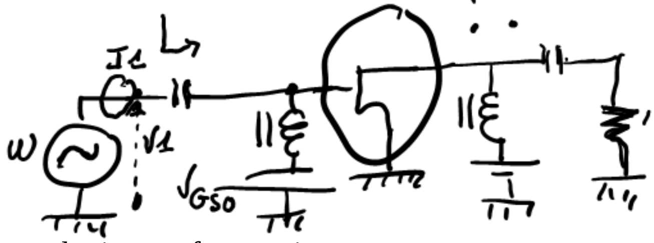
Semester S1 –Basics of active and non linear electronics

RF Power amplifiers (JM Nebus)

COURSE N° 3

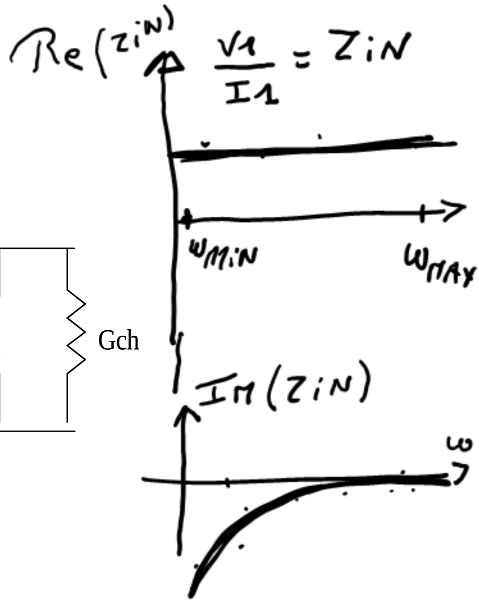
Chapter III : Operating classes of Power transistors

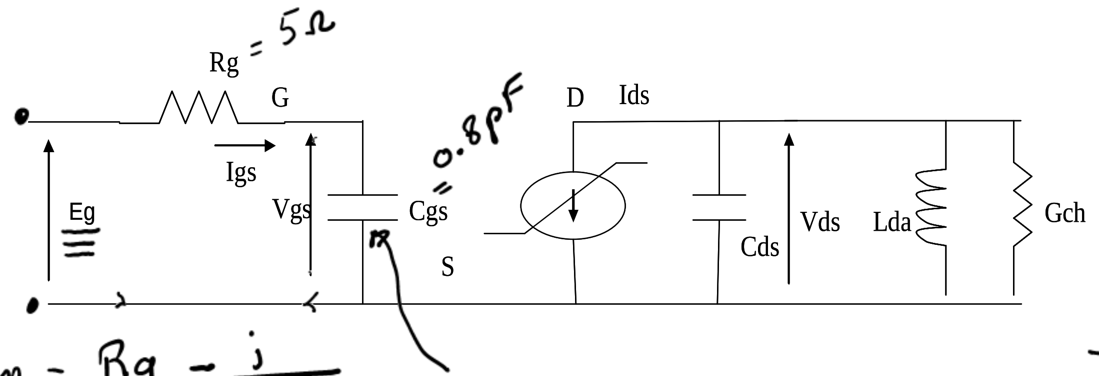


1) Equivalent circuit of the transistor input

We have to consider the fact that at high frequency the input of a transistor (gate port) does not behave as an ideal open circuit.

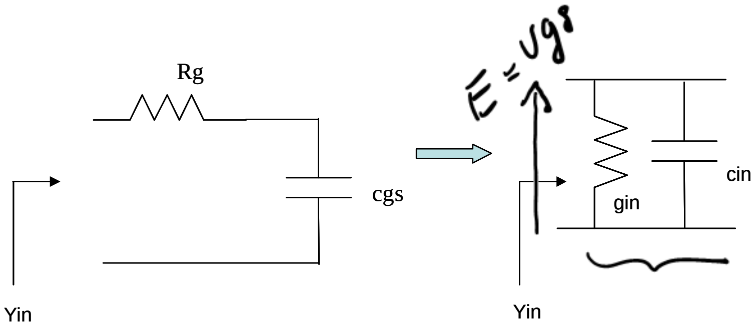
It behaves as a first order low pass circuit





$$Zin = Rg - \frac{j}{Cgs\omega}$$

- Serie to parallel équivalence



$$Yin_{serie} = \frac{1}{Rg + \frac{1}{jcgsw}} = \frac{rg.cgs^2.w^2 + jcgs.w}{1 + rg^2.\cancel{cgs^2}\cdot w^2} =$$

$$\omega^2 << \frac{1}{(rg\,Cgs)^2}$$

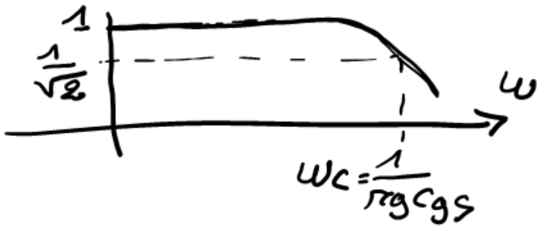
$$\omega << \frac{1}{rg\,Cgs}$$

$$Yin_{parallele} = gin + j.cin.w$$

Considering that $\underbrace{rg^2 \cdot cgs^2.w^2 << 1}$ we can write $\boxed{gin = rg \cdot cgs^2.w^2}$ and $\boxed{cin = cgs}$

