第9章　非线性电路

(nonlinear circuit)

9.1 非线性电路概念与非线性元件

1）非线性电路

电路元件的参数随着电压或电流而变化, 即电路元件的参数与电压或电流有关, 就称为非线性元件,含有非线性元件的电路称为非线性电路。

2）研究非线性电路的意义

①严格说,一切实际电路都是非线性电路。

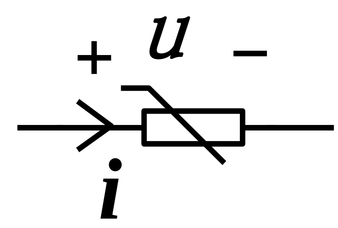
②许多非线性元件的非线性特征不容忽略，否则就将无法解释电路中发生的物理现象

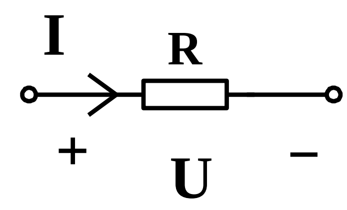
3）研究非线性电路的依据

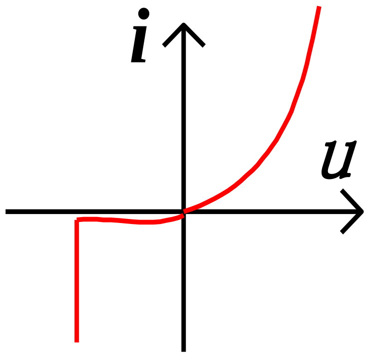
分析非线性电路基本依据仍然是KCL、KVL和元件的伏安特性。

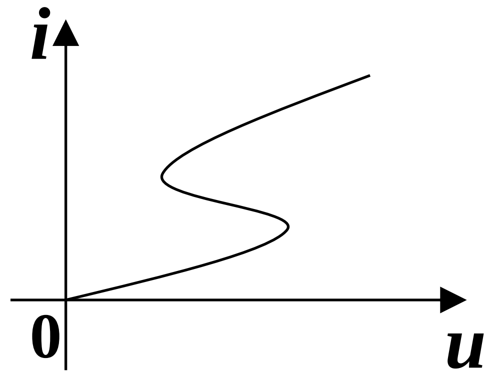
1. 线性元件与非线性元件：R、L、C 电路符号与参数

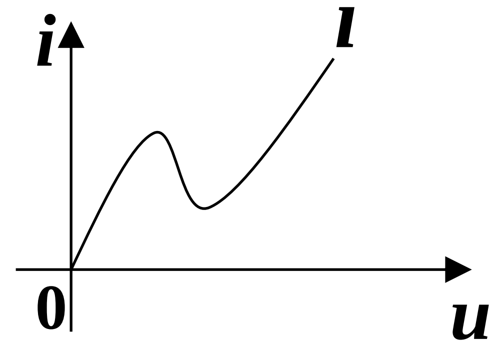
2. 单调型、流控型、压控型非线性电阻

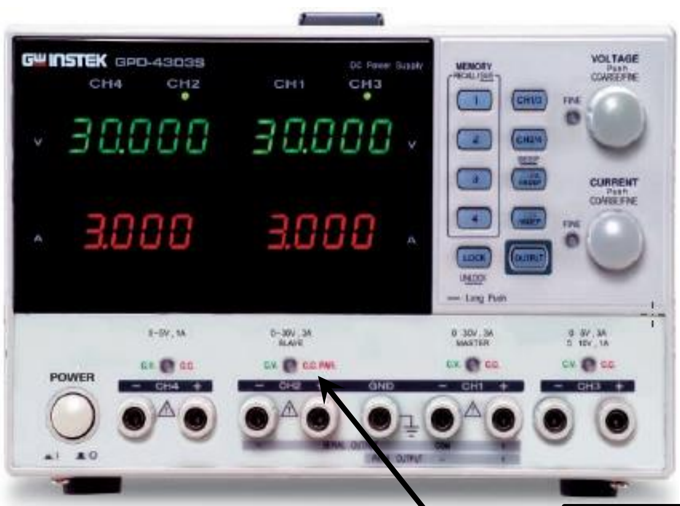


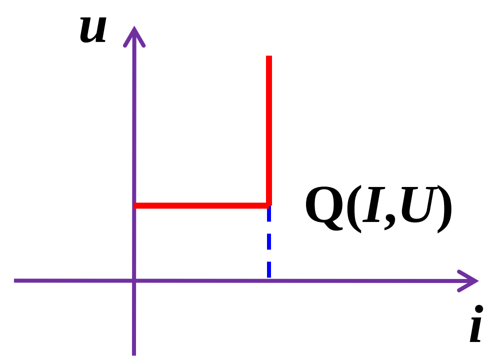












恒压/恒流交叉特性

例：一非线性电阻 $u = f(i) = 100i + i^3$

(1) 分别求 $i_1 = 2\text{A}$， $i_2 = 2\text{Sin}314t\ \text{A}$， $i_3 = 10\text{A}$时 对应电压 u_1， u_2， u_3；

(2) 设 $u_{12} = f(i_1 + i_2)$， 问是否有$u_{12} = u_1 + u_2$?

(3) 若忽略高次项， 当 $i = 10\text{mA}$时， 由此产生多大误差?

$$u_1 = 100i_1 + i_1^3 = 208\text{V}$$

$$\begin{aligned}u_2 &= 100i_2 + i_2^3 \\ &= 200\sin 314t + 8\sin^3 314t \quad (\because \sin 3\theta = 3\sin\theta - 4\sin^3\theta) \\ &= 200\sin 314t + 6\sin 314t - 2\sin 942t \\ &= 206\sin 314t - 2\sin 942t\text{V}\end{aligned}$$

$\boxed{u_2\text{中出现了3倍频}}$

$$u_3 = 100i_3 + i_3^3 = 2000\text{V}$$

$$u = f(i) = 100i + i^3$$

(2) 设 $u_{12} = f(i_1 + i_2)$，问是否有$u_{12} = u_1 + u_2$?

(3) 若忽略高次项，当 $i = 10\text{mA}$时，由此产生多大误差?

(2) $u_{12} = 100(i_1 + i_2) + (i_1 + i_2)^3$

$$= 100i_1 + 100i_2 + i_1^3 + i_2^3 + 3i_1 i_2(i_1 + i_2)$$

$$u_1 + u_2 = 100i_1 + i_1^3 + 100i_2 + i_2^3$$

$\therefore u_{12} \neq u_1 + u_2$ 　　非线性电路不满足叠加性

(3) $u = 100i + i^3 = 100 \times 0.01 + 0.01^3 = 1 + 10^{-6}\,\text{V}$

忽略高次项，$u' = 100 \times 0.01 = 1\text{V}$

此时，仅引起10^{-6}V误差（线性化）

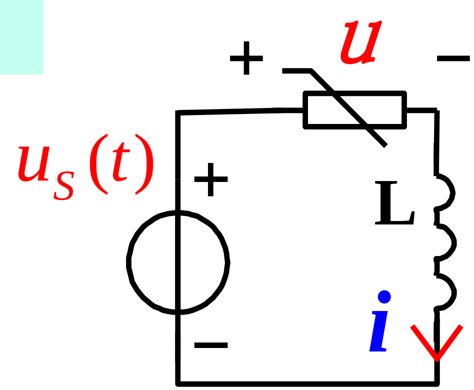
若i =（10+0.01）A可以怎样近似计算u? $\approx 2000 + \left(100 + 3\times 10^2\right)\times 0.01 = 2004$

泰勒展开式

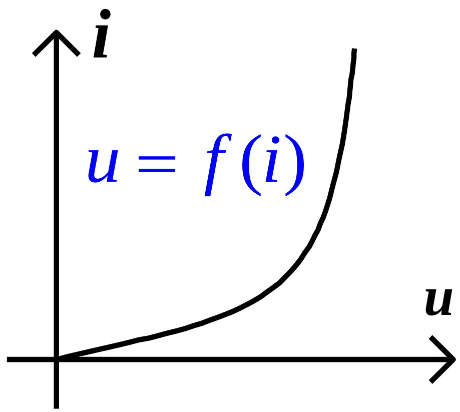
精确解 $= 100 \times 10.01 + 10.01^3 = 2004.003001$

$$u = f(I_0 + \Delta i) = f(I_0) + f'(I_0)\Delta i + \ldots\ldots$$

9.2 简单非线性直流电路分析



一阶动态电路



非线性元件电路分析特点与方法

已知:电源 $u_S(t)$, 非线性电阻特性 $u=f(i)$

建立电路方程 $L\dfrac{di}{dt}+u=u_S$

$\longrightarrow$ $L\dfrac{di(t)}{dt}=-f(i)+u_S(t)$ (非线性微分方程)

设: $u=i^2+e^i$,有

$$L\frac{di(t)}{dt}=-i^2-e^i+u_S(t)$$

1) 非线性方程数值解;

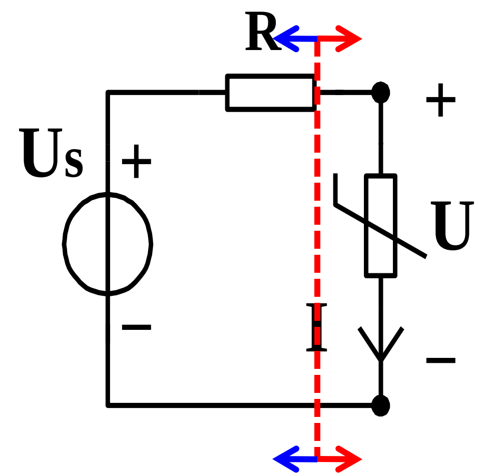
2) 直流非线性电路作图解(解析解);

3) 非线性电路(元件)线性化;

折线分段线性化

小信号分析(动态电阻线性化)

9.2 简单非线性直流电路分析



1. 作图法 (静态工作点计算)

非线性电阻伏安特性: $U = f(I)$

电路方程: $U_S - I \times R = U$

1) 作非线性电阻伏安特性曲线;

