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Fondamental Electronic 1

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Chapter I

Electrical networks

This chapter introduces some of the fundamental concepts needed to analyze electrical networks: Ohm's law, dipole association (series and parallel), Kirchhoff's laws and the rules of current and voltage division. These notions are used in the methods and theorems used to analyze electrical circuits.

I.1 Dipole [1] :

A dipole is defined as a circuit element with two terminals used to connect it to other circuit elements. Two categories are specified: passive dipoles such as resistors, and active dipoles such as generators.

I.2 Receiver and generator convention [2]:

To determine the voltage at the terminals of a dipole, we must first choose the convention, either the "receiver" convention or the "generator" convention (Fig I.1):

a) Generator convention: voltage has the same orientation as current.

b) Receiver convention: current and voltage are in opposite directions;

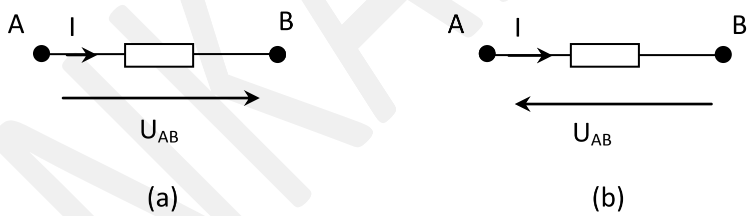


Fig I.1 (a) **Generator convention**; (b) **Receiver convention**

I.3 Ohm's law for a resistor [1,2,3] :

The electrical energy produced by the passage of a current I through a resistor is converted into heat by the Joule effect, expressed by the relationship :

$$P = R \cdot I^2 \qquad (I.1)$$

On the other hand, the power consumption is equal to :

$$P = U \cdot I \qquad (I.2)$$

Where U denotes the potential difference "t.p.d" across the resistor; these two powers are equal. We obtain the following equality:

$$U \cdot I = R.I^2 \qquad (I.3)$$

Dividing by I gives :

$$\mathrm{U = R.I} \qquad (\mathrm{I}.4) \qquad (\textbf{Ohm's law})$$

I.4 Dipole associations [1,2,3] :

Dipoles are said to be in series if the same electric current flows through them. Dipoles are also said to be in parallel if they have the same potential difference across their terminals.

I.4.1 Series combination of resistors:

Consider n resistors connected in series and carrying the same current I (figure I.2).

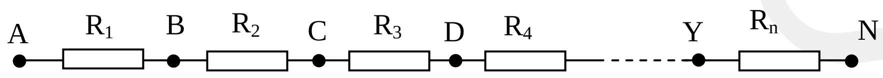


Fig I. 2

By applying Ohm's law to each of these resistors, we can write the following relationships:

$$U_{AB} = R_1 I \,;\, U_{BC} = R_2 I \,;\, U_{CD} = R_3 I \,;\, U_{DE} = R_4 I; \dots\, U_{YN} = R_n I \qquad (I.5)$$

The p.d. between ends A and N of the circuit is equal to the sum of the p.d. U_{AB} between A and B, U_{BC} between B and C, U_{CD} between C and D, ...and U_{YN} between Y and N.

$$U_{AN} = R_1 I + R_2 I + R_3 I + \cdots + R_n I \qquad (I.6)$$

$$U_{AN} = (R_1 + R_2 + R_3 + \cdots + R_n) I \qquad (I.7)$$

So everything happens as if a single resistor R were connected between A and N, and equal to:

$$R = R_1 + R_2 + R_3 + \cdots + R_n \qquad (I.8)$$

We adopt the following rule:

Resistors connected in series are equivalent to a single resistor equal to the sum of these resistors.

I.4.2 Parallel or shunt connection of resistors:

Let's place several resistors between two points N and M (e.g. four resistors, figure I.3). The current I in the circuit creates several derived currents, whose intensity is equal to the sum of the intensities of these derived currents.

$$I = I_1 + I_2 + I_3 + I_4 \qquad (I.9)$$

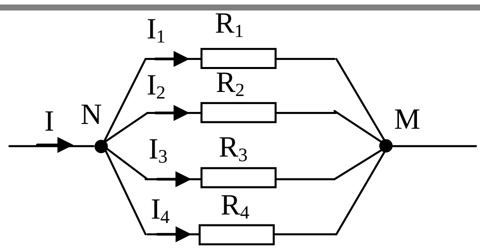


Fig I. 3

Ohm's law applied to each of the resistors R_1, R_2, R_3, R_4, gives us the following relationships:

$$U_{NM} = R_1 I = R_2 I = R_3 I = R_4 I \qquad (I.10)$$

We can therefore write the following equations:

$$I = \frac{U_{NM}}{R_1} + \frac{U_{NM}}{R_2} + \frac{U_{NM}}{R_3} + \frac{U_{NM}}{R_4} \qquad (I.11)$$

$$I = U_{NM}\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}\right) \qquad (I.12)$$

From the point of view of Ohm's law, everything happens as if the sum of the inverse of resistors R1, R2, R3, R4 were replaced by the inverse of a single resistor R given by the following relationship :

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \qquad (I.13)$$

The inverse of the resistance is known as the conductance G (G=1/R).

The general rule for derivative resistances is as follows:

The conductance of a set of shunt resistors is equal to the sum of the conductances of these resistors.

I.5 Elements of an electrical circuit [1]:

The components of an electrical circuit are as follows:

A Kirchhoff network is made up of a set of elements (R, L, C) connected together by means of terminals characterized by the two quantities: potential (V) and current (I).

A node (N) is a point where at least 3 conductors are connected.

A branch (B) groups together the elements located between 2 nodes and traversed by the same current.

A mesh (M) is a set of branches starting from a node and returning to it, without passing through the same branch twice.

I.6 Element connection rules [1]:

The rules for connecting elements are based on two main laws known as Kirchhoff's laws:

- ✓ **First law:** Law of currents (or nodes): The sum of outgoing currents equals the sum of incoming currents in a node: $\sum_k \pm I_k = 0$ $\qquad (I.14)$
- ✓ Second law: Law of voltages (or meshes): The sum of voltages in a mesh equals zero : $\sum_k \pm V_k = 0$ $\qquad (I.15)$

I.7 Divisor rules [1,2]:

a) Voltage divider rule: This is applied for elements (Ri) in series, with the same current flowing through them (Fig I.4).

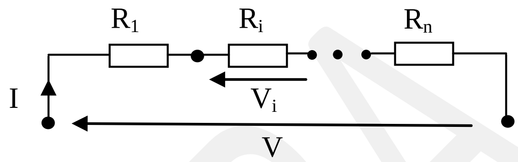


Fig. I.4 Voltage divider rule

$$V_i = R_i I = R_i \frac{V}{\sum_{k=1}^{n} R_k} \qquad (I.16)$$

b) Current divider rule: This is applied for elements (Gj) in parallel subjected to the same voltage V. (Gj: is the conductance) (See Fig I.5).

$$I_j = VG_j = \frac{I}{\sum_k G_k} \cdot G_j \qquad (I.17)$$

$$I_j = \frac{R_1 \parallel R_n}{R_1 \parallel R_n + R_J} \cdot I \qquad (I.18)$$

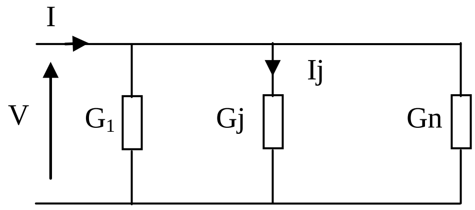


Fig. I.5 Current divider rule

I.8 Network analysis methods [1,4]:

Kirchhoff's laws are used to determine the current intensities and potential differences (p.d.) across each branch of the electrical network.

This operation is called circuit or electrical network analysis.

As all the elements making up the network are known, the complete calculation requires as many equations as there are branches. The analysis is simplified by the application of associative laws and appropriate theorems.

I.8.1 Mesh method:

It allows us to solve the problem by writing M mesh equations:

- A system of M independent meshes is chosen.
- Each mesh is assigned a fictitious current flowing in an arbitrarily chosen direction.
- Kirchhoff's 2nd law is applied to each of these meshes.
- The real current of a given branch is obtained by calculating the algebraic sum of the fictitious currents flowing in the branch in question.
- The branch d.p are deduced from the real currents.

Example:

The ACDA mesh :

$$-R_1I_1 - r(I_1 - I_2) - R_4(I_1 - I_3) = 0 \qquad (I.19)$$

The DCBD mesh:

$$-r(I_2 - I_1) - R_2I_2 - R_3(I_2 - I_3) = 0 \qquad (I.20)$$

The ADBA mesh:

$$-R_4(I_3 - I_1) - R_3(I_3 - I_2) - RI_3 = -E \qquad (I.21)$$

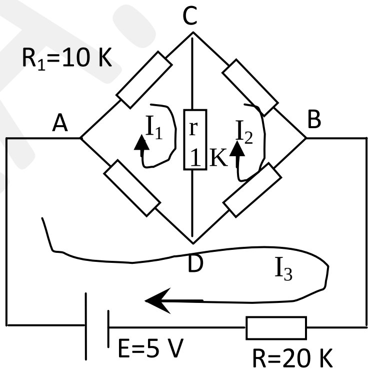


Fig. I.6 Mesh method, example: resistance bridge assembly

$$\begin{cases} -(R_1 + r + R_4)I_1 + rI_2 + R_4I_3 = 0 \\ rI_1 - (r + R_2 + R_3)I_2 + R_3I_3 = 0 \\ R_4I_1 + R_3I_2 - (R_4 + R_3 + R)I_3 = -E \end{cases} \qquad (I.22)$$

Using Cramer's method :

$$I_1 = \frac{\begin{vmatrix} 0 & r & R_4 \\ 0 & -(r+R_2+R_3) & R_3 \\ -E & R_3 & -(R_4+R_3+R) \end{vmatrix}}{\begin{vmatrix} -(R_1+r+R_4) & r & R_4 \\ r & -(r+R_2+R_3) & R_3 \\ R_4 & R_3 & -(R_4+R_3+R) \end{vmatrix}} = \frac{\begin{vmatrix} 0 & 1 & 15 \\ 0 & -16 & 5 \\ -5 & 5 & -40 \end{vmatrix}}{\begin{vmatrix} -26 & 1 & 15 \\ 1 & -16 & 5 \\ 15 & 5 & -40 \end{vmatrix}}$$

$$= 0{,}096\, mA \qquad (I.23)$$

In the same way we find I_2=0.059 mA and I_3=0.19 mA .

I.8.2 Knot or node method:

Represent by writing N equations at the nodes (Fig. I.7):

- Choose a reference node (usually the mass);
- Each of the remaining nodes is assigned an unknown potential V_1, V_2, ..., V_N ;
- Kirchhoff's 1st law is written for each of these N nodes.

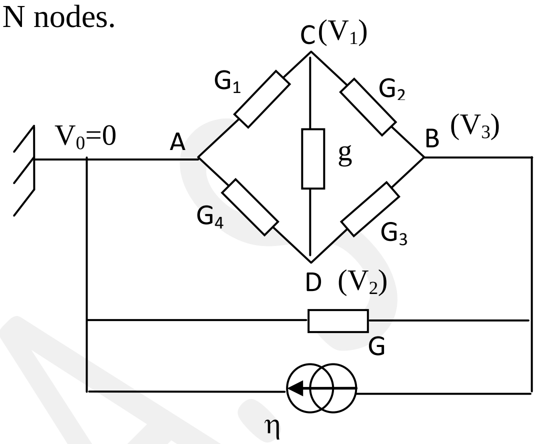


Fig. I.7 Node method, example: resistance bridge assembly

Node C :

$$(G_1 + g + G_2)V_1 - G_1 0 - gV_2 - G_2V_3 = 0 \quad (I.24)$$

Node B :

$$(G_2 + G_3 + G)V_3 - G_2V_1 - G_3V_2 = \varphi \quad (I.25)$$

Node D :

$$(G_4 + g + G_3)V_2 - G_3V_3 - gV_1 = 0 \quad (I.26)$$

$$\begin{cases} (G_1 + g + G_2)V_1 - gV_2 - G_2V_3 = 0 \\ G_2V_1 - G_3V_2 + (G_2 + G_3 + G)V_3 = \varphi \\ -gV_1 + (G_4 + g + G_3)V_2 - G_3V_3 = 0 \end{cases} \quad (I.27)$$

Using Cramer's method :

$$G_1 = G_2 = \frac{1}{R_1} = \frac{1}{10k} = 0{,}1m\Omega^{-1}; G_3 = \frac{1}{5k} = 0{,}2m\Omega^{-1}; G_4 = \frac{1}{15k} = 0{,}067m\Omega^{-1}; G = \frac{1}{20k} = 0{,}05m\Omega^{-1}; g = 1\ m\Omega^{-1}\ \ et\ \eta = \frac{E}{R} = 0{,}25\ mA$$

$$V_1 = \frac{\begin{vmatrix} 0 & -g & -G_2 \\ \varphi & -G_3 & G_2 + G_3 + G \\ 0 & G_4 + g + G_3 & -G_3 \end{vmatrix}}{\begin{vmatrix} G_1 + g + G_2 & -g & -G_2 \\ G_2 & -G_3 & G_2 + G_3 + G \\ -g & G_4 + g + G_3 & -G_3 \end{vmatrix}} = \frac{\begin{vmatrix} 0 & -1m & -0{,}1m \\ 0{,}25m & -0{,}2m & 0{,}35m \\ 0 & 1{,}267m & -0{,}2m \end{vmatrix}}{\begin{vmatrix} 1{,}2m & -1m & -0{,}1m \\ 0{,}1m & -0{,}2m & 0{,}35m \\ -1m & 1{,}267m & -0{,}2m \end{vmatrix}} = -20\ mV \quad (I.28)$$

In the same way we find : $V_2 = 95\ mV\ et\ V_3 = 654\ mV$.

I.9 Analysis theorems:

I.9.1 Superposition theorem [1,5] :

This theorem is used when we have a circuit containing several electrical sources (of voltage or current). The principle is to take a single source that supplies the circuit and cancel out the other sources (short-circuit any voltage source and open any current source). The voltage (or current) at the terminal of any element is the algebraic sum of the voltages (or currents) taken from each source taken alone.

The following example illustrates the principle of this theorem.

Example:

Consider the circuit shown in Figure I.8. Determine the current intensities in the three branches using the superposition method ?

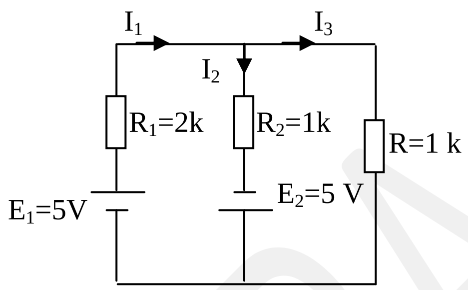


Fig. I.8 Single circuit powered by two sources

Solution :

The initial circuit is equivalent to two circuits according to two cases (Fig. I.9):

First case (Fig. I.9 (a))

Neutralize source E_2

Second case (Fig. I.9 (b))

Neutralize source E_1

Fig. I.9 Initial circuit is equivalent to the superposition of two states (a) and

Calculation of I'_1 from circuit (a):

$$\acute{I}_1 = \frac{E_1}{R_1 + R_2 \| R} = \frac{5}{2+0,5} = 2\ mA$$

Applying the current divider rule**:**

$$\acute{I}_2 = \frac{\mathrm{R}}{\mathrm{R}+\mathrm{R}_2}\acute{I}_1 = \frac{1}{1+1} \times 2 = 1\ \mathrm{mA}$$

$$\acute{I}_3 = \frac{\mathrm{R}_2}{\mathrm{R}+\mathrm{R}_2}\acute{I}_1 = \frac{1}{1+1} \times 2 = 1\ \mathrm{mA}$$

Calculation of I'_2 from circuit (b):

$$\acute{I}_2 = \frac{-E_2}{R_2 + R \| R_1} = \frac{-5}{1+\frac{2}{3}} = -3\ mA$$

Applying the current divider rule:

$$\acute{\acute{I}}_1 = \frac{\mathrm{R}}{\mathrm{R}+\mathrm{R}_1}\acute{\acute{I}}_2 = \frac{1}{1+2} \times 3 = 1\ \mathrm{mA}$$

$$\acute{\acute{I}}_3 = \frac{\mathrm{R}_1}{\mathrm{R}+\mathrm{R}_1}\acute{\acute{I}}_2 = \frac{2}{1+2} \times 3 = 2\ \mathrm{mA}$$

I_1, I_2 and I_3 are given by the following relationships from circuits (a) and (b):

$$\begin{aligned} I_1 &= I'_1 - I''_1 = 2 - 1 = 1\ \mathrm{mA} \\ I_2 &= I'_2 - I''_2 = 1 + 3 = 4\ \mathrm{mA} \\ I_3 &= I'_3 + I''_3 = 1 + 2 = 3\ \mathrm{mA} \end{aligned} \qquad (I.29)$$

I.9.2 Thevenin's theorem [1,2,5]:

Thevenin's theorem is used to reduce electrical networks of any complexity to a simple circuit consisting of a voltage generator in series with its internal resistance. It is stated as follows: Let any network be accessible via two terminals A and B. If there is a. UAB potential between these terminals, and a resistor R is connected between A and B (Fig. I.10), the current established is :

$$I = \frac{U_{AB}}{R_{AB} + R} \qquad (I.30)$$

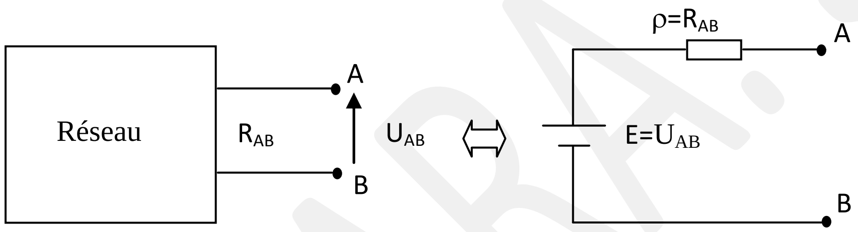


Fig. I.10 Thevenin's equivalent diagram of any network.

