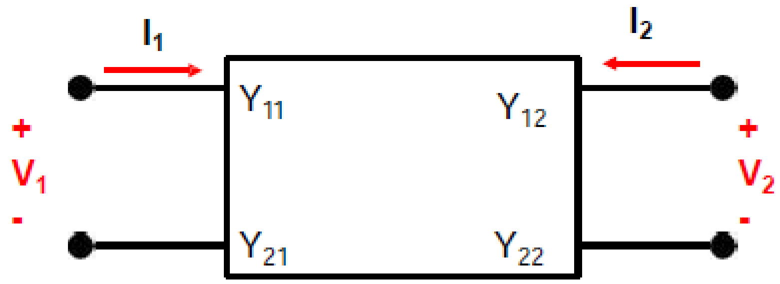


Figure 2. 3 : Y parameter model

Taking currents dependent and voltages independent yields admittance parameters Y_{11}, Y_{12}, Y_{21}, and Y_{22}.

When considering the variables I1 and I2 as dependent and V1 and V2 as independent, we can derive a set of two equations representing the behavior of the two port networks.

These equations are typically written in matrix form as:

$$I_1 = Y_{11}V_1 + Y_{12}V_2$$
$$I_2 = Y_{21}V_1 + Y_{22}V_2 \quad (2.2)$$

The Y parameters represent the two port network when the currents are considered as the dependent variables and voltages as the independent ones.

$$Y_{11} = \frac{I1}{V1}, when\ V2 = 0$$
$$Y_{12} = \frac{I1}{V2}, when\ V1 = 0$$
$$Y_{21} = \frac{I2}{V1}, when\ V2 = 0$$
$$Y_{22} = \frac{I2}{V2}, when\ V1 = 0$$

The Y parameters are defined as:

Y_{11} is the input admittance seen when port 2 is short circuited.

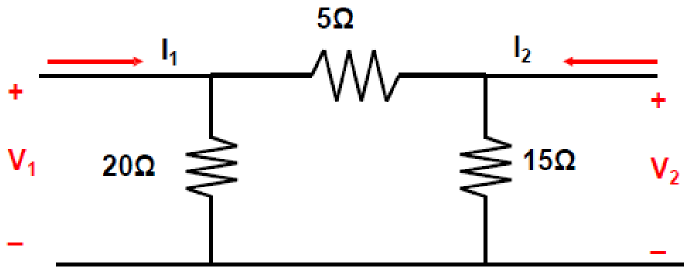
Y_{12} is the transfer admittance with port 1 short circuited.

Y_{21} is the reverse transfer admittance with port 2 short circuited.

Y_{22} is the output admittance with port 1 short circuited.

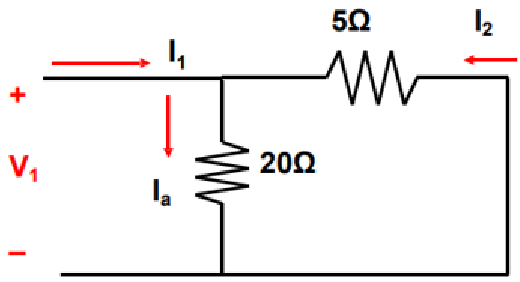
2.2.2.1. Example

Find the Y – parameter of the circuit shown below /



2.2.2.2. Solution

1) V2=0



$V1 = 20Ia$ (1)

$Ia = \frac{5}{25}I1$ (2)

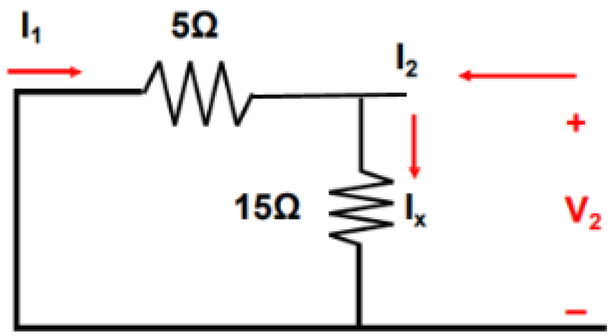
Replace 2 in 1, we obtain :

$$Y_{11} = \frac{I1}{V1} = \frac{1}{4}S$$

$$V1 = -5I2$$

$$Y21 = \frac{I2}{V2} = -\frac{1}{5}S$$

2) V1=0



$V2 = 15Ix$ (3)

$Ix = \frac{5}{25}2$ (4)

Replace 4 in 3, we obtain :

$$Y_{22} = \frac{I2}{V2} = \frac{4}{15}S$$

$$V2 = -5I1$$

$$Y12 = \frac{I1}{V2} = -\frac{1}{5}S$$

In matrix form : $[Y] = \begin{bmatrix} \frac{1}{4} & -\frac{1}{5} \\ -\frac{1}{5} & \frac{4}{15} \end{bmatrix} S$

2.2.3. h parameters of two port network

Considering the variables V1 and I2 as dependent and I1 and V2 as independent, we can formulate a set of two equations describing the behavior of the two-port network.

These equations can be represented in matrix form as:

$$\begin{bmatrix} V1 \\ I2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} I1 \\ V2 \end{bmatrix} \tag{2.3}$$

Or

$$\begin{aligned} V_1 &= h_{11} I_1 + h_{12} V_2 \\ I_2 &= h_{21} I_1 + Z h_{22} V_2 \end{aligned} \tag{2.4}$$

The h-parameters can be found as follows:

$$h_{11} = \frac{V1}{I1}, when\ V2 = 0$$
$$h_{12} = \frac{V1}{V2}, when\ I1 = 0$$
$$h_{21} = \frac{I2}{I1}, when\ V2 = 0$$
$$h_{22} = \frac{I2}{V2}, when\ I1 = 0$$

where

h11= Short-circuit input impedance

h12 = Open-circuit reverse voltage gain

h21 = Short-circuit forward current gain

h22 = Open-circuit output admittance

Hybrid parameters are referred to as h-parameters. The parameters, h12 and h21, don't have any units because they are dimensionless. The units of parameters, h11 and h22, are Ohm and Mho, respectively.

By shorting port 2, we may compute two parameters, h11 and h21. Similarly, we can determine the remaining two values, h12 and h22, by performing an open circuit at port 1.

2.3. Quantities characterizing the behavior of a quadrupole in circuits

To characterize a quadrupole, we connect a source dipole (EG, RG) to the two input terminals. At the two output terminals, we connect a load dipole denoted ZL as shown in the figure below.

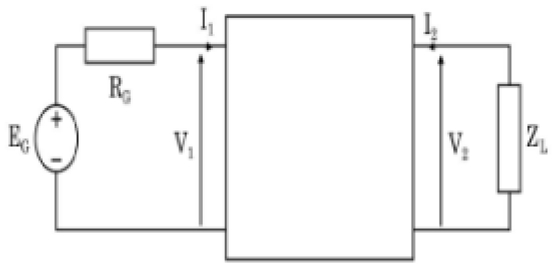


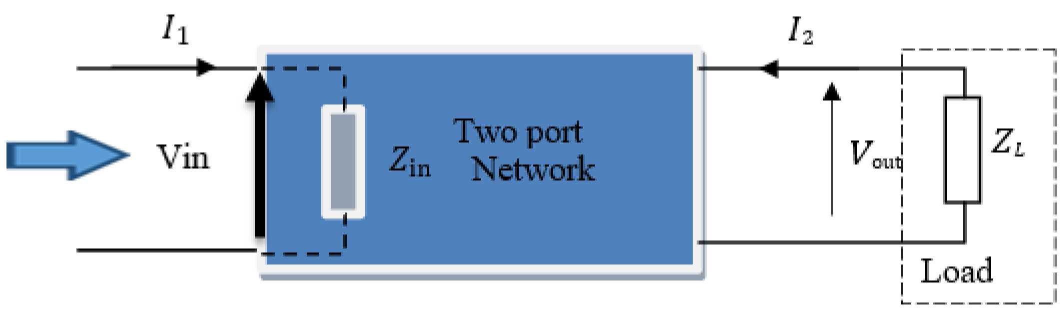
Figure 2. 4: Two port network attacked by a real voltage source

For example, we define a two port network Q by the matrix [Z], the equations which allow determining the state of the network are:

$$\begin{cases} V1 = Z11I1 + Z12I2 \\ V2 = Z21I1 + Z22I2 \\ EG = V1 + RGI1 \\ V2 = -ZLI2 \end{cases} \quad (2.5)$$

2.3.1. Input impedance

The input impedance is the impedance seen by the source which attacks the quadrupole empty or in charge.



Input impedance of two port network is given by:

$$Z_{in} = \frac{Vin}{I1} \quad (2.6)$$

If we use the previous equations relating to the parameters [Z] we find :

$$Z_{in} = \frac{R_L Z_L + \Delta Z}{R_L + Z_{22}} \quad (2.7)$$

Where ΔZ is the determinant of the matrix [Z].

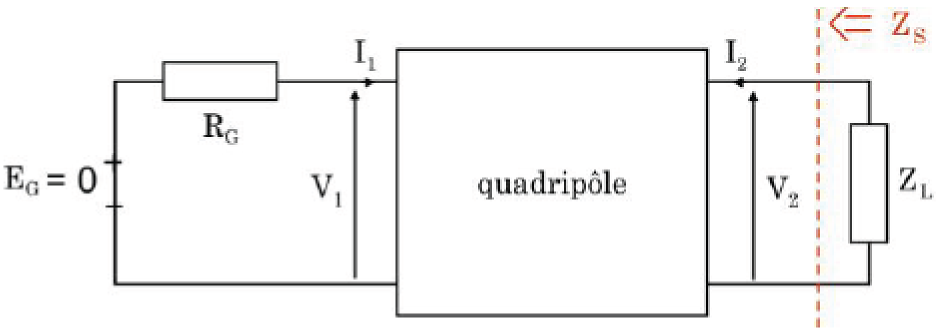
$$\Delta Z = Z_{11}Z_{22} - Z_{12}Z_{21} \quad (2.8)$$

2.3.2. Output impedance

The output impedance is expressed by the relation:

$$Z_{out} = \frac{Vout}{I2}\bigg|_{Eg=0} \tag{2.9}$$

This is the impedance seen at the output when the input is closed by an RG impedance, which is the impedance of the generator. A similar calculation to the previous case yields the following results:



$$V1 = Z11 \times I1 + Z12 \times I2 = -RG \times I1 \tag{2.11}$$

$$V2 = Z21 \times I1 + Z22 \times I2 \tag{2.12}$$

$$Z_{OUT} = \frac{V2}{I2} \tag{2.13}$$

By analogy with the previous one, we obtain the output impedance:

$$Z_{OUT} = \frac{R_G Z_{22} + \Delta Z}{R_G + Z_{11}} \tag{2.14}$$

2.3.3. Voltage gain

The voltage gain is defined by the ratio between the output voltage and the input voltage, i.e. :

$$G_V = \frac{V_2}{V_1} \tag{2.15}$$

If the quadrupole is defined by the parameters [Z] and by using the following equations:

$$\begin{cases} V1 = Z11I1 + Z12I2 \\ V2 = Z21I1 + Z22I2 \\ V2 = -ZLI2 \end{cases} \tag{2.16}$$

We obtain :

$$G_V = \frac{Z_L Z_{21}}{Z_L Z_{11} + \Delta Z} \quad (2.17)$$

2.3.4. Current gain

The current gain is defined by the ratio between the output current I2 and the input current I1.

$$G_A = \frac{I2}{I1} \quad (2.18)$$

If the quadrupole is defined by the parameters [Z] and by the use of equations:

$$\begin{cases} V_2 = Z_{21} I_1 + Z_{22} I_2 \\ V_2 = -Z_L\, I_2 \end{cases} \quad (2.19)$$

$V_2 = -Z_L I_2$

We obtain :

$$G_A = \frac{Z_{21}}{Z_{22} + \Delta Z} \quad (2.20)$$

2.4. Application of two port network

Two port networks serve as basic but useful models with wide-ranging applications across different domains:

- Circuit analysis: Used to represent circuits involving resistors, capacitors, coils, and basic electronic components.
- Transmission lines: Characterize voltage and current propagation along transmission lines.
- Antennas: Employed to model radiation properties and matching networks of antennas.
- Amplifiers: Describes small signal behavior of transistors in amplifiers.
- Networks: Model communication systems, control systems, mechanical and acoustic systems.
- Acoustics: Analogous to electric circuits in modeling acoustical/mechanical systems.

- Electrical machines: Represent transformers, motors, and generators through suitable parameter models.

Hence, the simple yet powerful two port network concept allows for addressing broader interdisciplinary problems in engineering. Its parameters provide designers valuable insights into system operation.

3. Passive filter

Filters are networks that has a frequency dependent gain that passes electric signals at certain frequencies or frequency ranges while preventing the passage of others. A filter is an electronic circuit, these circuits utilize a combination of resistors and capacitors as their fundamental construction blocks.

In principle, passive filters can be made from passive components that is resistors, capacitors and inductors.

3.1. Definitions

Some important notions concerning passive filters are given below:

3.1.1. Transfer function

The main parameter is the voltage transfer function in the frequency domain, $\underline{H}(w) = \frac{V_{out}}{V_{in}}$ is a complex number, it has both a magnitude and a phase, filters in general introduce a phase difference between input and output signals.

The module of the transfer function corresponds to the voltage amplification:

$$|\underline{H}(jw)| = \left|\frac{\underline{V_{out}}}{\underline{V_{in}}}\right| \tag{2.21}$$

The phase shift φ introduced by the filter can be calculated by:

$$\varphi(w) = Arg\left(\underline{H}(w)\right) = Arg\left(\frac{\underline{V_{out}}}{\underline{V_{in}}}\right) = Arg\left(\underline{V_{out}}\right) - Arg(\underline{V_{in}}) \tag{2.22}$$

3.1.2. Bode plots

Bode plots are plots of |H(jω)|dB (magnitude) and $\angle H(jw)$(phase) versus frequency in a semi-log format (i.e., ω axis is a log axis).

Two significant parameters can be calculated using this transfer function. The first can be obtained by taking the complex function's norm, which gives the gain/amplitude (G): **G=|H(jω)|.** To create Bode diagrams, the gain expressed in dB is taken into account: **G_{dB}=20log(G)**.

A gain G_{dB}=0 shows that there is equality between the input and output norms $|V_{in}|=|V_{out}|$, it's referred to as a unitary gain. When G_{dB} tends to infinite negative values, no output is observed despite the presence of an input.

3.1.3. Presentation of Bode diagrams

The Bode diagram of an electrical circuit is made up of two graphs illustrating separately the gain GdB and the phase difference as a function of the frequency in logarithmic scale. There are two possible representations for each among those graphs: the real or asymptotic representation. The analytical expression of the transfer function's magnitude and phase yields the real curve. The asymptotic approximation reflects a straight line.

3.1.4. Cut-off frequency

We define the cut-off frequency ωc of a system as that for which the maximum voltage gain is divided by $\sqrt{2}$.

$$|H(jw_c)| = \frac{|H_{max}|}{\sqrt{2}} \tag{2.23}$$

$$|H(jw_c)|_{dB} = 20log_{10}|H_{max}| \tag{2.24}$$

We can therefore also define the cut-off pulse as the pulsation which corresponds to a reduction of 3 dB (decibel) in maximum gain.

3.1.5. Pass band

The pass band refers to the range of frequencies in the input signal that can pass through the filter with an attenuation of less than 3 dB.

3.2. Low pass filter

The transfer function of a perfect low-pass filter is displayed in Figure 2. The frequency between the pass- and-stop bands is called the cut-off frequency (ωc). All other signals are stopped and only those with frequencies lower than ωc are transmitted.

As depicted, a low-pass filter is created via a series RC circuit. Considering no load or impedance (“an open-loop” transfer function).

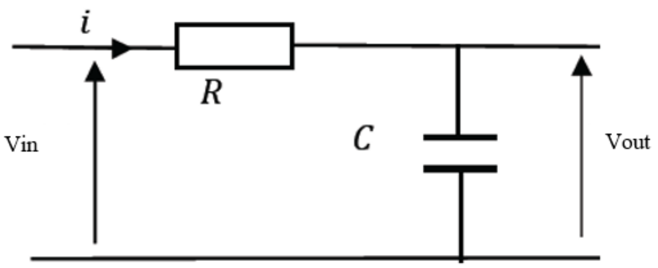


Figure 2. 5: Passive low pass filter

3.2.1. Transfer function

We have $Z_C = \frac{1}{JCw}$

$Vout$ can be found from the voltage divider formula:

$$V_{out} = \frac{Z_c}{R+Z_c}V_{in} = \frac{\frac{1}{JCw}}{R+\frac{1}{JCw}}V_{in} = \frac{1}{1+\text{JRCw}}V_{in} \quad (2.25)$$

$$\Rightarrow \frac{V_{out}}{V_{in}} = H(w) = \frac{1}{1+\text{JRCw}}$$

the voltage gain

$$|H(w)| = \left|\frac{1}{1+\text{JRCw}}\right| = \frac{1}{\sqrt{1+(RCw)^2}} \quad (2.26)$$

where: $w_0 = \frac{1}{RC}$

3.2.2. Bode plots

Bode plots of first-order low-pass RC filters are shown below (ω denotes ωc).

$$\varphi(w) = -\arctan(\frac{w}{w_0})$$

$$\begin{cases} G(w) = 20Log_{10}H(w) = 20Log_{10}\left(\frac{1}{\sqrt{1+\left(\frac{w}{w_0}\right)^2}}\right) = -10Log_{10}\left(1+\left(\frac{w}{w_0}\right)^2\right) \\ \varphi(w) = -arctan(\frac{w}{w_0}) \end{cases} \quad (2.27)$$

3.2.3. Cut-off frequency for RC circuits

To find the cut-off frequency, we note that the:

$H(w_c) = \frac{H_{max}}{\sqrt{2}}$

(2.22)

$\sqrt{1 + \left(\frac{w}{w_0}\right)^2} = \frac{H_{max}}{\sqrt{2}} \Rightarrow \frac{w_c}{w_0} = 1 ==> w_c = w_0 = \frac{1}{RC}$

(2.23)

3.2.3.1. *Magnitude*

We'll analyze three situations for the frequency value and then find the value of magnitude for each situation:

Case 1): $\omega < w_0$This refers to the low frequency case with $\frac{\omega}{w_0} \longrightarrow 0$. The transfer function's magnitude will be approximated as follow:

$$\sqrt{1 + (\frac{w}{w0})^2} \approx 1, \text{ and } |H(j\omega)|_{dB} \approx 20 \cdot log_{10}(\frac{1}{1}) = 0 \quad (2.28)$$

The graphic below displays the low frequency approximation in blue color.

Case 2): $\omega \gg w_0$ This refers to the low frequency case with $\frac{\omega}{w_0} \longrightarrow \infty$. The transfer function's magnitude will be approximated as follow:

$$\sqrt{1 + (\frac{w}{w0})^2} \approx \sqrt{(\frac{w}{w0})^2} \approx \frac{w}{w0}, \text{ SO } |H(j\omega)|_{dB} \approx 20 \cdot log_{10}(\frac{w0}{w}) = 0 \quad (2.29)$$

In the diagram below, the high-frequency approximation is indicated in green.