If $rg^2 \cdot cgs^2.w^2 << 1$ w i slow compared to the cut off frequency

wc of the circuit $wc = \frac{1}{rg.cgs}$



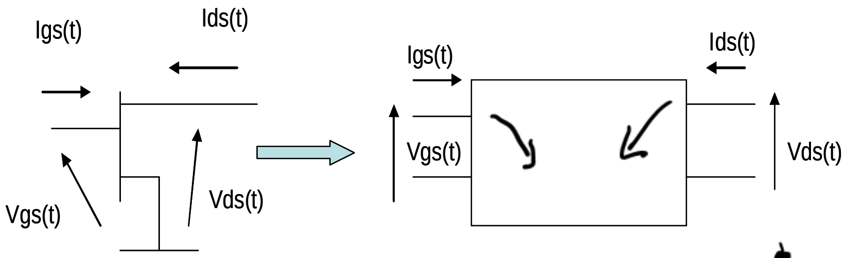
The RF input power is

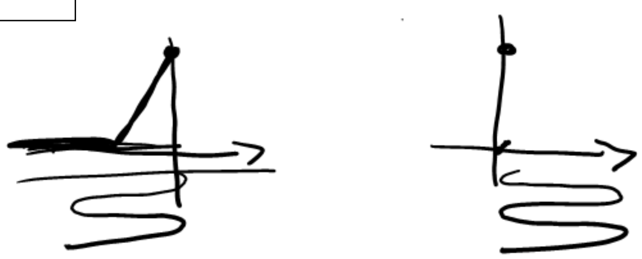
$$\underbrace{Pe}_{P_{in}=} = \frac{1}{2}.\mathrm{Re}(Vgs1.Igs1^*) = \frac{1}{2}.\mathrm{Re}(Vgs1.Yin^* Vgs1^*) = \frac{1}{2}.|Vgs1|^2\,\mathrm{Re}(Yin^*) = \frac{1}{2}.gin.|Vgs1|^2 = \frac{1}{2}.rg.cgs^2.w^2.|Vgs1|^2$$

$$\boxed{P_{in} = \frac{1}{2} Rg\, Cgs^2 \omega^2 |Vgs_1|^2}$$

2) Power budget

If we consider that a parallel resonant circuit (having a high quality factor) is connected at the output of the transistor , the drain source voltage Vds(t) is only the sum of a DC component and a fundamental frequency component .





$$Vgs(t) = Vgs0 + Vgs1.\cos(wt)$$
$$Igs(t) = Igs0 + Igs1.\cos(wt + \rho)$$
$$Vds(t) = Vds0 - Vds1.\cos(wt)$$
$$Ids(t) = Ids0 + Ids1.\cos(wt) + Ids.\cos(2wt) + ...$$

$\frac{1}{2} Re(vgs_1\, Igs_1^*) = P_{in}$

$$p(t) = Vgs(t).Igs(t) + Vds(t).Ids(t)$$
$$P = Pdiss = \frac{1}{T}\int_0^T p(t).dt$$

Pout

$$Pdiss = \underbrace{|Vgs0.Igs0|}_{=0} + \underbrace{Vds0.Ids0}_{P_{DC}} + \underbrace{\frac{1}{2}\cdot Vgs1.Igs1.\cos(\rho)}_{P_{IN}} - \frac{1}{2}\cdot Vds1.Ids1 = Pdc + Pe - Ps$$

$P_{diss} = P_{in} + P_{DC} - P_{out}$

$$Pdiss = Pdc\left(1 - \frac{Ps - Pe}{Pdc}\right) = Pdc(1 - \eta aj)$$

$\eta_{ADDED} = \eta_{Aj}$

$P_{IN} + P_{DC} = P_{OUT} + P_{DISS}$

PAE
Power added efficiency

3) Operating classes and efficiency performances

To reach the maximum value of the output drain current we need to have the maximum voltage swing at the input

$\eta_D = \frac{P_{OUT}}{P_{DC}}$

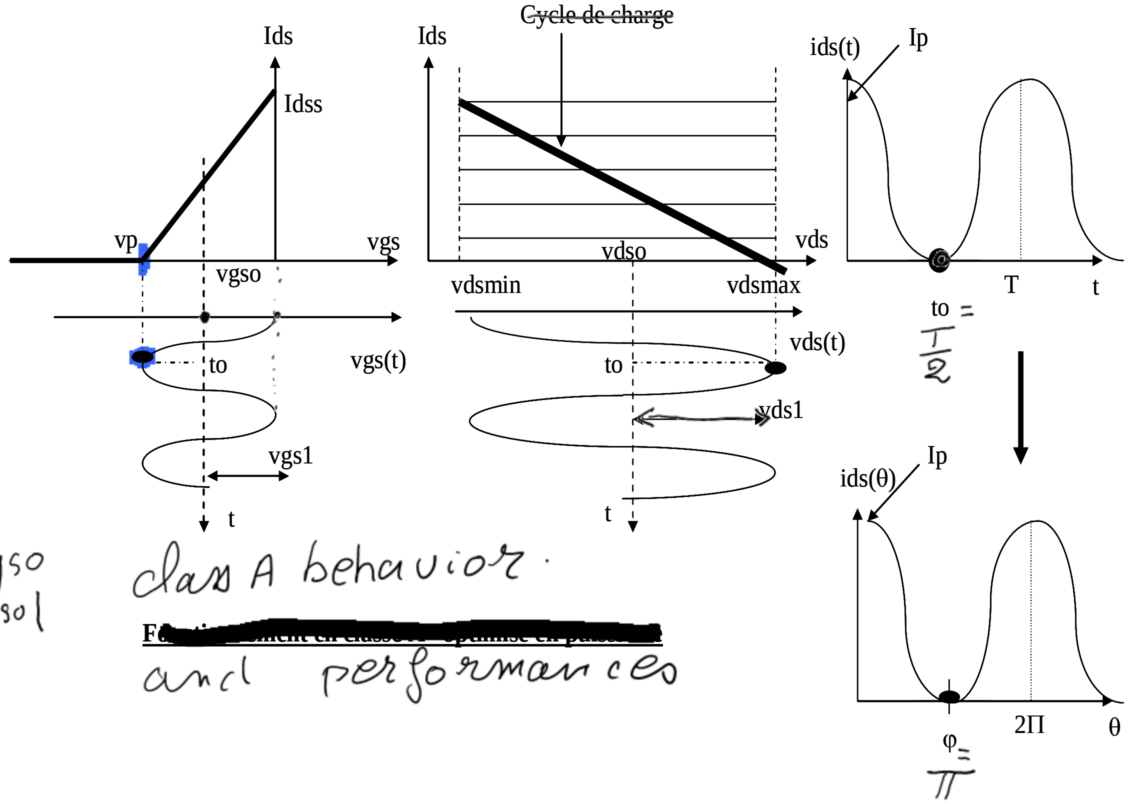
Consequently: $Vgs1 = |Vgs0| = -Vgs0$ and $Idss = Ip$

We assume here that the maximum acceptable value of Vgs(t) is equal to 0V

Vgs(t) > 0V can lead to a non-reliable behavior of the transistor .