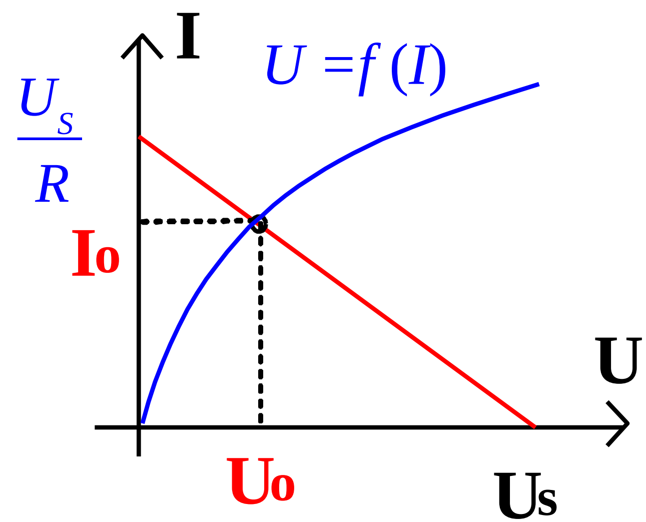
2) 作线性电路部分的伏安特性曲线;

开路电压: U_S

短路电流: $I_d = \dfrac{U_S}{R}$

连直线

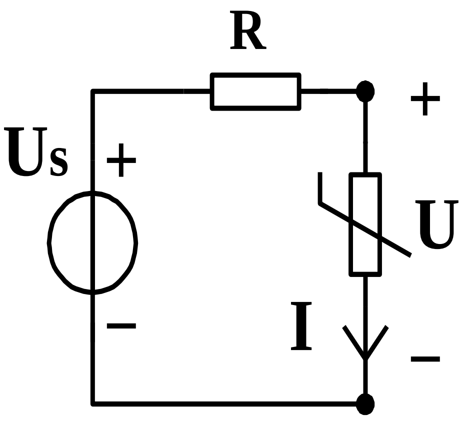
3) 交点解得非线性电阻的电压电流.



2. 解析法

(已知非线性电阻伏安特性的函数表达式)

$U = f(I)$ 或 $I = f(U)$



例:已知 $U_S = 12V, R = 2\Omega$, 非线性电阻

伏安特性 $I = 2U^2 - 2.5U + 2 \quad (U \geq 0)$,求 U_O 和 I_O .

解: $U_S - I \times R = U \longrightarrow U_S - (2U^2 - 2.5U + 2) \times R = U$

代入数据 $4U^2 - 4U - 8 = 0 \longrightarrow U = 2$ 或 $-1V$

由题意得: $U_O = 2V$

$$I_O = 2U_O^2 - 2.5U_O + 2 = 5A$$

代入数据 $4U^2-4U-8=0 \longrightarrow U=2$ 或 $-1V$

feixianxin1.m

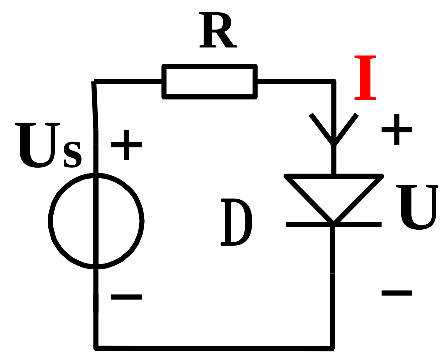
```
clc;
u=fzero(inline('4*u^2-4*u-8'),1);
i=2*u^2-2.5*u+2;
disp('u=');
disp(u);
disp('i=');
disp(i)
```

计算结果:

```
u=2
i=5
```

例:已知二极管伏安特性为 $I = g(U) = 20\times10^{-6}\times(e^{4.6U}-1)A$

$R = 10K\Omega, U_S = 12V$，求二极管电流 I?



解: $U_S - I\times R = U$

$$U_S - (20\times10^{-6}\times(e^{4.6U}-1))\times R = U$$

$$12 - 20\times10^{-2}\times(e^{4.6U}-1) - U = 0$$

feixianxin2.m

```
u=fzero(inline('12-0.2*(exp(4.6*u)-1)-u'), 0);
i= 0.2*(exp(4.6*u)-1)
```

$$I = (20\times10^{-6}\times(e^{4.6U}-1))$$

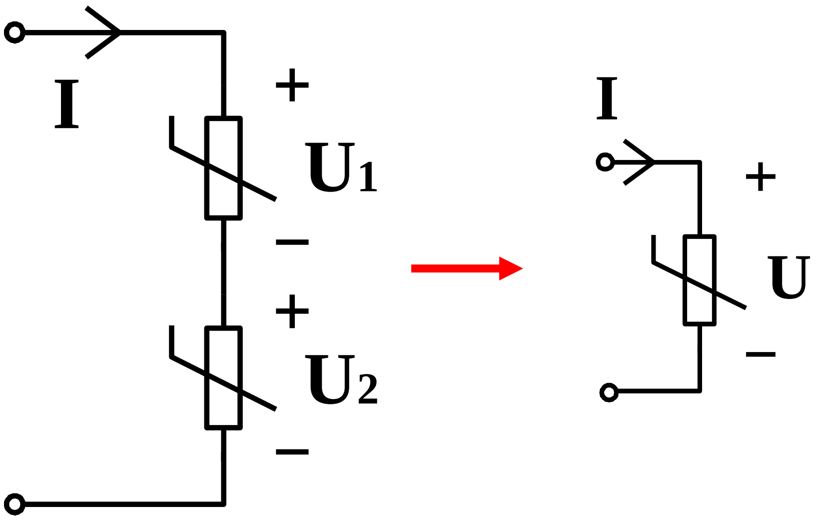
u=0.8774 V

i=11.1226 A

更广义地来说，列写非线性电路方程，求解非线性代数方程组也属于解析法

3. 多个非线性器件的等效简化

(作图法解题)

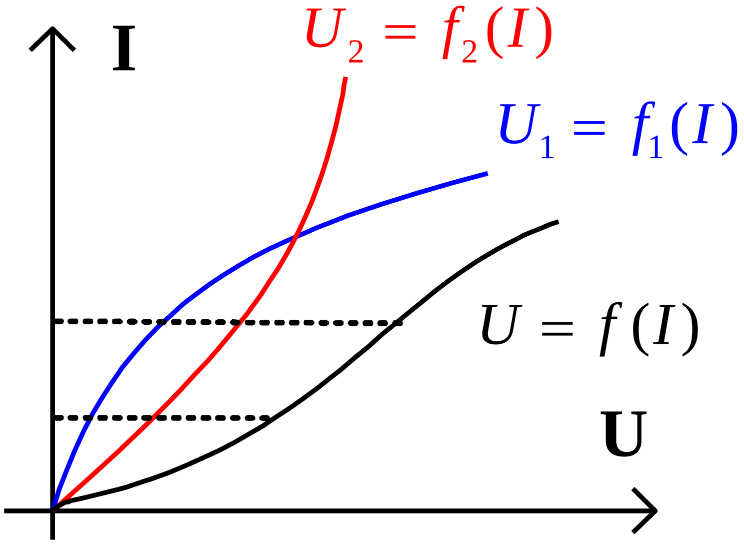


串联: $U_1 = f_1(I)$

$U_2 = f_2(I)$

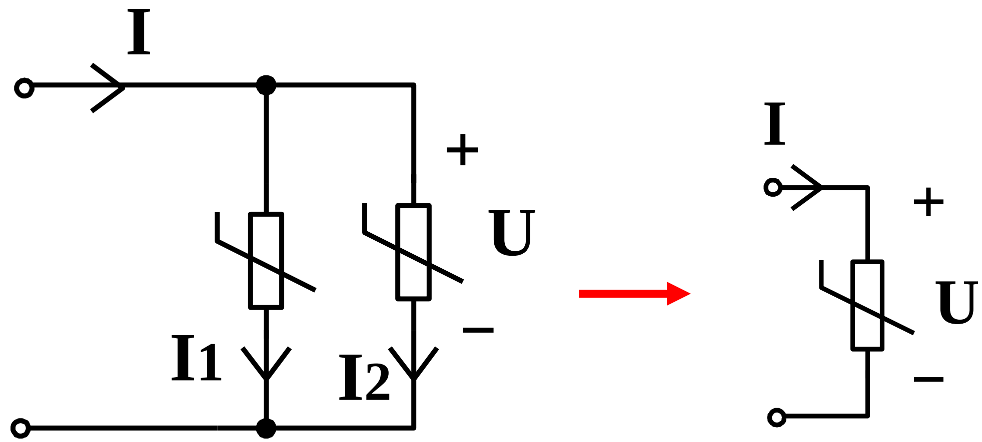
$$U = U_1 + U_2 = f_1(I) + f_2(I)$$

两个串联电阻用一个伏安特性等效的电阻来替代.

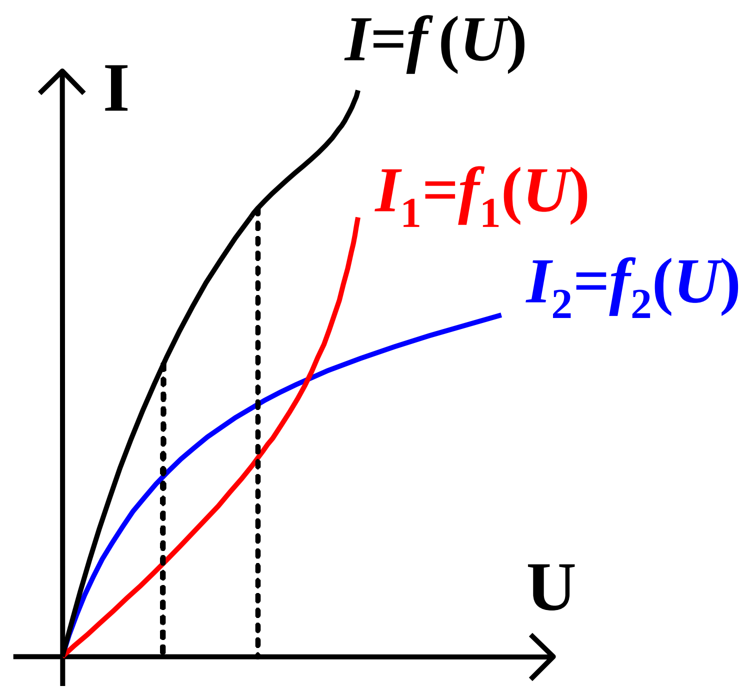


并联: $I_1 = f_1(U)$

$I_2 = f_2(U)$



$$I = I_1 + I_2 = f_1(U) + f_2(U)$$



两个并联电阻用一个伏安特性等效的电阻来替代.