The high frequency approximation is at shown in green on the diagram below. The break frequency is at 0 dB, and the approximation simplifies to 0 dB if ω=ω0. The line has a slope of -20 dB/decade ; ω=10·ω0 offers an estimated gain of 0.1 or -20dB and so on).

Case 3): $\omega = \omega 0$ at the break frequency.

$$|H(j\omega 0)|_{dB} = 20 \cdot log_{10}\left(\sqrt{\frac{1}{\sqrt{1+\left(\frac{w}{w0}\right)^2}}}\right) = 20 \cdot log_{10}\left(\sqrt{\frac{1}{\sqrt{2}}}\right) \approx -3dB \quad (2.30)$$

The location of this point is indicated as a red circle on the diagram.

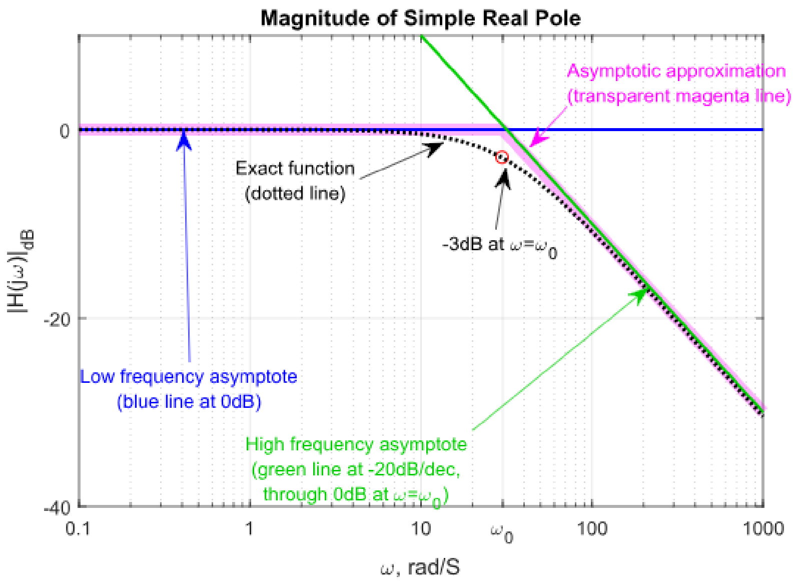


Figure 2. 6 : Plot of the gain of the circuit low pass filter

Use the high-frequency asymptote after the break frequency and the low-frequency asymptote up until the break frequency to create a piecewise linear approximation.

The subsequent asymptotic approximation is displayed and highlighted in transparent magenta. The biggest error between the asymptotic approximation and the exact magnitude function comes at the break frequency and is around -3 dB.

3.2.3.2. Phase

The phase of a single real pole is given by is provided by

$$\angle H(j\omega) = \angle(\frac{1}{1+j\frac{\omega}{\omega_0}}) = -\angle(1 + j\frac{\omega}{\omega_0}) = -arctan(\frac{\omega}{\omega_0}) \qquad (2.31)$$

Letting again explore three instances for the value of the frequency:

Case 1): $\omega \ll \omega_0$. This is the low frequency case with $\omega/\omega_0 \rightarrow 0$. We can approximate the transfer function's phase at these frequencies:

$$\angle H(j\omega) \approx -arctan(0) = 0^0 = 0rad \qquad (2.32)$$

The low frequency approximation is shown in blue on the diagram below.

Case 2): $\omega \gg \omega_0$. This is the high frequency case with $\omega/\omega_0 \rightarrow \infty$. We can write an approximation for the phase of the transfer function

$$\angle H(j\omega) \approx -arctan(\infty) = -90^{\circ} = -\frac{\pi}{2}rad \qquad (2.33)$$

The high frequency approximation is at shown in green on the diagram below. It is a horizontal line at -90°.

Case 3): ω=ω_0. The break frequency. At this frequency

$$\angle H(j\omega) = -arctan(1) = -45^{\circ} = -\frac{\pi}{4}rad \qquad (2.34)$$

This point is shown as a red circle on the diagram.

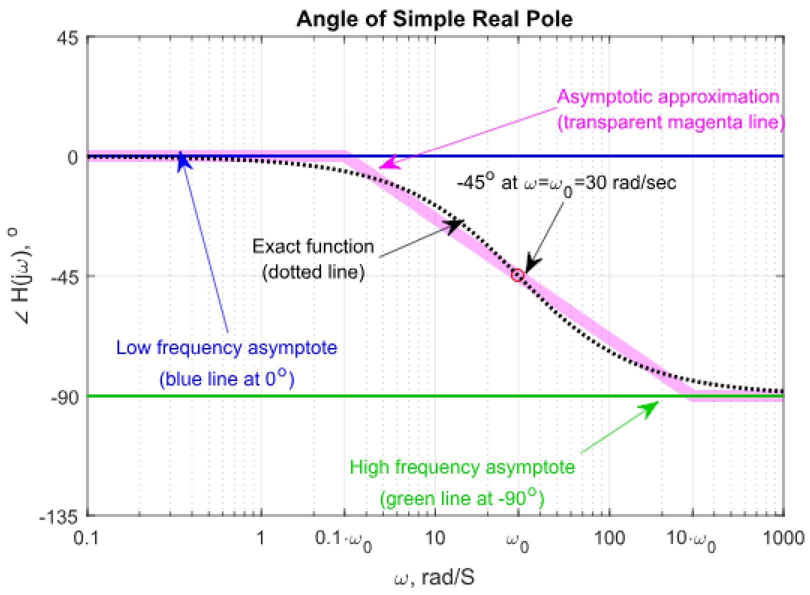


Figure 2. 7 : Plot of the phase of the circuit low pass filter

3.3. High pass filter

A high-pass filter passes all frequencies above a certain cutoff frequency and attenuates all frequencies below that cutoff frequency.

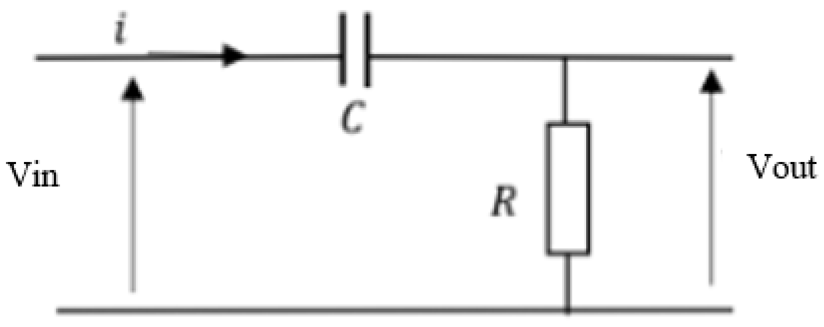


Figure 2. 8 : Passive high pass filter

3.3.1. Transfer function

We have $Zc = \frac{1}{JCw}$

$Vout$ can be found from the voltage divider formula:

$$V_{out} = \frac{R}{R+Z_c} V_{in} \rightarrow \frac{V_{out}}{V_{in}} = \frac{JRCW}{1+JRCW}$$

$$H(w) = \frac{JRCW}{1+JRCW} = \frac{J\frac{W}{w0}}{1+J\frac{W}{w0}} \tag{2.35}$$

The voltage gain is :

$$|H(w)| = \left|\frac{J\frac{W}{w0}}{1+J\frac{W}{w0}}\right| = \frac{1}{\sqrt{1+(\frac{w0}{w})^2}} \tag{2.36}$$

With $w0 = \frac{1}{RC}$

3.3.2. Bode plots

Bode plots of first-order low-pass RC filters are shown below (W denotes ωc).

$$\begin{cases} G(w) = 20Log_{10}H(w) = 20Log_{10}\left(\frac{1}{\sqrt{1+\left(\frac{w_0}{w}\right)^2}}\right) = -10Log_{10}\left(1+\left(\frac{w_0}{\text{w}}\right)^2\right) \\ \varphi(w) = \pi/2 - arctan(\frac{w_0}{w}) \end{cases} \tag{2.37}$$

3.3.3. Cut-off frequency for CR circuit

To find the cut-off frequency, we note that $H(w_c) = \frac{H_{max}}{\sqrt{2}}$.

$$\frac{1}{\sqrt{1+\left(\frac{w_c}{w_0}\right)^2}} = \frac{H_{max}}{\sqrt{2}} \rightarrow \frac{w_c}{w_0} = 1 ==> w_c = w_0 = \frac{1}{RC} \tag{2.38}$$

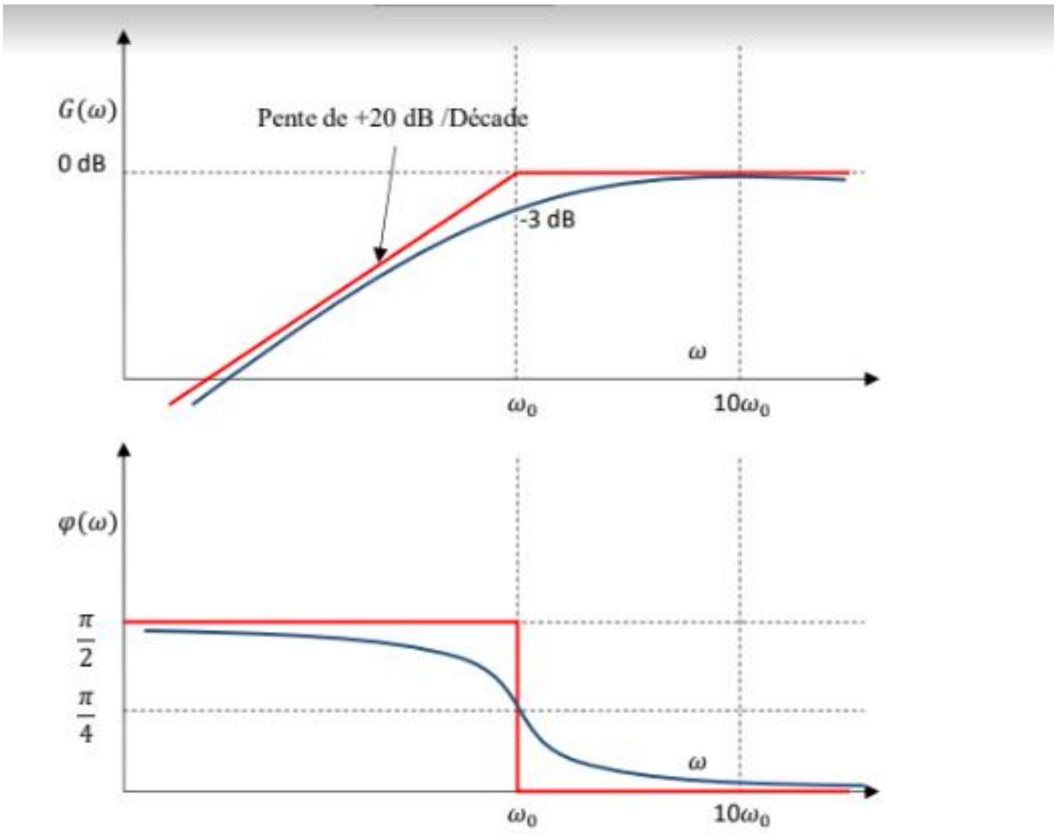
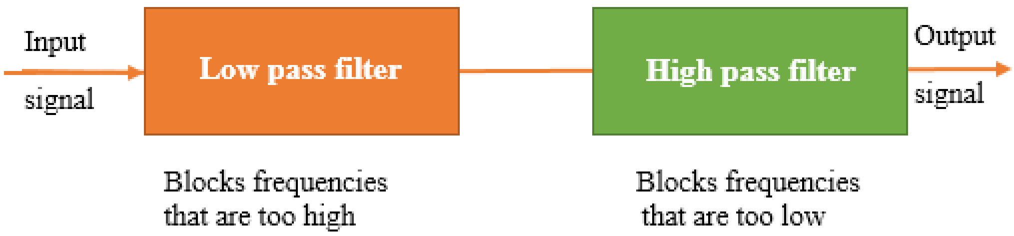


Figure 2. 9 : Gain and phase representation in Bode plan for pass high passive filter

3.4. Band-pass filter

If a high-pass filter and a low-pass filter are cascaded, a band pass filter is created. The band pass filter passes a band of frequencies between a lower cut-off frequency, fc_{LOW} , and an upper cutoff frequency, fc_{HIGH} . Frequencies below fc_{LOW} and above fc_{HIGH} are in the stop band. These bands of frequencies are commonly termed as Bandwidth.

The block diagram of a band pass filter is displayed in the image below.



A sample circuit diagram of a simple passive Bandpass filter is shown below.

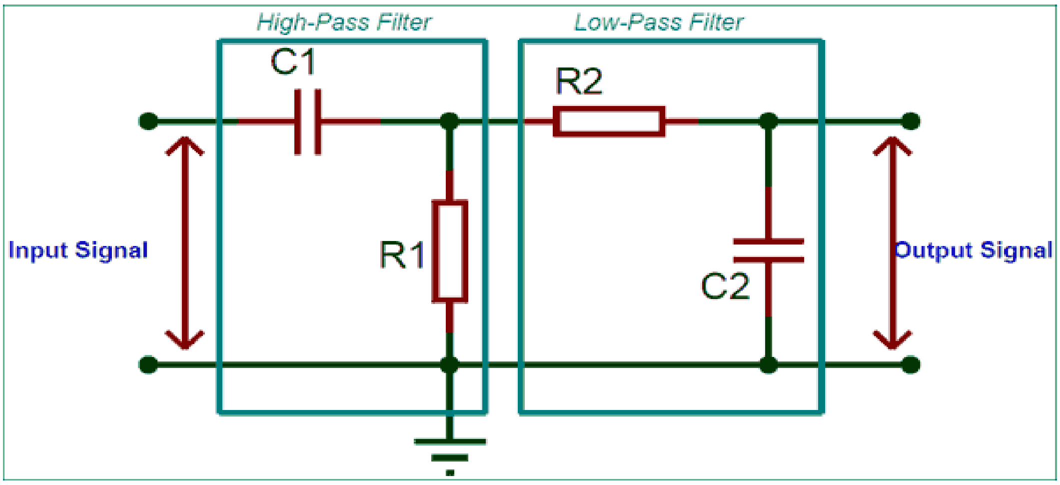


Figure 2. 10: Band pass filter circuit

A high-pass filter, which filters low frequencies and only allows frequencies higher than the high cut-off frequency, makes up the first part of the circuit(fc_{HIGH}). The following formula can be used to get the high cut-off frequency value:

$$fc_{HIGH} = \frac{1}{2\pi * R1 * C1} \quad (2.39)$$

The Low-Pass filter circuit, which filters higher frequencies and only allows frequencies lower than the specified low cut-off frequency, makes up the second half of the circuit (fc_{LOW}). The following formula can be used to get the high cut-off frequency value:

$$fc_{LOW} = \frac{1}{2\pi * R2 * C2} \quad (2.40)$$

The Frequency response for a passive Band pass filter is shown below.

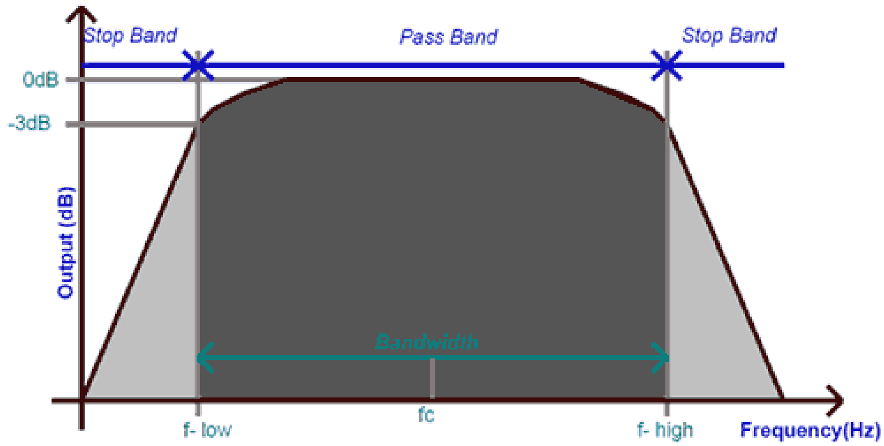


Figure 2. 11: Bandpass filter with low cutoff frequency (fL), center frequency (fC), and high cutoff frequency (fH) shown in relationship to bandwidth and pass band.

3.5. Band-reject filter

Low-pass and high-pass filters are combined to create the band stop filter, however, the connections are made in parallel rather than cascading. The statement itself indicates that it will stop a certain band of frequencies. Despite eliminating frequencies, it is also known as a band reject filter or band elimination filter (Notch filter).

The following graphic depicts the block diagram of a Band Reject Filter.

Band pass and band stop filters are distinct from high pass and low pass filters since they possess two cut-off frequencies. The signal passes above and below a specific range of frequencies, with the cut-off frequencies specified based on the components utilized throughout the circuit's design.

Any frequencies in between these two cut-off frequencies are attenuated. It has two pass bands and one stop band. The ideal characteristics of the Band pass filter are as shown below.

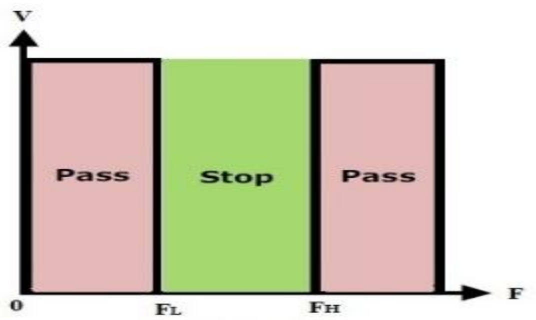


Figure 2. 12 : Band reject filter

The characteristics of a band stop filter are simply the inverse of the characteristics of a band pass filter.

Chapter 3: Diodes

1. Introduction

The diode is the simplest semiconductor component. It is an element that allows the current to pass only in one direction. The current circulates from the anode to the cathode, therefore the diode is an oriented component. This chapter will cover the diode's operating mechanisms, characteristic curve, and its areas of applications.

2. Principle of PN junction diode

A PN junction is constituted by the juxtaposition of two regions of different types of the same monocrystalline semiconductor.

When the two regions are combined, the concentration difference between the carriers of the P and N regions will cause the circulation of a diffusion current aimed at equalizing the concentrations in carriers from one region to another.

- In the zone P the majority carriers are holes, and the acceptor atoms constitute a reservoir of negative ions.

- In the N region the majority carriers are electrons, and the donor atoms constitute a set of positive ions.

A schematic representation of each region is shown in Figure (3.1). Fixed ionized impurities, majority and minority carriers are represented in each region.