U_{AB} is the p.d. determined in the absence of any load between A and B, i.e. when resistor R is disconnected.

R_{AB} is the equivalent resistance to the network, as seen from points A and B when all e.m.f. is removed and before resistor R is connected.

For resistor R, the network to which it is connected; is consider as a generator of emf $E=U_{AB}$, with internal resistance $\rho = R_{AB}$.

Example:

Find the characteristics of the Thévenin generator:

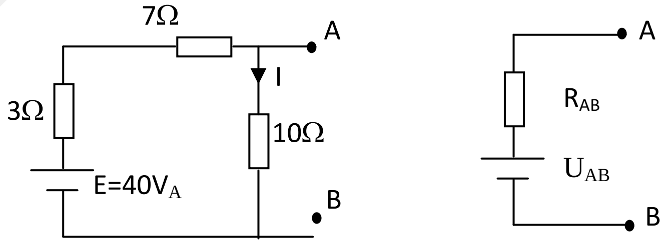
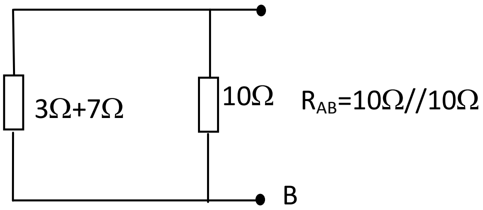


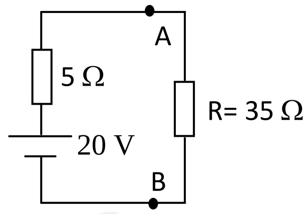
Fig. I.11 Thevenin's equivalent diagram of a simple circuit

$U_{AB} = 10\Omega \cdot \text{I} = 10 \cdot \frac{40}{3+7+10} = 20\text{V}$

$$R_{AB} = 10 \cdot \frac{3+7}{3+7+10} = 5\ \Omega$$



Si on branche entre A et B une résistance de 35 Ω,
elle serait traversée par un courant :



$$I = \frac{20}{35+5} = 0{,}5\ A$$

I.9.3 Norton's theorem [1,2,5] :

The principle :

Norton's theorem reduces circuits containing several passive elements and independent sources to a simple circuit with a single current source of current $I_N = I_{AB}$ (U_{AB}=0) in parallel with its internal admittance Y_N=Y_{AB} (canceling the sources).

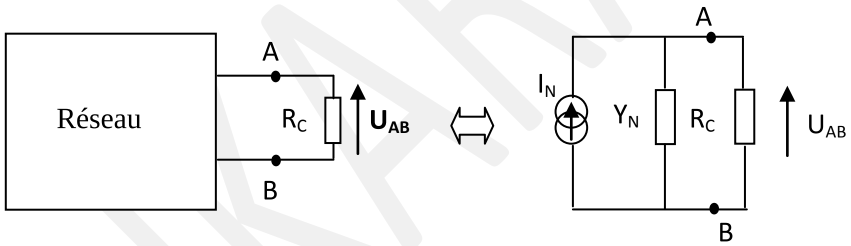


Fig. I.12 Norton equivalent diagram of any linear network

Example:

Determine the Norton generator seen to the left of N and M.

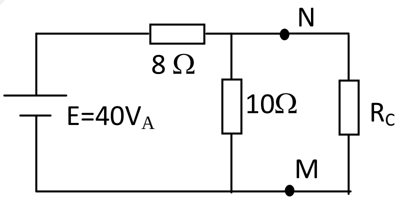
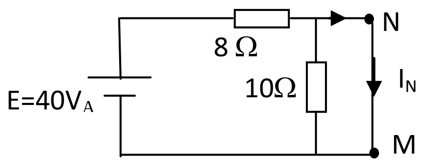


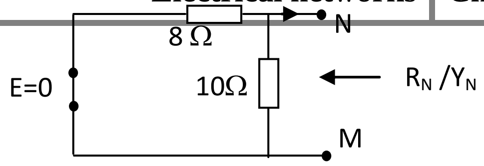
Fig. I.13 Norton equivalent diagram of a simple circuit.

Step 1: I_N calculation

$$I_N = \frac{E}{r} = \frac{40}{8} = 5\ A \quad (U_{NM} = 0)$$



Step 2: R_N calculation



$\frac{1}{R_N} = Y_N = \frac{1}{8} + \frac{1}{10} = 0 \cdot 225\ \Omega^{-1}$

1.9.4 Thevenin-Norton equivalence [1,2]:

Any Thévenin generator can be transformed into a Norton generator (and vice versa). This method makes it possible to transform electrical diagrams in order to simplify them: association of resistors in series; association of resistors in parallel; association of voltage sources in series; association of current sources in parallel.

The following equivalence can then be established (Fig. I.14):

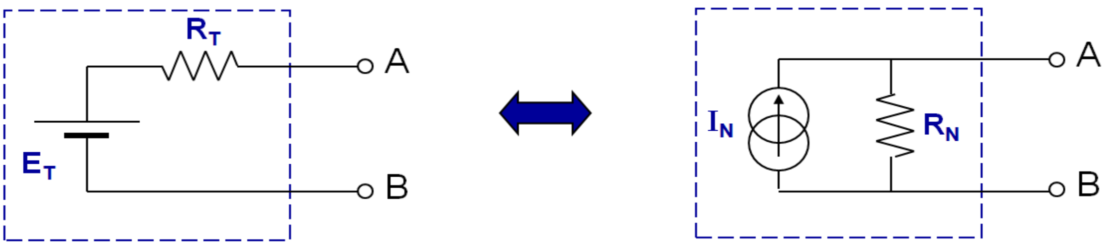


Fig. I.14 Thévenin-Norton Equivalence

That is :

$$I_N = \frac{E_T}{R_T},\quad E_T = R_T \cdot I_N \quad et\ R_T = R_N \qquad (I.31)$$

I.9.5 Millman's theorem [1,2,5] :

To determine the potential difference across several branches in parallel (EAB), this theorem is often applied because of its simplicity (Fig. I.15):

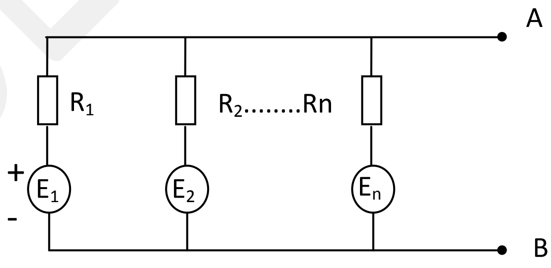


Fig. I.15 Equivalent diagram of a simple circuit by Millman.

E_{AB} is given by the following expression :

$$E_{AB} = \frac{\sum_{k=1}^{n} \pm \frac{E_K}{R_K}}{\sum_{K=1}^{n} \frac{1}{R_K}} \qquad (I.32)$$

I.9.6 Kennely's theorem [1,5]:

This theorem is used to transform triangular networks (Pi) into star networks (T) and vice versa (figure I.16).

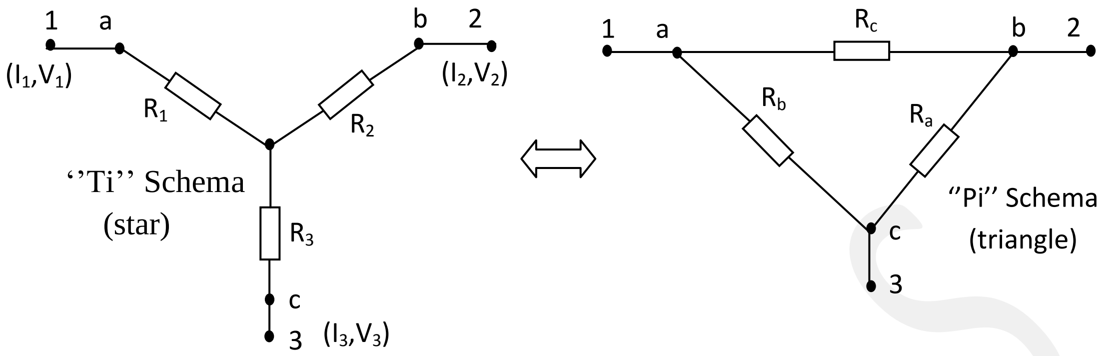


Fig. I.16 Ti (Star) ↔ Pi (Triangle)' transformation or Kennely's theorem

The parameters of each transformation are determined by the following formulas:

$$\begin{cases} R_{12} = R_1 + R_2 \\ R_{23} = R_2 + R_3 \\ R_{31} = R_3 + R_1 \end{cases} \quad (I.33) \qquad and \qquad \begin{cases} R_{ab} = \dfrac{(R_a + R_b)R_c}{(R_a + R_b + R_c)} \\ R_{bc} = \dfrac{(R_b + R_c)R_a}{(R_a + R_b + R_c)} \\ R_{ca} = \dfrac{(R_c + R_a)R_b}{(R_a + R_b + R_c)} \end{cases} \quad (I.34)$$

The two schemes are equivalent if :

$$\begin{cases} R_{12} = R_{ab} \\ R_{23} = R_{bc} \quad \rightarrow \\ R_{31} = R_{ca} \quad \rightarrow \end{cases} \qquad \begin{matrix} R_1 = R_b \cdot R_c / S & & R_a = P/R_1 \\ R_2 = R_c \cdot R_a / S & ou & R_b = P/R_2 \\ R_3 = R_a \cdot R_b / S & ou & R_c = P/R_3 \end{matrix} \qquad (I.35)$$

With : $$S = (R_a + R_b + R_c) \qquad (I.36)$$

and

$$P = R_1 \cdot R_2 + R_2 \cdot R_3 + R_3 \cdot R_1 \qquad (I.37)$$

Chapter II

Passive filters

II.1 Passive filters

We often need to cancel certain frequencies or keep only a particular frequency band. This is the function of filters. They are made up of the quadruples. Their role is to pass or block a precise band of frequencies in an alternating signal.

There are two families of filters:

Passive filters: comprise only resistors, inductors and capacitors. They do not amplify (output power is lower than input power).

Active filters: include operational amplifiers, transistors and passive components. They amplify the input signal or modify its shape.

II.1.1 The main types of filter [5,6,7]:

Depending on their main task, which is to allow or prevent certain frequencies from passing through, filters can be subdivided into 4 types (Fig II.1):

- **Low-pass filters**: pass only low frequencies;
- **High-pass filters**: pass only high frequencies;
- **Band-pass filters**: pass only one range of frequencies;
- **Band-stop filters**: do not pass a single range of frequencies.

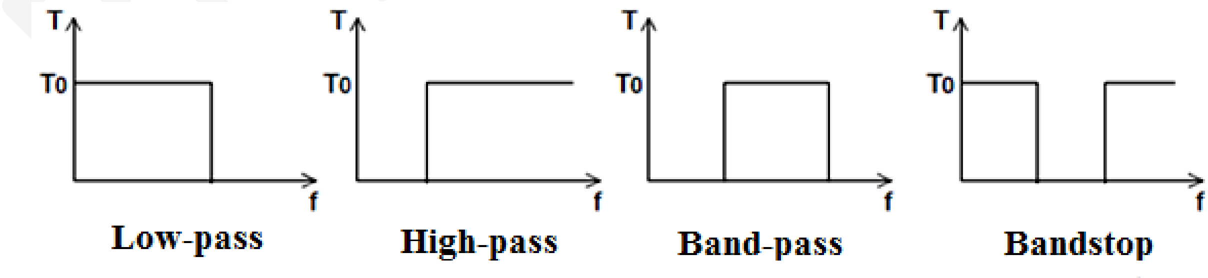


Fig II.1 The different types of filter.

II.6.2 Filter transfer function (or complex transmittance) [1-6]:

Filters are characterized by a very important parameter for describing their behavior: the transfer function. It's a mathematical function that describes the frequency behavior of a filter (in sinusoidal regime).

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

$$T(\omega) = |\underline{T}(\omega)| = \left|\frac{\underline{V_S}}{\underline{V_E}}\right| \quad (II.1)$$

The phase shift between output and input is given by the argument :

$$\arg\left(\underline{T}(\omega)\right) = \varphi(\omega) = \arg\left(\frac{\underline{V_S}}{\underline{V_E}}\right) = \arg(\underline{V_S}) - \arg(\underline{V_E}) \quad (II.2)$$

These two parameters, modulus and argument, are represented by curves, and are used to obtain data that can be used to predict the response of the system studied under any excitation conditions.

The Bode diagram is adopted to graphically represent the variation of T(ω) as a function of pulsation (or frequency). Because of the wide range of values for the modulus of T, we choose to plot the function G as a function of pulsation:

$$G = 20Log_{10}T(\omega) \qquad (II.3)$$

G is called the gain of the transfer function T and is expressed in decibels (dB).

II.6.3 Behavior of impedances at limit frequencies [3]:

The impedance of the coil at low frequencies tends towards zero, so it behaves like a short circuit, and at high frequencies it tends towards infinity, so it behaves like an open circuit. For the capacitor, the same phenomenon is observed, but in reverse. The following table summarizes these two behaviors:

	Low frequencies	High frequencies
$jL\omega$	0	∞
$\frac{1}{jC\omega}$	∞	0

II.6.4 First-order low-pass filter [1,3,5,7] :

a) Transfer function

Consider the RC circuit shown in figure II.2. Where the output voltage Vs is deduced from the voltage divider rule :

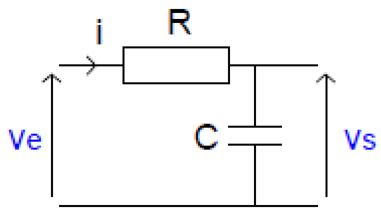


Fig II.2 Low-pass filter

$$V_S = \frac{Z_C}{Z_C + R} V_E = \frac{\frac{1}{jC\omega}}{\frac{1}{jC\omega} + R} V_E = \frac{1}{1 + jRC\omega} V_E \qquad (II.4)$$

$$\underline{T}(\omega) = \frac{1}{1 + jRC\omega} \qquad (II.5)$$

As well as the voltage amplification module:

$$T(\omega) = \left|\frac{1}{1 + jRC\omega}\right| = \frac{1}{|1 + jRC\omega|} = \frac{1}{\sqrt{1 + (RC\omega)^2}} = \frac{1}{\sqrt{1 + (\frac{\omega}{\omega_0})^2}} \qquad (II.6)$$

With $\omega_0 = \dfrac{1}{RC}$

a) Gain Bode diagram:

$$G(\omega) = 20Log_{10}T(\omega) = 20Log_{10}\frac{1}{\sqrt{1+\left(\frac{\omega}{\omega_0}\right)^2}} = -10Log\left(1 + \left(\frac{\omega}{\omega_0}\right)^2\right) \qquad (II.7)$$

$$\varphi = -arctan\frac{\omega}{\omega_0} \qquad (II.8)$$

b) Cut-off pulse at -3 dB

The cut-off pulsation is a solution of the equation :

$$T(\omega_C) = \frac{T_{max}}{\sqrt{2}} \qquad (II.9)$$

$$T_{max} = T(\omega \to 0) = 1$$

$$\Rightarrow \quad \frac{1}{\sqrt{1+(\frac{\omega}{\omega_0})^2}} = \frac{1}{\sqrt{2}} \qquad (II.10)$$

$$\text{Where } \frac{\omega}{\omega_0} = 1 \quad et \quad \omega_C = \omega_0 = \frac{1}{RC}$$

NA : For R=100 Ω and C=1 µF ; $\omega_C = 10^4$ rad/s

a) Limit value study

When the pulsation ω tends towards zero, the gain G tends towards zero and the argument φ tends towards zero.

And when ω tends to infinity, G tends to -∞ and φ tends to -π/2.

And for $\omega=\omega_C$; G=-3dB and φ=-π/4.

Determination of the asymptotes to the curves G(ω) and φ(ω):

For $\omega \ll \omega_0$; $G(\omega)\cong 0$ dB and $\varphi(\omega)\cong 0$

For $\omega \gg \omega_0$; $G(\omega)\cong 20\mathrm{Log}\frac{\omega_0}{\omega}$ This asymptotic line decreases as a function of pulse, with a slope of -20 dB/decade. It passes through the point $(\omega_0,0)$.