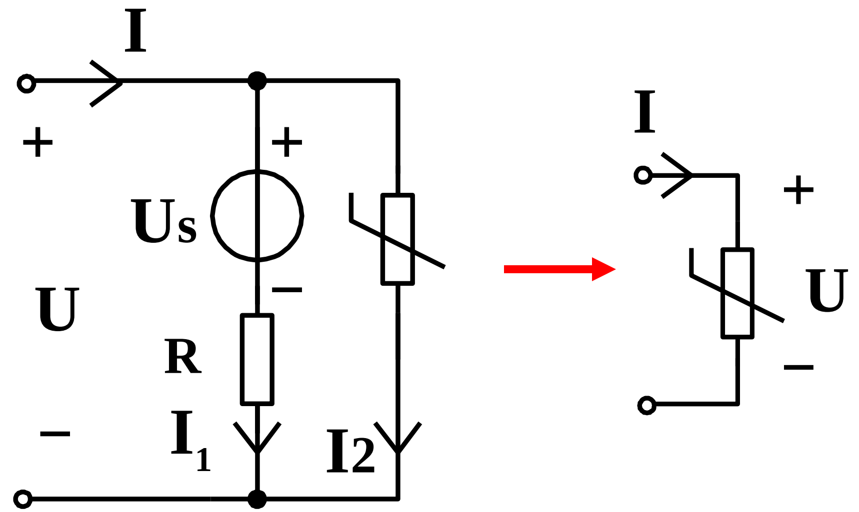
混联:

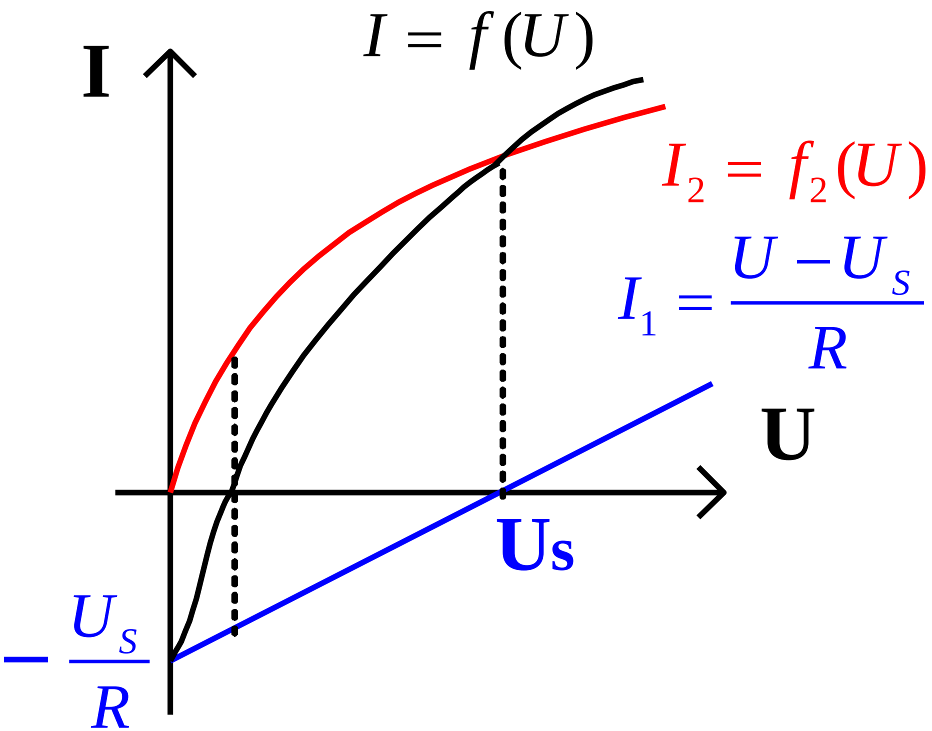
$$I_2 = f_2(U)$$

$$I_1 = \frac{U - U_S}{R}$$

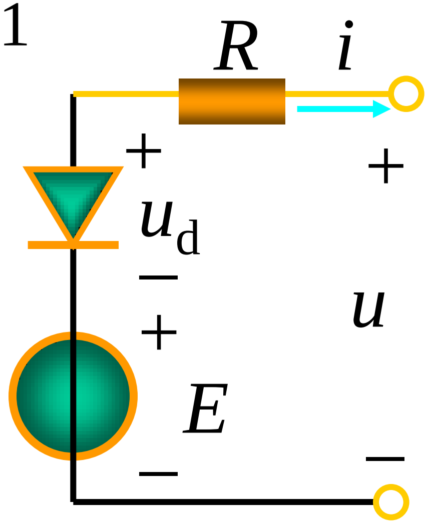
$$\downarrow$$

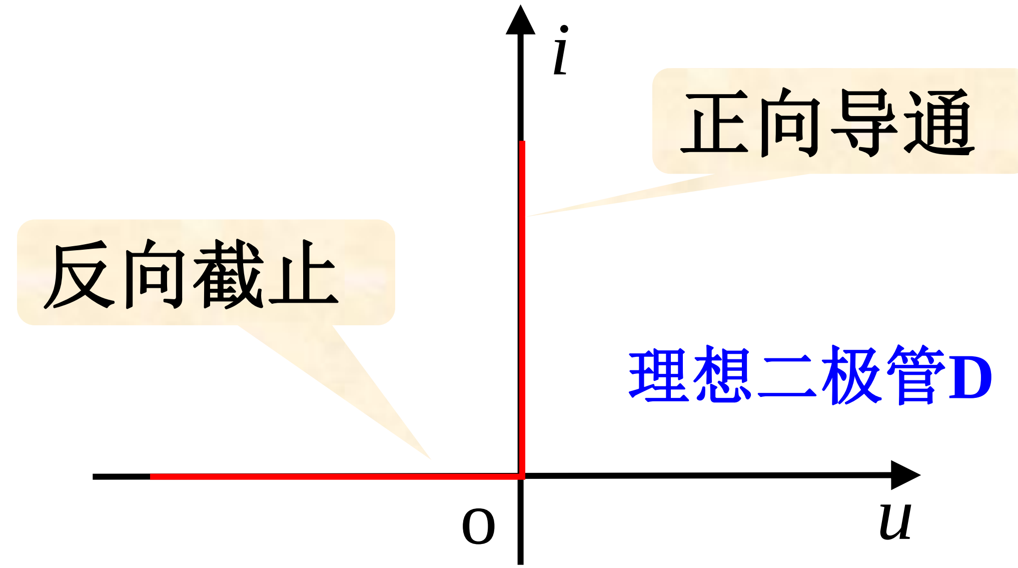
$$I = I_1 + I_2 = \frac{U - U_S}{R} + f_2(U)$$