~~Classe~~ Class A operation

Load-line



$V_p < 0$
$V_{GS0} < 0$
$V_{GS1} = -V_{gs0} = |V_{gs0}|$
$V_{GS1} > 0$

class A behavior.

F[redacted]
and performances

We have

$$to = \frac{T}{2}$$

$$\underbrace{Vgso = \left(\frac{Vp}{2}\right)}, \ \underbrace{Vgs1 = -\left(\frac{Vp}{2}\right)},$$ Vp is a negative value while Vgs1 is positive

$$Vgso + Vgs1 \cdot \cos(\varphi) = Vp \qquad \qquad \underline{Ip = Idss}$$

$$\frac{Vp}{2} - \frac{Vp}{2}\cos\varphi = Vp$$

$$\cos(\varphi) = -1 \quad \text{soit} \quad \varphi = \pi \rightarrow \begin{cases} I_{DSo} = \dfrac{I_{DSS}}{2} \\ I_{DS1} = \dfrac{I_{DSS}}{2} \end{cases}$$

Using the equations of Idso and Ids1 obtained in chapter II we obtain :

$$Idso = \left(\frac{Idss}{2}\right) \quad \text{and} \quad Ids1 = \left(\frac{Idss}{2}\right) \leftarrow$$

In order to have the maximum drain source voltage swing Vds1, we choose

$$R_{opt} = \frac{V_{DS1}}{I_{DS1}} = \frac{28}{7} = 4\,\Omega$$

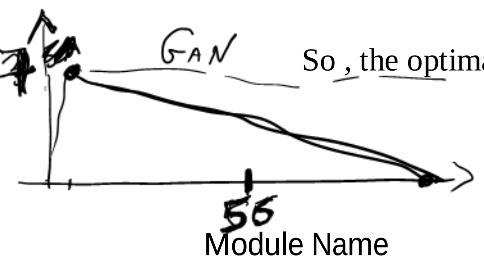
$$Vdso = \left(\frac{Vds\max + Vds\min}{2}\right) \leftarrow$$

Therefore $$Vds1 = \left(\frac{Vds\max - Vds\min}{2}\right) \leftarrow$$

$P_{out} = 100\,W$, Amplifier

$V_{DS1} = 28\,V$

$$P_{out} = \frac{1}{2} \cdot 28 \cdot \frac{I_{DS1}}{2} \rightarrow 100\,W$$



So , the optimal load resistance is $\underbrace{R} = \left(\frac{Vds1}{Ids1}\right) = \underbrace{\left(\frac{Vds\max - Vds\min}{Idss}\right)}$.

$$R_{opt} = \frac{56}{3.75} = 16\,\Omega$$

The output RF power absorbed by the load resistance R is

$$P_{out} = \frac{1}{2}\cdot Vds1\cdot Ids1 = \frac{1}{8}\cdot\left(Vds\max - Vds\min\right)\cdot Idss$$

The required DC power is :

$$Pdc = Vdso\cdot Idso = \frac{1}{4}\cdot\left(Vds\max + Vds\min\right)\cdot Idss$$

η_D = output efficiency

We define the output efficiency (also named the drain efficiency):

$$\eta_{\cancel{s}\,D} = \frac{Ps}{Pdc} = \left(\frac{Vds\max - \cancel{Vds\min}}{2\cdot\left(Vds\max + \cancel{Vds\min}\right)}\right) \qquad \eta_D = 50\%$$

If we assume that Vdsmin is very low (close to 0) or Vdsmin is very small compared to Vdsmax

We have :

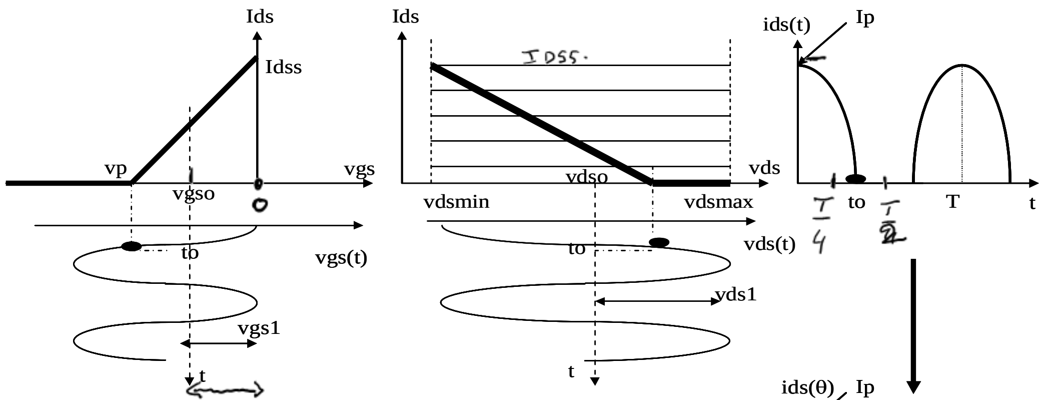
$$R = \frac{Vds\max}{Idss} \quad , \quad Ps = \frac{1}{8}\cdot Vds\max\cdot Idss \quad , \quad \eta s = 50\%$$

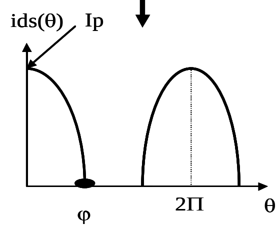
Nevertheless, note that we need to calculate also the power added efficiency which depends on the input RF power

We will see several numerical applications during the tutorials .