And $\varphi(\omega)\cong -\pi/2$

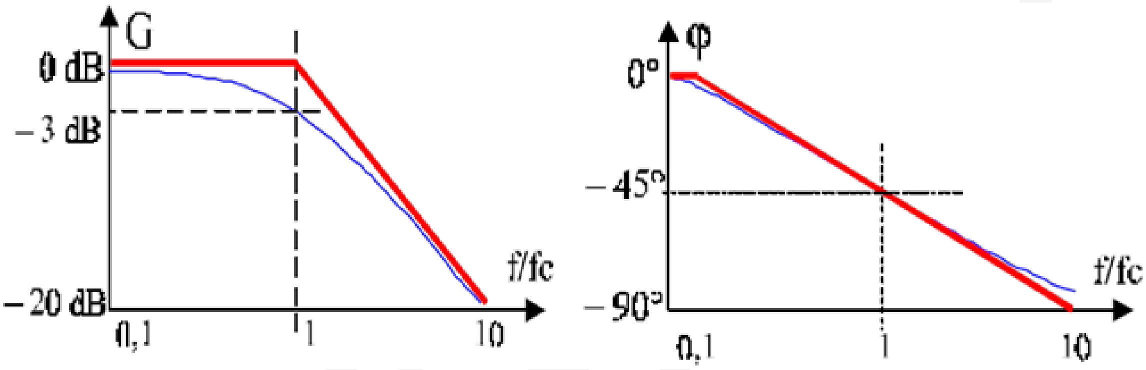


Fig II.3 Representation of G(ω) and φ(ω) curves.

II.6.5 Filtre passe-haut du premier ordre [3,5,6]:

a) Transfert Function:

Le même circuit que le précédent avec l'inversement de l'emplacement de la résistance et la capacité (fig II.4) :

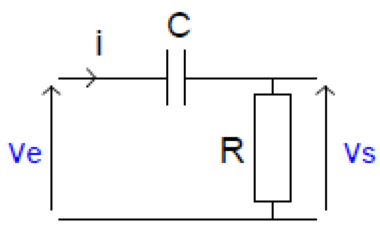


Fig II.4 High-pass filter

$$\underline{T}=\frac{R}{R+Z_C}=\frac{R}{R+\frac{1}{jC\omega}}=\frac{jRC\omega}{1+jRC\omega}=\frac{j\frac{\omega}{\omega_0}}{1+j\frac{\omega}{\omega_0}} \qquad (II.11)$$

$$\text{Wiyh } \omega_0=\frac{1}{\mathrm{RC}}$$

b) Expression of T, G and φ as a function of the pulsation ω :

$$T(\omega) = \frac{1}{\sqrt{1 + \frac{\omega_0^2}{\omega^2}}} \qquad (II.12)$$

$$G = 20\, Log\, T = -10\, Log\left(1 + \frac{\omega_0^2}{\omega^2}\right) \qquad (II.13)$$

$$\varphi = \frac{\pi}{2} - arctan\frac{\omega}{\omega_0} \qquad (II.14)$$

c) Limit value study

$For\ \omega \to 0; G \to -\infty;\ \varphi \to \frac{\pi}{2}$

$For\ \omega \to \infty; G \to 0;\ \varphi \to 0$

$For\ \omega = \omega_0; G - 3\ dB;\ \varphi = \frac{\pi}{4}$

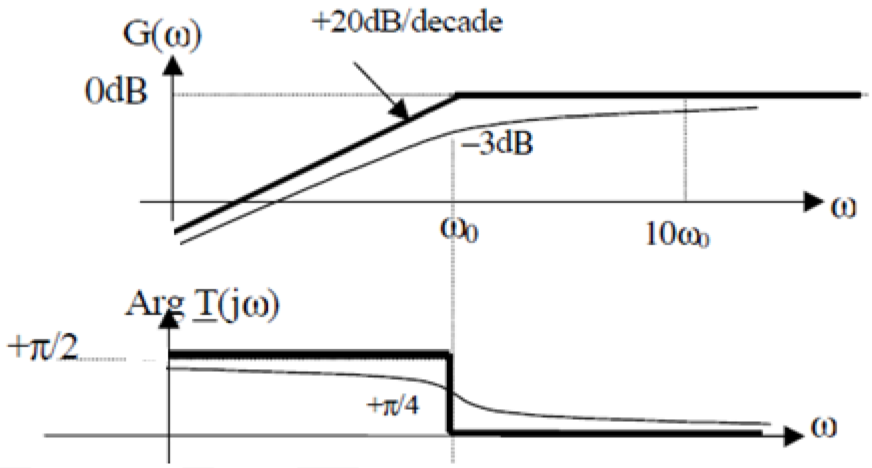


Fig II.5 Representation of G(ω) and φ(ω) curves.

II.6.6 Band-pass filter [3,5]:

For this type of filter we adopt the series RLC circuit where the output is taken between the resistor terminals (Fig. II.6):

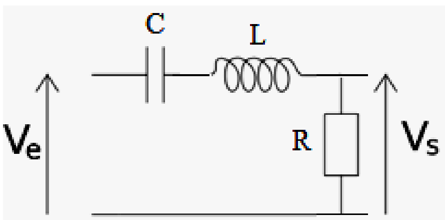


Fig II.6 Band-pass filter

Since the capacitor behaves like an open circuit at low frequencies, no current flows through the resistor. At high frequencies, on the other hand, it's the inductance that behaves like an open circuit, so no current flows through the resistor. So the transfer of energy from input to output takes place between high and low frequencies. At a certain frequency, the impedance of the capacitor (which is negative) cancels the impedance of the inductor, the amplitude of the transfer function is real, and the output voltage is the same as that of the input.

a) Transfer function

$$\underline{T}(\omega) = \frac{R}{R + Z_L + Z_C} = \frac{jRC\omega}{1 - LC\omega^2 + jRC\omega} = \frac{1}{1 + j(\frac{L}{R}\omega - \frac{1}{RC\omega})} \qquad (II.40)$$

Which is the form:

$$\underline{T}(\omega) = \frac{1}{1 + jQ(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega})} \qquad (II.41)$$

Q: Quality coefficient.

$$With \quad \omega_0 = \frac{1}{\sqrt{LC}} \quad and \; Q = \frac{1}{R}\sqrt{\frac{L}{C}}$$

b) The modulus and phase of T:

$$T(\omega) = \frac{1}{\sqrt{1 + Q^2(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega})^2}} \; ; \; \varphi(\omega) = -\arctan Q\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right) (II.42)$$

c) Cut-off frequencies: are obtained by solving the equation :

$$T(\omega_c) = \frac{T_{max}}{\sqrt{2}} = \frac{1}{\sqrt{2}}$$

The two cut-off frequencies are :

$$\omega_{C_1} = -\frac{R}{2L} + \sqrt{(\frac{R}{2L})^2 + \frac{1}{LC}} \; ; \; \omega_{C_2} = +\frac{R}{2L} + \sqrt{(\frac{R}{2L})^2 + \frac{1}{LC}} \quad (II.43)$$

d) Filter bandwidth: is the difference between ω_{C1}et ω_{C2} :

$$\beta = \omega_{C_2} - \omega_{C_1} = \frac{R}{L}$$

Figure II.7 shows the response of a band-pass filter. The cut-off frequencies are defined by the points where the amplitude reaches 1/√2 of the maximum value.

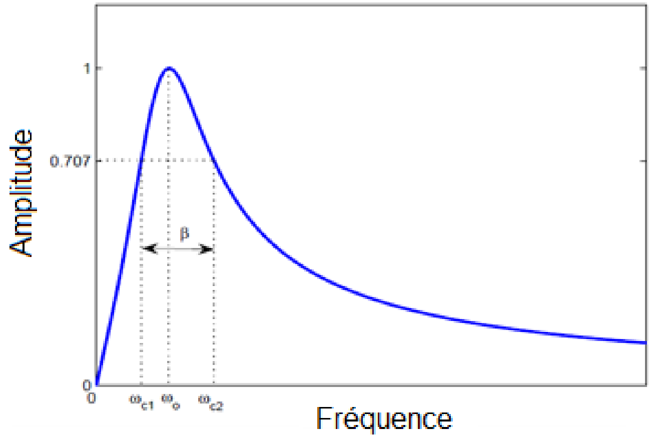


Fig II.7 Response of Band-pass filter

II.6.7 Band-stop filter[3,5]:

We use the same RLC series circuit as the previous filter, but this time the output is taken across the inductance and the capacitance in series (Fig. II.8) .

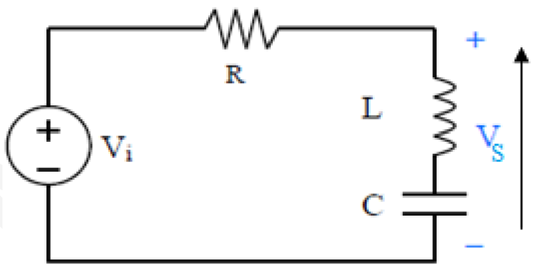


Fig II.8 Band-stop filter

Operating principle:

At low frequencies: the capacitor behaves like an open circuit, so the output voltage is the same as the input voltage.

At high frequencies: the inductor behaves like an open circuit, and the output is the same as the input.

At resonant frequency, the impedance of the inductor cancels out the impedance of the capacitor, so there's a short-circuit, and the output is zero.

a) **The transfer function of this circuit is :de transfert** de ce circuit est :

$$\underline{T}(\omega) = \frac{jL\omega + \frac{1}{jC\omega}}{R + jL\omega + \frac{1}{jC\omega}} = \frac{\frac{1}{LC} - \omega^2}{\frac{1}{LC} - \omega^2 + j\omega\frac{R}{L}} \qquad (II.44)$$

b) **Amplitude and phase shift et le déphasage** :

$$T(\omega) = \frac{\left|\frac{1}{LC} - \omega^2\right|}{\sqrt{(\frac{1}{LC} - \omega^2)^2 + (\omega\frac{R}{L})^2}}; \quad \varphi(\omega) = -\arctan\left(\frac{\omega\frac{R}{L}}{\frac{1}{LC} - \omega^2}\right) \qquad (II.45)$$

The response of a notch filter and the argument are shown in Figure II.9.

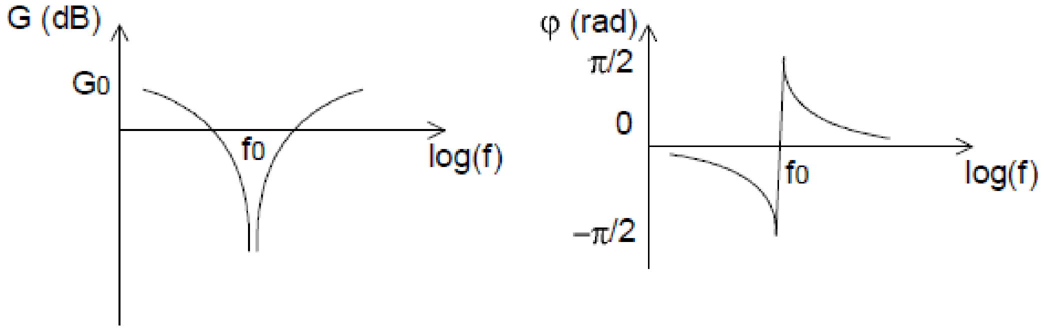


Fig II.9 Representation of G(ω) and φ(ω) curves.

Chapter III

PN junction and diode

In this chapter, we will study the PN junction and the diode, starting with the notions of energy bands, where we will distinguish three types of materials. We'll focus much more on the type of semiconductor. Hence the joining of two semiconductor parts to form what we call the PN junction. The diode is the component formed by the PN junction. A somewhat exhaustive study of this component is presented, such as its forward and reverse polarization and its applications, in particular rectification, and we'll give a few special types of diode.

III.1 Notions of energy bands

To better understand the notion of energy bands in a solid, let's start with its simple representation, which is none other than the atom. If we consider a single atom separated from the others, its electrons occupy energy levels “Ei” separated from each other, as shown in figure III.1..

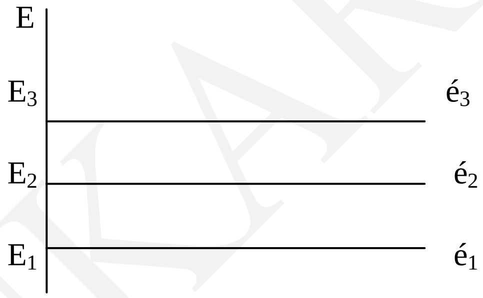


Fig III.1 Distribution of electrons on energy levels.

In a crystal, because of the large number of atoms, there will be interactions, and the discrete energy levels become energy bands occupied by electrons, known as conduction and valence bands, and forbidden bands. Figure III.2 illustrates these energy bands.

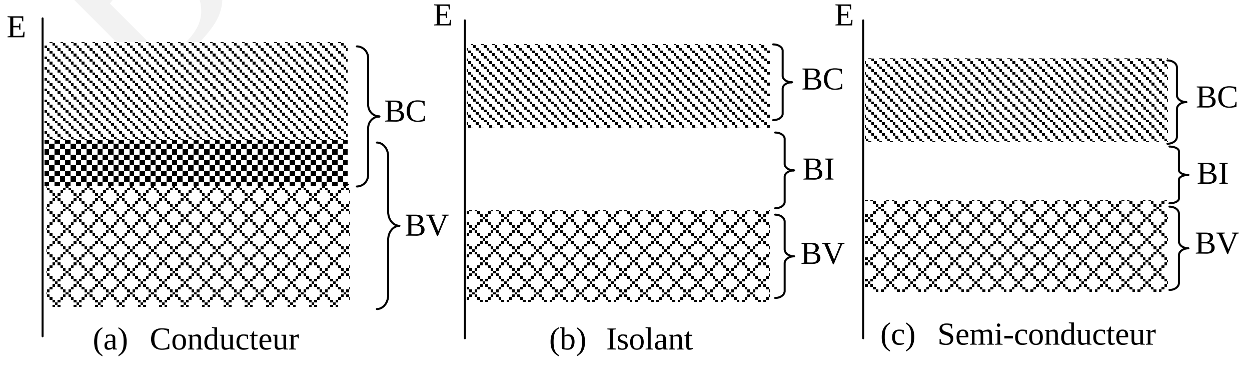


Fig III.2 The quantum model of energy bands in insulators, conductors and semiconductors.

Conduction band: designated BC, it groups together the energy levels that can be occupied by electrons arriving from the valence band, known as conduction electrons and responsible for the conduction of electricity.

Valence band: referred to as BV, this is the set of energy levels that can be occupied by valence electrons. These provide the covalent bonds between the different atoms of a solid.

Forbidden band: referred to as FB, this is the set of states that are not permitted.

III.2 Different types of material for different energy bands:

From Figure III. 2, we can see that there are three types of material, distinguished from each other by their bandgap width:

- In **conductors**: The conduction and valence bands overlap. The band gap is completely absent (figure III .2. a).

- In **insulators** : Conduction and valence bands are separated by a band gap FB whose height is greater than 3 eV. There are no affordable energy levels and no conduction (figure III .2. b).

Example: Diamond has Eg=5.47 eV.

- For semiconductors (S/C): The conduction and valence bands are separated by a band gap whose width EG is less than 2 eV. (figure III .2. c).

Example: Silicon (Si), Eg=1.12 eV.
Germanium (Ge), Eg=0.66 eV.
Galium arsenide (AsGa), Eg=1.43 eV

III.3 Semi-conductors

By definition, a semiconductor is often known as a material whose conductivity (or resistivity) depends on temperature as follows:

- If temperature T increases, conductivity δ increases (resistivity ρ decreases).
- If temperature T decreases, conductivity δ decreases (resistivity ρ increases).

Semiconductors are therefore insulators at low temperatures and conductors at high temperatures.

III.3.1 Structure des semi-conducteurs:

Silicon and germanium are the first and most widely used semiconductor elements. Their structure is identical to that of diamond (cubic Fd3m, figure III.3). These elements are tetravalent. Each atom is covalently bonded to four neighbors on the peaks of a tetrahedron. A reproduction of the structure on a plane is shown in figure III.4. The lines represent valence electrons.

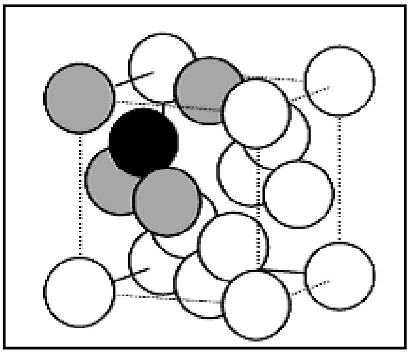


Fig III.3 La structure cubique du Diamant.

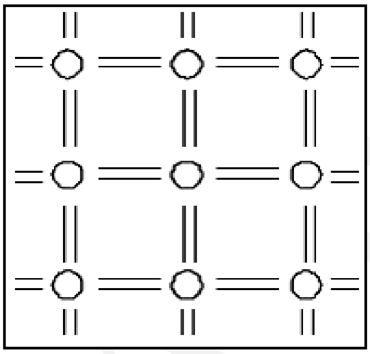


Fig III.4 Semiconductor structure on a plane.

III.3.2 Intrinsic semiconductor :

Peripheral electrons in non-excited semiconductors are tightly attached to atoms by links called covalent bonds. No mobile charge appears on the surface, and consequently no electric current. So this material can be considered an insulator, where its valence band is full, while its conduction band is empty.