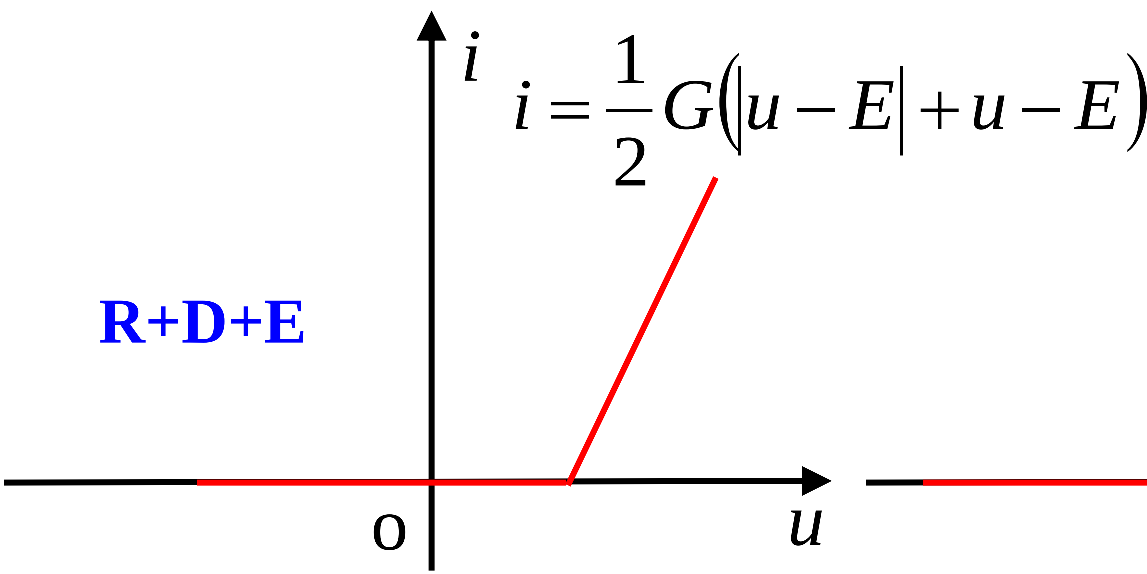


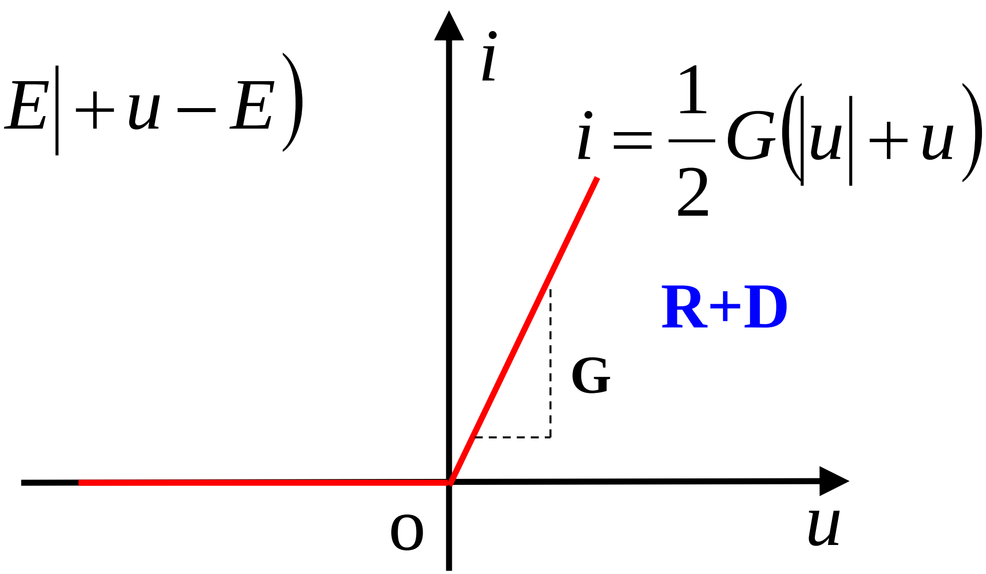


例1

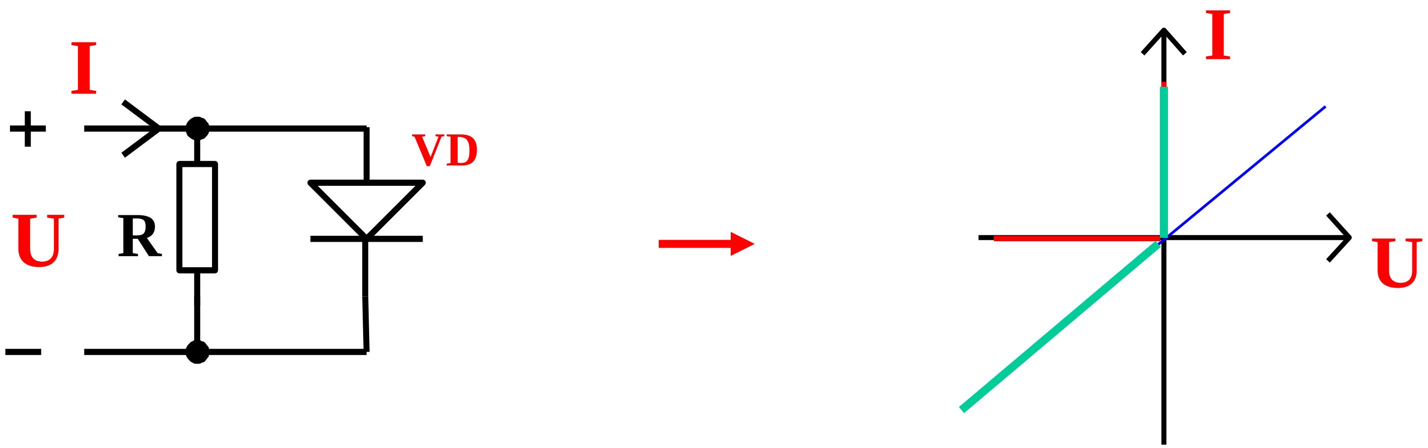

R
i
+
+
u_d
−
+
u
E
−
−

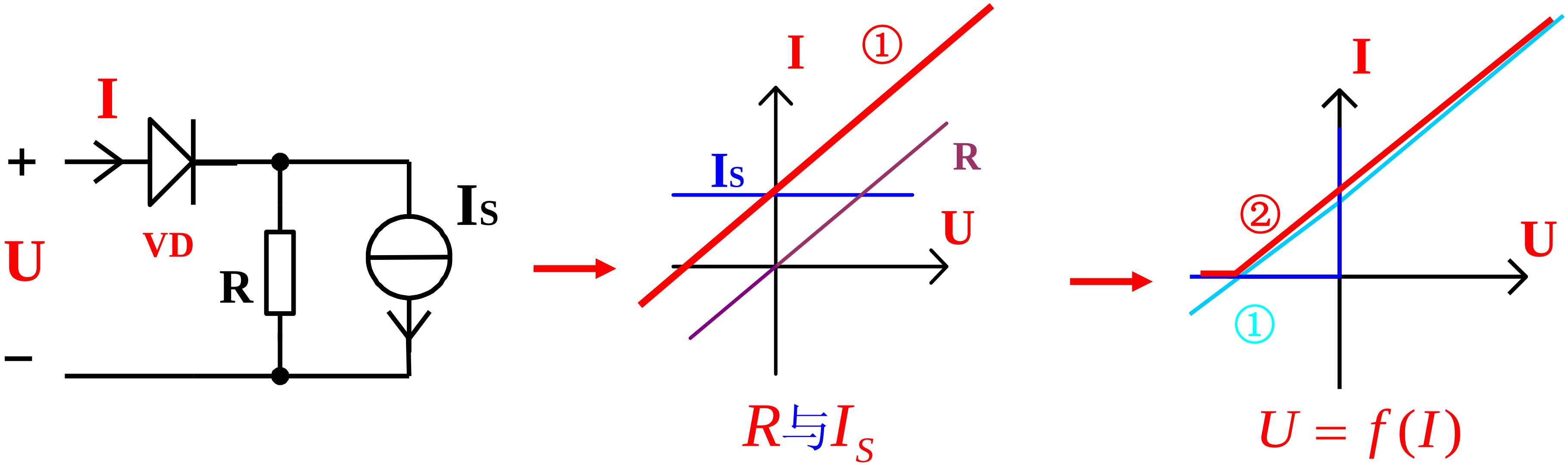

i
正向导通
反向截止
理想二极管D
o
u


i
$i=\frac{1}{2}G\left(\left|u-E\right|+u-E\right)$
R+D+E
o
u

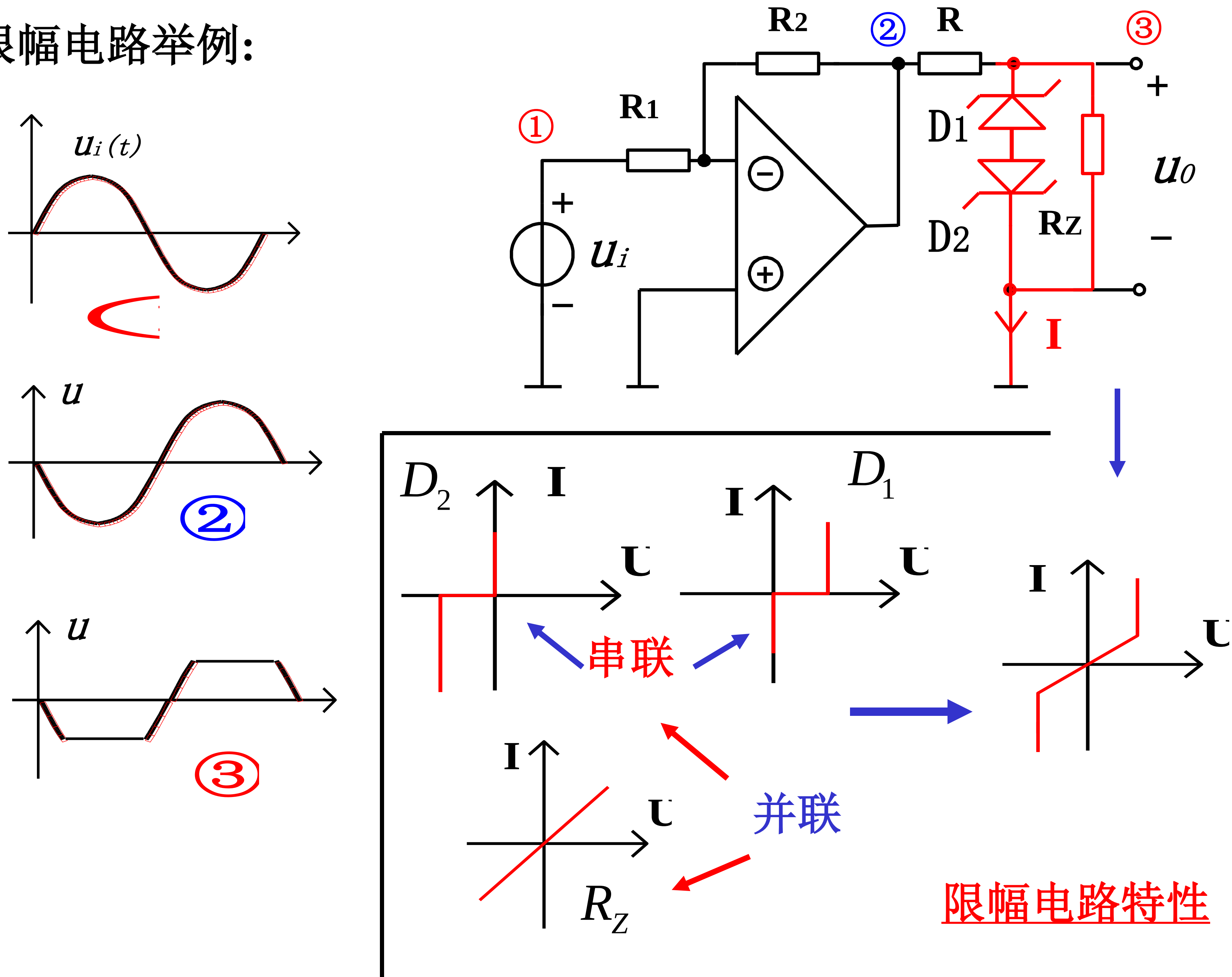

i
$i=\frac{1}{2}G\left(\left|u\right|+u\right)$
R+D
G
o
u

例: 求各二端网络的伏安特性. (VD为理想二极管)





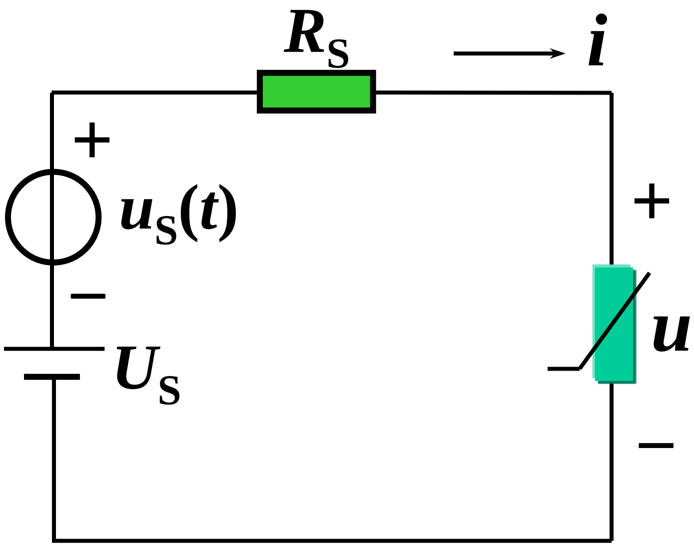
限幅电路举例:



$u_i(t)$
u
②
u
③
R2
②
R
③
R1
①
D1
+
u_i
u_o
D2
Rz
−
I
D_2
I
I
D_1
U
U
串联
I
U
I
U
并联
R_Z
限幅电路特性

9.4 小信号分析方法

小信号分析方法是工程上分析非线性电路的一个极其重要的方法，即“工作点处线性化”



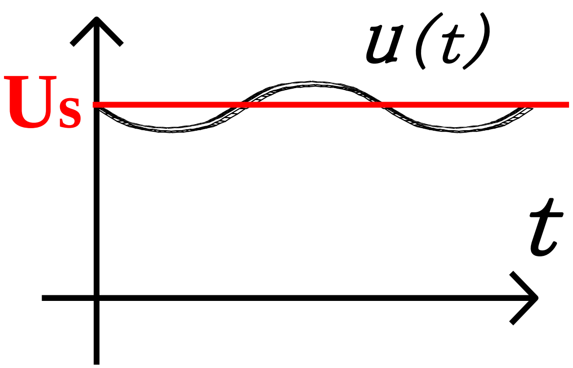
U_s 为直流电源(建立静态工作点)

$u_s(t)$ 为交流小信号电源

$U_s >> u_s(t)$

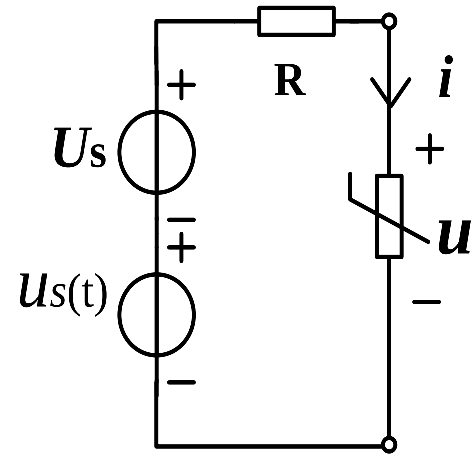
R_s 为线性电阻

非线性电阻 $i = g(u)$



列 KVL 方程：$U_s + u_s(t) = R_s i + u$

小信号分析法是一种把非线性电路线性化的方法。利用等效线性电路来计算小信号的电路响应.

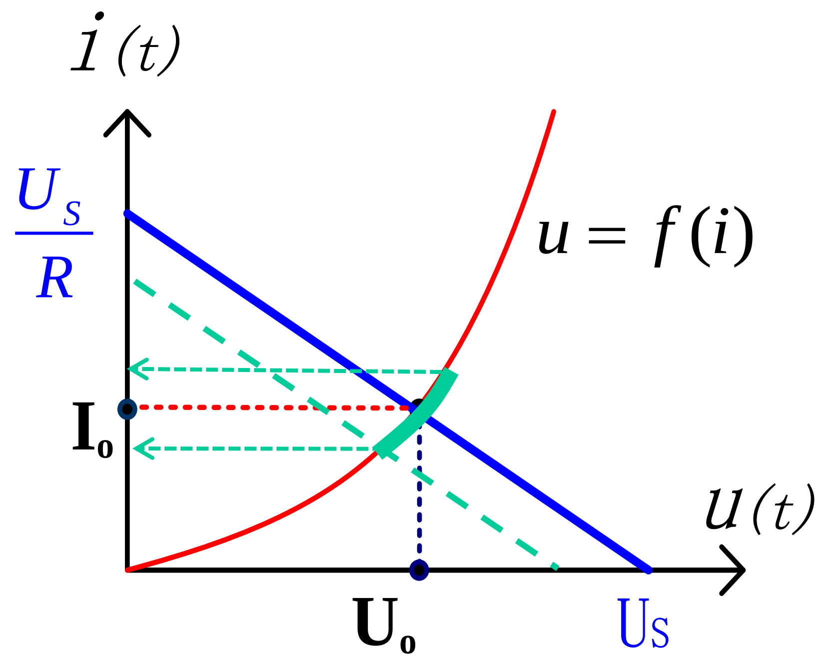


1) 直流电压作用时:

$$U_S - I \times R = U$$

(静态工作点 I_O, U_O)

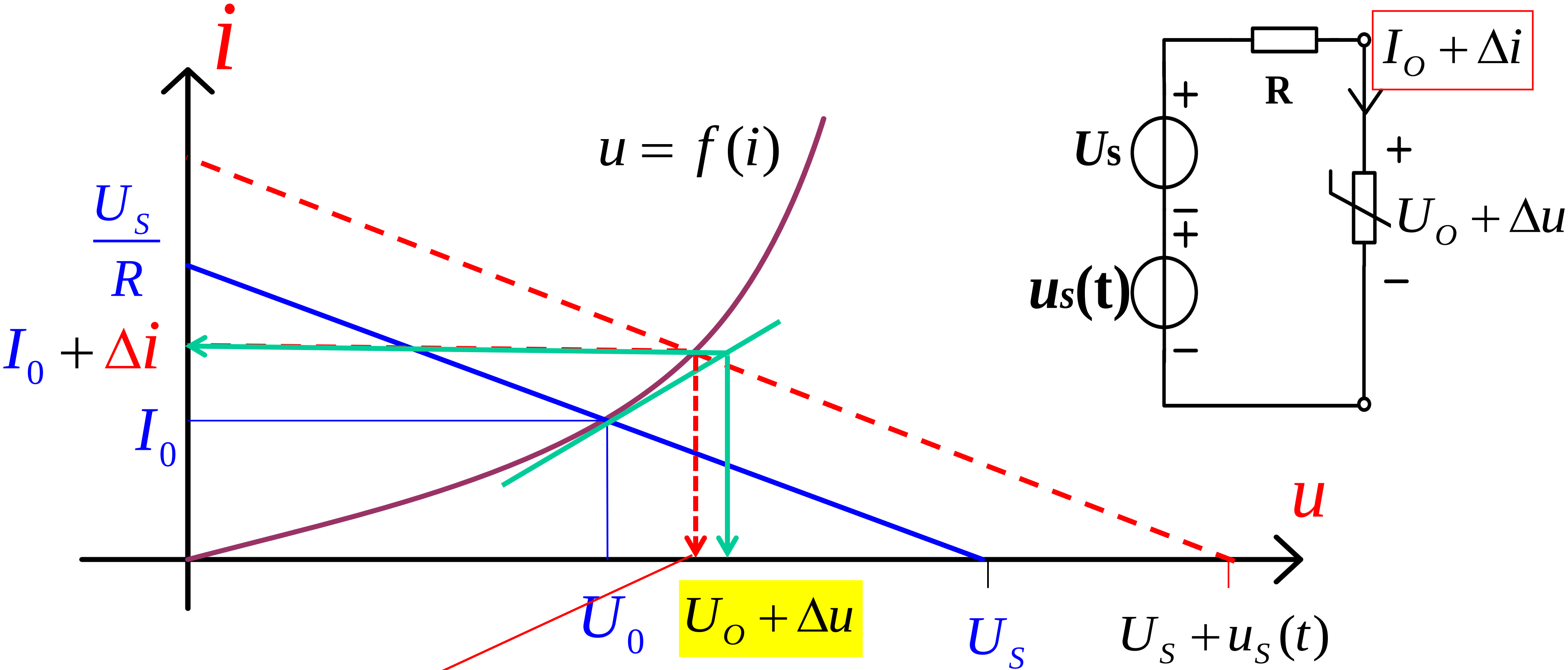
得: $U_S - I_O \times R = U_O$



2) 加入小信号时:

设: $u(t) = \Delta U \sin(\omega t)$

电流增加量为: Δi



精确解： $U_S + u_S(t) - Ri = u = f(i)$

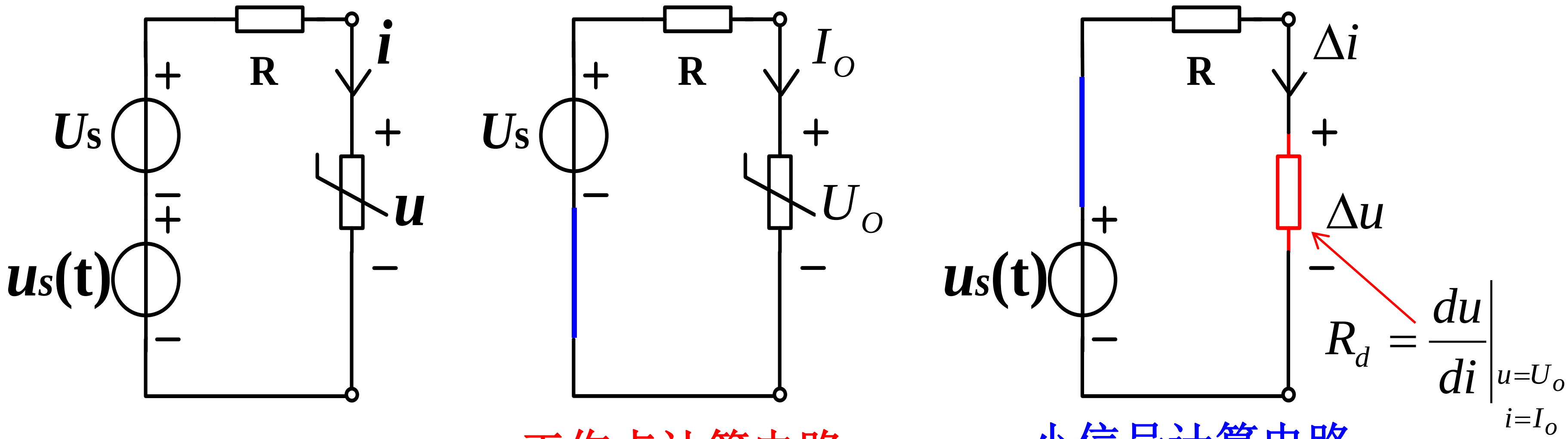
精确解： $U_S + u_S(t) - R(I_O + \Delta i) = f(I_O + \Delta i)$

泰勒展开式

某时刻： $U_S + u_S(t) - RI_O - R\Delta i \approx f(I_O) + \frac{du}{di}\Delta i$

小信号响应

静态工作点



工作点计算电路　　小信号计算电路

$$R_d = \left.\frac{du}{di}\right|_{\substack{u=U_O \\ i=I_O}}$$

$$i = I_O + \Delta i$$

$$u = U_O + \Delta u$$

精确解：$U_S + u_S(t) - Ri = U = f(i)$

精确解：$U_S + u_S(t) - R(I_O + \Delta i) = U(I_O + \Delta i)$

某时刻：$U_S + u_S(t) - RI_O - R\Delta i \approx U(I_O) + \frac{du}{di}\Delta i$

泰勒展开式

静态工作点

小信号响应

小信号电路计算是把非线性元件线性化等效为一个动态电阻, 计算电路的小信号激励下的响应.