$$\begin{cases} P_{in} = \dfrac{1}{2} \cdot rg \cdot cgs^2 \cdot w^2 \cdot \left|\dfrac{Vp}{2}\right|^2 \longrightarrow \underline{\underline{VGS1}} \\ \text{PAE} \quad \eta aj = \dfrac{P_{out} - P_{in}}{Pdc} \\ Gp = \dfrac{P_{out}}{P_{in}} \longrightarrow 10 \log\left(\dfrac{P_{out}}{P_{in}}\right) \end{cases}$$

Class~~e~~ AB operation





Class AB Behaviour

~~Fonctionnement en classe AB optimisé en puissance~~

For Class AB operation we have :

$$\underbrace{\frac{T}{4} \le to \le \frac{T}{2}}$$

$Vp \le Vgso \le \dfrac{Vp}{2}$, and $Vgs1 = -Vgso$ to have the maximum swing of the input Voltage Vgs

Let us take for example $\boxed{Vgso = \frac{2}{3} \cdot Vp}$

The aperture angle φ cn be calculated by using the following equation .

$$\frac{2Vp}{3} - \left(\frac{2Vp}{3}\right) \cdot \cos(\varphi) = Vp \quad \text{soit} \quad \underbrace{\cos[\varphi] = -\frac{1}{2}}$$

$VGso + VGs1 \cos \varphi = Vp.$

$$I_{DSO} = \frac{Ip}{\pi} \cdot \frac{\sin \varphi - \varphi \cos \varphi}{(1 - \cos \varphi)}$$

$I_{DS1} = \ldots\ldots\ldots$

Therefore $\boxed{\varphi = \frac{2\pi}{3}}$

As $Ip = Idss$, we can calculate the DC drain current Idso and the drain current component at the fundamental frequency Ids1

$\underbrace{Idso = 0.4 \cdot Idss}$ and $\underbrace{Ids1 = 0.54 \cdot Idss}$

We still choose $Vdso = \left(\dfrac{Vds\max + Vds\min}{2}\right)$

so the maximum value of Vds1 is $Vds1 = \left(\dfrac{Vds\max - Vds\min}{2}\right)$

The optimal load resistance is now : $R = \left(\dfrac{Vds1}{Ids1}\right) = \left(\dfrac{Vds\max - Vds\min}{1.08 \cdot Idss}\right)$

The output RF power absorbed by R is

$$P_{\substack{s\\out}} = 0.135 \cdot (Vds\max - Vds\min) \cdot Idss$$

The DC power supplied by the DC power supply is :

$$Pdc = 0.2 \cdot (Vds\max + Vds\min) \cdot Idss$$

$$V_{DS1} = \frac{V_{DSMAX} - V_{DSMIN}}{2}$$

$$I_{DS1} = 0.54\, I_{DSS}$$

$$R = \frac{V_{DS1}}{I_{DS1}} = \frac{(V_{DSMAX} - V_{DSMIN})}{1.08\, I_{DSS}}$$

The drain efficiency is :

$$\eta s = 0.675 \cdot \left(\frac{Vds\max - Vds\min}{(Vds\max + Vds\min)} \right)$$

In an ideal case where Vdsmin<< Vdsmax

$$R = \frac{Vds\max}{1.08 \cdot Idss} \quad , \quad Ps = 0.135 \cdot Vds\max \cdot Idss \quad , \quad \boxed{\eta s = 67.5\%}$$

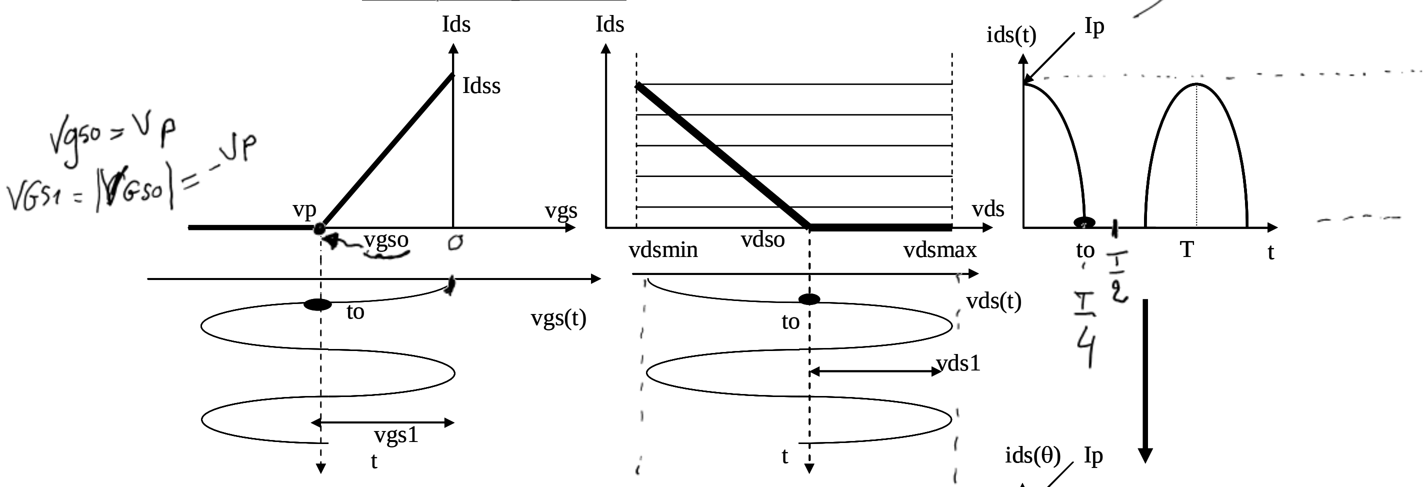
$$I_{DS0} = \frac{I_P}{\pi}$$

$$I_{DS1} = \frac{I_{DSS}}{2}$$

Class~~e~~ B operation

$$V_{gs0} = V_P$$

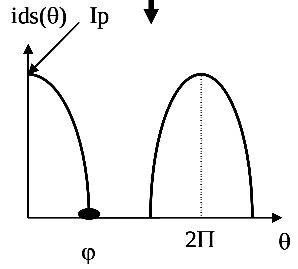
$$V_{GS1} = |V_{GS0}| = -V_P$$



class B Behavior

~~**Fonctionnement en classe B optimisé en puissance**~~

and performances



For Class B operation :