III.3.2.1 Ionisation thermique :

As the temperature rises, covalent bonds are broken, and electrons become free to move around, leaving behind positive charges. These voids or gaps will be occupied by other electrons released by the thermal effect, which will in turn leave holes. It's as if the holes are moving, but with a lower mobility than the electrons.

II.3.2.2 The n_i concentration of free electrons and holes in the semiconductor:

The generation of electron-hole pairs is offset by another phenomenon called recombination, in which free electrons are captured by holes. In equilibrium between these two phenomena, the number of electrons is equal to the number of holes.

Let n be the concentration of free electrons in the conduction band per unit volume (cm^3), and p the concentration of free holes in the valence band per unit volume (cm_3), these concentrations are equal to ni the intrinsic concentration. :

$$np = n_i^2 \qquad (\text{III}.1)$$

III.3.3 Extrinsic semiconductor :

III.3.3.1 N-type doping:

Strange pentavalent atoms such as Sb antimony are introduced into the germanium crystal lattice. Each antimony atom engages an excess valence electron. This electron is weakly attached to the nucleus and easily passes into the conduction band. This increases conductivity. Donor antimony atoms become positive ions when they release the fifth electron. In this case, electrons are the majority carriers, while holes are the minority carriers.

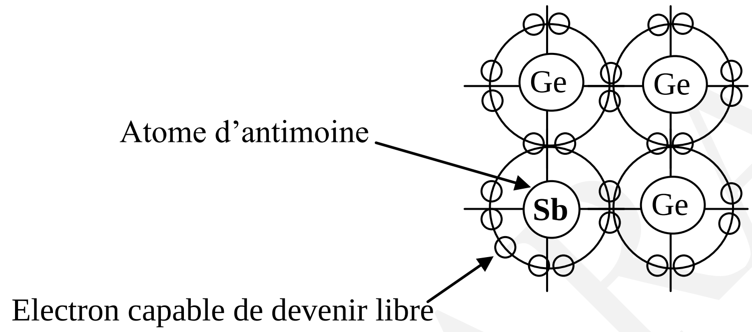


Fig III.5 N-type doping.

III.3.3.2 P -type doping :

This is provided by trivalent impurities such as indium In. These impurities lack an electron for the structure to be stable, so the electron from the germanium will be captured by the impurity, creating a hole. Holes become majority carriers because they are more numerous.

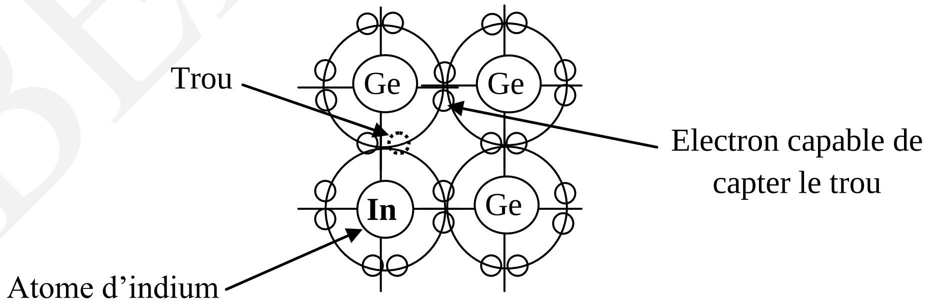


Fig III.6 P -type doping .

III.3.3.3 Load-carrying mechanism:

In the presence of the electric field $\vec{E}$, the movement of charge carriers, becomes ordered, it favors the movement of free electrons in the opposite direction of the field and the movement of holes in the direction of the field. Their velocities Vn and Vp respectively are proportional to the electric field E.

For electrons, we have :

$$\overrightarrow{v_n} = -\mu_n \vec{E} \;\; d'où \;\; V_n = \mu_n E \qquad (III.2)$$

and for the holes we have :

$$\overrightarrow{v_p} = -\mu_p \vec{E} \;\; d'où \;\; V_p = \mu_p E \qquad (III.3)$$

μ_n et μ_p are respectively the electron and hole mobilities, ($\mu_p<\mu_n$).

Example: For silicon, $\mu_n = 0{,}14 \; {m^2}/_{\text{V.s}} \;\; et \;\; \mu_p = 0{,}05 \; {m^2}/_{\text{V.s}}$

For germanium, $\mu_n = 0{,}38 \; {m^2}/_{\text{V.s}} \;\; et \;\; \mu_p = 0{,}17 \; {m^2}/_{\text{V.s}}$

III.3.3.4 Current due to an electric field:

The electrostatic force F=qE created by the electric field moves the charge carriers, where electrons move in the opposite direction to the field, while holes move in the same direction as the field.

From the fundamental law of dynamics: $F = \frac{mdV}{dt}$, we deduce the current density expressions for electrons and holes:

$$J_n = qnV_n = qn\mu_n E \qquad et \qquad J_p = qpV_p = qp\mu_p E \qquad (III.4)$$

Then the total current due to the field will be :

$$J = J_n + J_p = (qn\mu_n + qp\mu_p)E = \sigma E = \frac{1}{\rho}E \qquad (III.5)$$

Where σ: is the conductivity of the material and ρ: the resistivity.

III.4 PN junction:

A junction is defined as the assembly of two semiconductor parts, N and P, with a common boundary called the junction plane.

In reality, N and P semiconductors are not bonded together, but a P-doped zone is diffused into an N-doped silicon wafer.

III.4.1 Description of the phenomenon

Because of the different concentrations of charge carriers in the N and P regions, the majority carriers will tend to diffuse to the side where they are in the minority, so electrons will diffuse from the N side to the P side, and holes from the P side to the N side. In the proximity of the junction, holes and electrons are in large quantities, and therefore have a high probability of recombination. These electrons will leave fixed positive ions in the N region at the junction boundary, as will the holes, creating a zone called the space charge zone (SCZ) around the junction, empty of free carriers (see figure III.7). The result is an electric field directed from N to P, which favors the passage of minority carriers.

Equilibrium is established when the diffusion currents of the majority and minority carriers are equal.

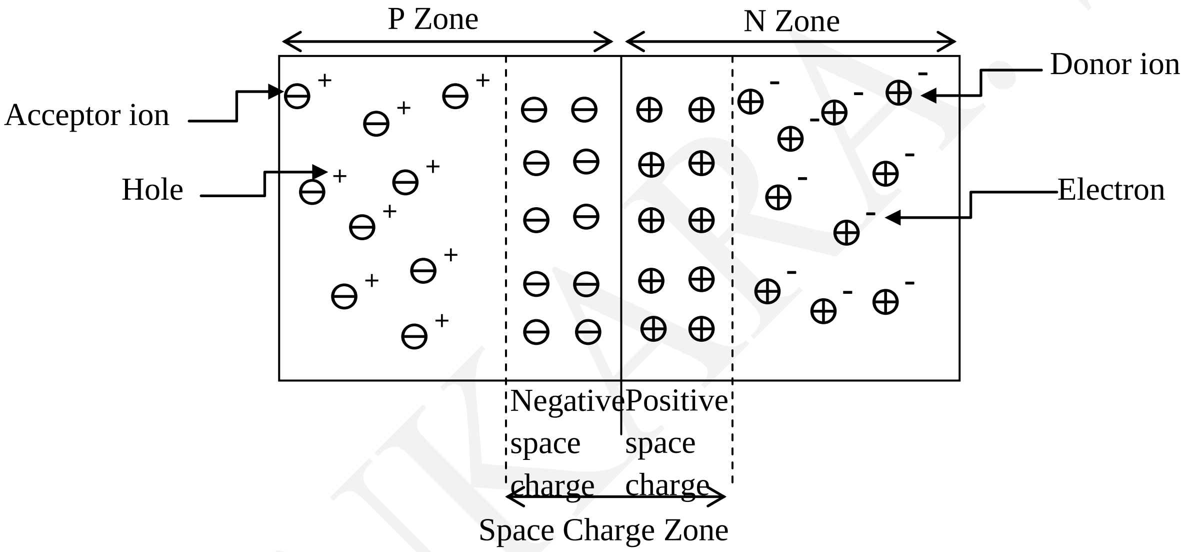


Fig III.7 Principle of creating a transition zone.

The transition zone contains :

- in the P zone, a region negatively charged by ionized acceptor atoms ;

- in the N zone, a region positively charged by ionized donor atoms.

III.4.2 Energy band diagram:

The energy bands for the PN junction are always continuous, but there will be a curvature at the interface because the passage of carriers from the N region to the P region takes place gradually.

The difference in energy levels, as shown in figure III.8, defines the potential barrier or threshold voltage V_D due to the electric field that will oppose the passage of carriers from regions of high concentration to regions of low concentration.

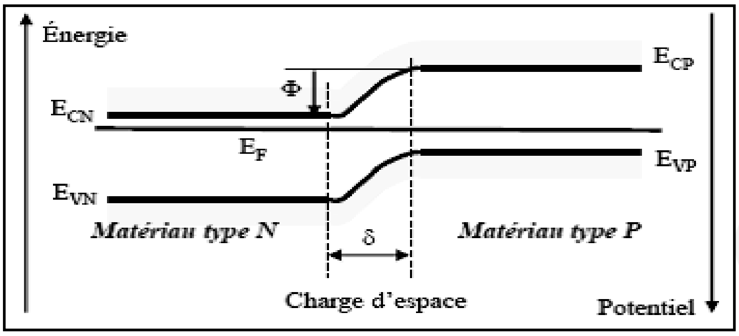


Fig III.8 Energy band diagram of the NP junction.

III.4.3 The PN junction at equilibrium:

The internal electric field resulting from the space charge in the depletion zone prevents majority carriers from passing and favors the passage of minority carriers, creating a current opposite to the majority diffusion current. At equilibrium, these two currents are equal, so there is no conduction.

III.4.4 The PN junction out of equilibrium:

III.4.4.1 Direct polarized PN junction:

By applying a voltage V as shown in figure III.9, the voltage Vj at the junction terminal: $Vj=V_D-V$, will be lower than V_D.

As a result, the barrier that carriers must overcome to pass from one region to the other is now smaller, and more of them will be able to pass, leading to an increase in the majority carrier current.

Note: The applied voltage V must be greater than the threshold voltage VD.

Example for Si: $V_D \approx 0.55$ V and for Ge: $V_D \approx 0.15$ V

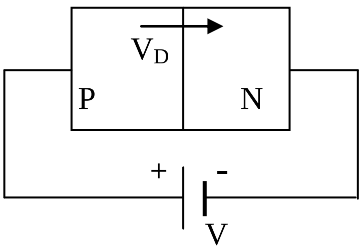


Fig III.9 Direct polarized PN junction.

III.4.4.2 Reverse-polarized PN junction:

In this case, the applied voltage V < 0, i.e. Vj greater than V_D, and the potential barrier will be greater than the threshold voltage, preventing any passage of majority carriers.

Only a minority current can flow through the junction. This is the reverse current or leakage current (Fig. III.10).

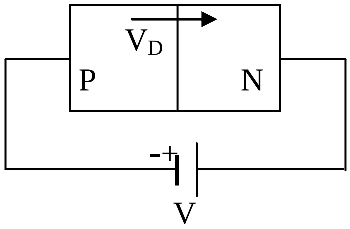


Fig III.10 Reverse-polarized PN junction.

III.5 The junction diode :

In practice, the PN junction (made of germanium or silicon) is simply the diode, a well-known device used by everyone whose graphic symbol is shown in figure III.11. The direction of conduction of the diode is indicated by the direction of the arrow.

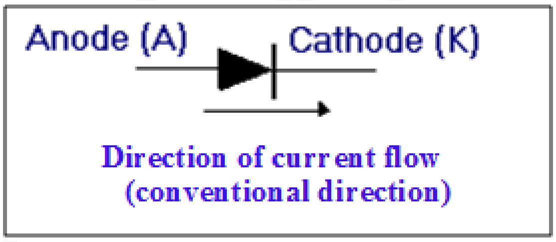


Fig III.11 Diode symbol.

The anode (A) corresponds to the P area of the junction and the cathode (K) to the N area; the "A" end requires a positive voltage with respect to the other "K" end.

III.5.1 Diode characteristics:

The direct voltage applied generates a current. This current, mainly due to the majority carriers, is related to the voltage V by an exponential relationship:

$$I = I_S\left(e^{\frac{eV}{KT}} - 1\right) \qquad (III.6)$$

Is is the saturation current (reverse current).

Figure III.12 shows the diode's I(V) characteristic. Where VD is the diode's threshold voltage, and VB, called the breakdown voltage, corresponds to the value of the reverse voltage that triggers the avalanche phenomenon.

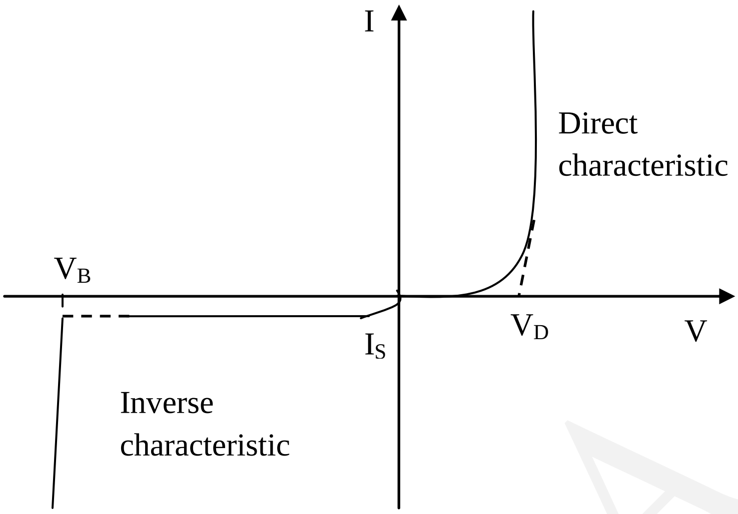


Fig III.12 Direct and inverse characteristics of a diode.

III.5.2 Electrical diagram equivalent to a real diode:

In electrical networks, the diode is replaced by its equivalent diagram. The latter is deduced from its blocking or conduction state:

- A passing diode is replaced by an voltage generator, the diode's threshold, in series with a resistor R_d (direct resistance),

- In the blocked state, the diode is replaced by a high-value resistor Ri (Figure III. 13).

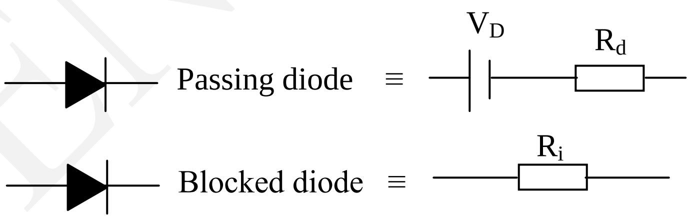


Fig III.13 Diode equivalent diagram.

III.5.3 Static resistance :

The static resistance RS of a diode is defined as the equivalent resistance of the diode when a constant current (in time) flows through it:

$$R_S = \frac{V}{I} \qquad (III.7)$$

The value of this resistance can also be determined graphically. The circuit in figure III.14 allows us to express I as a function of V.

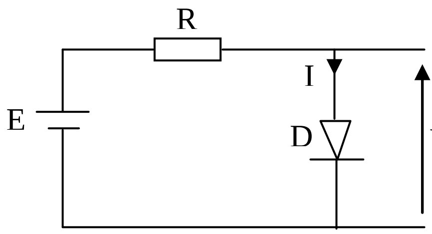


Fig III.14 Circuit containing a diode.

$$E = RI + V \qquad (III.8)$$

$$I = -\frac{V}{R} + \frac{E}{R} \qquad (III.9)$$

The coordinates of the intersection point Q of the load line represented by equation (III.9) and the diode characteristic, determine the value of the static resistance. Point Q with coordinates (I0, VD) is the operating point of the diode: $R_S = \frac{V_D}{I_0}$.

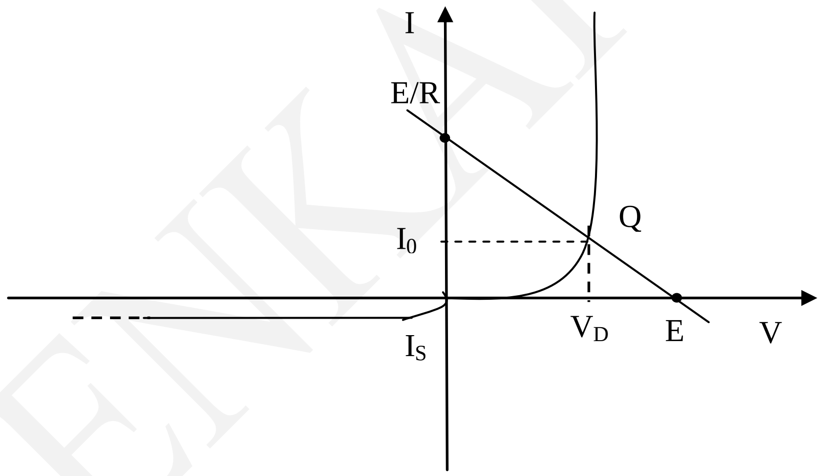


Fig III.15 Coordinates of the operating point.