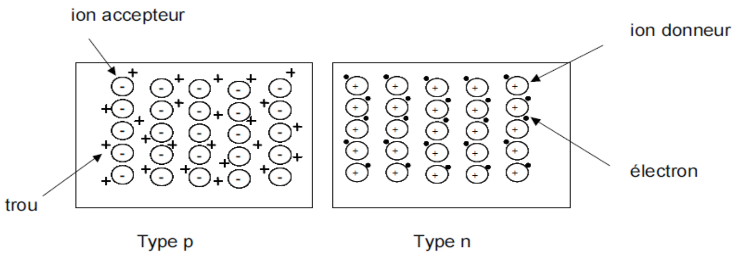


Figure 3. 1: PN junction diode

3. Bias of PN junction

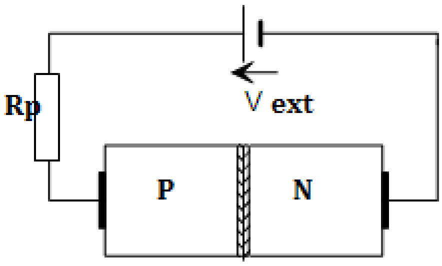
The polarization is obtained by applying, between its region P and its region N, an external tension, Vext. It can have two modes of connecting the external source, its plus on the P side, or its plus on the N side.

3.1. Zero bias

The PN junction diode is not exposed to any external voltage.

3.2. Forward bias of the PN junction

The negative borne of Vext is connected to the N region of the PN junction and the positive borne to the P region. A representation of direct polarization for a PN junction is illustrated in the figure below:



$$I = I_S(e^{V_D/U_T} - 1)$$

Is: reverse saturation current.
K: Boltzman constant.
T: temperature, at ambient temperature (300K) UT=KT/q=26mv.

Figure 3. 2: Forward bias circuit

Two cases may be occurring:

1) Vext>Vi

When the forward voltage of the diode (VD) is larger than Vo, a greater number of majority carriers will cross the junction. This causes the forward current to grow exponentially with the forward voltage VD. At this time, the diode is conducting, or in other words, the diode is in the ON state.

2) Vex<Vi

Barrier voltage (V0) dominates the behavior of the diode, preventing the majority of carriers from passing the junction. Consequently, the forward current is almost nil (usually 10^{-12} to 10^{-15}A), and the diode is in a forward-biased, non-conducting condition, commonly known as the OFF state.

3.3. Reverse Bias of the PN junction

The figure below illustrates a voltage source connected to provide reverse bias of diode. Note that the positive borne of Vext is connected to the N region of the junction and the negative borne to the P region.

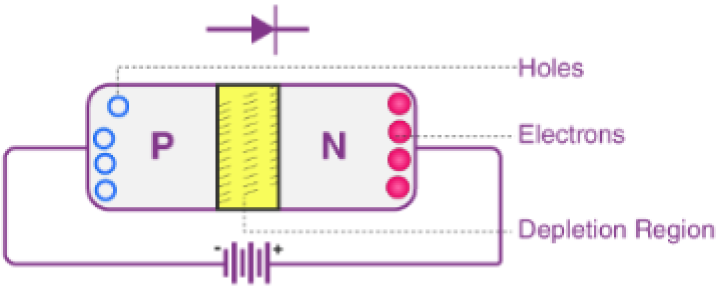


Figure 3. 3: Reverse bias circuit

The reverse-bias voltage causes the depletion region of the diode to widen, creating a high resistance barrier that prevents the flow of current. and the diode is now revese biased and non-conducting, i.e., it is in an OFF state.

4. Symbol

The schematic symbol for the general-purpose diode is illustrated in Figure 4. The region N is the cathode (K) and the region P is called the anode (A).

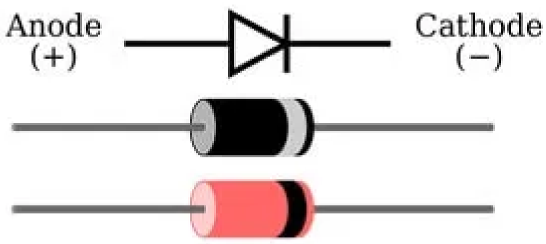


Figure 3. 4: Diode symbol

Note: The ring indicates the cathode.

5. Diode equivalent scheme

5.1. The ideal diode

In this case the diode is a switch controlled by the Anode-Cathode voltage.

1) VAK>0 ⇒ The diode is “on” ⇒ The switch is closed.
2) VAK<0 ⇒ The diode is “off” ⇒ The switch is open.

5.2. The real diode

The real diode model takes into account the potential barrier, the low dynamic resistance and the high reverse resistance.

When the diode is under forward biasing, it acts as a closed serial switch with the potential barrier and dynamic resistance rd.

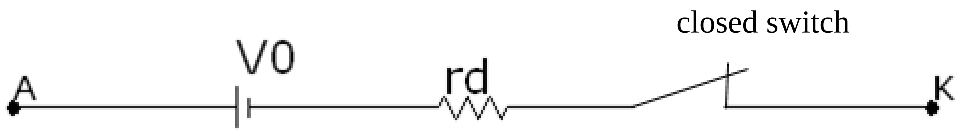


Figure 3. 5: Real diode under direct polarization

V0 : threshold voltage (potential barrier) from which the diode begins to drive.

rd: dynamic resistance of the diode

When the diode is under reverse biasing, it acts as an open switch in parallel with the high internal reverse resistance r.

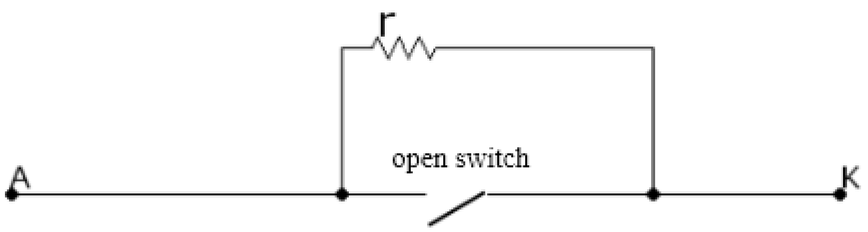
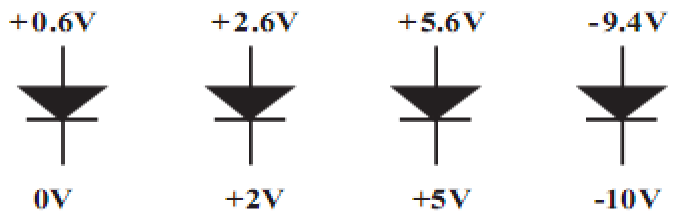
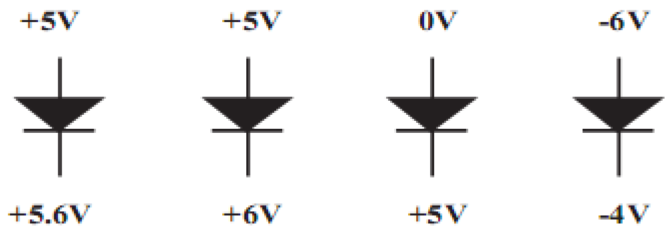


Figure 3. 6: Real diode under reverse polarization

1. Example of forward bias



2. Example of reverse bias:



6. $I_D(V_D)$ characteristic of PN junction diode

The characteristic of a diode is the curve representing the variation of the current I passing through the diode depending on the voltage V applied to it.

The characteristic in the direct direction relative to the diode is defined using the following equation : $I = I_S(e^{V_D/U_T} - 1)$

I: is the current flowing through the diode

I_s : reverse saturation current.

K_B : Boltzman constant ($KB=1.38\times10^{-23}JK^{-1}$).

T : is the absolute temperature in Kelvin, at ambient temperature KT/q=26mv (q the charge on electron).

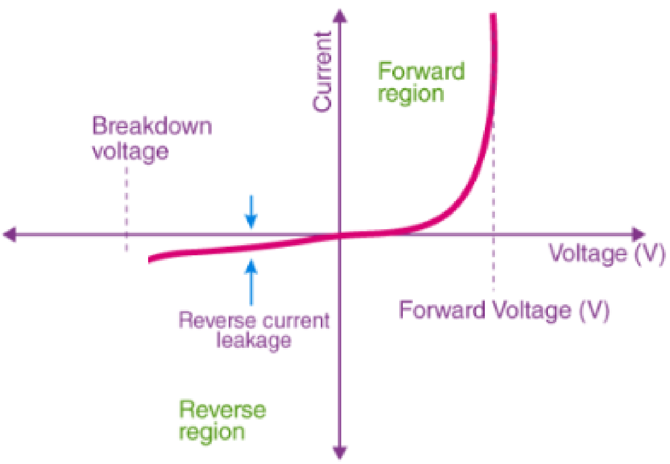


Figure 3. 7: ID(VD) characteristic of PN diode

7. Load line and operating point

The purpose of this study is to determine the current and voltage of the Q(ID,VD) diode called the resting point or operating point.

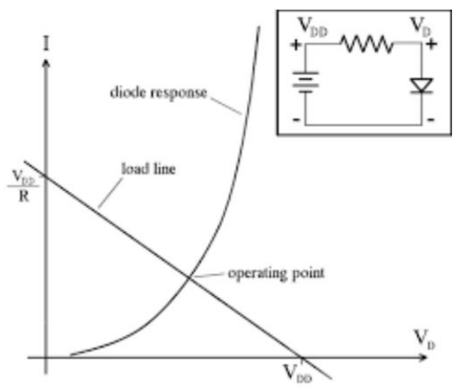


Figure 3. 8: Load line

For this, there are two methods for determining these two parameters.

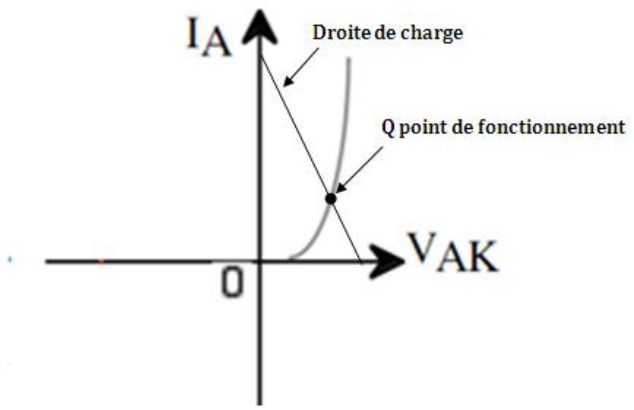
7.1. Analytical method

It consists of solving the following system of equations:

$$\begin{cases} I = I_S\left(e^{V_D/U_T} - 1\right) \; diode\ current - voltage\ equation \\ \qquad\qquad VD\ (ID)\ circuit\ load\ line\ equation \end{cases}$$

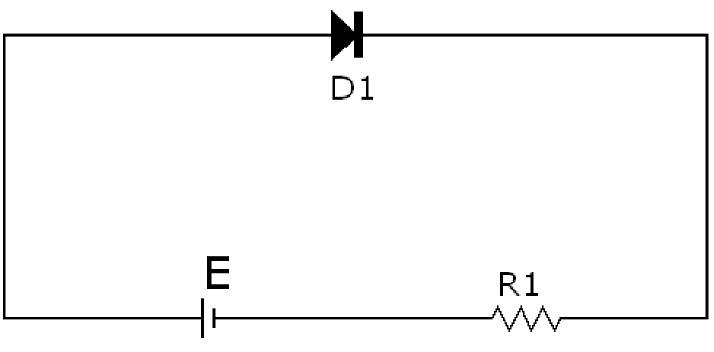
7.2. Graphical method

This method consists of determining the intersection point of the static charge line with the diode's voltage-current characteristic VD(ID).



7.2.1. Example 1

Consider the circuit of the figure below:

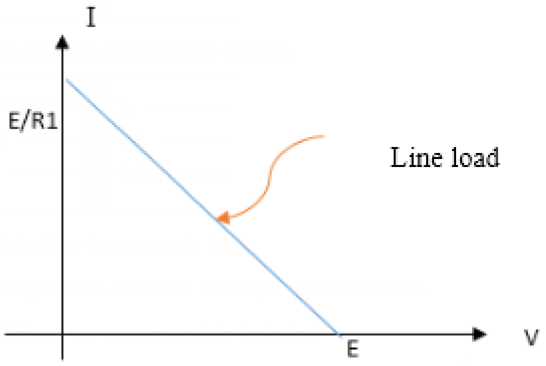


1) Draw the load line equation.

7.2.2. Solution

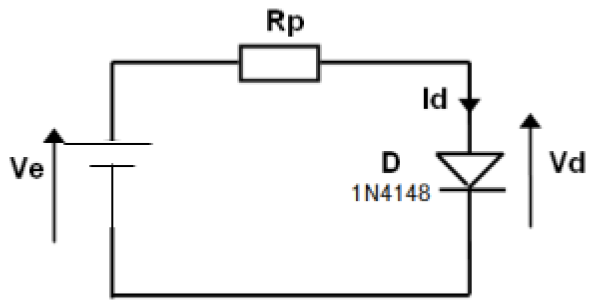
The equation of the charge line is:

$$V_D = E - R_1 I_D \Rightarrow I_D = \frac{E}{R_1} - \frac{V_D}{R_1}$$



7.2.3. Example 2

Consider the circuit of the figure below:



Given: Ve=+5V, Rp=1KΩ et V0=0.6V.

1) Determine the current Id.

7.2.4. Solution

The current Id= ?

VD+RpID-Ve=0➔ID=(Ve-VD)/Rp

NA:ID=(5-0.6)/1000=4.4mA

8. Diode in circuits

In all of the following circuits the diode is considered ideal, and $Ven(t) = Vmsin(wt)$.

8.1. Diode as rectifiers

The main application of PN junction diode is in rectification circuits. Diode rectifier circuits allow alternating (AC) current to be converted into one-way current (DC). Rectifiers are used in AC to DC power supplies.

8.1.1. Half wave rectifier

We consider the following circuit , where Ve(t)=Vm×sinwt

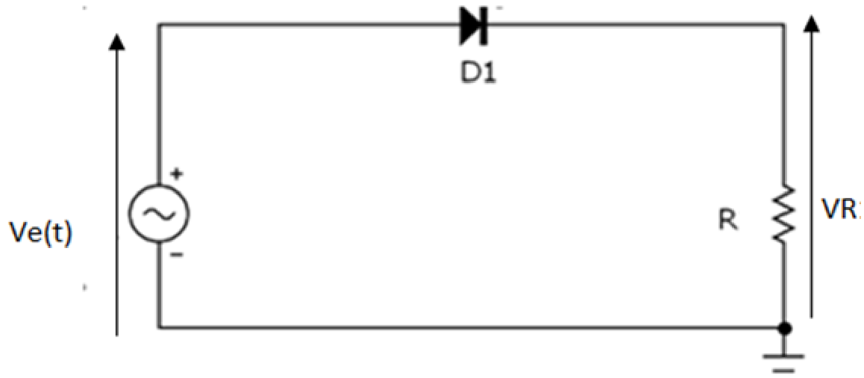


Figure 3. 9: Half wave rectifier circuit

Work: Analyze the circuit and draw Ve(t) and VR(t) in the same graph.

- ✓ During the positive wave of Ve(t)⇒the diode is forward biased (D is "on")⇒VR=Ve(t).
- ✓ During the negative wave of Ve(t)⇒the diode is reverse biased(D is "off")⇒VR=0.

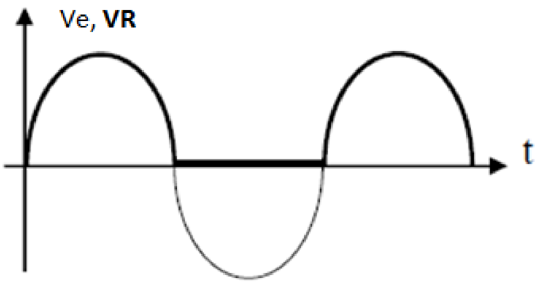


Figure 3. 10: Input/ output voltage form

8.1.2. Full-wave rectifier with a transformer

Consider the circuit below:

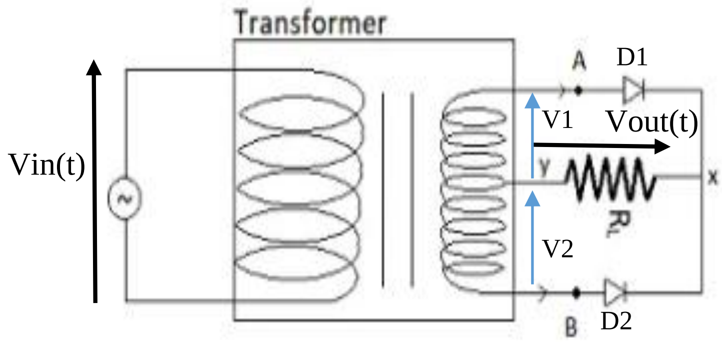


Figure 3. 11: Full wave rectifier with a transformer circuit

Work: Analyze the operation and plot the shape of the input signal Vin(t) and Vout(t) in the same graph.

During the positive half cycle, diode D1 is forward biased as it is connected to the top of the secondary winding while diode D2 is reverse biased as it is connected to the bottom of the secondary winding. Due to this, diode D1 will conduct acting as a short circuit and D2 will not conduct acting as an open circuit. ➔$Vs(t) - V1(t) = 0$➔ Vs(t)= $V1(t)$

During the negative half cycle, the diode D_1 is reverse biased and the diode D_2 is forward biased because the top half of the secondary circuit becomes negative and the bottom half of the circuit becomes positive. Thus in a full wave rectifier, DC voltage is obtained for both positive and negative half cycle. ➔$Vs(t) - V2(t) = 0$➔ Vs(t)=$-V2(t)$

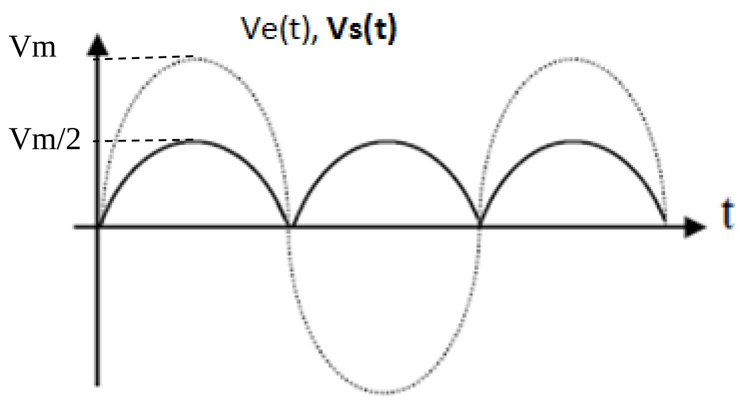


Figure 3. 12: Input/Output voltage form

7.3. Clipping circuits

These clipping circuits (also called limiters) aim to modify the amplitude of a voltage or more precisely to eliminate part of it.

A clipper is a device that removes either the positive half (top half) or negative half (bottom half), or both positive and negative halves of the input AC signal.

8.2. Positive clipper

Consider the circuit below, where $Ve(t) = VmSin(wt)$; $Vm > E$

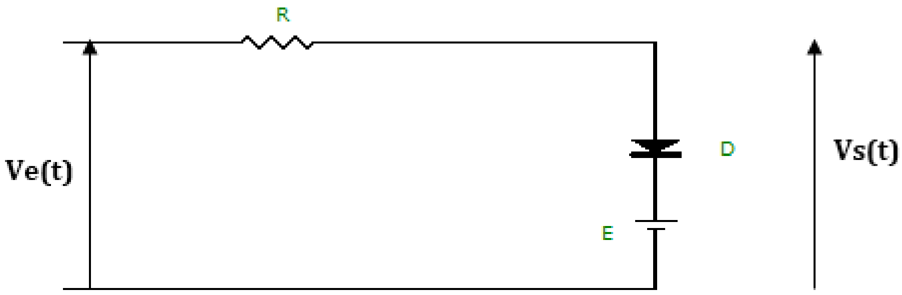


Figure 3. 13: Positive clipper circuit

Work : Analyze the circuit and draw the shape of Ve(t) and Vs(t) in the same graph.