$to = \frac{T}{4}$

$\underline{Vgso = Vp}$, and $\underline{Vgs1 = -Vgso}$ for a maximum input voltage RF swing

Concerning the aperture angle , we have now the equation :

VGS0 + VGS1 cos φ = Vp

$\boxed{Vp - Vp \cdot \cos(\varphi) = Vp}$ therefore $\cos[\varphi] = 0$

And $\boxed{\varphi = \frac{\pi}{2}}$

$$I_{DS0} = \frac{I_P}{\pi} \frac{\sin\varphi - \varphi\cos\varphi}{1-\cos\varphi}$$

$$I_{DS1} = \frac{I_P}{\pi} \frac{\varphi - \sin\varphi\cos\varphi}{1-\cos\varphi}$$

!!! φ in rad

We still have

$\underline{Ip = Idss}$

The Drain current components at Dc and at the fundamental frequency are :

$\boxed{Idso = \frac{Idss}{\pi}}$ et $\boxed{Ids1 = \frac{Idss}{2}}$

$Vdso = \underbrace{\left(\frac{Vds\max + Vds\min}{2}\right)}$ and $Vds1 = \left(\frac{Vds\max - Vds\min}{2}\right)$

The optimal load resistance is $R = \left(\frac{Vds1}{Ids1}\right) = \left(\frac{Vds\max - Vds\min}{Idss}\right)$

The output RF power is

$Ps = \frac{1}{8} \cdot (Vds\max - Vds\min) \cdot Idss$

The DC power is

$$Pdc = \frac{1}{2\pi}\cdot\left(Vds\max + Vds\min\right)\cdot Idss \quad = V_{DSO} \cdot I_{DSO}$$

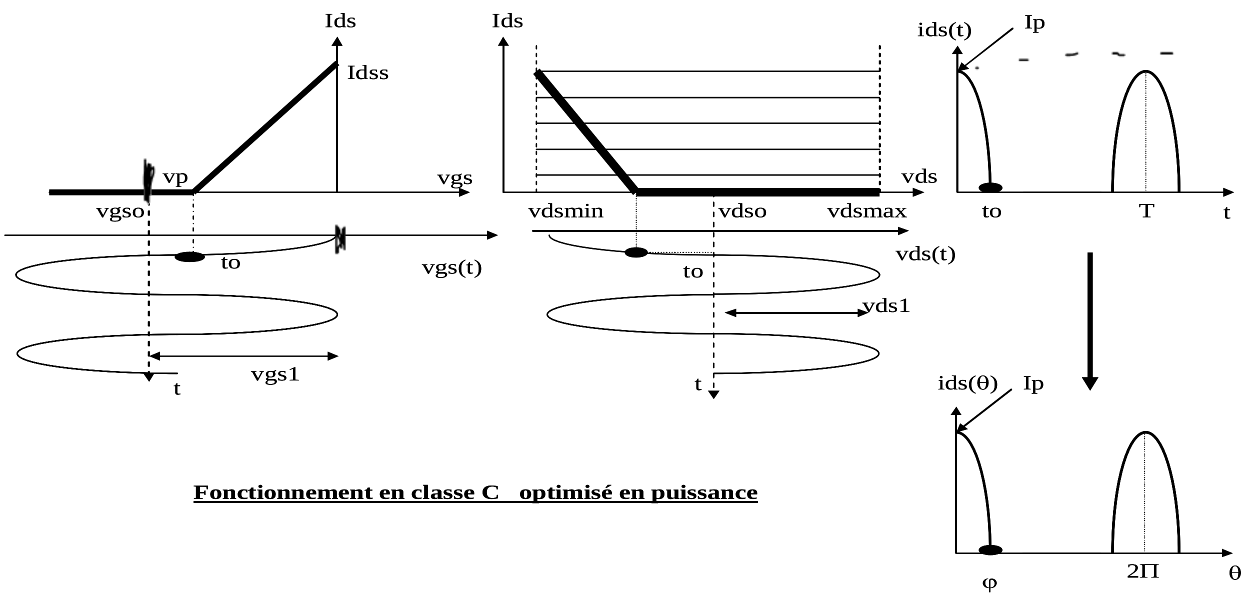
The drain efficiency is : $= \dfrac{P_{out}}{P_{DC}}$

$$\eta_s = \left(\frac{\pi}{4}\right)\cdot\left(\frac{Vds\max - Vds\min}{\left(Vds\max + Vds\min\right)}\right)$$

If Vdsmin << Vds max

$$\underbrace{R = \frac{Vds\max}{Idss}} \quad , \quad \underbrace{Ps_{out} = \frac{1}{8}\cdot Vds\max\cdot Idss} \quad , \quad \eta s = 78.5\% \quad = \frac{\pi}{4}$$

Classe C operation



Fonctionnement en classe C optimisé en puissance

For Class C

$to \le \frac{T}{4}$

$Vgso \le Vp$ and $Vgs1 = -Vgso$ to have a maximum input voltage swing

Let us take for example : $Vgso = \frac{3}{2} \cdot Vp$

The equation used to calculate the aperture angle is :

$\frac{3}{2} \cdot Vp - \frac{3}{2} \cdot Vp \cdot \cos(\varphi) = Vp \quad \rightarrow \quad \cos[\varphi] = \frac{1}{3}$

$\varphi = 1.23Rd$

$Ip = Idss$; $Idso = 0.25 \cdot Idss$ and $Ids1 = 0.44 \cdot Idss$

$$Vdso = \left(\frac{Vds\max + Vds\min}{2}\right) \quad \text{and} \quad Vds1 = \left(\frac{Vds\max - Vds\min}{2}\right)$$