III.5.4 Dynamic resistance:

The dynamic resistance is the equivalent resistance of the diode in variable operation, also known as the differential resistance. Its expression is given by the ratio of the variation in voltage across the diode to the variation in current through it, i of which :

$$R_d = \frac{\Delta V}{\Delta I} \qquad (III.10)$$

Differentiating equation (III.6) from the characteristic of a diode, we obtain :

$$\frac{dI}{dV} = \frac{e}{KT} I_S e^{\frac{eV}{KT}} = \frac{e}{KT}(I + I_S) \qquad (III.11)$$

$$R_d = \frac{dV}{dI} = \frac{\frac{KT}{e}}{I + I_S} \qquad (III.12)$$

As Is is insignificant compared to I, we have :

$$R_d = \frac{dV}{dI} = \frac{\frac{KT}{e}}{I} = \frac{U_T}{I} \qquad (III.13)$$

$U_T = \frac{KT}{e}$ is the thermal voltage, which assumes a value of around 0.026 V at T=300°C.

The dynamic resistance can be given by the relation :

$$R_d = \frac{0{,}026}{I}\frac{[V]}{[A]} = \frac{26}{I}\frac{[mV]}{[mA]} \qquad (III.14)$$

III.5.5 Rectification:

III.5.5.1 Simple alternating rectification :

Rectification is an essential function in electronics, converting a bipolar signal into a unipolar one. There are two possible cases: obtaining a positive DC signal or a negative DC signal from an AC signal.

a) Conversion from AC to positive DC :

The circuit used in this conversion removes the negative part of the AC signal and keeps the positive part. Figure III.16 shows a simple circuit for converting a sinusoidal signal to a positive DC signal.

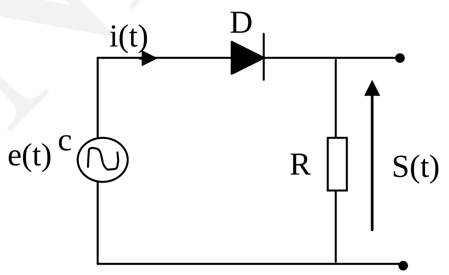


Fig III.16 Basic circuit of a positive simple-wave rectifier.

The operating principle is illustrated by the chronogram in Figure III.17, where the diode used is assumed to be ideal:

- For 0 < t < T/2 ⇒ e(t) > 0 the diode is conducting. It behaves like a short circuit. All the positive alternation of e(t) is then recovered at the terminals of R.

- For T/2 < t <T⇒ e(t) < 0 i(t) tends to be less than zero, blocking the diode. In this case, the diode can be replaced by an open circuit, resulting in zero current i(t). Consequently, the voltage across R will be zero.

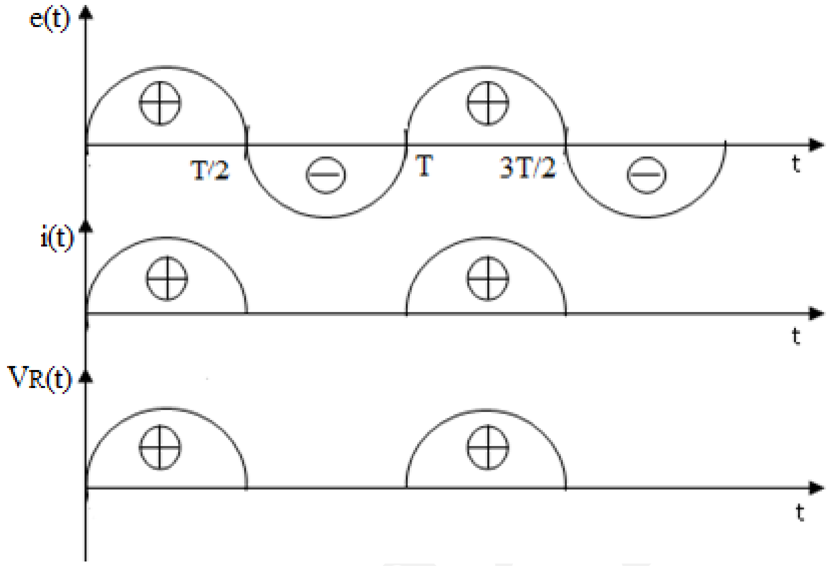


Fig III.17 Chronogram illustrating the circuit's operating principle

b) Conversion from AC to negative DC :

The circuit shown in Figure III.18 eliminates the positive part of the alternating signal, allowing only the negative part to pass through:

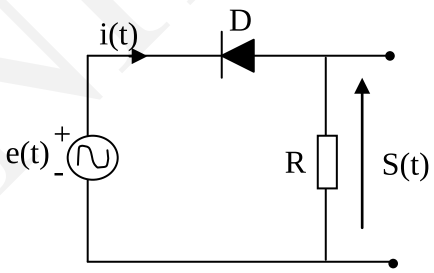


Fig III.18 Basic circuit of a negative simple-wave rectifier.

The operating principle is illustrated by the chronogram in Figure III.19 :

- For 0 < t < T/2 ⇒ e(t) > 0 i(t) tends to be greater than zero, positive current from cathode to anode blocks the diode. In this case, the diode can be replaced by an open circuit, resulting in zero current i(t). Consequently, the voltage across R will be zero.
- For T/2 < t <T⇒ e(t) < 0 i(t) tends to be less than zero, the diode has a positive current flowing through it from anode to cathode. The diode is therefore conductive. It

behaves like a short-circuit. All the negative alternation of e(t) will then be recovered at the terminals of R.

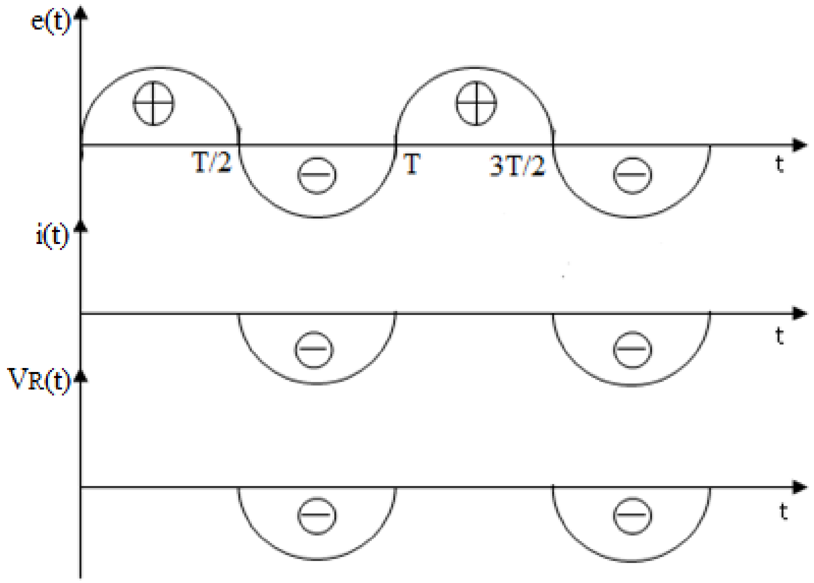


Fig III.19 Chronogram illustrating the circuit's operating principle

III.5.5.2 Dual alternation rectification:

Double-wave rectification also makes it possible to switch from an AC signal to a DC signal, while retaining both parts of the AC signal.

- If you want to obtain a positive unipolar signal, the positive alternation of the alternating signal is retained, but the negative alternation is converted to positive alternation.
- If you want to obtain a negative unipolar signal, the negative alternation of the alternating signal is retained, but the positive alternation is converted to negative alternation.

In practice, two main circuits are often used for double-wave rectification. The choice of one or the other depends on the type of application. The two circuits are :

- Double-wave rectification with a mid-point transformer.
- Double-wave rectification with diode bridge or Graetz bridge.

a) Double-wave rectification with midpoint transformer:

The output variable at the transformer secondary is subdivided into two signals of equal amplitude but opposite phase.

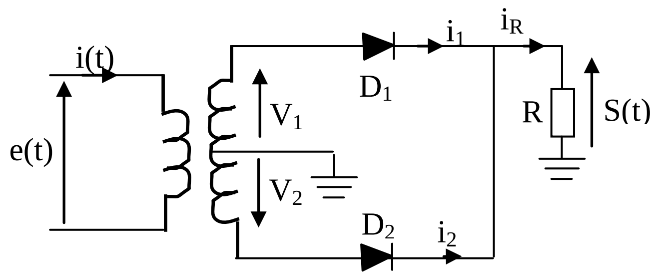


Fig III.20 Double-wave rectification with midpoint transformer.

To study the operation of the circuit shown in Fig. III.20, we take a sinusoidal voltage e(t) to be rectified. The transformer is chosen so that voltage V_1 is in phase with e(t).

$$For\ 0 < t < \frac{T}{2} \Rightarrow e(t) > 0 \Rightarrow \begin{cases} V_1 > 0 \Rightarrow D_1\ pass \\ V_2 < 0 \Rightarrow D_2\ blocked \end{cases}$$

Diode D1 is replaced by a short circuit (SC), while D2 is replaced by an open circuit (OC) (figure III.21).

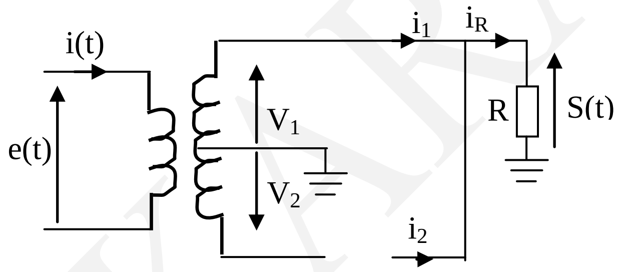


Fig III.21 Passing D_1 replaced by SC and blocked D_2 replaced by OC.

$$For\ \frac{T}{2} < t < T \Rightarrow e(t) < 0 \Rightarrow \begin{cases} V_1 < 0 \Rightarrow D_1\ blocked \\ V_1 > 0 \Rightarrow D_2\ pass \end{cases}$$

Diode D_1 is blocked, replaced by an open circuit (OC), while D_2 is conducting, replaced by a short circuit (SC) (figure III.22). As the current i1 is zero because D_1 is blocked, the current in load R is equal to i_2.

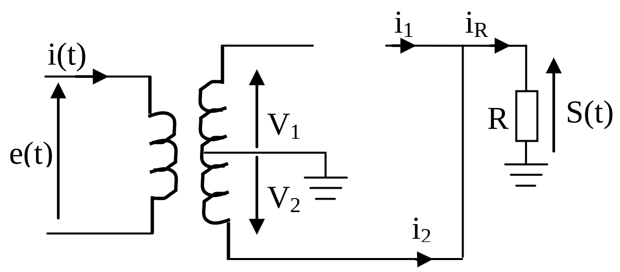


Fig III.22 D_1 blocked replaced by OC and D_2 passing replaced by SC.

Figure III.23 shows the chronogram of the various signals:

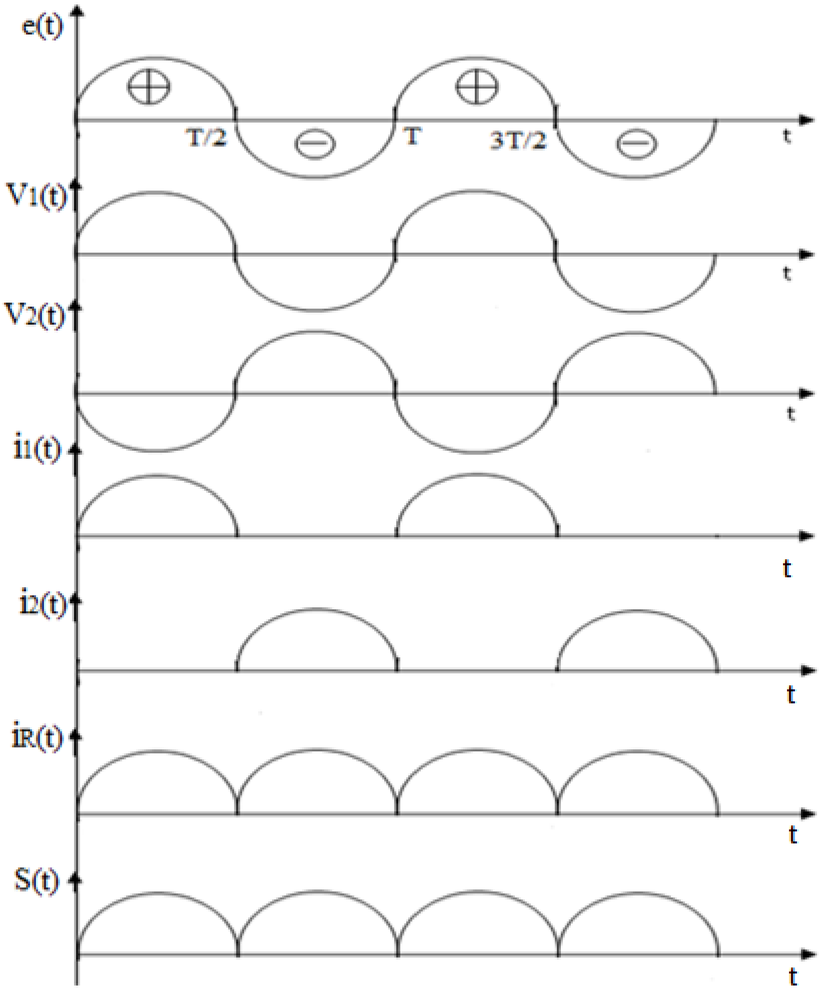


Fig III.23 Chronogram illustrating the circuit's operating principle.

We can see that the two diodes work alternately. During each of the two alternations, a single diode is connected in series with load R.

b) Double-wave rectification with diode bridge:

In this type of rectifier (Figure III.24), a transformer is not required, which minimizes the size and cost of the device.

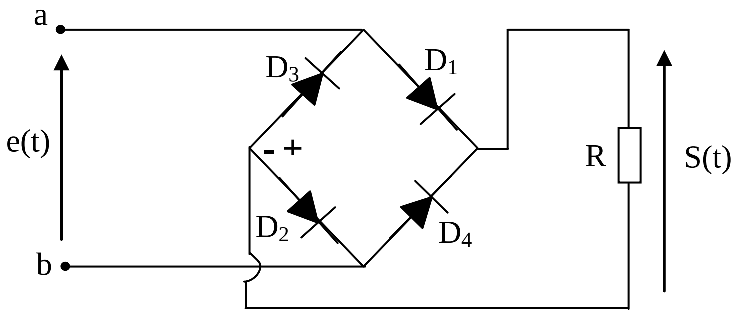


Fig III.24 Schematic of a diode bridge rectifier.

The + terminal of the bridge indicates the positive current output. Whatever the sign of e(t), a positive current always flows through the load in the same direction from + to -.

Operating principle :

$Pour\ 0 < t < \frac{T}{2} \Rightarrow e(t) > 0 \Rightarrow$ A positive current flows out of terminal a and into terminal b. This causes D3 and D4 to block and D1 and D2 to conduct. The circuit corresponding to this state is the one shown in figure III. 25.

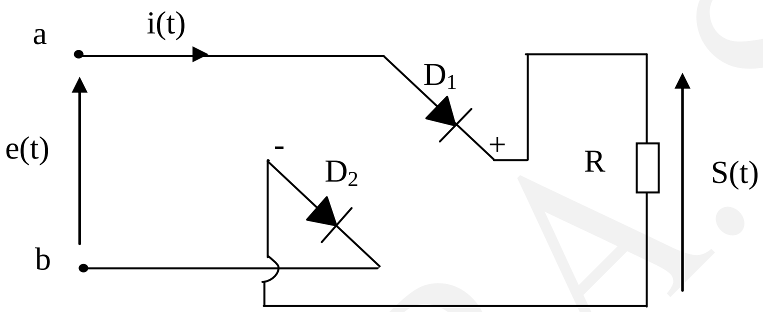


Fig III.25 Diodes D_1 and D_2 are passed and D_3 and D_4 are replaced by OC.

$Pour\ \frac{T}{2} < t < T \Rightarrow e(t) < 0 \Rightarrow$ A positive current flows out of terminal b and into terminal a. Diodes D1 and D2 are blocked, but diodes D3 and D4 are conducting. The circuit corresponding to this state is shown in figure III.26.

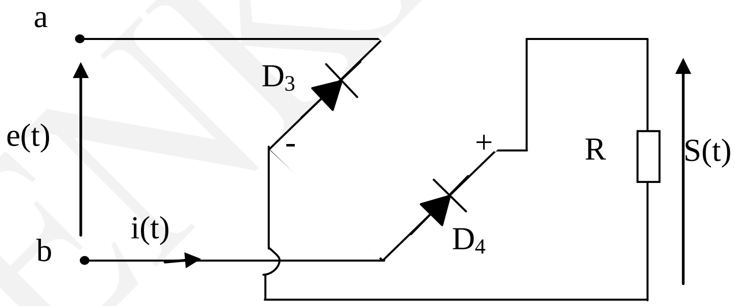


Fig III.26 Diodes D_3 and D_4 are passed and D_1 and D_2 are replaced by OC.

Remark: This type of circuit should not be used for rectifying low-amplitude signals, especially those below twice the diode threshold, as the R load is connected in series with two diodes.