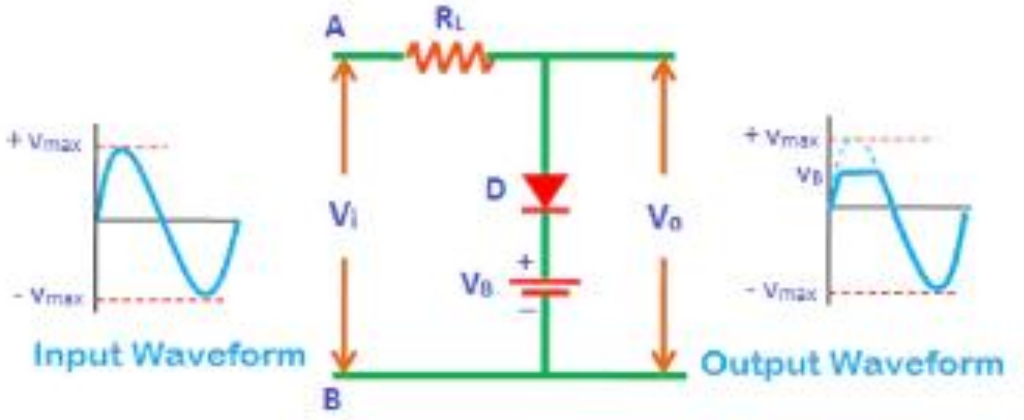
1) During the positive wave (+) of Ve(t)

- Ve<E⇒ D is reverse biased by ve(t) (i=0) ⇒ D ⇔ Open switch ⇒V_S=Ve(t).

- Ve>E⇒ D is forward biased by ve(t) ⇒ D ⇔ Closed switch ⇒ V_s=E.

2) During the negative wave (-) of Ve(t)

D is reverse biased by ve(t) (i=0) ⇒ D ⇔ Open switch ⇒V_S=Ve(t).



8.3. Dual clipper

Sometimes it is desired to remove a small portion of both positive and negative half cycles. In such cases, the dual clippers are used.

The dual clippers are made by combining the biased shunt positive clipper and biased shunt negative clipper.

1) We clip the positive part and the negative part. Both levels are adjustable.
2) It is necessary that the amplitude of the signal to be clipped is greater than E1 and E2, so that the circuit can correctly fulfill the function for which it was designed.
3) $Ve(t) = Vm \sin wt$ et $Vm > E1\ et\ E2$.

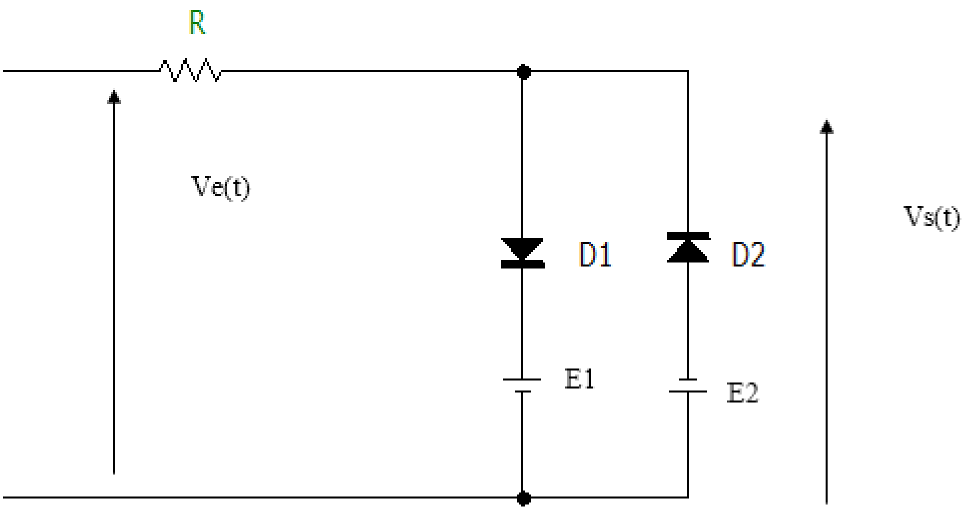


Figure 3. 14: Dual clipper circuit

Work: Draw the shape of the output signal.

Analysis:

✓ During the (+) wave of Ve(t) : D2 is always off

1) Ve(t)>E1 ➔D1 on ➔ VS=E1
2) Ve(t)<E1 ➔D1 off➔ VS=Ve(t)

✓ During the (-) wave of Ve(t) : D1 is always off

1) Ve(t)>E2 ➔D2 off ➔ VS=Ve(t)
2) Ve(t)<E2 ➔D2 on ➔ VS=-E2

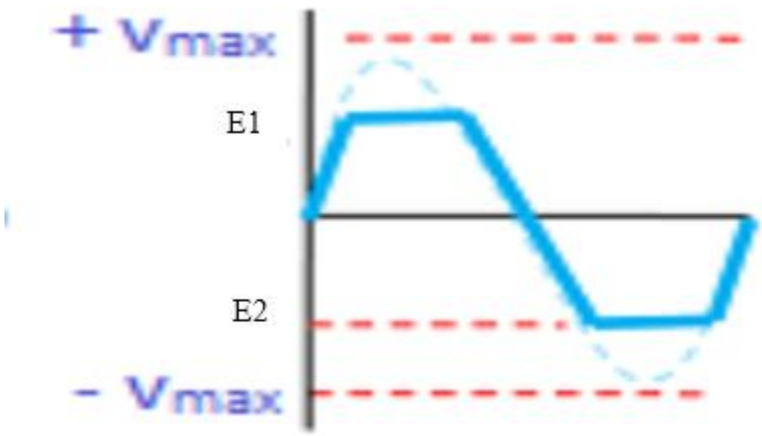


Figure 3. 15: Input/output voltage form

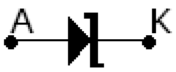
9. Zener Diode

The Zener diode is a PN junction component that differs from a rectifier diode since it is designed to be operated in reverse bias.

- When a Zener diode reaches reverse breakdown, its voltage remains almost constant.
- If a forward bias is applied to a Zener diode, it functions as a rectifier diode.

9.1. Symbol

The symbolic representation of Zener diode is shown in the figure below.



9.2. Zener diode biasing

The circuit diagram of the Zener diode is shown in the figure (3.16). The Zener diode is employed in reverse biasing.

When the reverse bias applies across the diode and the supply voltage is equal to the Zener voltage then it starts conducting in the reverse bias direction. So in order to obtain a constant voltage we will use the circuit below:

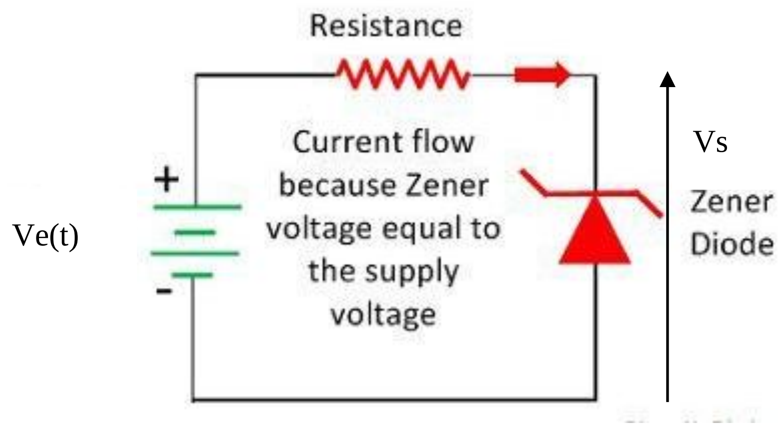


Figure 3. 16 : Reverse bias

- If Ve(t) is lower than the reverse voltage of the Zener, so Vs=Ve(t).
- if Ve(t) exceeds the Zener voltage, the Zener diode conducts strongly, and we have Vs=Vz (Zener voltage)

Its Zener equivalent circuit is given in the figure below :

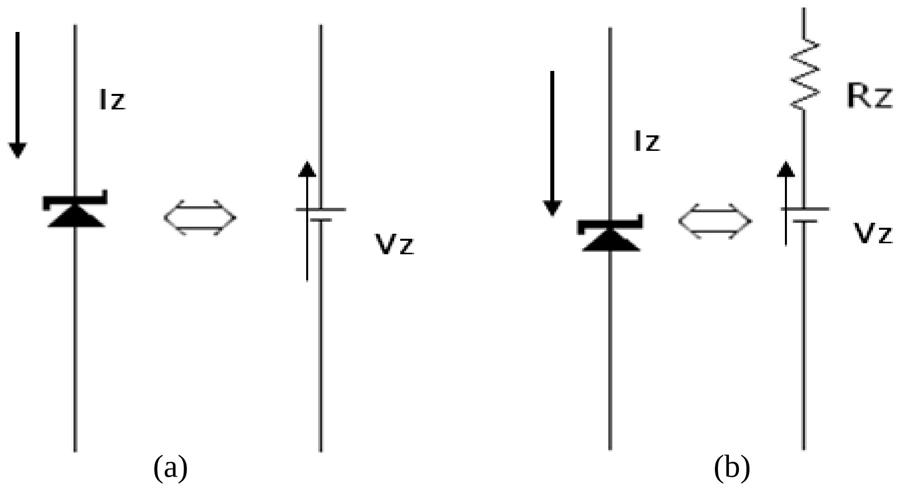


Figure 3. 17: Zener diode:(a) Perfect Model , (b): Real Model

9.3. V(I) characteristic of Zener diode

The VI characteristic graph of the Zener diode is shown in the figure (3.18). This curve shows that the Zener diode behaves like:

- Zener diodes have a characteristic similar to that of a normal (ordinary) diode in forward bias.

- When the reverse voltage applies across it and the reverse voltage rises beyond the predetermined rating, the Zener breakdown occurs in the diode.

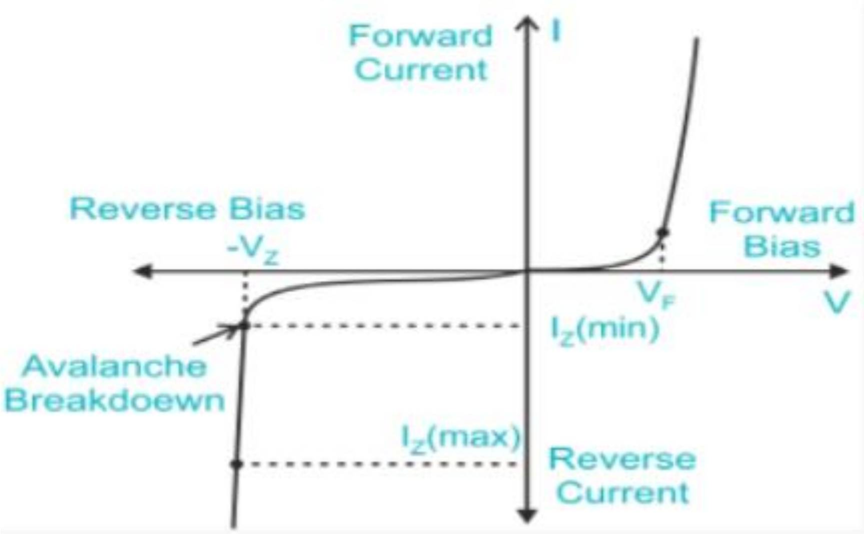


Figure 3. 18 : V(I) characteristic of Zener diode

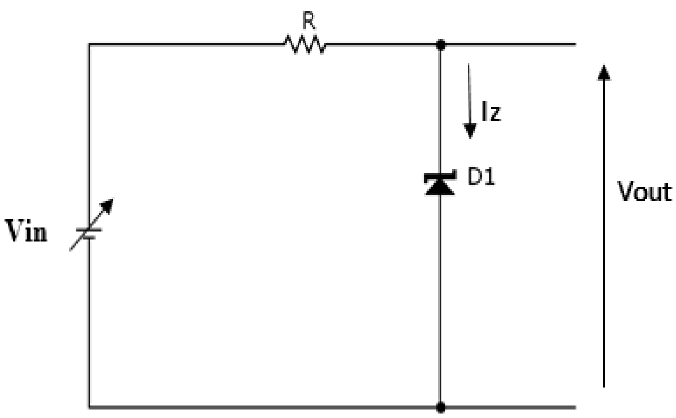
9.4. Applications of Zener Diode

As a Voltage Stabilizer – The Zener diode is used for regulating the voltage in the power supplies.

9.4.1. Zener regulation with variable input voltage

We consider the following circuit :

Given : Vz=10 V ; Izmin=0.25mA ; R=220Ω ; Izmax = 100mA.



1) Determine the lowest and highest input voltages that the Zener diode can maintain regulation.

   Ve(max)= ? and Ve(min)= ?

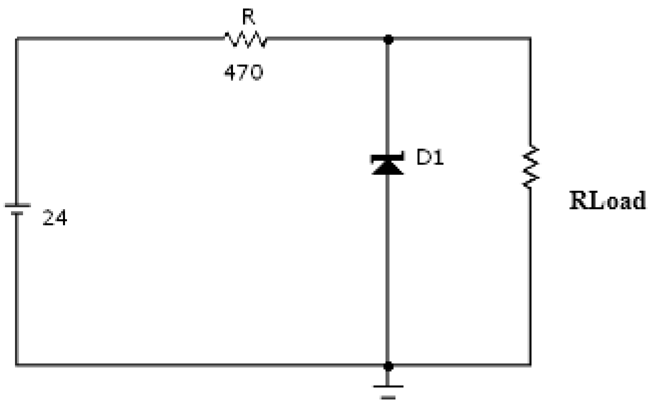
$$Vin = VZ + VR$$

$$\rightarrow \begin{cases} Vin(min) = VZ + RIZ(min) = 10 + 220 \times 0.25 \times 10^{-3} = 10.055V \\ Vin(max) = VZ + RIZ(max) = 10 + 220 \times 100 \times 10^{-3} = 32V \end{cases}$$

9.4.2. Zener regulation with variable load

The Zener diode maintains a constant voltage across RLoad as long as the Zener current is greater than Izmin and lesser than Izmax. This process is called load regulation.

Consider the circuit in the figure below:



Given : Vin=24V ; V_z = 12V ; I_{zmin} =1mA ; I_{zmax}=50 mA ?

Vin

1) Determine the minimum and maximum load currents for which the Zener diode will be able to maintain regulation.
2) What is the minimum value that can be used for RLoad?

IL(min)=? and IL(max)=?

$I = IZ + IL$ ➔ $IL = I - IZ$

$IL(min) - --\rightarrow$ IZ(max)

$IL(max) - --\rightarrow$ IZ(min)

$$I = \frac{Vin - Vz}{R} = \frac{24 - 12}{470} = 25.5mA$$

$IL(min) = I - IZ(max) = 25.5 - 50 = -24.5$ ×

$IL(max) = I - IZ(min) = 25.5 - 1 = 24.5mA$ √

3) RL(min)= ?

$$RL(min) = \frac{VZ}{IL(max)} = \frac{12}{24.5 \times 10^{-3}} 490\Omega$$

9.4.3. Zener limiter

In addition to voltage regulation applications, Zener diodes can be used in AC applications to limit voltage ripples to desired levels.

Given: V1(t)=Vm×sin wt; Vz=5V; Vth=0.7V.

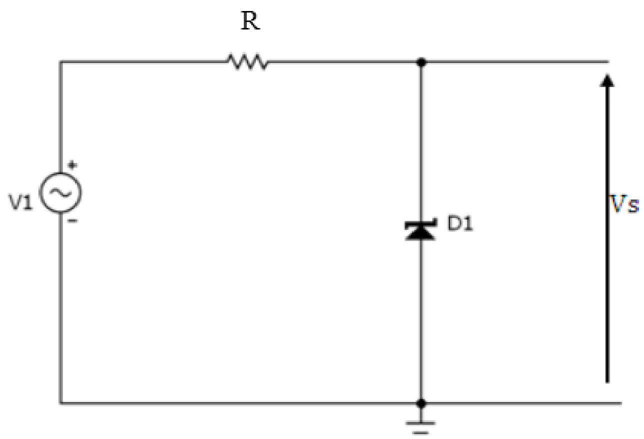


Figure 3. 19 : Zener limiter

- ➢ Analyze the circuit, and then plot the shape of the output signal VS(t) and V1(t) on the same graph.

1) Analysis of operation

During the positive wave A(+) :

- V1>Vz : The Zener diode works as a voltage limiter ➔ **Vs=Vz**

- V1<Vz : Zener diode works as a rectifier diode in the state “off “➔ **Vs=Ve**

During the negative wave A(-)

During the negative wave, the Zener diode acts like a diode in forward bias ➔ **Vs=0,7V**

The shape of the output voltage is drawn in the figure below:

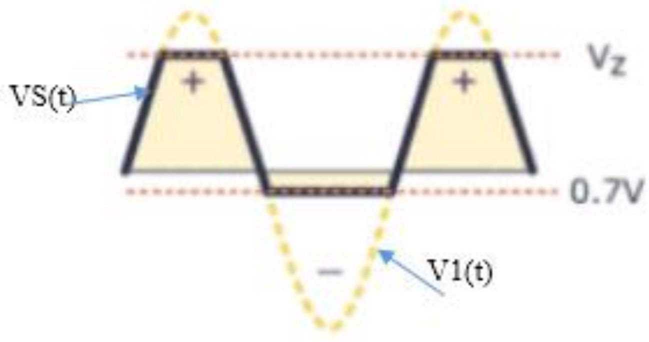


Figure 3. 20: Input/ output voltage form of Vs(t)

Chapter 4: Bipolar junction transistor (BJT)

1. Introduction

A bipolar transistor (BJT) is a semiconductor that has two PN junctions. According to the orientation of these junctions, we obtain two types of transistors: PNP transistors and NPN transistors. There are consequently three parts: P, N, P for a PNP transistor and N, P, N for an NPN transistor. Each of these parts is anmed: base (B) for the central region, emitter (E)and collector (C) for the other two.

Transistors are solid-state devices made up of semiconductor materials, primarily silicon, germanium, or gallium arsenide. They normally have three terminals: one common terminal for input and output signals, while a signal on one of the remaining terminals regulates the current in the other terminal.

In this chapter, we will describe the bipolar transistor, study its properties and operating modes, and analyze its usage and applications.