The optimal load resistance is $R = \left(\frac{Vds1}{Ids1}\right) = \left(\frac{Vds\max - Vds\min}{0.88 \cdot Idss}\right)$

The output RF power is :

$Ps = 0.11 \cdot (Vds\max - Vds\min) \cdot Idss$

The DC power is :

$Pdc = 0.125 \cdot (Vds\max + Vds\min) \cdot Idss$

The drain efficiency is :

$$\eta s = 0.88 \cdot \left(\frac{Vds\max - Vds\min}{(Vds\max + Vds\min)}\right)$$

If Vdsmin << Vdsmax

$$R = 1.136 \cdot \frac{Vds\max}{Idss} \quad , \qquad Ps = 0.11 \cdot Vds\max \cdot Idss \quad , \quad \eta s = 88\%$$

4) The load line equation:

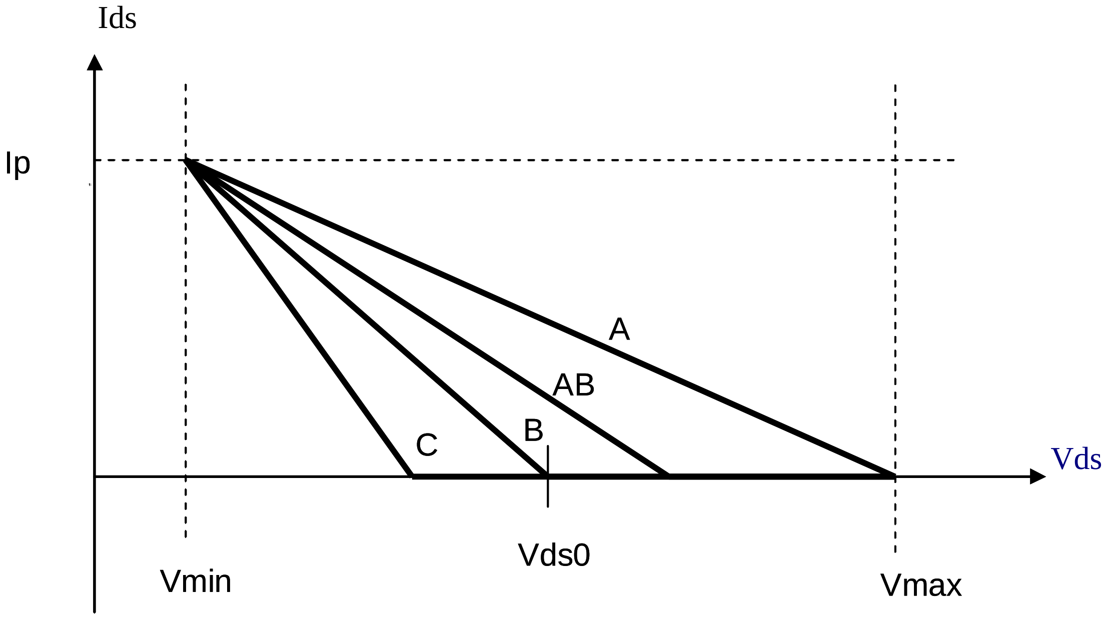
During the conduction time of the transistor

$$Ids(\theta) = \frac{Ip}{1-\cos(\varphi)}(\cos(\theta) - \cos(\varphi))$$
$$Vds(\theta) = Vds0 - Vds1.\cos(\theta)$$