III.6 The different types of diodes or special diodes:

III.6.1 Zener diode [1-4]:

Before studying the Zener diode, we will define two important effects:

a) Zener effect :

Reverse polarization of a PN junction increases the internal electric field. At a certain value, this field is capable of breaking bonds and releasing electron-hole pairs, a phenomenon known as the Zener effect.

b) Avalanche effect :

Due to the high intensity of the internal electric field caused by reverse polarization, electrons with relatively high kinetic energy are accelerated and collide with other atoms, tearing off electrons and in turn creating electron-hole pairs - the avalanche effect.

These two phenomena therefore cause a sudden increase in the reverse current.

III.6.1.1 Definition of a Zener diode and its symbol:

The Zener diode is obtained by exploiting the Zener effect. To avoid destroying the junction and exploit this phenomenon, simply keep the reverse current within a limited range. The symbols of a Zener diode are :

Figure III.27 shows that in the forward direction, the Zener diode behaves like an ordinary diode. However, in the reverse direction, as long as the current is between I_{Zmax} and I_{Zmin}, the voltage V_Z applied between the diode's cathode and anode will be kept constant, hence its main function.

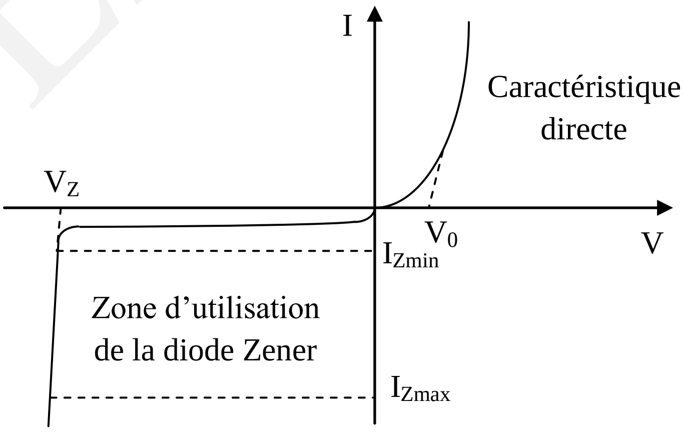


Fig III.27 The Zener diode is operated in the reverse

III.6.1.2 Zener diode voltage regulation principle:

One voltage regulation technique is the Zener diode. It is used to maintain a stable voltage in a circuit, regardless of variations in other elements of the circuit.

Given the circuit in figure III. 28, the load RC is supplied with voltage V across diode D_Z. As long as the current I_Z satisfies the condition : $I_{Zmin}<I_Z<I_{Zmax}$ the voltage V will be constant and equal to the Zener diode voltage V_Z.

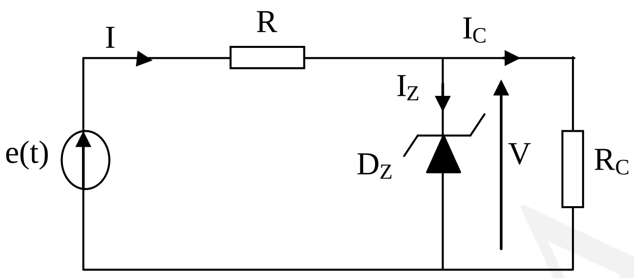


Fig III.28 La diode D_Z comme un régulateur de tension pour la charge R_C.

III.6.1.3 Zener diode protection:

The Zener diode is characterized by its fixed reverse voltage. It can be used as an essential element in clipping circuits and for circuit protection, by being connected in parallel with the load. In this way, the voltage across the load does not exceed a threshold corresponding to the diode's Zener voltage.

III.6.2 Light-emitting diode or LED:

The principle of the light-emitting diode (LED) is to convert electrical energy into light energy. They emit light when current flows through them in the forward direction. In these diodes, the passage of electrons from the valence band to the conduction band requires the input of a certain amount of energy, and the reverse change of state is obviously accompanied by the output of the same energy. This energy appears in the form of luminous radiation.

LEDs offer the possibility of modulating the intensity of the radiation by acting on the intensity of the current, and are also used as indicator lights.

III.6.3 Photodiode:

A photodiode is a semiconductor formed by a simple P-N junction that can be illuminated.

When photons of sufficient energy penetrate the semiconductor, they can create excess photo-carriers in the material. These photo-carriers are electron-hole pairs. Each pair created results in the circulation of an elementary charge in the external circuit. The result is an increase in current. Since the photo-currents created are very low, the junction must be reverse-biased, firstly to avoid the photodiode's forward current, which is much greater than the photo-current, and secondly to increase its efficiency.

Operating principle : The diode must be inserted into an electrical circuit supplied in reverse by a DC generator. In the dark, the diode allows only an extremely small current to flow, known as the dark current. As soon as it is illuminated, the current increases, because a certain number of carriers created in the vicinity of the junction are accelerated by the electric field that exists in the junction.

III.6.4 Varicap Diode :

The varicap diode behaves like a variable capacitor, modulated by an inverse voltage Vm applied across its terminals. It consists of a capacitor of capacitance C_0 in series with a diode. The capacitance of the varicap diode is given by the following expression :

$$C(V_m) = \frac{C_0}{\left(1 + \frac{V_m}{V_S}\right)^n} \qquad (III.15)$$

Where C_0 and VS (diode threshold voltage) are constants. Varicap diodes are widely used in electronic circuits, especially in FM modulation.

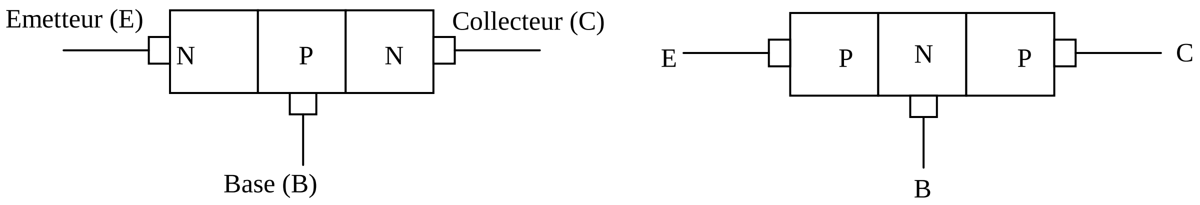
Chapter IV

Bipolar Transistor

The transistor is the basic element of all electronic components, from small amplifiers to integrated circuits. It's a combination of two junctions, one forward-polarized and the other reverse-polarized to ensure normal transistor operation. It's called bipolar because electrical conduction is achieved by two types of charge carriers: electrons and holes. A static study is carried out to determine the transistor's operating mode, based on the position of the rest point. The dynamic study is characterized by four parameters: input and output impedance, voltage and current gain. The values of these quantities determine the transistor's characteristics and, consequently, its application.

IV.1 Definition :

A transistor is made up of three pieces of semiconductor, alternately doped "N" or "P". Consequently, there are two types of transistor:



Transistor NPN

Transistor PNP

Fig IV.1 Structure of a bipolar transistor.

The NPN transistor is symbolized by the outgoing emitter current and vice versa for PNP :

NPN Transistor (outgoing emitter current)

PNP Transistor (incoming emitter current)

Fig IV.2 Electrical symbol for a bipolar transistor.

IV.2 Static bipolar transistor:

Three conditions must be met for normal bipolar transistor operation:

- The base-emitter junction (B.E.) must be forward-biased, and the base-collector junction must be reverse-biased.
- The emitter and collector are heavily doped, and the emitter is more heavily doped than the collector.
- The base is narrow and low-doped.

IV.2.1 Operating principle (Transistor effect) :

Consider the PNP transistor shown in figure IV.3-a. The emitter-base junction is forward-biased.

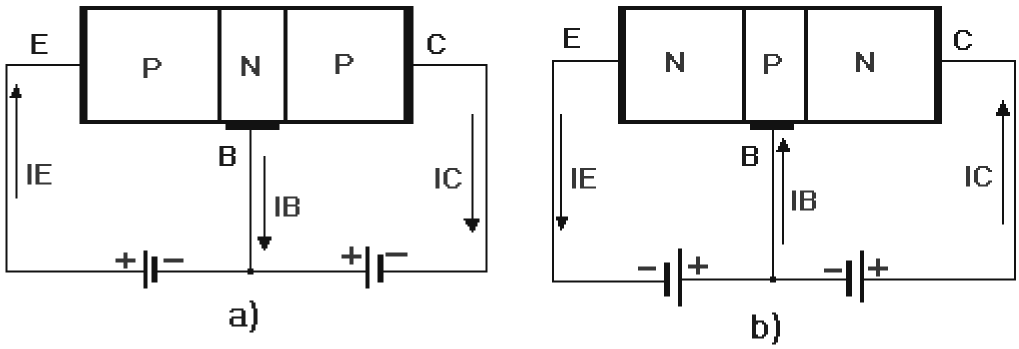


Fig IV.3 Polarized PNP and NPN

The electrons arriving at the emitter recombine with the holes present, while the same number of electrons are added to the base by the power source linked between this base and the emitter.

At the same time, the same stack attracts an equal number of electrons from the emitter, in which new holes are formed to replace those that have disappeared due to recombination.

As the collector-base junction is reverse-polarized, it prevents majority carriers from advancing and favours the passage of minority carriers, so that holes arriving at the base are forced to cross the collector-base junction and rejoin the collector.

In reality, not all the holes coming from the emitter reach the collector, as a small proportion of them recombine with electrons present in the base. This helps form the base current known as I_B.

To make the collector current as equal as possible to the emitter current, a number of conditions must be met: recombination at the base must be reduced by shrinking the base and doping it lightly. This reduces the number of free electrons in the base.

IV.2.2 Translating the operating principle into equations:

The illustration above can be translated as follows:

$$I_E = I_C + I_B \qquad \text{(IV.1)}$$

$$I_C = \beta I_B \qquad \text{(IV.2)}$$

$$I_C = \alpha I_E \qquad (\alpha \to 1) \qquad \text{(IV.3)}$$

(IV.1), (IV.2) et (IV.3) $\Longrightarrow \alpha = \frac{\beta}{\beta+1}$ or $\beta = \frac{\alpha}{1-\alpha}$

IV.2.3 Basic assemblies :

To facilitate the study of transistors in electronic circuits, the transistor is transformed into a quadrupole by pooling one of the three connections, giving us three basic circuits:

Common Emitter (CE) **Common Collector (CC)** **Common Base (CB)**

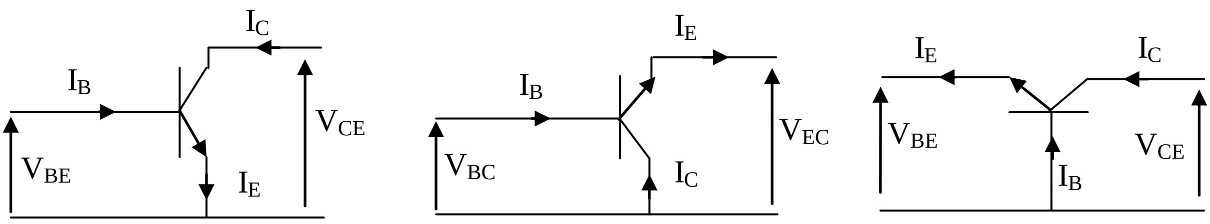


Fig IV.4 Basic bipolar transistor circuits.

IV.2.4.1 Base resistor polarization:

a) Without RE emitter resistor:

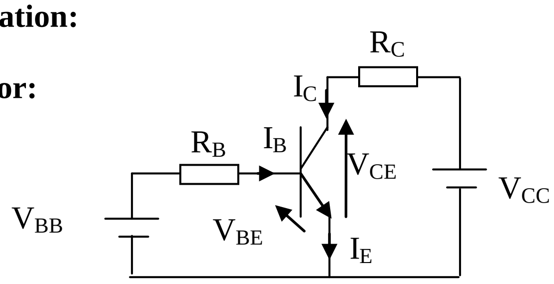


Fig IV.5 Transistor polarization.

Attack and load polarization point are used to determine the transistor's operating state. The coordinates of these points are determined by the variables: I_B, V_{BE}, I_C and V_{CE} :

$$V_{BB} = R_B \cdot I_B + V_{BE} \qquad \text{(IV. 4)}$$

$$V_{CC} = R_C \cdot I_C + V_{CE} \qquad \text{(IV. 5)}$$

Equation (IV.4) gives us: $I_B = \frac{V_{BB} - V_{BE}}{R_B}$ (IV. 6)

Equation (IV.5) gives us: $I_C = \frac{V_{CC} - V_{CE}}{R_C}$ (IV. 7)

With $I_B = f(V_{BE}) = \frac{V_{BB} - V_{BE}}{R_B}$ is called **: Static attack line.**

$I_C = f(V_{CE}) = \frac{V_{CC} - V_{CE}}{R_C}$ is called: **Static load line.**

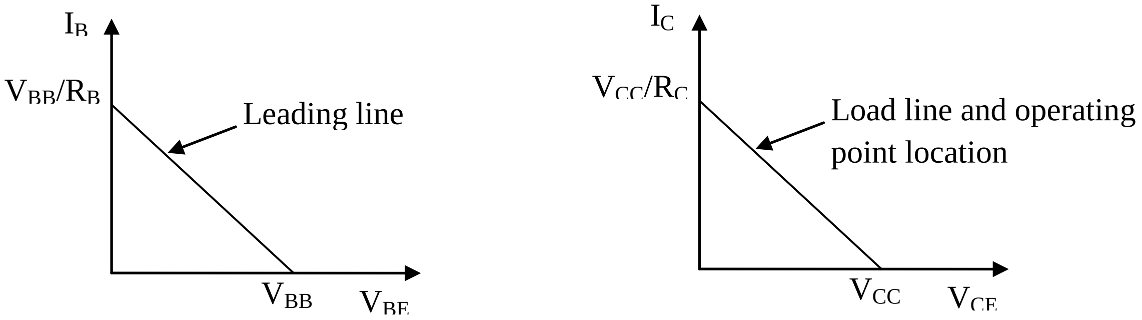


Fig IV.6 The attack line and the static load line.

a) Basic resistance polarization with RE:

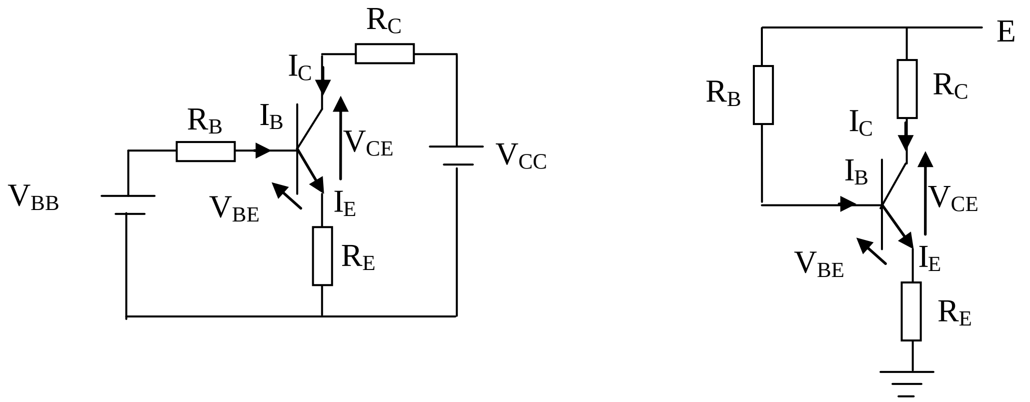


Fig IV.7 (a) Base resistance polarization with RE, (b) when VBB=VCC=E.

The principle for calculating the operating point is the same as for the previous case, where we first need to find the expressions for the equations of the attack line and the load line.

$$V_{BB} = R_B \cdot I_B + V_{BE} + R_E \cdot I_E \quad avec \quad I_E = (\beta + 1) I_B \qquad \text{(IV. 8)}$$

So

$$I_B = -\frac{V_{BE}}{R_B + (\beta+1)R_E} + \frac{V_{BB}}{R_B + (\beta+1)R_E} \quad \text{(IV.9)}$$

For $\beta \gg 1$ we obtain : $I_E \approx I_C$:

$$I_B = -\frac{V_{BE}}{R_B + \beta R_E} + \frac{V_{BB}}{R_B + \beta R_E} \quad \text{(IV.10)}$$

$$I_C = -\frac{V_{CE}}{R_C + R_E} + \frac{V_{CC}}{R_C + R_E} \quad \text{(IV.11)}$$

In the case of figure IV .7 (b), V_{CC} and V_{BB} will be replaced in equations IV.10 and IV.11 by a single supply voltage E.