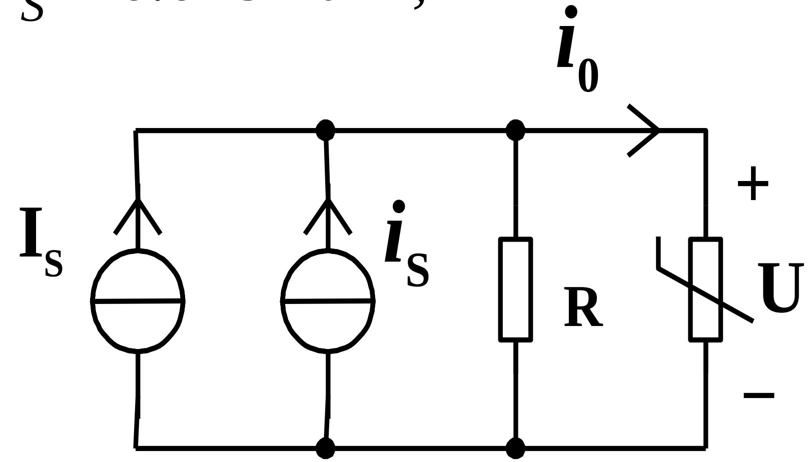
动态小信号分析过程包括:

1) 直流激励时的静态工作点计算.
2) 动态电阻计算, 建立小信号等效电路.
3) 计算小信号激励下的响应.
4) 迭加得电路总响应.

例1 电路如图, $I_S = 10A$, $R = \frac{1}{3}\Omega$, $i_S = 0.07\sin t \ A$,

非线性电阻的伏安特性为:

$$i = g(u) = \begin{cases} u^2 & (u > 0) \\ 0 & (u < 0) \end{cases}$$



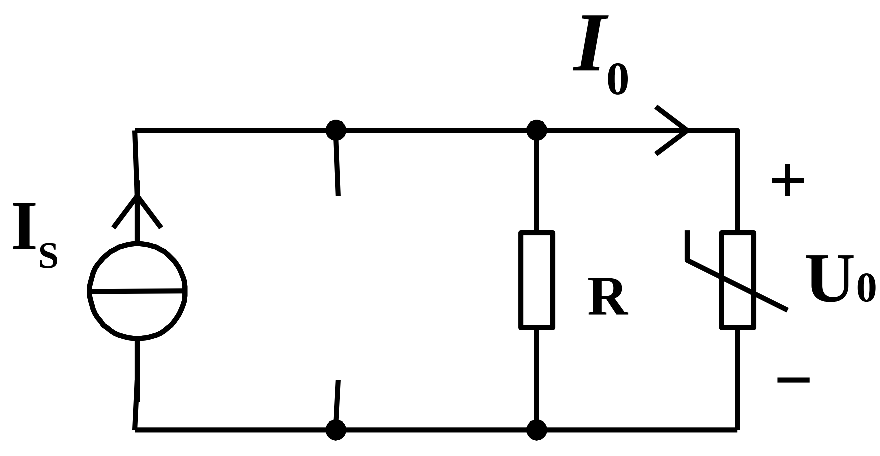
求非线性电阻的电压,电流.

解: 1) 计算静态工作点

$$I_S = \frac{U_0}{R} + i(U_0)$$

$$I_S = \frac{U_0}{R} + U_0^{\ 2}$$ 代入数据

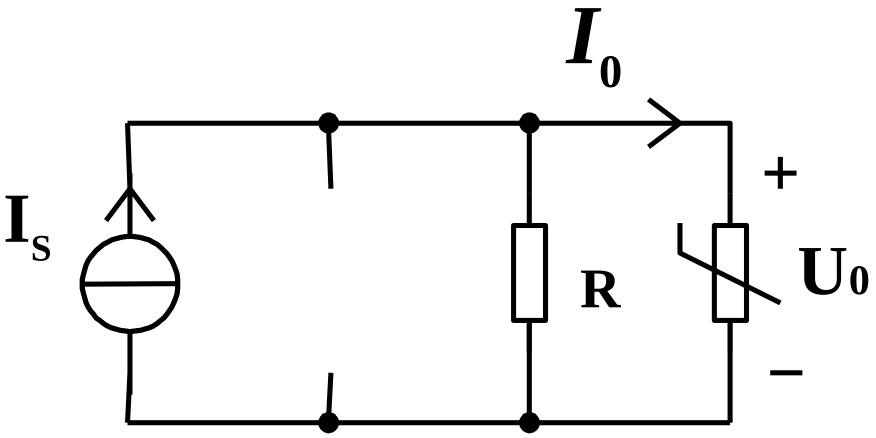
$$10 = 3U_0 + U_0^{\ 2}$$



解得

$$U_0 = 2V \text{或} -5V \quad \textbf{(舍去)}$$

$$I_0 = U_0^{\,2} = 4A$$



2) 计算动态电阻, 等效电路

$$R_{\text{动}} = \left.\frac{dU}{dI}\right|_{\substack{U=U_O \\ I=I_O}}$$

$$i = g(u) = \begin{cases} u^2 & (u > 0) \\ 0 & (u < 0) \end{cases}$$

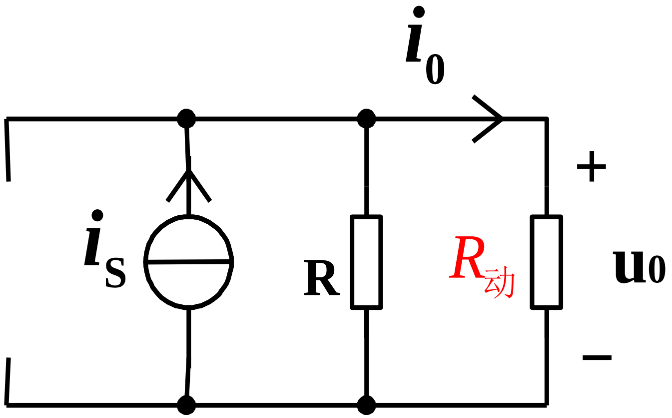
$$di = 2udu$$

$$\frac{du}{di} = \frac{1}{2u}$$

$$R_{\text{动}} = \left.\frac{dU}{dI}\right|_{\substack{U=U_O \\ I=I_O}} = \left.\frac{1}{2u}\right|_{U=U_O} = \frac{1}{4}\Omega$$

动态等效电路

(移去直流电源,非线性元件用动态电阻替代)



$$i_S = 0.07\sin t \ \ A$$

$$R = \frac{1}{3}\Omega \quad R_{动} = \frac{1}{4}\Omega$$

3) 计算动态小信号电路响应

$$i_0 = \frac{R}{R+R_{动}} i_S = \frac{4}{7} i_S = 0.04\sin t \ \ A$$

$$u_0 = R_{动} i_S = 0.01\sin t \ \ V$$

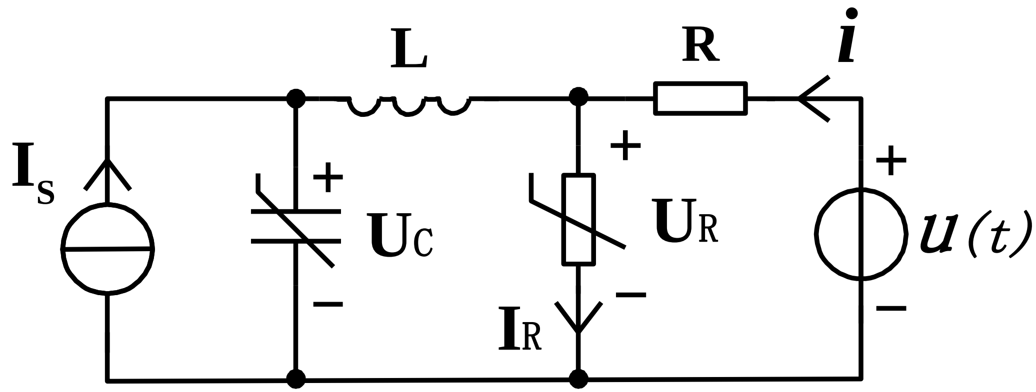
4) 计算电路响应

电压: $u = U_0 + u_0 = 2 + 0.01\sin t \ \ V$

电流: $i = I_0 + i_0 = 4 + 0.04\sin t \ \ A$

例2 电路如图， $R=10\Omega$, $I_S=6A$, $L=0.01H$

$u(t)=\sqrt{2}\times 0.1\sin 100t\ \ V$,

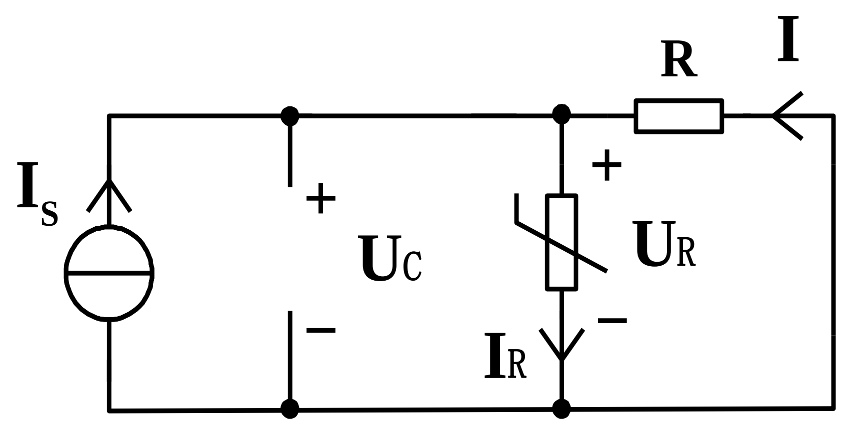


非线性电阻伏安特性为 $U_R=10I_R^2 \quad (I_R>0, U_R>0)$

非线性电容库伏特性为 $q=\frac{1}{8}10^{-3}U^2$ 求稳态电流 i.