2. BJT construction and symbols

- ✓ Its made up of alternating layers of N and P type semiconductor materials joined metallurgically.
- ✓ The bipolar junction transistor (BJT) is a three-element (emitter, base, and collector) device
- ✓ Its operation involves conduction by two carriers, electrons and holes in the same crystal.
- ✓ There are two types of bipolar junction transistors:
    - PNP bipolar junction transistor
    - NPN bipolar junction transistor
- ✓ The transistor can be of PNP type (principal conduction by positive holes) or of NPN type (principal conduction by electrons), as shown in in the figure (4.1):

✓ Transistors are just two diodes with their cathodes (or anodes) tied together

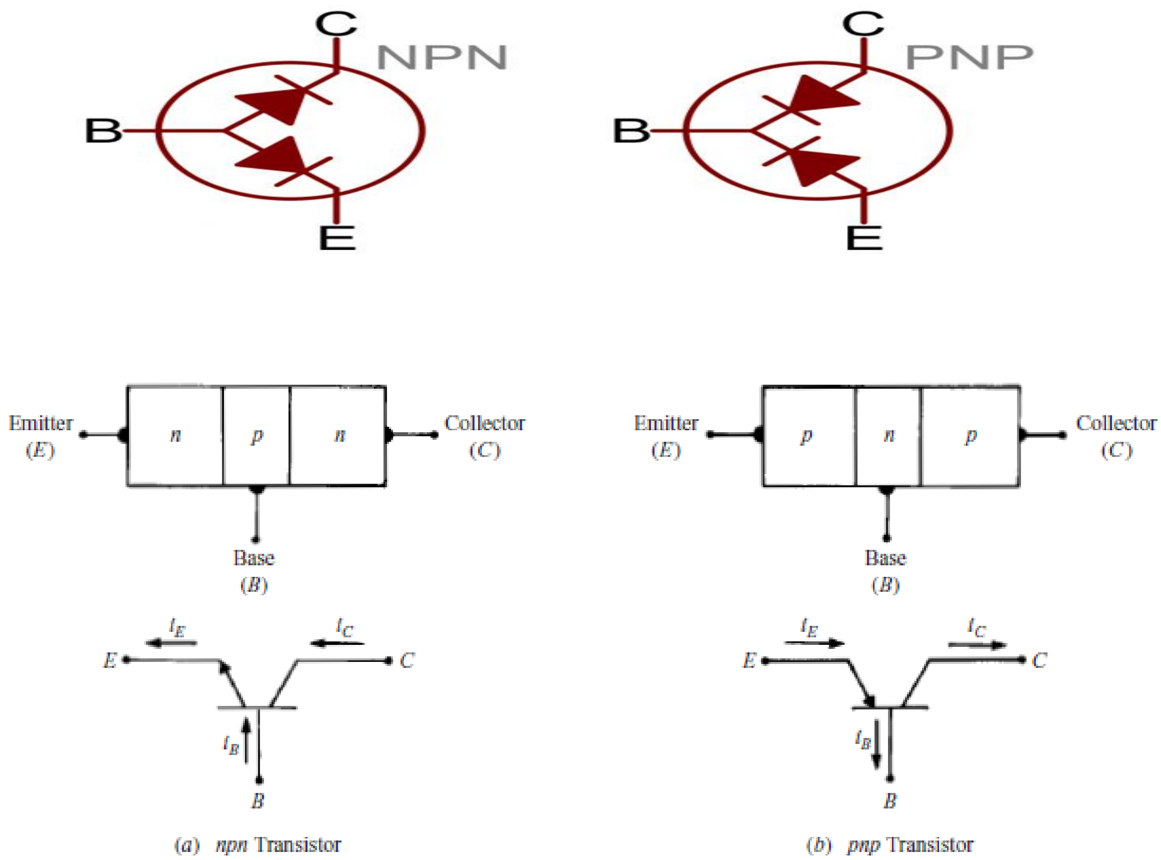


Figure 4. 1 : Equivalent model for BJT transistor: a) NPN transistor; b): PNP transistor

On the symbol of a transistor, an arrow is carried by the emitter; the direction of the arrow identifies the type of transistor.

The ratio between the collector current IC and the current IB is called the gain β (betat) such that:

$$\beta = \frac{I_C}{I_B} \tag{4.1}$$

$$\begin{cases} I_E = I_C + I_B \\ V_{CE} = V_{BE} + V_{CB} \end{cases} \tag{4.2}$$

3. BJT working principle

Usually, the base of NPN transistors are thin and lightly doped, so it has fewer holes while compared with the electrons in the emitter. The recombination of holes in the base with electrons in the emitter region will constitute the flow of the base current. Usually, the direction of conventional current flow will remain opposed to the flow of electrons.

The two PN junctions must be properly biased with voltages to work correctly.

For the transistor NPN:

- ✓ The BE junction is forward biased :$VB > VE$.
- ✓ The BC junction is reverse biased :$VB < VC$.

Conditions : ⇔VC>VB>VE

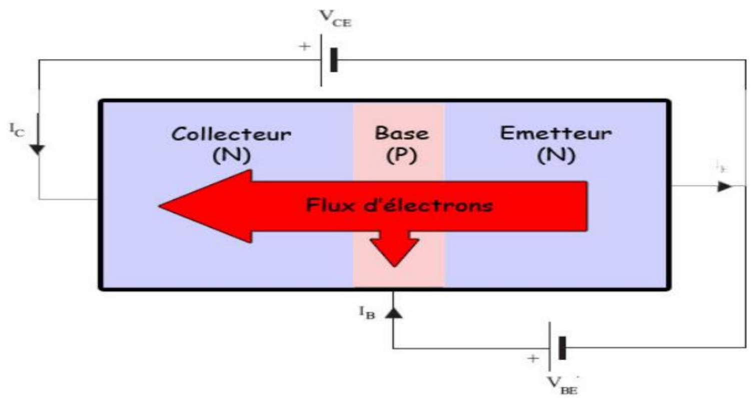
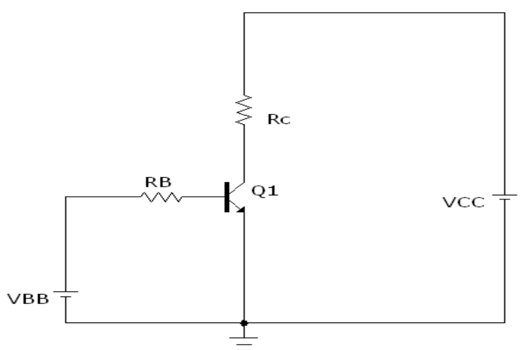


Figure 4. 2 : Transistor biasing

3.1. Example

Consider the circuit based on a bipolar transistor given in the figure below:



Given : VBB=5V, RB=10KΩ, RC=100Ω, VCC=10V, VBE=0.7V, β=150.

1. Determine the collector, base, and emitter currents I_B, I_C, I_E.
2. Determine the voltages: V_{CE}, V_{CB}.

3.2. Solution

I_B =?, I_C =? , I_E =? , V_{CE} =? , V_{CB} =?

$$I_B = \frac{\mathrm{VBB} - \mathrm{VBE}}{\mathrm{RB}} = \frac{5 - 0.7}{10\mathrm{K}} = 430\mu\mathrm{A}$$

$$I_c = \beta\mathrm{IB} = 150(430\mu\mathrm{A}) = 64.5\mathrm{mA}$$

$$I_E = \mathrm{IC} + \mathrm{IB} = 150(430\mu\mathrm{A}) = 64.5\mathrm{mA} + 430\mu\mathrm{A} = 64.9\mathrm{mA}$$

$$\mathrm{VCE} = \mathrm{VCC} - \mathrm{RCIC} = 10 - (64.5)(100) = 3.55\mathrm{V}$$

$$\mathrm{VCB} = \mathrm{VCE} - \mathrm{VBE} = 3.55 - 0.7 = 2.85\mathrm{V}$$

4. Characteristics of bipolar junction transistors

Manufacturers provide a series of curves for each type of transistor. We will mainly focus on the characteristics of the common emitter circuit shown in the following figure:

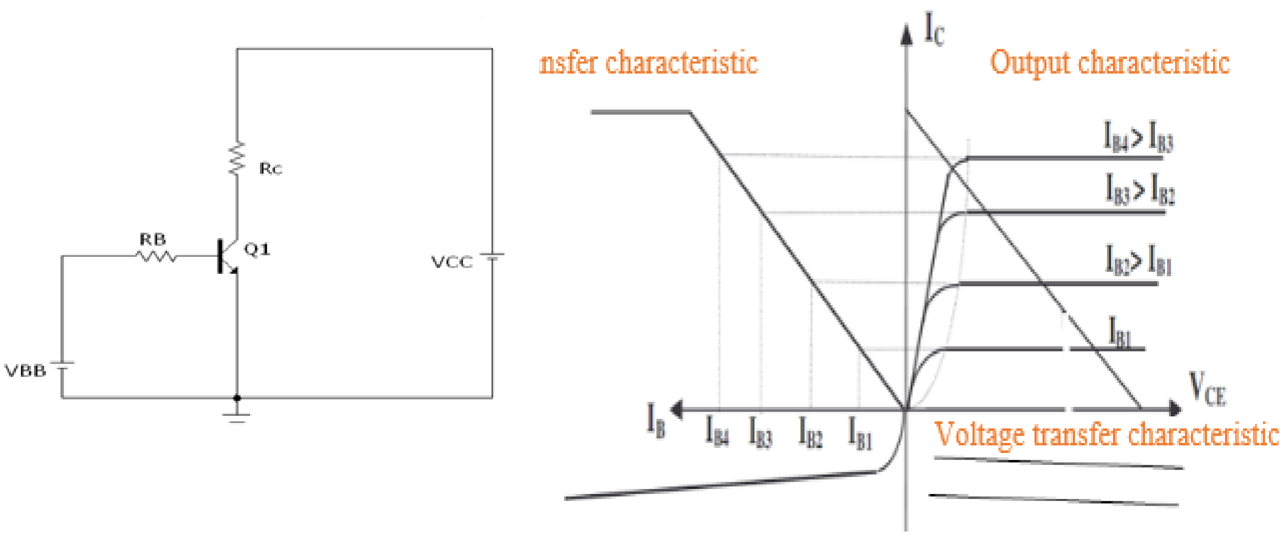


Figure 4. 3 : Bipolar Junction Transistor characteristics

4.1. Output characteristic Ic = f(VCE)

Output characteristic curves, are the curves IC = f(VCE) with IB = Cte. The IC = f(VCE) curves are plotted for different values of IB to define the behavior of the transistor output and the circuit that charges it.

There are **three operating regions** of a bipolar junction transistor:

1) **Active region**: The region in which the transistors operate as an amplifier.

2) **Saturation region**: The region in which the transistor is fully "**on**" and operates as a switch such that collector current is equal to the saturation current.
3) **Cut-off region**: The region in which the transistor is fully off and collector current is equal to zero (Ic=0).

4.2. Input characteristic $I_B = f(V_{BE})$

Input characteristic curves, are the curves IB = f(VBE) for different values of VCE. Almost all curves are confused. The curve is identical to the characteristic of a diode (basic emitter junction). For a silicon transistor VBE varies very little and remains near the threshold voltage of the base-emitter junction, i.e. 0.7V.

4.3. Current transfer characteristic

The curve IC = f(IB) is a current transfer network, the curve is linear and passes through the point IB =0 and ICEO.

4.4. Voltage transfer characteristic

The VBE = f(VCE) curves for different values of IB give the reaction of the output circuit on the input circuit.

5. DC load line and attack line

5.1. DC load line

The DC load line of a transistor shows the relationship between the current I_C and voltage V_{CE} of the circuit under consideration for a given load.

5.2. Attack line

The attack line is the equation that relates the input current I_B to the input voltage V_{BE}.

5.3. Q-point

Q-point or operating point is a point in transistor characteristics in which the transistor works. Variations of currents and voltages takes place around this point when input AC signal is applied.

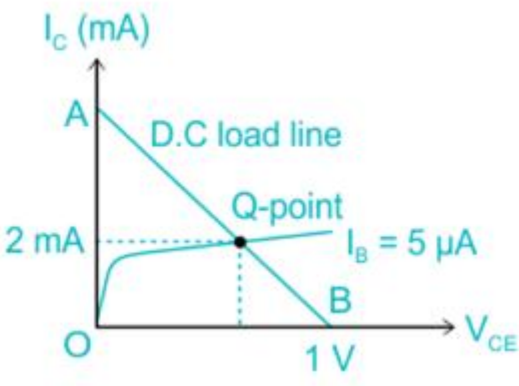


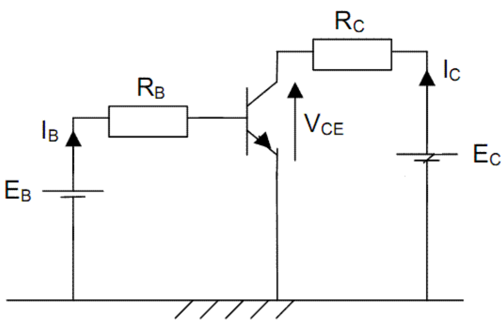
Figure 4. 4: The DC load line and the operating point

6. BJT biasing circuits

Biasing a transistor means defining the continuous (static) quantities IB, IC, VCE and VBE. Knowing the value of these parameters makes it possible to set an operating (rest) point Q.

6.1. The fixed-bias circuit

We consider the following fixed bias circuit:



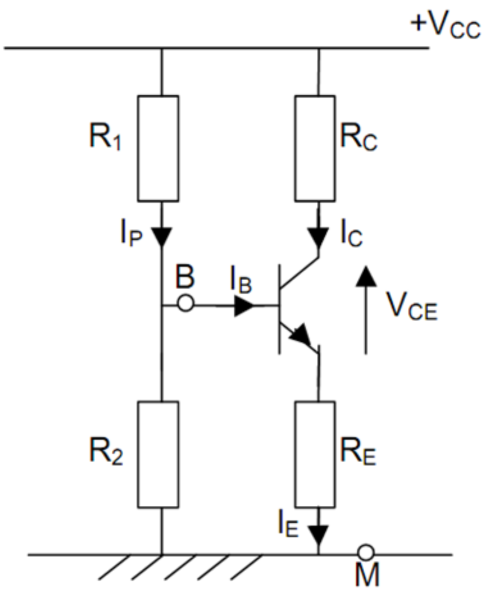
1. Find the load and attack line equation.
   - The load line equation is: $I_C = \frac{V_{CC}}{R_C} - \frac{V_{CE}}{R_C}$
   - The attack line equation is: $I_B = \frac{V_{BB}}{R_B} - \frac{V_{BE}}{R_B}$

6.2. The voltage-divider bias circuit

In this configuration we use only one supply.

6.2.1. Exercise

Consider the following circuit:



β=100, Vcc=10V and we want an operating point Q(Ic=5mA, VCE=5V), RE=495Ω, R2=6.8K Ω, VBE=0.6V.

IB is negligible compared to the current passing through the two resistors R1 and R2.

Determine the value of R1.

6.2.2. Solution

$VB = \frac{R2}{R1+R2} Vcc$ (1)

$VE = Re.IE = RE(1 + 1/\beta)Ic$ (2)

$VBE = VB - VE = 0.6V$ (3)

NA :

Equation 2 →VE=495(1+1/100).5.10^{-3}=2.49V

Equation 3 → VB=0.6+VE=0.6+2.49=3.1V

Equation 1 → R2VCC=(R1+R2)×3.1

R1=2.22×R2

N.A: R1=2.22×R2=2.22 ×6.8 10^3=15KΩ

6.3. Biasing by base-collector resistance

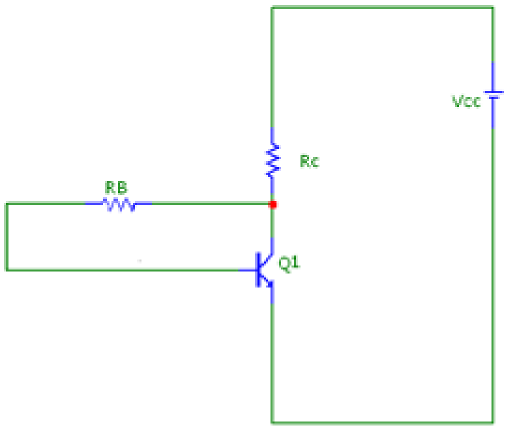
In this configuration we use only one supply.

6.3.1. Exercise

We consider the following circuit:

Vcc=10V, VCE0=5V ; IC0=5mA ; β=200, VBE=0.6V.

Determine the value of the resistors RC and RB=?.



6.3.2. Solution

RC= ?; RB= ?.

The value of the resistor Rc=?

$$VCC = RC(ICQ + IB) + VCQ = RC(1 + 1/\beta)ICQ + VCEQ$$

⇨ $RC = \frac{VCC-VCEQ}{(1+1/\beta)\mathrm{ICQ}}$

NA:

$$RC = \frac{10 - 5}{(1 + 1/200)5 \times 10^{-3}} = 995\Omega$$

RB=?

$$VCE = VBE + RBIB = VBE + RB.\frac{ICQ}{\beta} \rightarrow RB = \frac{(VCEQ-VBE)}{ICQ}\beta$$

NA:

$RB = \frac{(5-0.6)}{5\times10^{-3}}$200= 176 KΩ

7. Applications of BJTs

BJTs have a wide range of applications due to their versatile properties. This makes them useful as switches or amplifiers. Here are some of the key areas where they are used:

- **Amplification:** BJTs can be used in various circuits to amplify small signals, thanks to their property of transforming a low-power input into a high-power output. This is particularly useful in audio and radio frequency applications.

- **Switching:** BJTs can also function as electronic switches. When a BJT is in the cut-off region, it behaves as an open switch, while in the saturation region it acts as a closed switch.

- **Regulation:** BJTs are integral components in voltage regulation circuits, including the design of power supplies.

7.1. Transistors BJT as amplifier

The transistor will operate as an amplifier if the transistor is biased into the linear region. We add to the continuous regime (DC) a signal which varies over time (Vin(t)), with use the connection capacitors (C1 and C2) and decoupling capacitor (CE) as shown in figure below (common emitter amplifier).

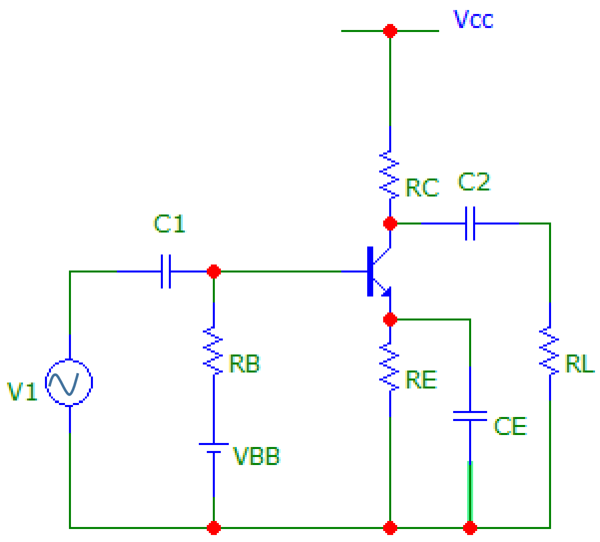


Figure 4. 5: Common Emitter (CE) Configuration

The electrical values envisaged depend on time (e.g. emitter-base voltage vbe(t), collector current ic(t)).

A dynamic regime is the small signal regime where the electrical quantities are formed by adding a small dynamic variation to a static value around this value:

$$\begin{cases} VBE(t) = VBE + vbe\,(t) = VBE + \Delta vbe\, sin\,(wt) \\ IC(t) = IC + ic\,(t) = IC + \Delta ic\, sin\,(wt) \end{cases} \quad (4.3)$$

Note :

- The continuous quantities, noted in uppercase (capita) letters, (VBE, IC, ...) define the static operating point.