IV.2.4.2 Resistance polarization between base and collector [1,4]:

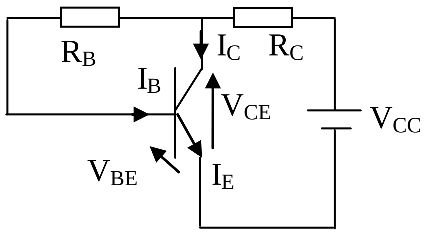


Fig IV.8 Resistance polarization between base and collector.

$$V_{BE} = -R_B \cdot I_B - R_C(I_C + I_B) + V_{CC} \quad \text{(IV.12)}$$

$$I_B = -\frac{V_{BE}}{R_B + (\beta+1)R_C} + \frac{V_{CC}}{R_B + (\beta+1)R_C} \quad \text{(IV.13)} \ \textbf{Static attack line}$$

$$I_C = -\frac{V_{CE}}{\left(\frac{1}{\beta}+1\right)R_C} + \frac{V_{CC}}{\left(\frac{1}{\beta}+1\right)R_C} \quad \text{(IV.14)} \ \textbf{Static load line}$$

IV.2.4.3 Polarization by divider bridge [1,7]:

Applying Thévenin's theorem to the circuit as seen from the base of the transistor gives the equivalent diagram shown in Figure IV.9 :

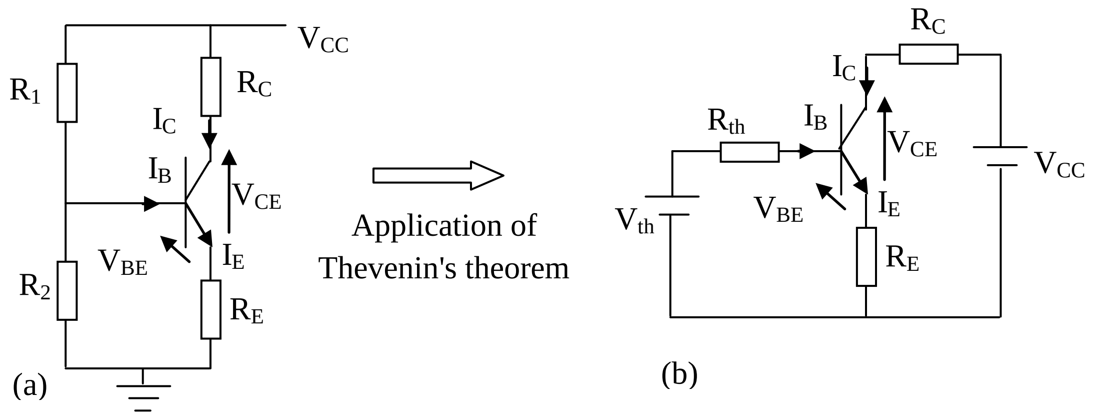


Fig IV.9 (a) Basic bridge polarization, (b) Thévenin equivalent circuit.

$$V_{th} = V_{CC} \cdot \frac{R_2}{R_2 + R_1} \quad et \quad R_{th} = R_1 \parallel R_2 = \frac{R_1 \cdot R_2}{R_1 + R_2} \qquad (\text{IV}.15)$$

$$I_B = f(V_{BE}) = -\frac{V_{BE}}{R_{th} + (\beta + 1)R_E} + \frac{V_{th}}{R_{th} + (\beta + 1)R_E} \quad (\text{IV}.16)\ \textbf{Static attack line}.$$

$$V_{CC} = R_C I_C + V_{CE} + R_E \left(1 + \frac{1}{\beta}\right) I_C = (R_C + R_E) I_C + V_{CE} \ \ (\beta \gg 1) \qquad (\text{IV}.17)$$

$$I_C = f(V_{CE}) = -\frac{V_{CE}}{R_C + R_E} + \frac{V_{CC}}{R_C + R_E} \qquad (\text{IV}.18)\ \ \textbf{Static load line}$$

IV.3 Transistor in dynamic regime:

The study of an amplifier circuit is subdivided into two parts: the static study already carried out and the dynamic study. :

Static study = transistor polarization, static load line and calculation of operating point.

Dynamic study = Calculation of voltage amplification, current amplification, input impedance, output impedance.

IV.3.1 Equivalent diagram of an alternative transistor:

Let's take the common emitter circuit shown in figure IV.10 as an example.

The electrical quantities (voltage and current) that exist at the various terminals of the transistor are made up of two components: A DC component due to the bias circuit and an AC component due to the useful signal.

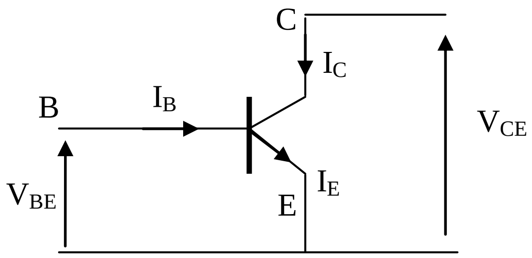


Fig IV.10 Emitter mounting.

The various electrical quantities are given by the following expressions :

$v_{BE} = v_{be} + V_{BE}$ Voltage between base and emitter

$i_B = i_b + I_B$ Base current

$v_{CE} = v_{ce} + V_{CE}$ Voltage between collector and emitter

$i_C = i_c + I_C$ Collector current

With V_{BE}, I_B, V_{CE} et I_C : Continuous components, and v_{be}, i_b, v_{ce} et i_c : Alternating components.

The results of the sum of continuous and alternating quantities are related to each other:

$$v_{BE} = f(i_B, v_{CE})$$
$$i_C = g(i_B, v_{CE})$$

The difference between these two expressions gives :

$$\Delta v_{BE} = \frac{\partial f}{\partial i_B}\Delta i_B + \frac{\partial f}{\partial v_{CE}}\Delta v_{CE} \qquad \text{(IV. 19)}$$

$$\Delta i_C = \frac{\partial g}{\partial i_B}\Delta i_B + \frac{\partial g}{\partial v_{CE}}\Delta v_{CE} \qquad \text{(IV. 20)}$$

Where : $\Delta v_{BE} = v_{be}$ et $\Delta i_B = i_b$

$$\Delta v_{\mathrm{CE}} = v_{ce} \;\; et\; \Delta i_{C=} i_c$$

The equations thus become :

$$v_{be} = \frac{\partial f}{\partial i_B} i_b + \frac{\partial f}{\partial v_{CE}} v_{ce} \qquad \text{(IV. 21)}$$

$$i_c = \frac{\partial g}{\partial i_B} i_b + \frac{\partial g}{\partial v_{CE}} v_{ce} \qquad \text{(IV. 22)}$$

These two equations are similar to the hybrid matrix representation in quadrupoles such as :

$$v_{be} = h_{11} i_b + h_{12} v_{ce} \qquad \text{(IV. 23)}$$

$$i_c = h_{21} i_b + h_{22} v_{ce} \qquad (IV.24)$$

With:

$$h_{11} = \frac{\partial f}{\partial i_B} = \frac{\Delta v_{BE}}{\Delta i_B}\bigg|_{v_{ce}=cte} \quad cte \quad et \quad h_{12} = \frac{\partial f}{\partial v_{CE}} = \frac{\Delta v_{BE}}{\Delta v_{CE}}\bigg|_{i_B=cte}$$

$$h_{21} = \frac{\partial g}{\partial i_B} = \frac{\Delta i_c}{\Delta i_B}\bigg|_{v_{ce}=cte} \quad cte \quad et \quad h_{22} = \frac{\partial g}{\partial v_{CE}} = \frac{\Delta i_c}{\Delta v_{CE}}\bigg|_{i_B=cte}$$

From equations (IV.23) and (IV.24), we can deduce the equivalent schematic of a transistor for small signals by studying the input and output characteristics.

a) Input characteristics:

Equation (IV.23) gives the input, equivalent to a single-mesh circuit containing a resistor h_{11} through which the current ib flows and $h_{12}v_{CE}$ as a controlled voltage source. h_{12} represents the transistor's internal feedback coefficient ($h_{12} \approx 0$). As a result, the circuit seen between the transistor's base and emitter is as follows:

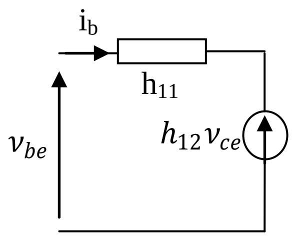


Fig IV.11 Equivalent circuit diagram.

b) Output characteristics:

The output circuit seen between the transistor's collector and emitter is deduced from equation (IV.24), and comprises a single node with two branches having ic as the total current, h_{22}^{-1} resistance of one branch across which we have the voltage vce and the second branch is a controlled current source $h_{21}i_b$. h_{21} represents the transistor's current gain in common emitter (h_{21} is usually very large):

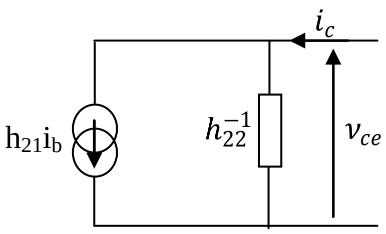


Fig IV.12 Equivalent output circuit diagram.

Consequently, combining the two circuits (input and output) gives us the following overall diagram:

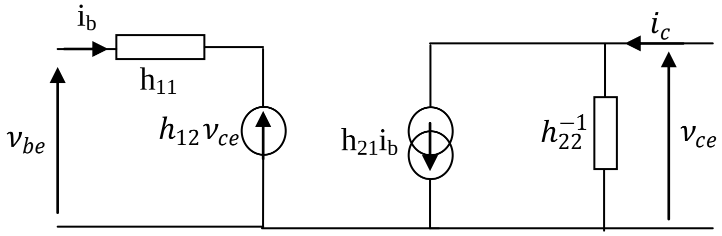


Fig IV.13 Global equivalent diagram of the bipolar

The previous circuit can be simplified by neglecting h12 (very small value), giving :

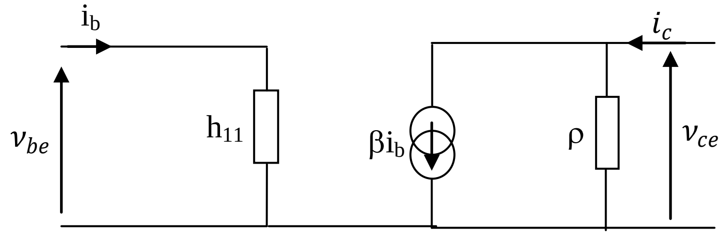


Fig IV.14 Simplified equivalent diagram of the bipolar

IV.3.2 Study of a common emitter (CE) with decoupled RE:

The circuit shown in Figure IV.15 is a common emitter with decoupled RE, representing a single-stage low-frequency amplifier loaded by a resistor RL.

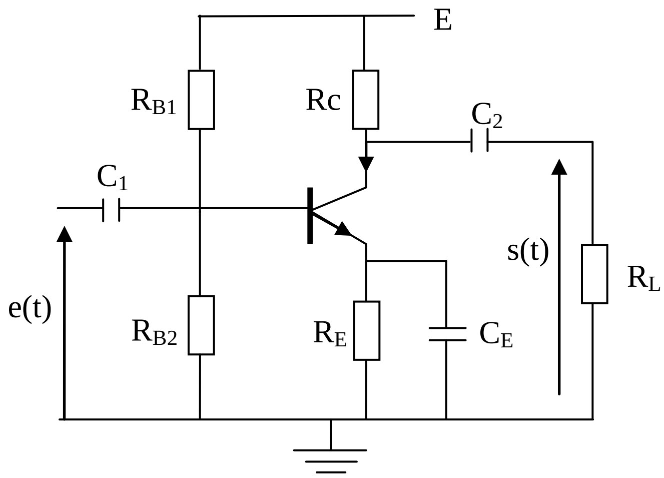


Fig IV.15 Transistor-based low-frequency amplifier.

We assume that the static study has already been carried out. For the dynamic study, follow these steps:

- Short-circuit the DC voltage source (E=0) and leave the AC excitation e(t) ;
- Connecting capacitors (such as C_1 and C_2) and decoupling capacitors (such as C_E) will be replaced by AC short-circuits;

- Replace the transistor with its AC equivalent diagram.

The AC amplifier circuit becomes that shown in Figure IV. 16 :

With $R_B = R_{B1} // R_{B2}$

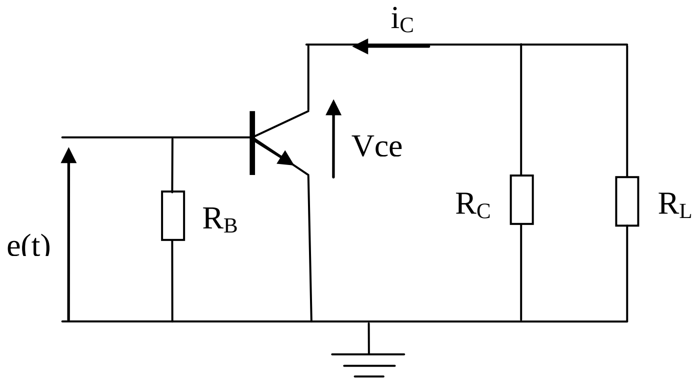


Fig IV.16 Amplificateur en alternatif.

Its complete equivalent diagram is as follows:

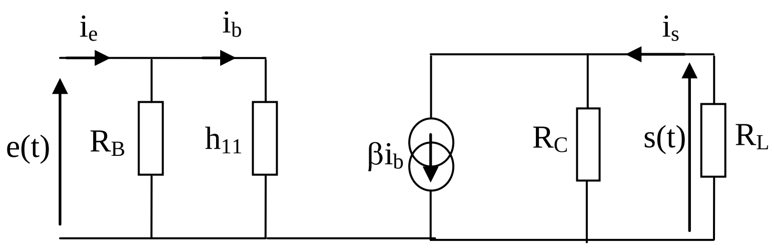


Fig IV.17 Equivalent diagram of the EC amplifier in AC, RE decoupled.

Four parameters to be determined in the dynamic study: voltage amplification, current amplification, input impedance and output impedance.

a) Voltage amplification

Voltage amplification is given by :

$$A_V = \frac{s}{e} \qquad \text{(IV. 25)}$$

$$\left.\begin{aligned} s &= -R_C \parallel R_L \cdot \beta i_b \quad &\text{(IV. 26)} \\ e &= h_{11}\, i_b \quad &\text{(IV. 27)} \end{aligned}\right\} \Rightarrow \quad A_V = -\frac{\beta R_C \parallel R_L}{h_{11}} \qquad \text{(IV. 28)}$$

b) Current amplification

Current amplification is given by :

$$A_i = \frac{i_s}{i_e} \qquad \text{(IV. 29)}$$

$$i_s = \frac{R_C}{R_C + R_L} \beta i_b \qquad \text{(IV. 30)}$$

$$i_e = \frac{R_B + h_{11}}{R_B} i_b \qquad (IV.31)$$

To get:

$$A_i = \frac{\beta R_C}{R_C + R_L} \frac{R_B}{R_B + h_{11}} \qquad (IV.32)$$

c) Input impedance:

This is the ratio of input voltage to input current:

$$Z_i = \frac{e}{i_e} \qquad (IV.33)$$

$$i_e = \frac{e}{R_B} + \frac{e}{h_{11}} \qquad (IV.34)$$

Therefore : $$Z_e = R_B \parallel h_{11} = \frac{R_B h_{11}}{R_B + h_{11}} \qquad (IV.35)$$

d) Output impedance:

This is the ratio of output voltage to output current with the input short-circuited and RL disconnected (Figure IV.18):

$$Z_S = \left. \frac{s(t)}{i_S} \right|_{e_g = 0} \qquad (IV.36)$$

Resistor R_L is disconnected because its driver circuit has been reduced to a Thévenin (Z_S impedance voltage source) or Norton (Z_S impedance current source) circuit.

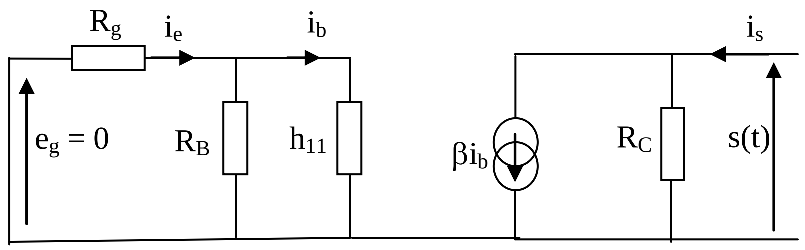


Fig IV. 18 Equivalent amplifier diagram when e =0 and RL disconnected.