解：1) 计算静态工作点

$$I_S=\frac{U_R}{R}+I_R$$



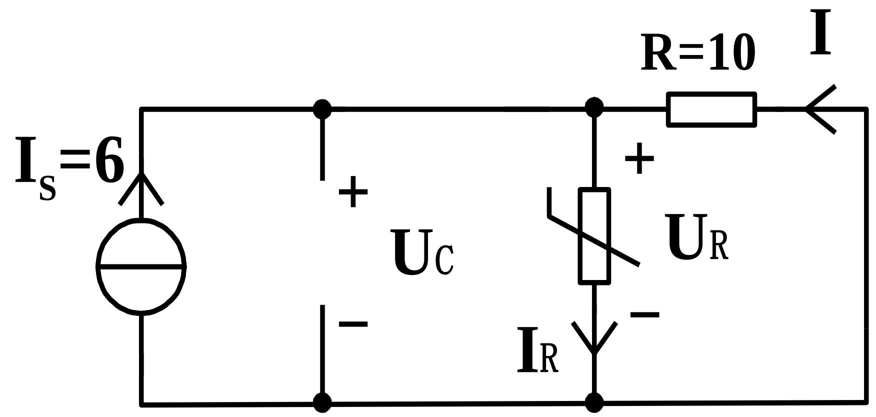
$RI_S - RI_R = U_R$ 代入数据

$60 - 10I_R = 10I_R^2$ 解得

$I_{R0} = 2A$或$-3A$ (舍去)

$U_R = U_C = 40V$

$I = -\frac{U_R}{R} = -4A$



$U_R = 10I_R^2$

$q = \frac{1}{8}10^{-3}U^2$

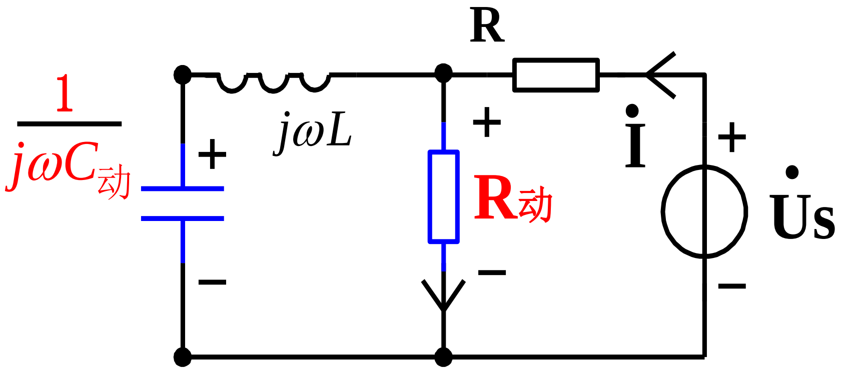
2) 计算动态电阻和动态电容

动态电阻: $R_动 = \frac{dU}{dI}\Big|_{I=I_O} = 20I_R\Big|_{I=I_O} = 40\Omega$

动态电容: $C_动 = \frac{dq}{dU}\Big|_{U=U_O} = \frac{1}{4}10^{-3}U\Big|_{U=U_O} = 0.01F$

3) 动态等效电路及计算

$$\omega L = 1\Omega \qquad \frac{1}{\omega C} = 1\Omega$$



$C_{动} = 0.01F \quad L = 0.01H$

$u(t) = 0.1\sin 100t$

LC串联谐振

$$\dot{I} = \frac{\dot{U}_S}{R + R_{动}} = \frac{0.1}{10 + 40} = 0.002\angle 0^0$$

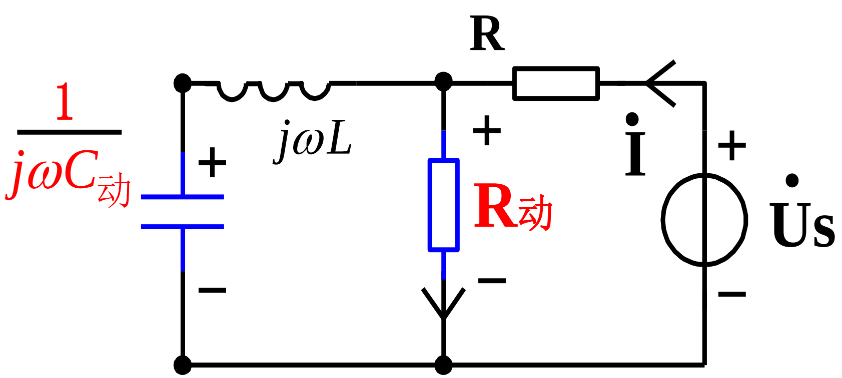
$$i_1(t) = \sqrt{2} \times 0.002\sin(100t)$$

4) 总电流

$$i(t) = I + i_1(t) = -4 + \sqrt{2} \times 0.002\sin(100t)A$$

3) 动态等效电路及计算

$$\omega L = 1\Omega \qquad \frac{1}{\omega C} = 1\Omega$$



$C_{动} = 0.01F \quad L = 0.01H$

$u(t) = 0.1\sin 100t$

LC串联谐振

$$\dot{I} = \frac{\dot{U}_S}{R + R_{动}} = \frac{0.1}{10+40} = 0.002\angle 0^0$$

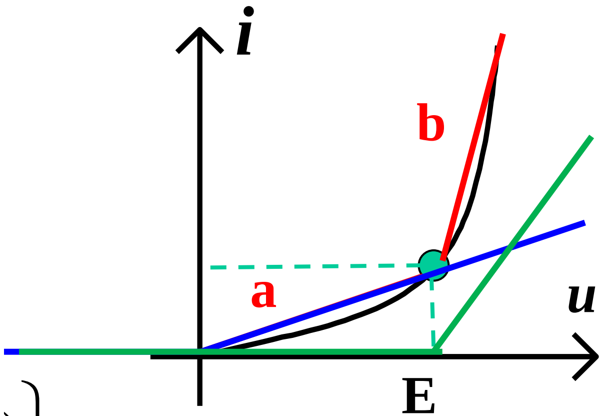
$$i_1(t) = \sqrt{2}\times 0.002\sin(100t)$$

4) 总电流

$$i(t) = I + i_1(t) = -4 + \sqrt{2}\times 0.002\sin(100t)A$$

9.5　分段线性化方法*

把非线性的求解过程分成几个线性区段，对每个线性区段应用线性电路的计算方法，也称折线法 。



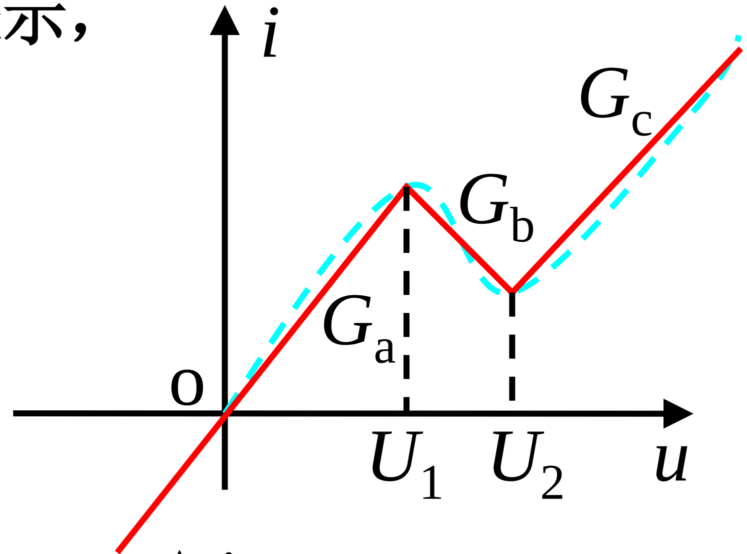
方法1：用分段函数表示

方法2：在整个区间用统一函数表示

$$i=\left\{\frac{1}{2}G_1\left(|u|+u\right)\right\}+\left\{\frac{1}{2}G_2\left(|u-E|+u-E\right)\right\}$$