- The dynamic quantities, noted in lowercase, (vbe, ic....) define the dynamic operation.

- The small signal regime is always characterized by peak amplitudes of dynamic quantities much smaller than the values of static quantities (∆vbe << VBE, ∆ic << IC ....)

7.1.1. BJT in small-signal dynamic

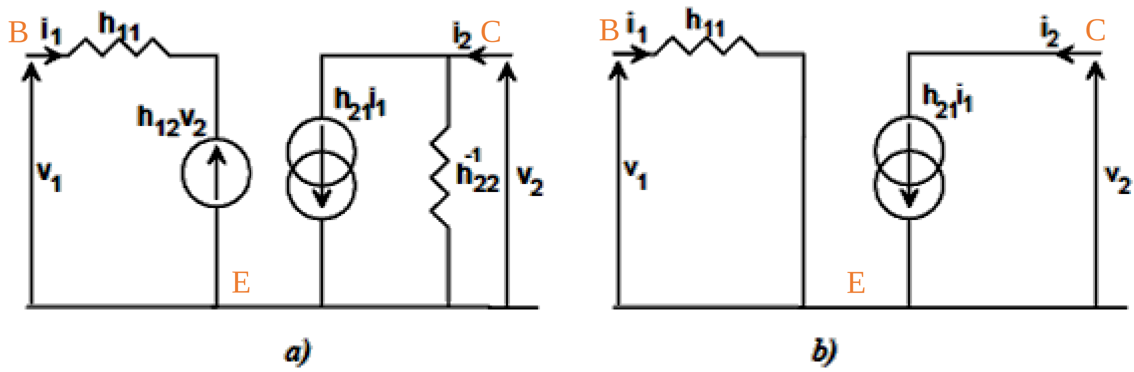


Figure 4. 6: Low-frequency small-signal equivalent circuits of a BJT (a): Complete Scheme; (b) Simplified Scheme

$\boldsymbol{h11}$: input impedance; $\boldsymbol{h12}$: Reverse transfer ratio; $\boldsymbol{h22}$: Output conductance ;$\boldsymbol{h21}$: current gain.

The exploitation of the equivalent model of the transistor will make it possible to calculate the following quantities:

- Current amplification $A_i = \frac{i_2}{i_1}$

- Voltage amplification $A_v = \frac{v_2}{v_1}$

- Input impedance $Z_e = \frac{v_1}{i_1}$

- Output impedance $Z_s = \frac{v_2}{i_2}$

Notes :

In the dynamic regime:

□ The capacitors C are replaced by short circuits at the signal frequency.

□ DC source is replaced by a ground.

7.1.2. Bipolar Transistor Configurations

A BJT can be configured into three types, they are a common collector configuration, common base configuration and common emitter configuration.

AC equivalent of a network is obtained by:

1) Setting all DC sources to zero and replacing them by a short – circuit equivalent
2) Replacing all capacitors by short – circuit equivalent
3) Redrawing the network in a more convenient and logical form.

In all the configuration determine the four parameters:

- Current amplification $A_i = \frac{i_2}{i_1}$
- Voltage amplification $A_v = \frac{v_2}{v_1}$
- Input impedance $Z_e = \frac{v_1}{i_1}$
- Output impedance $Z_s = \frac{v_2}{i_2}$

7.1.2.3.Common-Emitter configuration

The common –Emitter configuration is shown in the figure below:

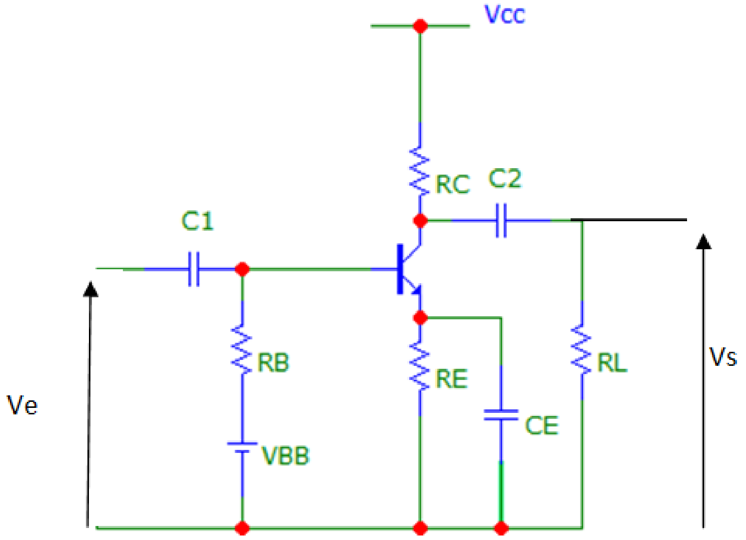


Figure 4. 7: Common –Emitter circuit

Remark

- In dynamic mode the capacitors C1, C2 and CE are replaced by short circuits

The equivalent dynamic scheme is represented in the figure below:

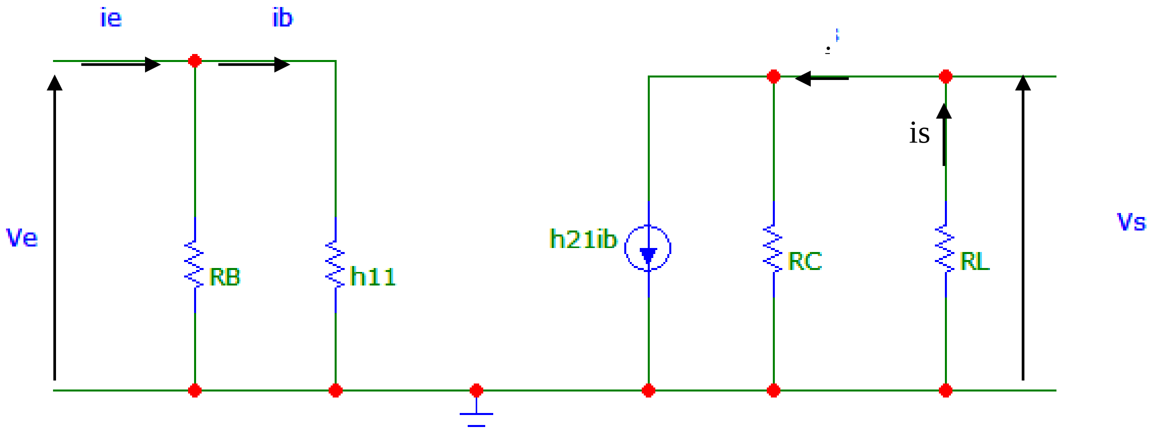


Figure 4. 8: Equivalent dynamic scheme for common-Emitter configuration

- The voltage gain of the circuit: $G_V = \frac{V_s}{V_e}$

$v_s = -h_{21}\frac{R_c R_L}{R_c+R_L} i_b$ (1)

$v_e = h_{11} i_b \Rightarrow$ (2)

We take the ratio eq1/eq2, we obtain:

$$G_V = \frac{v_s}{v_e} = -h_{21}\frac{R_C R_L}{(R_C + R_L)h_{11}}$$

- The current gain of the circuit : $A_i = \frac{i_s}{i_e}$

$i_s = \frac{R_c}{R_c+R_L} h_{21} i_b$ (3)

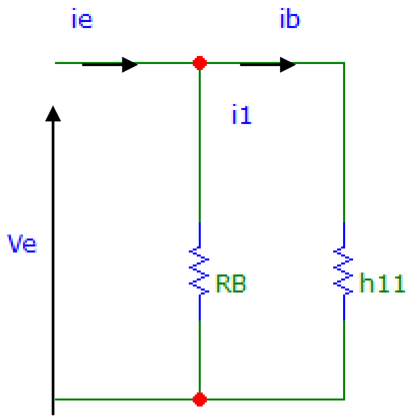
$i_b = \frac{R_B}{R_B+h_{11}} i_e \Rightarrow i_e = \frac{R_B+h_{11}}{R_B} i_b$ (4)

then :

$$A_i = \frac{i_s}{i_e} = \frac{R_c}{R_c + R_L} \cdot \frac{R_B}{R_B + h_{11}} h_{21}$$

The input impedance

$$z_e = \frac{v_e}{i_e}$$



$$v_e = h_{11} i_b \qquad (5)$$

$$i_b = \frac{R_B}{R_B + h_{11}} i_e \Rightarrow i_e = \frac{R_B + h_{11}}{R_B} i_b \qquad (6)$$

$$\frac{i_e}{v_2} = \frac{1}{R_b} + \frac{1}{h_{11}} = R_b // h_{11}$$

$$z_e = R_B // h_{11}$$

- The output impedance

$$z_s = \left. \frac{Vs}{i_s} \right|_{eg=0}$$

$$z_s = \frac{v_s}{i_s} \text{ with } \begin{cases} R_L & \textbf{disconnected} \\ & v_e = 0 \end{cases}$$

$$v_e = 0 \Rightarrow i_e = 0 \Rightarrow i_b = 0 \Rightarrow h_{21} i_b = 0 \Rightarrow z_s = R_c$$

7.1.2.2.Common Collector Configuration

The corresponding circuit to the common collector configuration is given in the figure below:

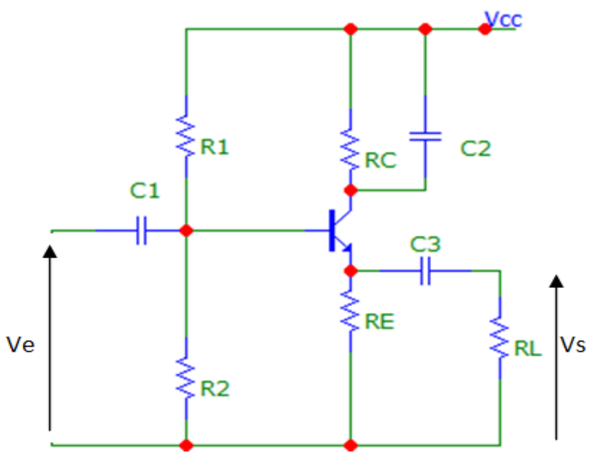


Figure 4. 9: Common collector configuration

The equivalent scheme is given in the figure below :

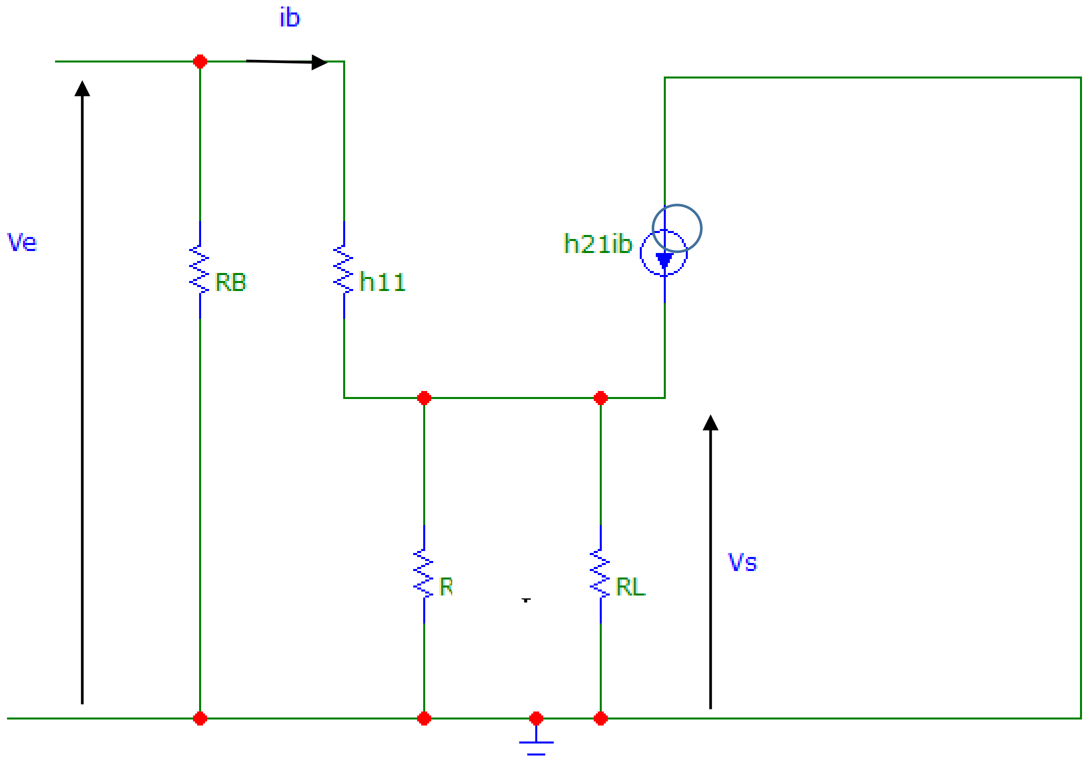
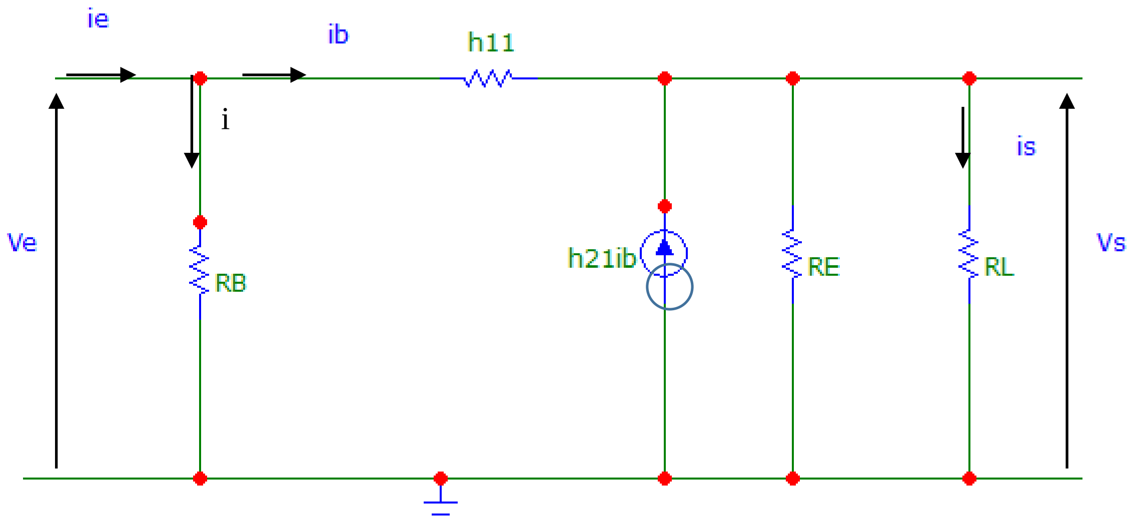


Figure 4. 10: Equivalent dynamic scheme for common-Collector configuration

we pose $RB = R1//R2$



➢ The voltage gain: $G_v = \frac{V_s}{V_e}$

$$v_S = (R_E//R_L)(1 + h_{21})i_b \qquad (1)$$

$$v_e = h_{11}i_b + V_s = [h_{11} + (R_E//R_L)(1 + h_{21})]i_b \qquad (2)$$

Equation (1)/(2) gives us :

$$G_v = \frac{(R_E//R_L)(1+h_{21})}{h_{11}+(R_E//R_L)(1+h_{21})}$$

- The input impedance: $Z_e = \frac{V_e}{i_e}$

we have: $i_e = i + i_b = \frac{V_e}{R_B} + i_b$ (3)

From equation (2) $\Rightarrow$ $i_b = \frac{V_e}{h_{11}+(R_E//R_L)(1+h_{21})}$ (4)

Eq (4) in eq (3), we obtain:

$$i_e = \frac{v_e}{R_B} + \frac{v_e}{h_{11}+(R_E//R_L)(1+h_{21})}$$

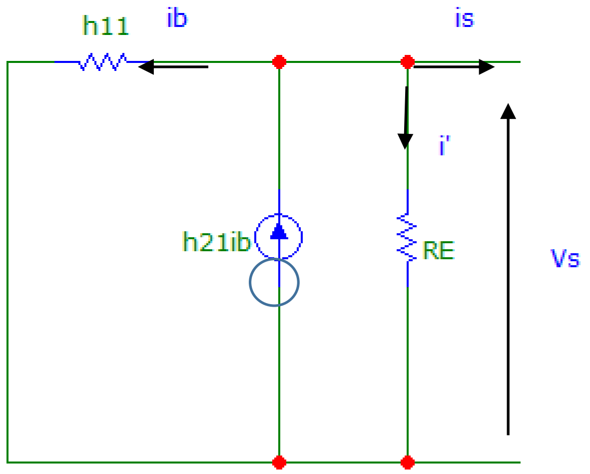
$$\frac{i_e}{v_e} = \frac{1}{R_B} + \frac{1}{h_{11}+(R_E//R_L)(1+h_{21})}$$

so

$$Z_e = R_B//[h_{11}+(R_E//R_L)(1+h_{21})]$$

- The output impedance: z_s =?

$z_s = \frac{V_S}{i_s}\Big|_{V_e(t)=0}$ and R_L disconnected (see figure below)



- Disconnect the load
- Short circuited the input voltage

$$i_s = i' - (1 + h_{21})i_b = \frac{V_s}{R_E} - (1 + h_{21})i_b \quad (5)$$

$$V_s = -h_{11}i_b \quad (6)$$

We replace equation 5 in equation 6 we obtain:

$$i_s = \frac{V_s}{R_E} + \frac{V_s}{h_{11}}(1 + h_{21})$$

$$\frac{i_s}{V_s} = \frac{1}{z_s} = \frac{1}{R_E} + \frac{(1 + h_{21})}{h_{11}}$$

$$Z_s = R_E // (h_{11}/1{+}h_{21})$$

- The current gain of the circuit : $G_i = \frac{i_s}{i_e} = \frac{i_s}{i_b}.\frac{i_b}{i_e}$

Using the current divider:

$$i_s = \frac{R_E}{R_E+R_L}(1 + h_{21})i_b \Rightarrow \frac{i_s}{i_b} = \frac{R_E}{R_E+R_L}(1 + h_{21}) \quad (7)$$

You have to search $i_e = f(i_b)$

$\frac{1}{z_e} = \frac{1}{R_B} + \frac{1}{h_{11}+(R_E//R_L)(1+h_{21})}$ (see the section Ze)

$$V_e = h_{11}i_b + (1 + h_{21})(R_E//R_L)i_b \Rightarrow \frac{V_e}{i_b} = h_{11} + (R_E//R_L)(1 + h_{21})$$

$$V_e = z_e i_e \Rightarrow i_e = \frac{V_e}{z_e} = [h_{11} + (RE \parallel RL)(1 + h_{21})].ib/Ze$$

$$\frac{i_e}{i_b} = [h_{11} + (R_E//R_L)(1 + h_{21})]/z_e \Rightarrow$$

$$\frac{i_e}{i_b} = \frac{[h_{11}+(R_E//R_L)(1+h_{21})]}{R_B//[h_{11}+(R_E//R_L)(1+h_{21})]} \quad (8)$$

The multiplication of eq (7) and (8) gives :

$$G_i = \frac{R_E(1 + h_{21})}{R_E + R_L}.\frac{R_B//[h_{11} + (R_E//R_L)(1 + h_{21})]}{[h_{11} + (R_E//R_L)(1 + h_{21})]}$$

7.1.2.3.Common Base Configuration

The base terminal in this arrangement is grounded and serves as the common terminal for both the transistor's input and output. Emitter–base is the input while the signal to be amplified is linked and the output signal is drawn across the collector and base as illustrated in Figure below.