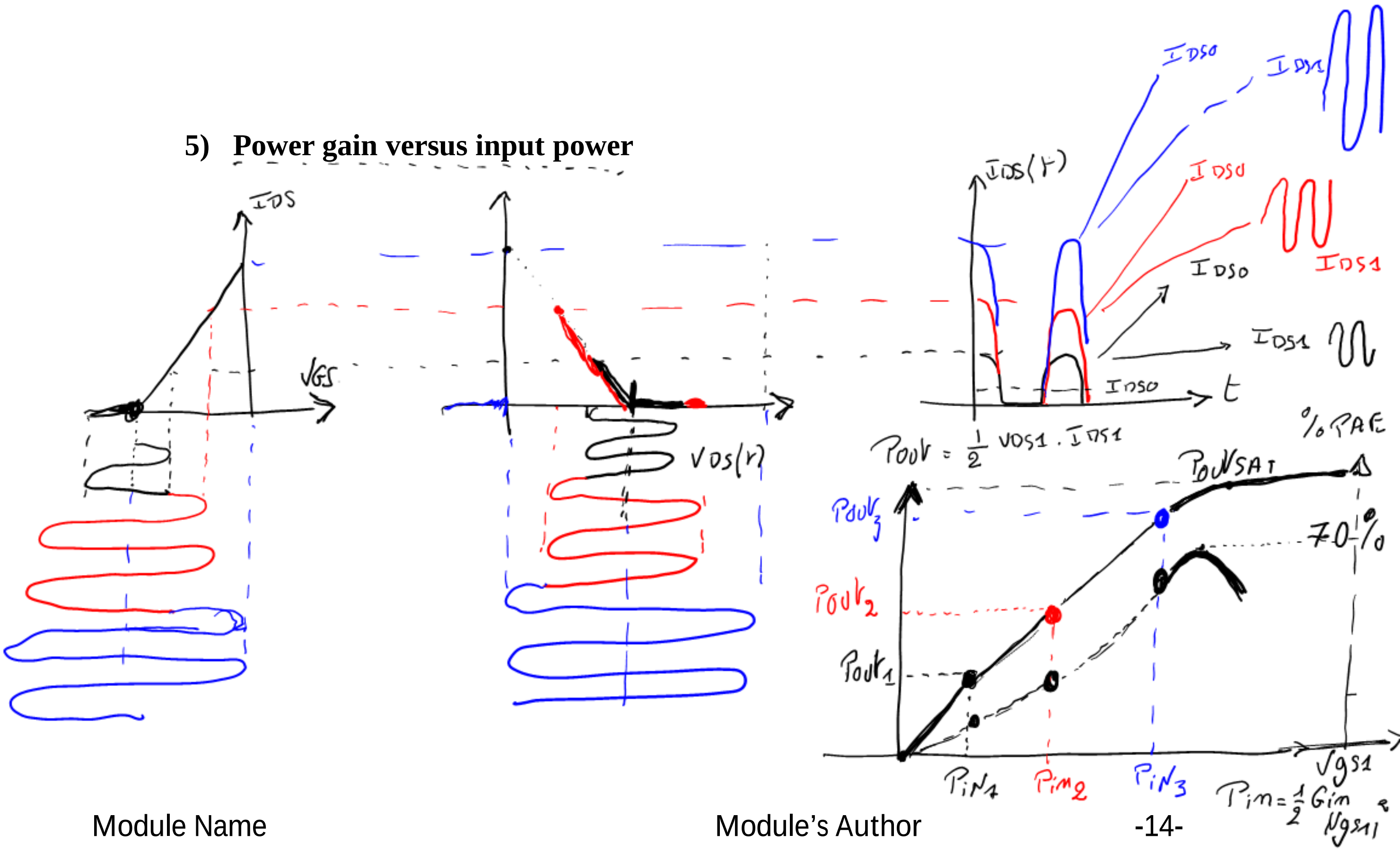
So

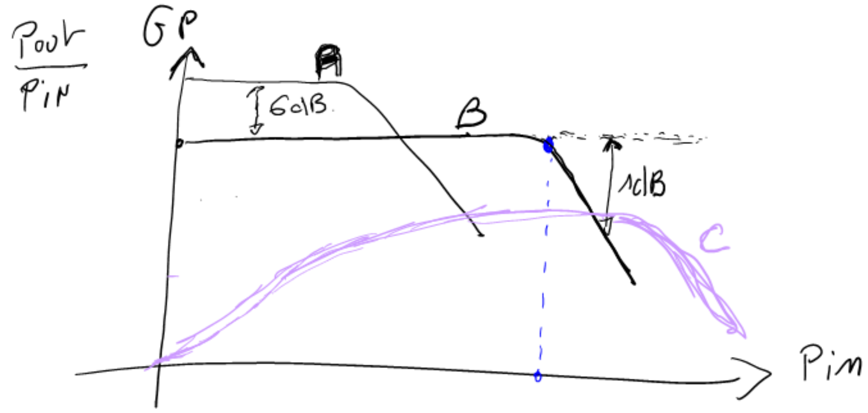
$$\cos(\theta) = \frac{Vds0 - Vds}{Vds1}$$
$$Ids = \frac{Ip}{1-\cos(\varphi)}.(\frac{Vds0 - Vds}{Vds1} - \cos(\varphi)) = \frac{Ip}{1-\cos(\varphi)}.(\frac{Vds0}{Vds1} - \cos(\varphi)) - \frac{Ip}{(1-\cos(\varphi)).Vds1}.Vds$$