Applying the law of meshes on the input side, we find: $i_b = 0$

On the output side of the same circuit, applying the law of nodes :

$$i_s = \frac{S(t)}{R_C} + \beta i_b \qquad as\ i_b = 0 \quad on\ a\ \ i_s = \frac{S(t)}{R_C} \qquad (IV.37)$$

$$\text{So} \qquad Z_S = R_C \qquad (IV.38)$$

IV .3.3 Common Emitter (CE) with non-decoupled RE :

We use the same circuit as in the previous paragraph, but remove the decoupling capacitor CE. The resulting circuit is shown in the figure below:

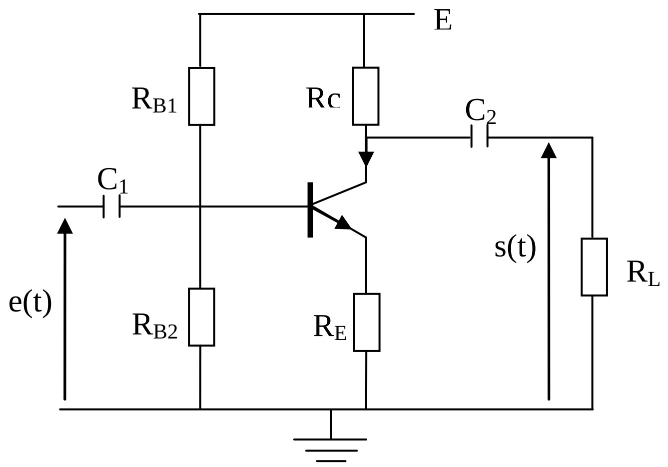


Fig IV.19 Common Emitter (CE) with non-decoupled

The equivalent dynamic circuit is shown in Figure IV.20 :

With $R_B = R_{B1} // R_{B2}$

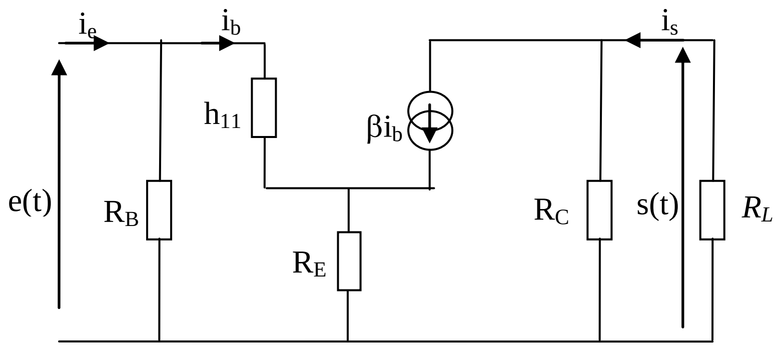


Fig IV.20 Equivalent diagram of the EC amplifier in AC with non-decoupled RE.

a) Voltage amplification

Voltage amplification is given by : $A_V = \frac{s}{e}$

$$s = -(R_C \parallel R_L) \cdot \beta i_b \qquad (IV.39)$$

$$e = h_{11}\, i_b + (\beta + 1) i_b R_E = (h_{11} + (\beta + 1) R_E) i_b \qquad (IV.40)$$

$$A_V = -\frac{\beta R_C \parallel R_L}{(h_{11} + (\beta+1)R_E)} \qquad (IV.41)$$

b) Current amplification :

Current amplification is given by :

$$A_i = \frac{i_s}{i_e}$$

$$i_s = \frac{R_C}{R_C + R_L}\beta i_b \qquad (IV.42)$$

$$i_e = \frac{R_B + (h_{11} + (\beta+1)R_E)}{R_B} i_b \qquad (IV.43)$$

$$A_i = \frac{\beta R_C}{(R_C + R_L)(}\frac{R_B}{R_B + (h_{11} + (\beta+1)R_E)} \qquad (IV.44)$$

c) Input impedance:

This is the ratio of input voltage to input current:

$$Z_i = \frac{e}{i_e}$$

$$i_e = \frac{e}{R_B} + \frac{e}{(h_{11} + (\beta+1)R_E)} \qquad (IV.45)$$

Where :

$$Z_e = R_B \parallel (h_{11} + (\beta+1)R_E) = \frac{R_B(h_{11} + (\beta+1)R_E)}{R_B + (h_{11} + (\beta+1)R_E)} \qquad (IV.46)$$

d) Output impedance:

This is the ratio of output voltage to output current with the input short-circuited and RL disconnected.

$Z_S = \frac{s(t)}{i_S}\Big|_{e_g=0,\, R_L\ débranc\ hée}$

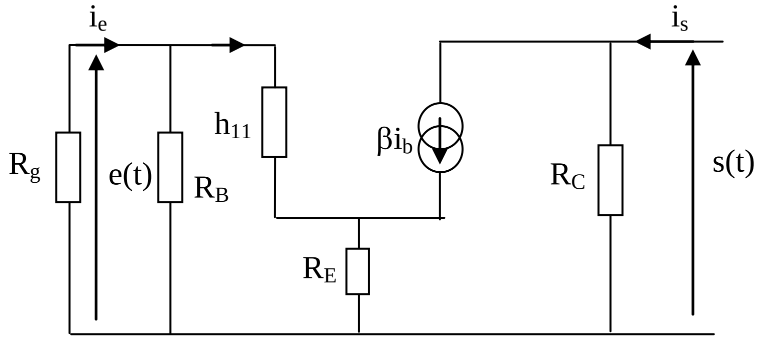


Fig IV.21 Equivalent amplifier diagram when e =0 and RL disconnected.

Applying the law of meshes on the input side, we find: ib = 0

On the output side of the same circuit, applying the law of nodes :

$$i_s = \frac{S(t)}{R_C} + \beta i_b \qquad comme\ i_b = 0 \quad on\ a\ \ i_s = \frac{S(t)}{R_C} \qquad (IV.47)$$

$$\text{Donc} \qquad Z_S = R_C \qquad (IV.48)$$

IV.3.4 Common collector (CC) :

To determine the type of circuit, we must first determine the input and output signal terminals, the remaining terminal defining the type of circuit.

In the case of the circuit shown in the following figure, the input is applied to base B, the output is taken from emitter E, so the circuit is a common collector.

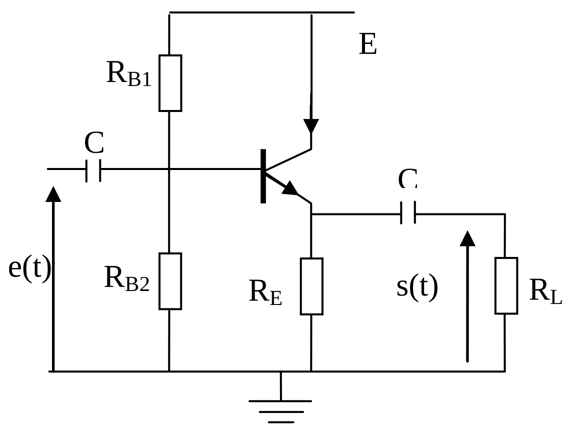


Fig IV.22 Low-frequency amplifier based on a DC transistor.

a) Voltage amplification

Voltage amplification is given by : $A_V = \frac{s}{e}$

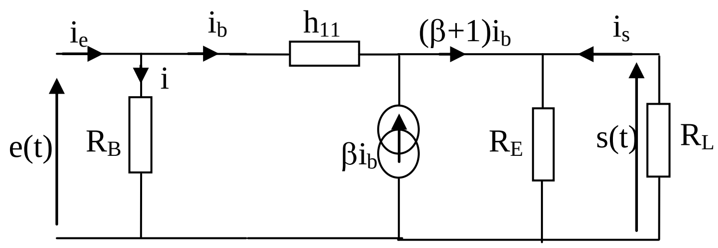


Fig IV.23 Schéma équivalent de l'amplificateur CC en alternatif.

$$s = (R_E \parallel R_L)(\beta + 1)i_b \qquad (IV.49)$$

$$e = h_{11}\, i_b + (R_E \parallel R_L)(\beta + 1)i_b \qquad (IV.50)$$

$$A_V = \frac{(R_E \parallel R_L)(\beta + 1)}{\left(h_{11} + (\beta + 1)(R_E \parallel R_L)\right)} \qquad (IV.51)$$

b) Current amplification :

Current amplification is given by :

$$A_i = \frac{i_s}{i_e}$$

Applying the current divider to the output gives i_S :

$$i_s = \frac{R_E}{R_E + R_L}(\beta + 1)i_b \qquad (IV.52)$$

At the input we have : $i_e = i + i_b = \frac{e(t)}{R_B} + \frac{e(t)}{h_{11} + (\beta+1)(R_E \parallel R_L)}$ (IV. 53)

From this equation we can see that the current ie is divided into two currents along two branches of resistance R_B and $(h_{11} + (\beta + 1)(R_E \parallel R_L))$

Applying the current divider :

$$i_e = \frac{R_B + h_{11} + (\beta + 1)(R_E \parallel R_L)}{R_B} i_b \qquad (IV.54)$$

$$A_i = -\frac{R_E(\beta + 1)}{R_E + R_L} \frac{R_B}{R_B + h_{11} + (\beta + 1)(R_E \parallel R_L)} \qquad (IV.55)$$

c) Input impedance:

This is the ratio of input voltage to input current:

$$Z_i = \frac{e}{i_e}$$

By replacing ie as a function of e(t) in this ratio, we find :

$$Z_e = R_B \parallel \left(h_{11} + (\beta + 1)(R_E \parallel R_L)\right) \qquad (IV.56)$$

d) Output impedance:

This is the ratio of output voltage to output current with the input short-circuited and RL disconnected.

$$Z_S = \left.\frac{s(t)}{i_S}\right|_{e_g=0,\, R_L\ débranc\ hée}$$

With these conditions, the circuit will be replaced by the one shown in the following figure:

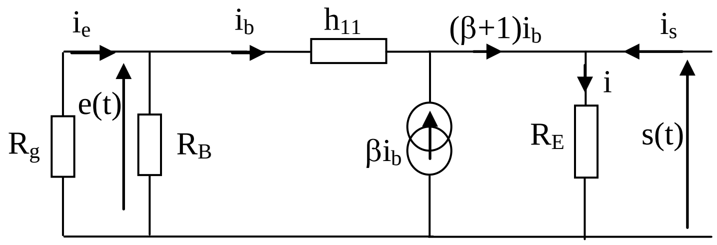


Fig VI.24 Equivalent amplifier diagram when e =0 and RL disconnected.

According to the figure, the expression of iS will be given by :

$$i_S = i - (\beta+1)i_b = \frac{s(t)}{R_E} + (\beta+1)\frac{s(t)}{h_{11}} \qquad (\text{IV}.57)$$

$$\text{As} \quad i_b = -\frac{s(t)}{h_{11}}$$

$$i_S = \frac{s(t)}{R_E} + \frac{s(t)}{\frac{h_{11}}{\beta+1}} \Rightarrow Z_S = R_E \parallel \left(\frac{h_{11}}{\beta+1}\right) \qquad (\text{IV}.58)$$

As h_{11} represents the dynamic resistance of a pass diode (small value resistance) and β the static current gain (usually very large) the output impedance Zs is in most cases approximated by :

$$Z_S = \left(\frac{h_{11}}{\beta+1}\right) \qquad (\text{IV}.59)$$

IV.3.5 Common Base (CB) :

In a common-base (CB) circuit, excitation is provided by the emitter, and the output is taken from the collector.

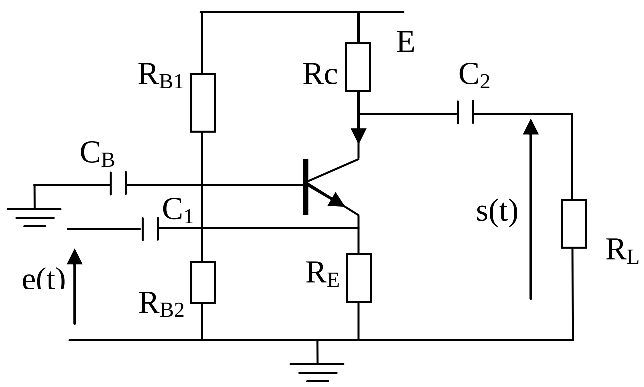


Fig IV.25 Low-frequency amplifier based on a BC transistor.

In AC, E= 0, the capacitors are replaced by zero impedances and the transistor is replaced by its equivalent diagram :

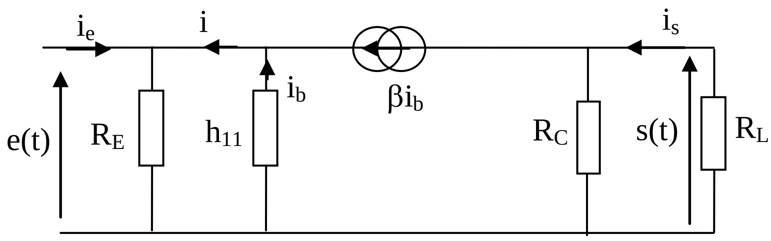


Fig IV.26 Equivalent schematic of the BC AC amplifier.

a) Voltage amplification

Voltage amplification is given by : $A_V = \frac{s}{e}$

$$s = -(R_C \parallel R_L) \cdot \beta i_b \qquad \text{(IV.60)}$$

$$e = -h_{11}\, i_b \qquad \text{(IV.61)}$$

$$A_V = \beta \frac{R_C \parallel R_L}{h_{11}} \qquad \text{(IV.62)}$$

b) Current amplification :

Current amplification is given by :

$$A_i = \frac{i_s}{i_e}$$

$$i_s = \frac{R_C}{R_C + R_L} \beta i_b \qquad \text{(IV.63)}$$

$$i_e = \frac{e(t)}{R_E} - i \quad with \quad i = (\beta + 1) i_b \quad and \quad e = -h_{11}\, i_b \qquad \text{(IV.64)}$$

Replacing i as a function of ib in the expression for ie , we obtain:

$$i_e = -\frac{h_{11}\, i_b}{R_E} - (\beta + 1) i_b \qquad \text{(IV.65)}$$

$$i_e = -\left(\frac{h_{11}}{R_E} + (\beta + 1)\right) i_b \qquad \text{(IV.66)}$$

As a result, the expression for current gain is:

$$A_i = \frac{\beta R_C}{R_C + R_L} \frac{R_E}{h_{11} + (\beta + 1) R_E} \qquad \text{(IV.67)}$$

c) Input impedance:

This is the ratio of input voltage to input current:

$$Z_i = \frac{e}{i_e}$$

In the expression for ie as a function of e(t), divide left and right by e(t) to obtain the expression for Ze:

$$Z_e = R_E \parallel \left(\frac{h_{11}}{\beta+1}\right) = \frac{h_{11}}{\beta+1} \qquad (IV.68)$$

d) Output impedance:

This is the ratio of output voltage to output current with the input short-circuited and RL disconnected.

$$Z_S = \left.\frac{s(t)}{i_S}\right|_{e_g=0,\, R_L\ débranc\ hée}$$

With these conditions, the circuit will be replaced by the one shown in the following figure:

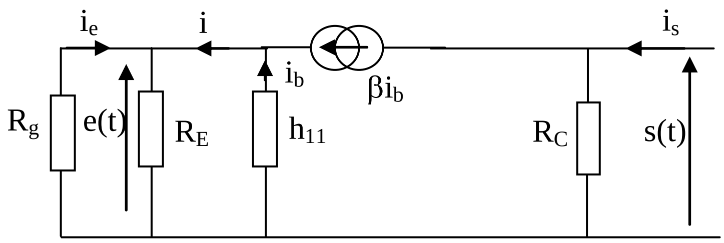


Fig IV.27 Equivalent amplifier diagram when e =0 and RL disconnected.

$e_g(t) = 0$ gives $i_b = 0$

$$i_S = i - \beta i_b = \frac{s(t)}{R_C} \;\Rightarrow\; Z_S = R_C \qquad (IV.69)$$

IV.4 Multi-stage amplification :

If a single-transistor or single-stage amplifier is not sufficient, or its input or output impedance is not compatible with the other elements in which it is integrated, the solution is to cascade several stages so that the total amplification is equal to the product of the amplifications of the constituent stages. For two stages, for example :

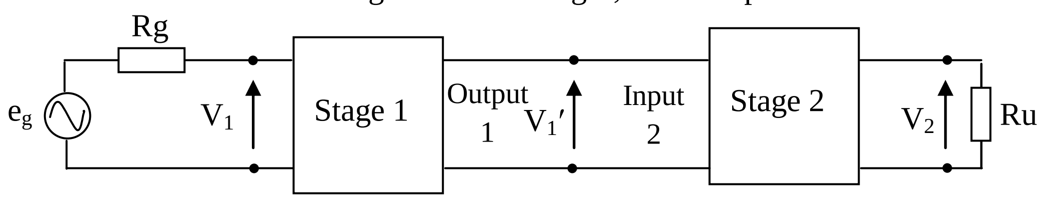


Fig IV.28 Two-stage amplification. Output 1= Input 2.

$$A_V = \frac{V_2}{V_1} = \frac{V_2}{\acute{V}_1}\cdot\frac{\acute{V}_1}{V_1} = A_{V2}\cdot A_{V1} \qquad (IV.70)$$

The input impedance is that of the first stage, and the output impedance is that of the last stage.

There are various ways of connecting the stages together in the amplifier: coupling capacitors, transformers or direct connections such as the Darlington circuit.

Darlington circuit :

This is the connection of two transistors (common collector), to obtain a high input impedance:

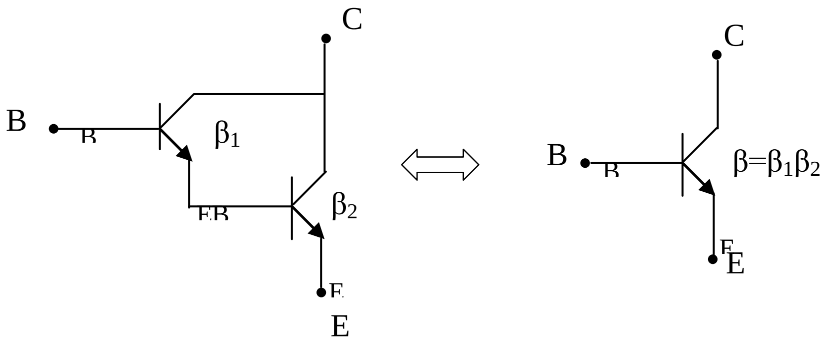


Fig IV.29 Darlington circuit.

The two transistors are treated as a single transistor with a very high current gain. They are mounted in the same case, from which three pins emerge: E, B and C.