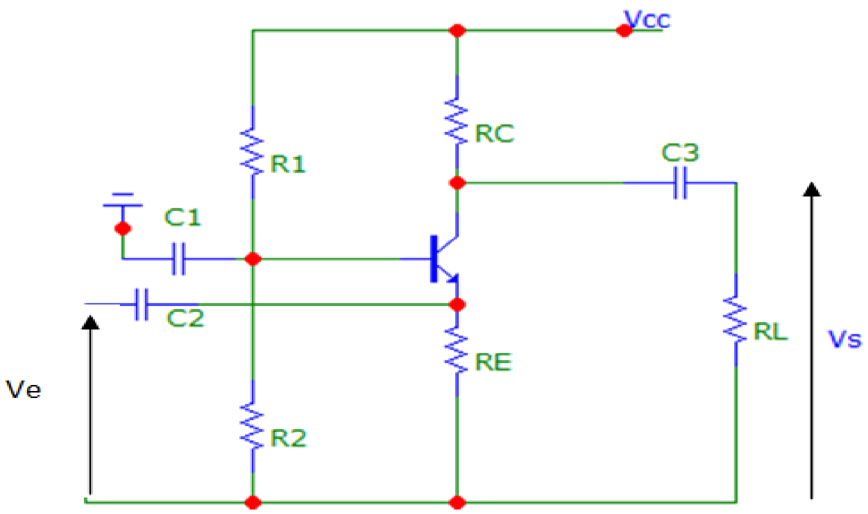


Figure 4. 11: Common base configuration

The equivalent scheme is depicted in the figure below:

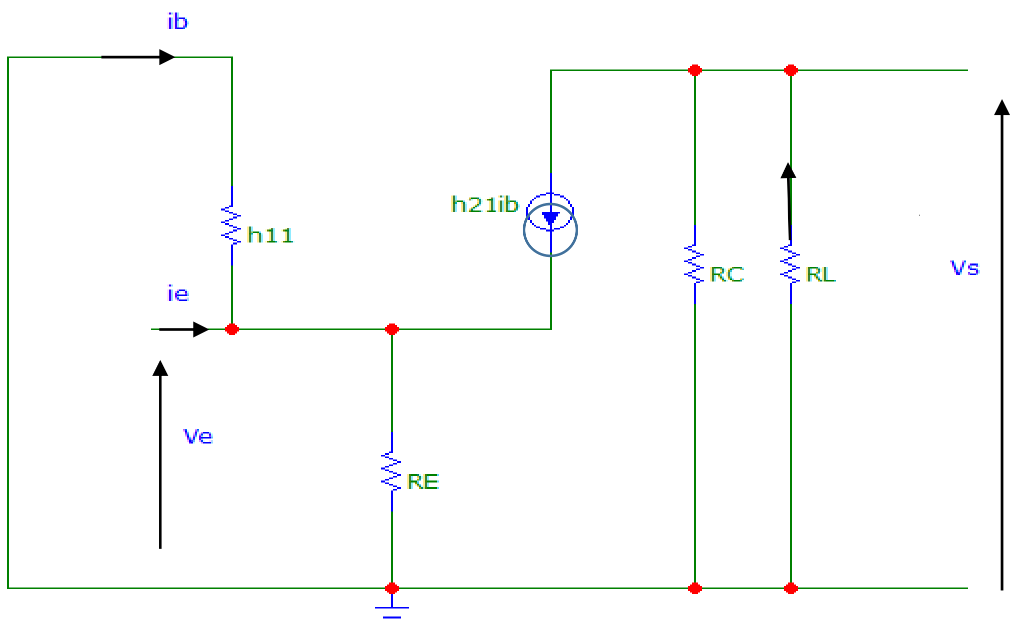


Figure 4. 12: Equivalent dynamic scheme for common-Base configuration

The voltage gain of the circuit : $G_v = \frac{V_s}{V_e}$

$$v_s = -(R_c//R_L)h_{21}i_b \quad (1)$$

$$v_e = -h_{11}i_b \Rightarrow \quad (2)$$

$$G_v = h_{21}\frac{(R_c//R_L)}{h_{11}} \quad (3)$$

- The current gain of the circuit : $G_i = \frac{i_s}{i_e}$

$$ve = RE(ie + ib(1 + h21)) \quad (4)$$

$$ve = -h11ib \quad (5)$$

We replace equation (5) in (6), we obtain:

$$ie = -ib(\frac{h11}{RE} + 1 + h21) \quad (6)$$

We apply the current divider:

$$i_s = \frac{-R_c}{R_c+R_L}h_{21}i_b \quad (7)$$

$$eq(4)/eq(3) = G_i = \frac{R_c h_{21}}{R_c+R_L}.\frac{R_E}{h_{11}+R_E(1+h_{21})} \quad (8)$$

- Input impedance $z_e = \frac{v_e}{i_e}$ =?

$$ve = RE(ie + ib(1 + h21)) \quad (9)$$

$$ve = -h11ib \Rightarrow ib = -\frac{ve}{h11} \quad (10)$$

Equation (9) in (10), we obtain:

$$i_e = \frac{ve}{R_E} - i_b(1 + h_{21}) \text{ avec } Ve = -h_{11}i_b \quad (11)$$

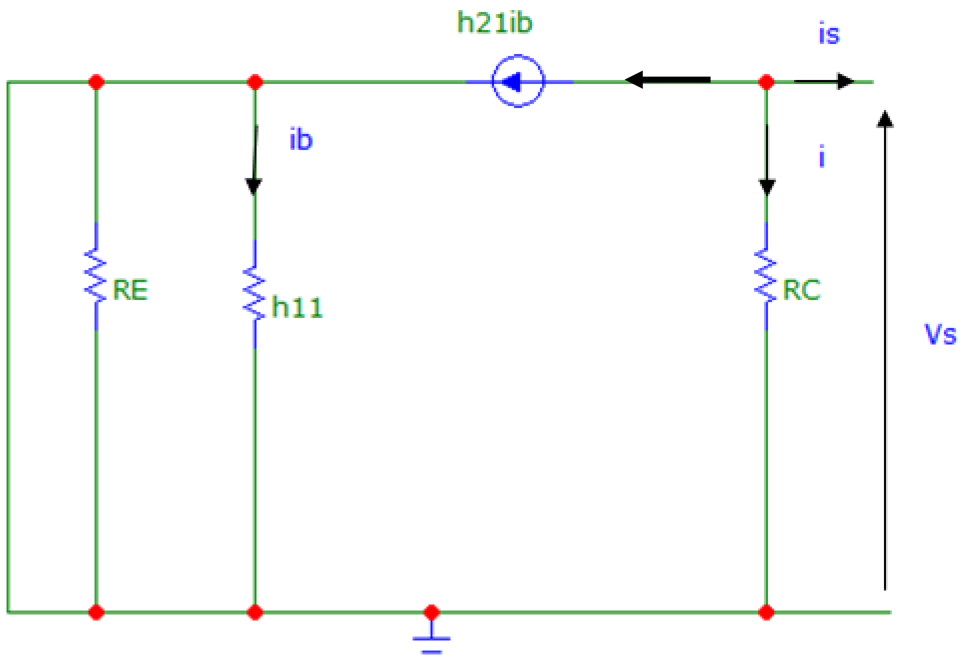
Alors : $ve\left(1 + \frac{RE}{h11}(1 + h21)\right] = REie$

$$\frac{i_e}{v_e} = \frac{1}{z_e} = \frac{1}{R_E} + \frac{(1+h_{21})}{h_{11}} = \frac{1}{R_E} + \frac{1}{h_{11}/(1+h_{21})} \Rightarrow$$

$$z_e = R_E//\big(h_{11}/(1 + h_{21})\big)$$

□ The output impedance:

$z_s = -\frac{s}{i_s}\Big|_{V_e=0}$ with R_L disconnected (see the figure below)



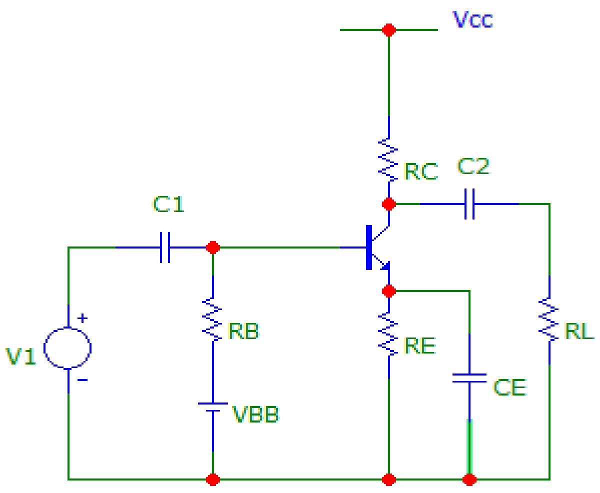
$i_s = \frac{V_s}{R_c} + h_{21}i_b$ since $h_{11}i_b = 0 \Rightarrow i_b = 0$ then

$\frac{V_s}{i_s} = R_c \Rightarrow$

$z_s = R_c$

7.1.3. Exercise

Consider the circuit in the figure below:

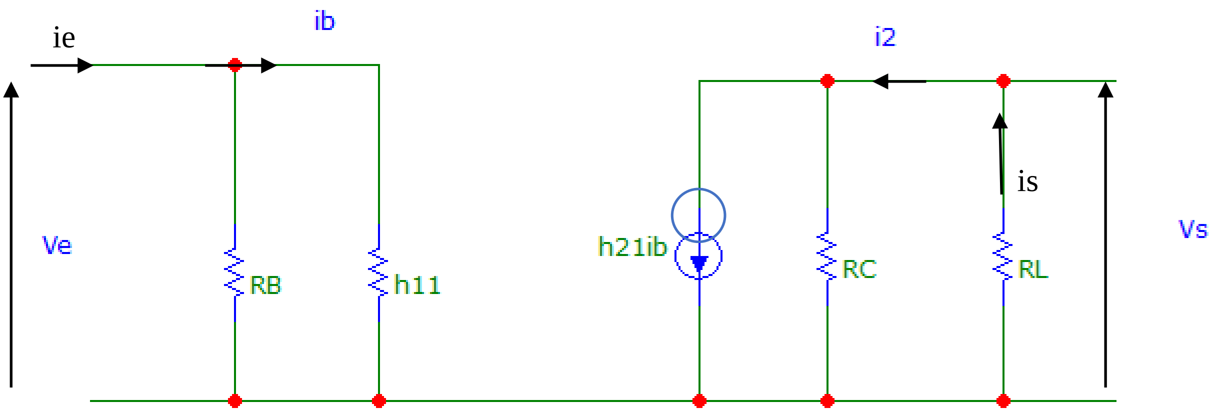


1) Represent the equivalent diagram of the simplified transistor alone.
2) Establish the small low frequency signal equivalent diagram of the complete stage.
3) Calculate the voltage amplification Av, the current amplification Ai as well as the input impedances Ze and output Zs of the stage.
4) CE is disconnected, repeat the same questions.

7.1.4. Solution

1. The equivalent alternative diagram

The capacitors C1, C2 and CE are replaced by short circuits



2. The voltage gain of the assembly : $G_V = \frac{V_s}{V_e}$

$v_s = -h_{21}.\frac{R_c R_L}{R_c + R_L} i_b$ et $v_e = h_{11} i_b \Rightarrow$

$$G_V = \frac{v_s}{v_1} = -h_{21}\frac{R_C R_L}{(R_C + R_L)h_{11}}$$

3. The current gain of the assembly : $A_i = \frac{i_s}{i_e}$

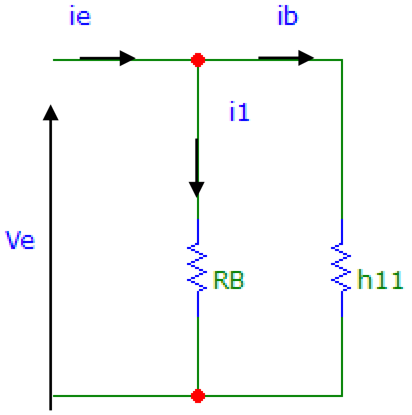
$v_s = -R_L i_s = -\frac{R_c R_L}{R_c + R_L} h_{21} i_b \Rightarrow i_s = \frac{R_c}{R_c + R_L} h_{21} i_b$ avec

$i_b = \frac{R_B}{R_B + h_{11}} i_e \Rightarrow i_e = \frac{R_B + h_{11}}{R_B} i_b$

so :

$$A_i = \frac{i_s}{i_e} = \frac{R_c}{R_c + R_L}.\frac{R_B}{R_B + h_{11}} h_{21}$$

4. The input impedance Ze



$$z_e = \frac{v_e}{i_e}$$

$$v_e = h_{11} i_b$$

$$i_e = i_1 + i_b = \frac{v_e}{R_B} + \frac{v_e}{h_{11}}$$

$$\frac{i_e}{v_2} = \frac{1}{R_B} + \frac{1}{h_{11}} = R_B // h_{11}$$

$$z_e = R_B // h_{11}$$

1. The output impedance Ze

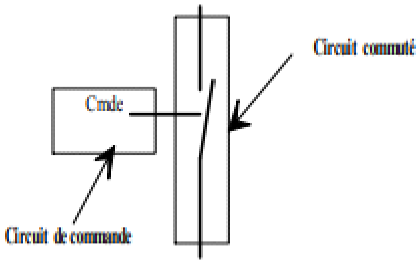
$$z_s = \frac{v_2}{i_2} \text{ avec } \begin{cases} R_L & \text{disconnected} \\ & v_e = 0 \end{cases}$$

$$v_e = 0 \Rightarrow i_1 = 0 \Rightarrow i_b = 0 \Rightarrow \beta i_b = 0 \Rightarrow$$

$$z_s = R_c$$

7.2. Transistor BJT as switch

The switching transistor is used to open or close a circuit. Thus it can control an LED, a relay, a motor...etc... We generally compare the transistor output circuit to a switch which is controlled either by a voltage or by a current depending on the type of transistor chosen.



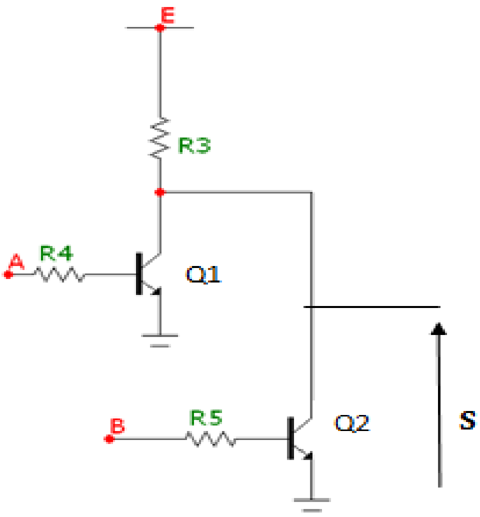
The transistor behaves like a switch between C and E controlled by the base.

- ✓ Transistor blocked if (Vbe=0), Ib is zero →Ic=0, BJT "off" ⇔ open switch;
- ✓ Vbe≥0.7V⇔ closed switch ; BJT " on": Ib>Ic/Bmin (Vcesat=0V).

7.2.2. Example

We consider the two transistors Q1 and Q2 operate in switching mode.

- Analyze the operation of the circuit in the figure below, and deduce the logical function performed.



7.2.3. Solution

Analyses :

- if VA=VB=0V both transistors are "OFF"⟹S=E.
- - If one of the input voltages (or both) is equal to E, the corresponding transistor "ON" ⟹S=0.

- $S = \overline{A + B}$

B	A	S
0	0	1
0	1	0
1	0	0
1	1	0

The logical operation carried out is **NOR**.

Chapter 5: Operational Amplifiers

1. Introduction

Electronic circuits with operational amplifiers can accomplish numerous operations and functions such as phase inversion, addition, subtraction, derivation, integration, multiplication, taking exponentials, and logarithms. These devices have applications as comparators, discriminators, voltage followers, and memory registers...

The operational amplifier (OA), or op-amp, is a DC-coupled high-gain electronic voltage amplifier. it amplifies DC signals, but AC signals are amplified exclusively in a specified frequency interval (band). An OA has a differential input (two inputs) and usually a single-ended output.

An operational amplifier is a complex type of differential multi-stage amplifier that typically comprises a minimum of three stages: I. Differential amplifier at the input, II. Common-emitter transistor amplifier, III. Voltage follower at the output.

In this chapter, we will explore operational amplifiers (OAs), beginning with their schematic symbol, examining their key characteristics, and delving into their various applications.

2. Schematic symbol

The schematic symbol for the op amp is a triangle having two inputs and one output. as shown. Note that all voltages shown in this diagram are node voltages, and they are measured relative to a common reference or ground node which is established by the power supplies, as described below.

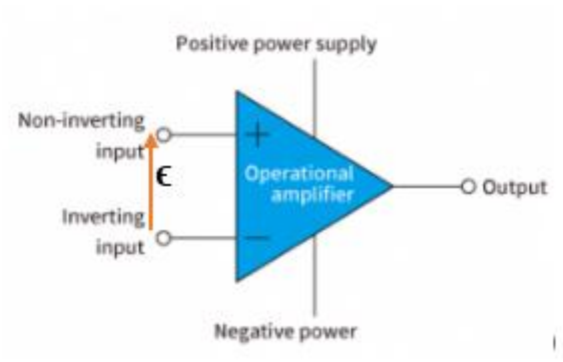


Figure 5. 1 : Op amp schematic symbol

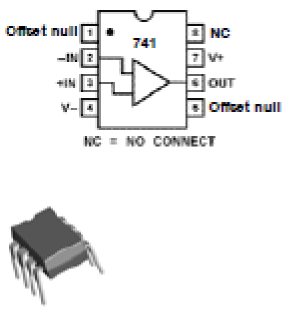
- Two inputs
  V+ : non-inverting input

  V- : inverting input

- Need a source of tension symmetry ($\pm E$) avec E=10 à 15V
- Vout : output

3. Internal circuit of LM741

Most op-amps come in the form of an 8-pin integrated circuit (IC) (Figure (5.2))

 *Figure 5. 2 : National Semiconductor LM741 Wiring Diagram*	(+IN) ou (u): non-inverting (-IN) ou (v): inverting input (OUT) ou (s): output (V+) ou (+Vcc) : Positive symmetrical power supply (V-) ou (-Vcc) : Negative symmetrical power supply (Offset null) : Input offset voltage cancellation (NC) : Not connected

The internal circuit of the LM741 (see figure below) includes around twenty bipolar transistors, around ten resistors and a so-called compensation capacitor (30pF).