$$Ids = A - B.Vds$$

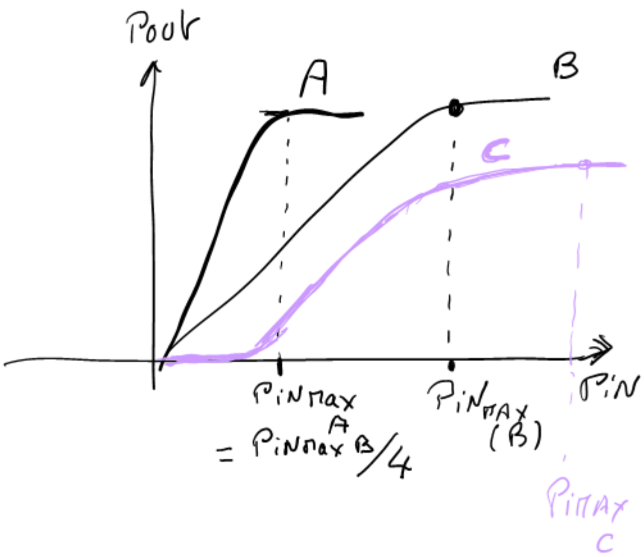


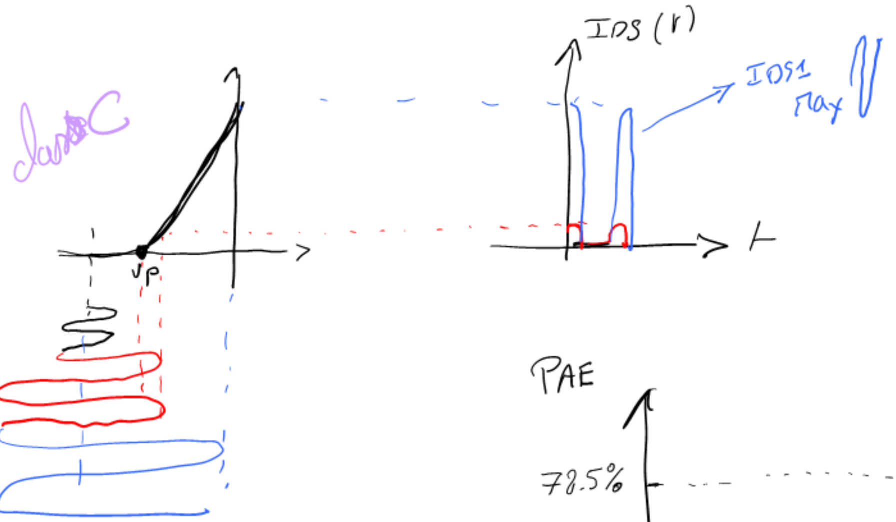
5) Power gain versus input power

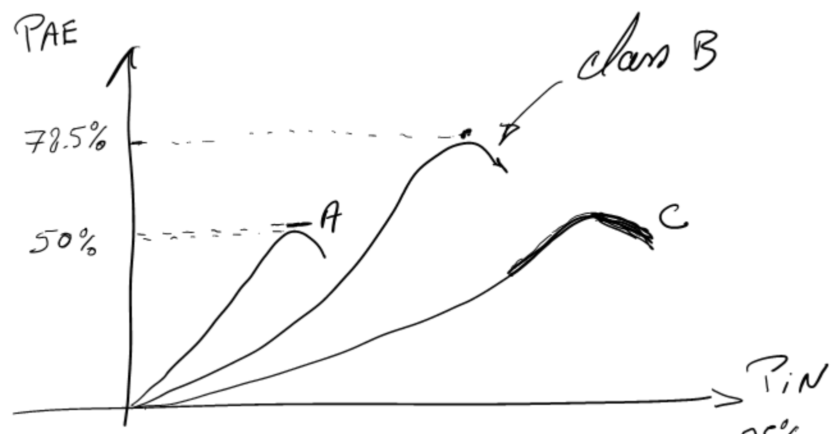


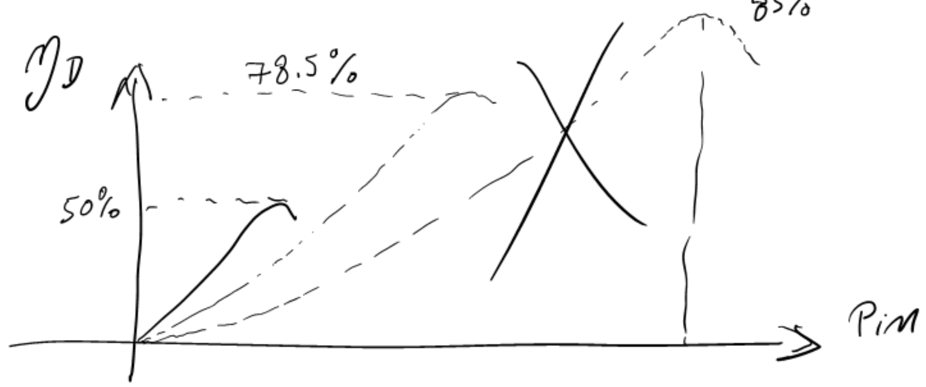


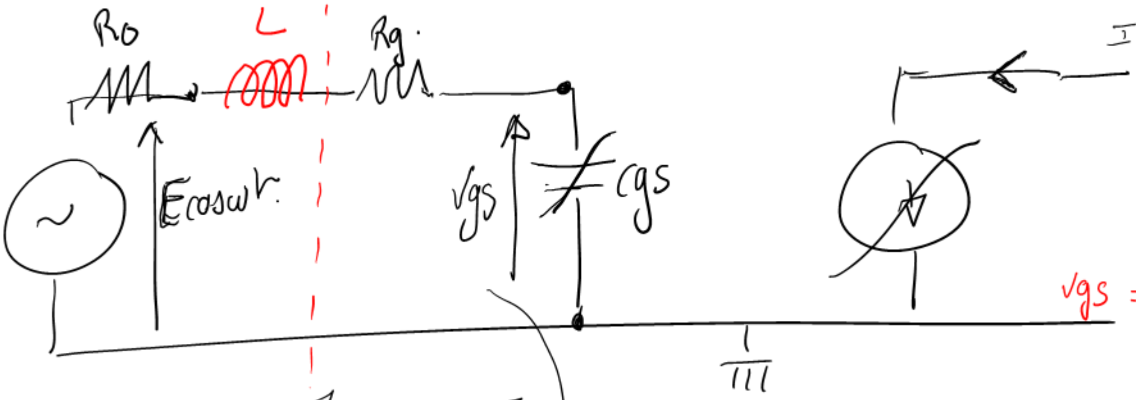
$$G_p = 10 \log\left(\frac{P_{out}}{P_{in}}\right)$$







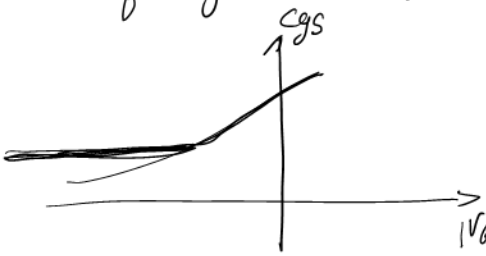




$$v_{gs} = \frac{\frac{1}{jc_{gs}\omega}\,E}{(R_0+R_g)+jL\omega+\frac{1}{jc_{gs}\omega}}$$

$$v_{gs} = \frac{E}{(1-Lc_{gs}\omega^2)+jc_{gs}(R_0+R_g)}$$

if $|v_{gs}| \nearrow$ $C_{gs} \nearrow$

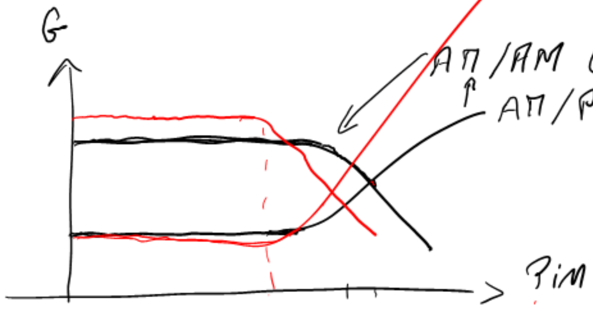


$$v_{gs} = \frac{E \times \frac{1}{jc_{gs}}}{R_g + \frac{1}{jc_{gs}\omega}} = \frac{E}{1+jR_gc_{gs}\omega}$$

$$|v_{gs}| = \frac{E}{\sqrt{1+R_g^2c_{gs}^2\omega^2}}$$

$$\angle v_{gs} = -\mathrm{Arctg}\left(R_g c_{gs}\omega\right)$$

$$\angle v_{gs} = -\mathrm{Arctg}\left(\frac{c_{gs}(R_0+R_g)}{1-Lc_{gs}\omega^2}\right)$$



AM/AM conversion
AM/PM conversion
} Non linear distorsion.

6) Drain efficiency and power added efficiency versus input power