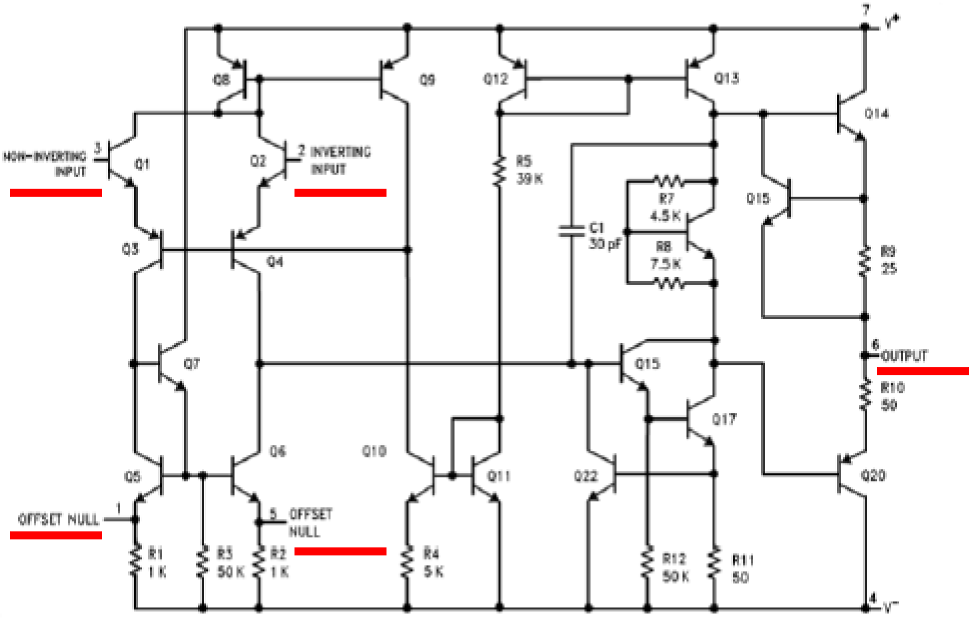


Figure 5. 3 : Structure of the operational amplifier

Note :

The diagram is taken from the Texas Instruments data sheet. It is given for information purposes only, do not try to understand it!

4. Ideal operational amplifier characteristics

We define an ideal OA by OA which has the following properties:

1. 1. Infinite input impedance (Zin=∞)⟹ no current passes through the two inputs $i+ = i- = 0$ (Infinite input resistor)
2. Zero output impedance $Zout = 0$⟹All the output voltage of the OA passes across the load without any attenuation
3. OA has infinite gain in open loop (OL)
   - OL : absence of any external connection of electronic components
4. Bandwidth infinite
5. Identical entry ⟹ the volatge between the 2 OA inputs is zero $\varepsilon = e^{+} - e^{-} = 0$

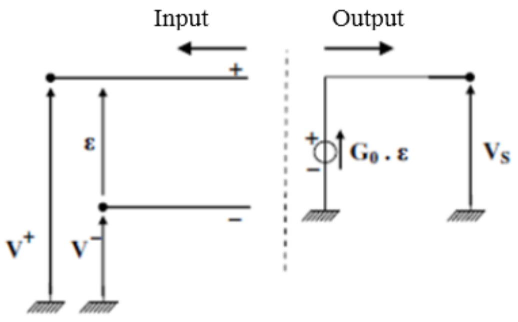


Figure 5. 4 : Equivalent circuit of an ideal operational amplifier

5. Operational amplifier in electric circuit with feedback

In the following sections we will express the output voltage as a function of the input voltage and the elements of the circuit.

5.1. Non inverting circuit

Input voltage that needs to be amplified is fed to the non-inverting input of the operational amplifier as can be seen in figure 6 of the non-inverting circuit of the OA.

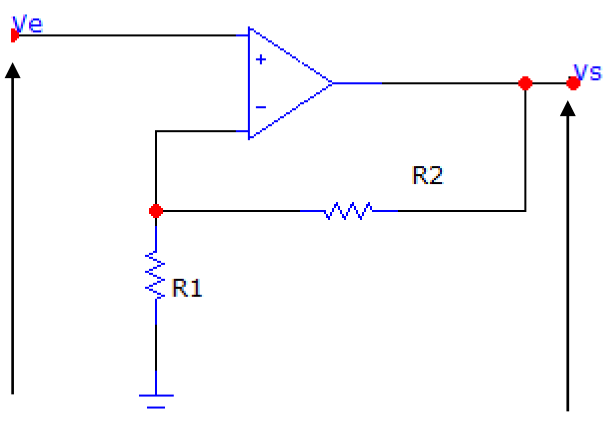


Figure 5. 5 :Non inverting circuit

Work required: Express the voltage Vs/Ve as a function of R1 and R2.

$$ve^- = \frac{R1}{R1+R2}Vs \qquad (1)$$

We have : $ve^- = ve^+ = Ve$ (2)

We replace the equation (2) in equation (1) we obtain : $Ve = \frac{R1}{R1+R2} Vs$ so $\frac{Vs}{Ve} = \frac{R1+R2}{R1} = 1 + \frac{R2}{R1}$

- ✓ The non-inverting circuit is a voltage amplifier, because its closed loop gain is greater than 1
- ✓ Since A is positive, the output voltages Vs and input voltage Ve are in phase, hence the name non-inverting amplifier

5.2. Summing amplifier circuit

Consider the following OA-based circuit:

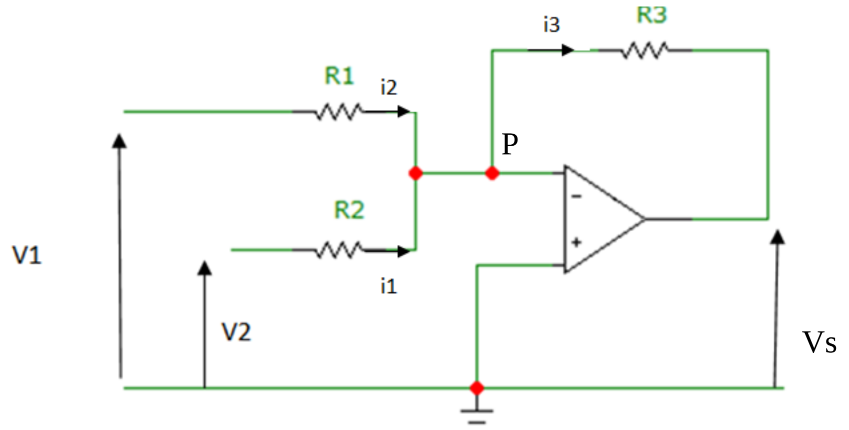


Figure 5. 6 : Summing amplifier

Required work: Express the voltage Vs as a function of V1, V2, R1, R2 and R3.

We have $\begin{cases} i- = i+ = 0 \\ v+ = v- \end{cases}$

$i1 + i2 = i3$ (1)

Millman's theorem at the point P:

$\frac{v1}{R1} + \frac{v2}{R2} = -\frac{Vs}{R3} \Rightarrow Vs = -R3(\frac{v1}{R1} + \frac{v2}{R2})$

Method 2

$$\begin{cases} \boldsymbol{V3 + R3i3 = 0} \\ \boldsymbol{V2 - R2i2 = 0} \\ \boldsymbol{V1 - R1i1 = 0} \end{cases} \rightarrow \begin{cases} \boldsymbol{i3 = -\frac{Vs}{R3}} \\ \boldsymbol{i2 = \frac{V2}{R2}} \\ \boldsymbol{i1 = \frac{V1}{R1}} \end{cases} \quad (2)$$

We replace the system of equation (2) in equation (1), we obtain :

$$Vs = -R3(\frac{v1}{R1} + \frac{v2}{R2})$$

Note : in the case where $R1 = R2 = R$

$$Vs = -\frac{R3}{R}(v1 + v2)$$

5.3. Difference amplifier (subtractor)

We consider the following circuit :

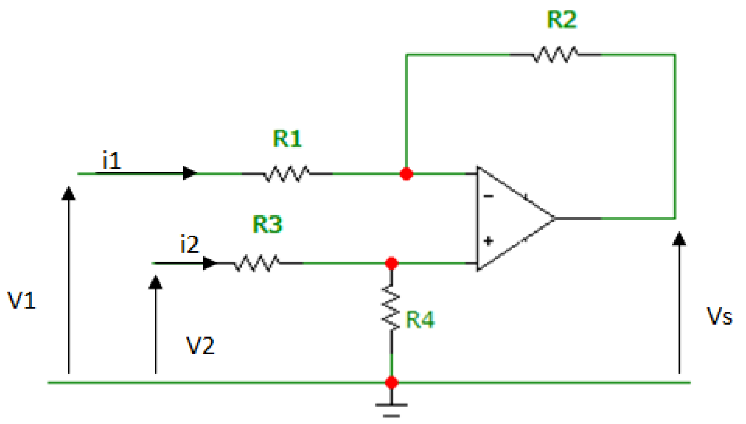


Figure 5. 7 : Subtractor circuit

Required work: Express the voltage Vs as a function of V1, V2, R1, R2, R3 and R4.

$$v1 = R1i1 + R4i2 \quad (1)$$

$$v2 = (R3 + R4)i2 \quad (2)$$

$$Vs = -R2i1 + R4i2 \quad (3)$$

From equation (2) $\Longrightarrow i2 = \frac{v2}{R3+R4}$ (4)

We replace equation (4) in equation (1), we obtain:

$$v1 = R1i1 + \frac{R4}{R3+R4}v2 \Longrightarrow i1 = \frac{v1}{R1} - \frac{R4}{R1(R3+R4)}v2 \quad (5)$$

We replace equation (4) & (5) in equation (3), we obtain:

$$vs = R2i1 + R4i2 = -R2\left(\frac{v1}{R1} - \frac{R4}{R1(R3+R4)}v2\right)$$

$$vs = \frac{R4(R1+R2)}{R1(R3+R4)}v2 - \frac{R2}{R1}v1$$

5.4. Integrator circuit

We consider the following circuit:

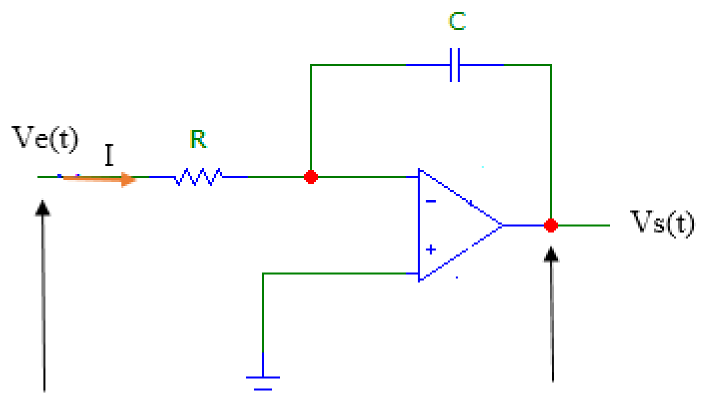


Figure 5. 8 : Integrator circuit

Required work: Express the voltage Vs(t) as a function of Ve(t), R and C.

$$I = \frac{Ve(t)}{R} = -C\frac{dVs(t)}{dt} \Longrightarrow \frac{Ve(t)}{R} = -C\frac{dVs(t)}{dt}$$

$$\Longrightarrow Vs(t) = -\frac{1}{RC}\int Ve(t)dt$$

5.5. Differentiator circuit

Soit le circuit à base d’OA suivant :

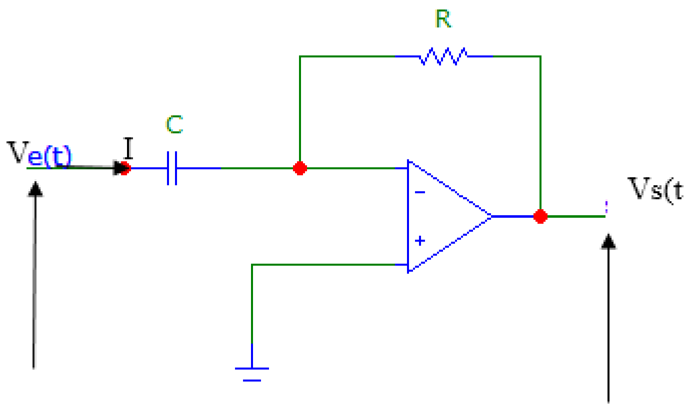


Figure 5. 9: Differentiator circuit

Required work: Express the voltage Vs as a function of Ve(t), R and C.

$\boldsymbol{I} = \mathrm{c}\frac{\mathrm{dVe(t)}}{\mathrm{dt}} = -\frac{\mathrm{Vs(t)}}{\mathrm{R}} \Longrightarrow Vs(t) = -Rc\frac{\mathrm{dVe(t)}}{\mathrm{dt}}$

Vs(t

5.6. Logarithmic amplifier

We consider the following circuit :

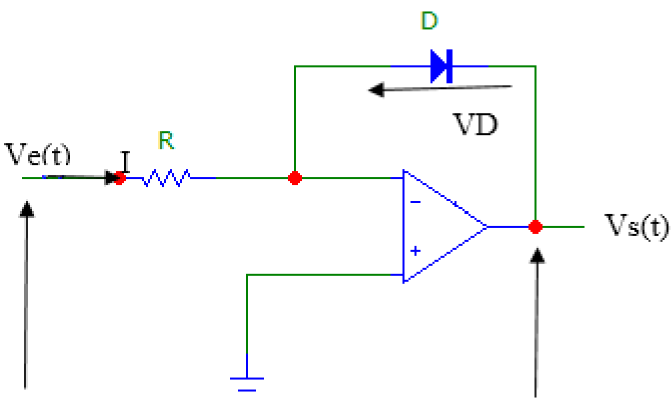


Figure 5. 10 : Logarithmic circuit

$$Ve = RI \qquad (1)$$

The equation which expresses the current flowing through a diode is:

$$I = Is\left(exp\frac{VD}{VT} - 1\right) \approx Is.exp\frac{VD}{VT} \qquad (2)$$

o Is is the constant specific to the type of diode considered, homogeneous with a current. This constant is also called the “saturation current” of the diode.

o VD is the voltage across the diode;

- VT (called thermal voltage) is equal to $\frac{K_B T}{q}$, where kB is the Boltzmann constant, T the absolute temperature of the junction and q the charge of an electron.
- Is est la constante spécifique au type de diode considéré, homogène à un courant. Cette constante est aussi appelée « courant de saturation » de la diode.
- VD est la tension aux bornes de la diode ;

$$VD = -Vs \quad (3)$$

We replace equation (1) in equation (2), we obtain :

$$Ve = R.Is.exp\frac{VD}{VT} \quad (4)$$

We replace equation (3) in equation (4), we obtain :

$$Ve = R.Is.exp\frac{Vs}{VT} \Longrightarrow Vs = -VT \ln\frac{Ve(t)}{RIs} + cste$$

5.7. Exponential amplifier

We consider the following circuit :

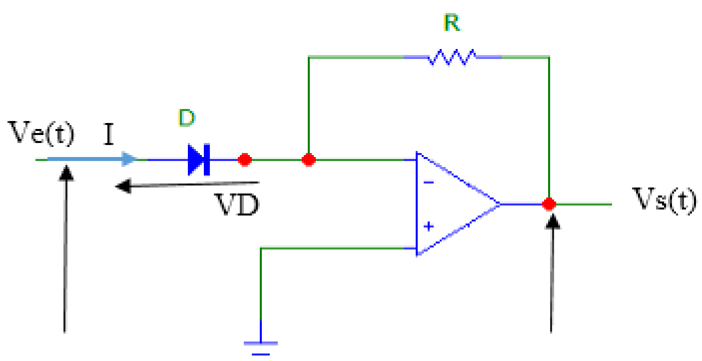


Figure 5. 11: Exponential circuit

$$Vs = -R.\mathrm{I} \quad (1)$$

$$I = Is.exp\frac{Ve}{VT} \quad (2)$$

$$Ve = VD \quad (3)$$

We replace equation (2) & (3) in equation (1), we obtain : $Vs = -R\ Is.exp\frac{Ve}{VT}$

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Program detailed overview

Unité d'enseignement: UEF 2.1.2
Matière 1: Electronique fondamentale 1
VHS: 45h00 (Cours: 1h30, TD: 1h30)
Crédits: 4
Coefficient: 2

Objectifs de l'enseignement:

Expliquer le calcul, l'analyse et l'interprétation des circuits électroniques. Connaitre les propriétés, les modèles électriques et les caractéristiques des composants électroniques : diodes, transistors bipolaires et amplificateurs opérationnels.

Connaissances préalables recommandées

Notions de physique des matériaux et d'électricité fondamentale.

Contenu de la matière :

Le nombre de semaines affichées sont indiquées à titre indicatif. Il est évident que le responsable du cours n'est pas tenu de respecter rigoureusement ce dimensionnement ou bien l'agencement des chapitres.

Chapitre 1. Régime continu et Théorèmes fondamentaux **3 semaines**

Définitions (dipôle, branche, nœud, maille), générateurs de tension et de courant (idéal, réel), relations tension-courant (R, L, C), diviseur de tension, diviseur de courant. Théorèmes fondamentaux : superposition, Thévenin, Norton, Millmann, Kennelly, Equivalence entre Thévenin et Norton, Théorème du transfert maximal de puissance.

Chapitre 2. Quadripôles passifs **3 semaines**

Représentation d'un réseau passif par un quadripôle. Grandeurs caractérisant le comportement d'un quadripôle dans un montage (impédance d'entrée et de sortie, gain en tension et en courant), application à l'adaptation. Filtres passifs (passe-bas, passe-haut, ...), Courbe de gain, Courbe de phase, Fréquence de coupure, Bande passante.

Chapitre 3. Diodes **3 semaines**

Rappels élémentaires sur la physique des semi-conducteurs : Définition d'un semi-conducteur, Si cristallin, Notions de dopage, Semi-conducteurs N et P, Jonction PN, Constitution et fonctionnement d'une diode, polarisations directe et inverse, Caractéristique courant-tension, régime statique et variable, Schéma équivalent.. Les applications des diodes : Redressement simple et double alternance. Stabilisation de la tension par la diode Zener. Ecrêtage, Autres types de diodes : Varicap, DEL, Photodiode.

Chapitre 4. Transistors bipolaires **3 semaines**

Transistors bipolaires : Effet transistor, modes de fonctionnement (blocage, saturation, ...), Réseau de caractéristiques statiques, Polarisations, Droite de charge, Point de repos, ... Etude des trois montages fondamentaux : EC, BC, CC, Schéma équivalent, Gain en tension, Gain en décibels, Bande passante, Gain en courant, Impédances d'entrée et de sortie. Etude d'amplificateurs à plusieurs étages BF en régime statique et en régime dynamique, condensateurs de liaisons, condensateurs de découplage. Autres utilisations du transistor : Montage Darlington, transistor en commutation, ...

Chapitre 5 - Les amplificateurs opérationnels : **3 semaines**

Principe, Schéma équivalent, Ampli-op idéal, Contre-réaction, Caractéristiques de l'ampli-op, Montages de base de l'amplificateur opérationnel : Inverseur, Non inverseur, Sommateur, Soustracteur, Comparateur, Suiveur, Dérivateur, Intégrateur, Logarithmique, Exponentiel, ...

Mode d'évaluation :

Contrôle continu : 40 % ; Examen final : 60 %.

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