例1　用分段线性化法讨论隧道二极管的伏安特性。

解 伏安特性用三段直线粗略表示，其斜率分别为：

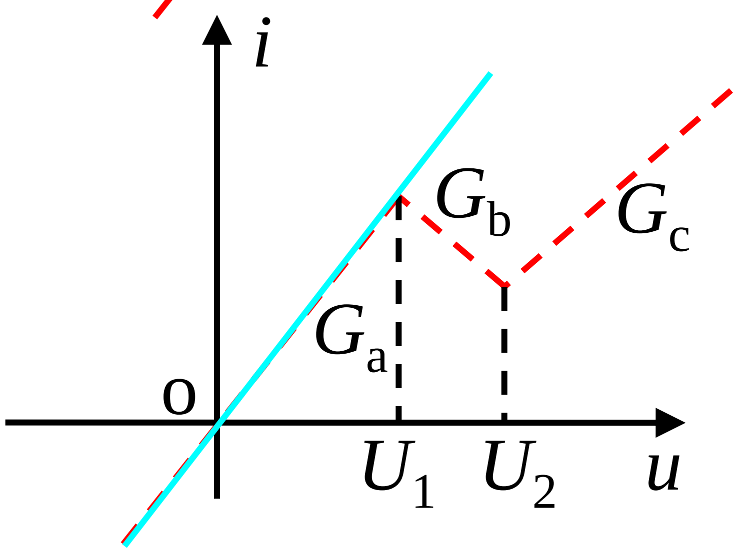


$$G=G_a \quad 当u<U_1$$

$$G=G_b \quad 当U_1<u<U_2$$

$$G=G_c \quad 当u>U_2$$

把伏安特性分解为三个特性：



当$u<U_1$有：　　$G_1u=G_au$

→　$G_1=G_a$

当$U_1 < u < U_2$，有：

$$G_1u+G_2u = G_bu$$

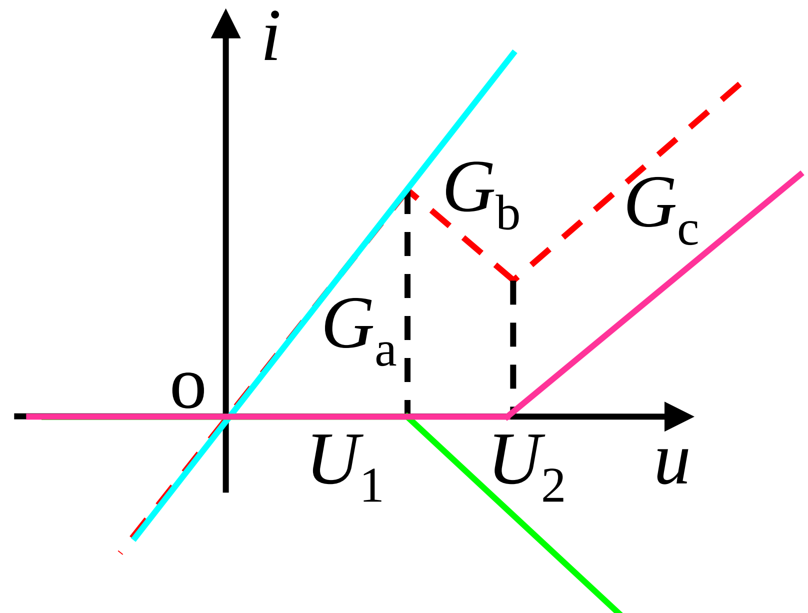
$\rightarrow$ $G_1+G_2 = G_b$

当$U_2 < u$，有：

$$G_1u+G_2u+G_3u=G_cu$$

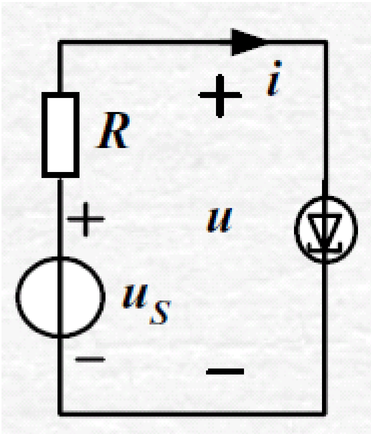
$\rightarrow$ $G_1+G_2+G_3=G_c$

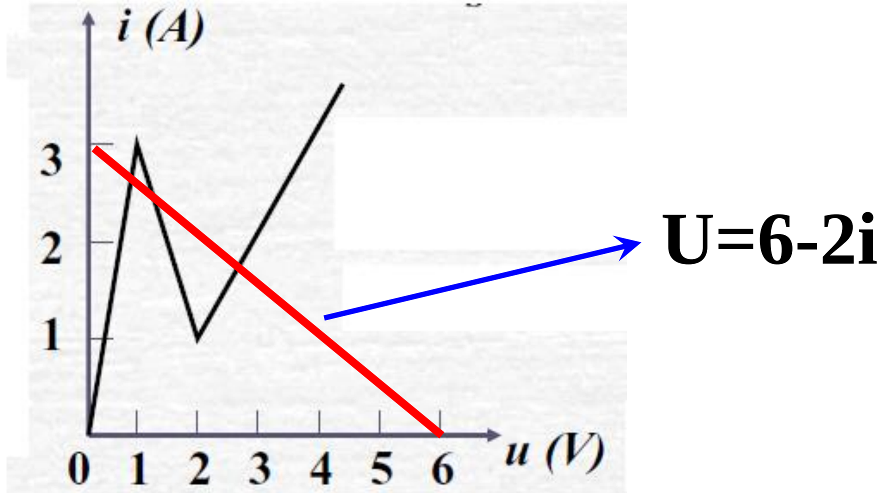
解得：
$$\begin{cases} G_1=G_a \\ G_2=G_b-G_a \\ G_3=G_c-G_b \end{cases}$$



结论 隧道二极管的伏安特性可以看成G_1、G_2、G_3三个电导并联后的等效电导的伏安特性。

例：已知隧道二极管的伏安特性如图所示，$u_S=6V, R=2\ \Omega$，求工作点。





解法一：图解法

0≤u<1: i=3u

$$Q_1:(\frac{6}{7}V,\frac{18}{7}A)$$

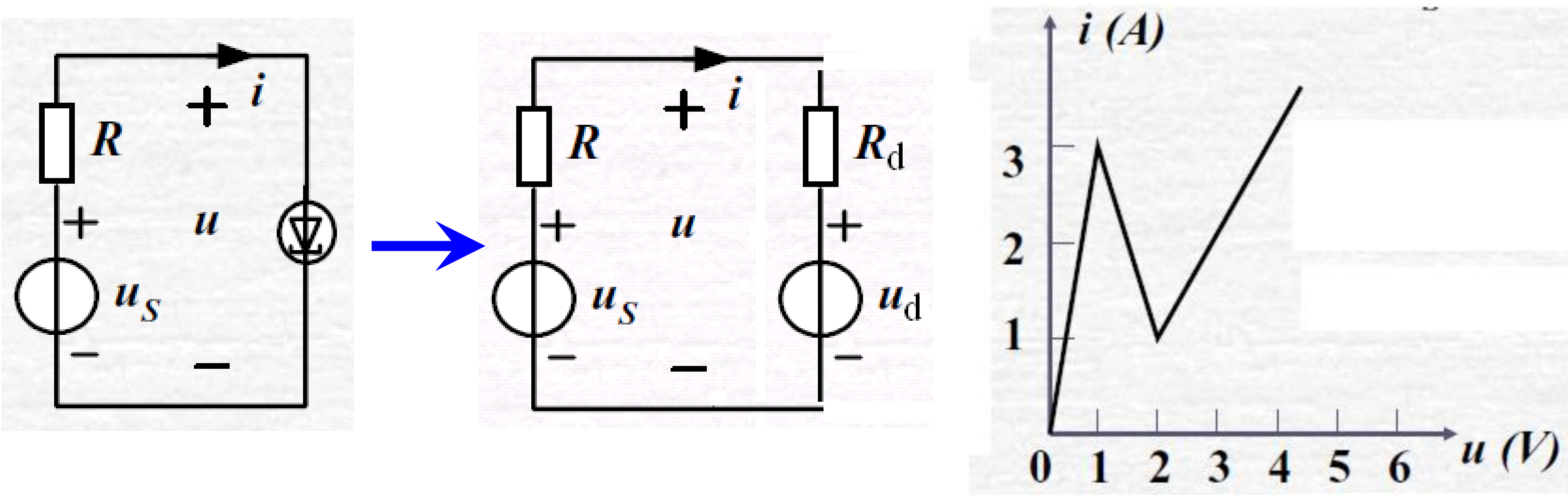
1≤u<2: i=-2u+5

$$Q_2:(\frac{4}{3}V,\frac{7}{3}A)$$

2≤u: i=u-1

$$Q_3:(\frac{8}{3}V,\frac{5}{3}A)$$

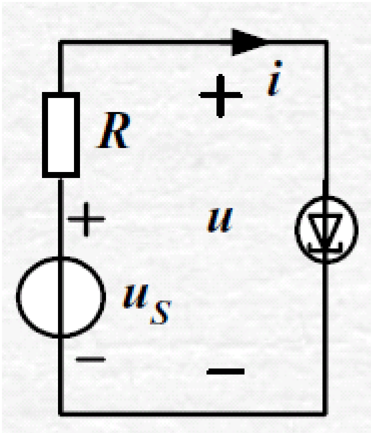
例：已知隧道二极管的伏安特性如图所示，$u_S=6V, R=2\ \Omega$，求工作点。

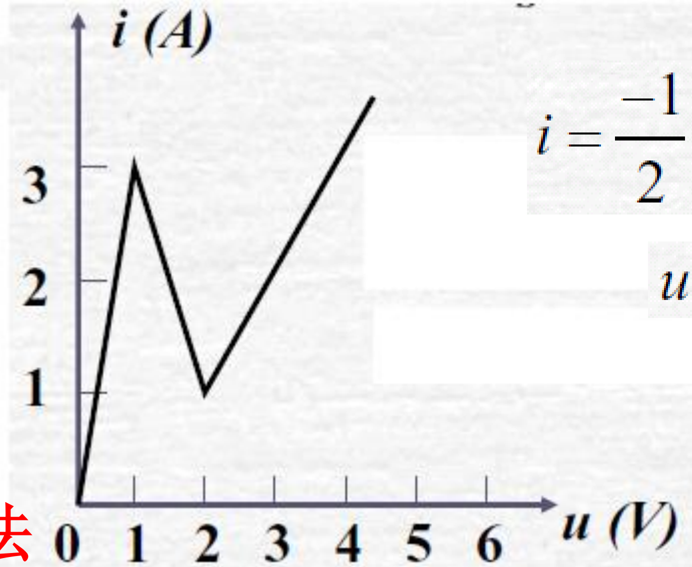


解法二：等效电路法

$$Q_k: \quad i_k = \frac{u_s - u_d}{R + R_d} \qquad k = 1, 2, 3$$

例：已知隧道二极管的伏安特性如图所示，u_S=6V,R=2 Ω，求工作点。





$$i=\frac{-1}{2}+2u-\frac{5}{2}|u-1|+\frac{3}{2}|u-2|$$

$$u=U_S-Ri=6-2i$$

解法三：折线方程法

E1＝1V , E2=2V , Ga=3S , Gb=−2S , Gc=1S

G0= Ga=3S , G1=−Ga+Gb=−5S , G2=−Gb+Gc=3S

$$i=G_0u+\frac{1}{2}G_1\left[|u-E_1|+(u-E_1)\right]+\frac{1}{2}G_2\left[|u-E_2|+(u-E_2)\right]$$

$$i=3u-\frac{5}{2}\left[|u-1|+(u-1)\right]+\frac{3}{2}\left[|u-2|+(u-2)\right]$$

$$i=\frac{-1}{2}+2u-\frac{5}{2}\left|u-1\right|+\frac{3}{2}\left|u-2\right|$$

$$u=U_S-Ri=6-2i$$

$$u=6-2\times\left[\frac{-1}{2}+2u-\frac{5}{2}\left|u-1\right|+\frac{3}{2}\left|u-2\right|\right]$$

$$7-5u+5\times\left|u-1\right|-3\times\left|u-2\right|=0$$

feixianxin4.m

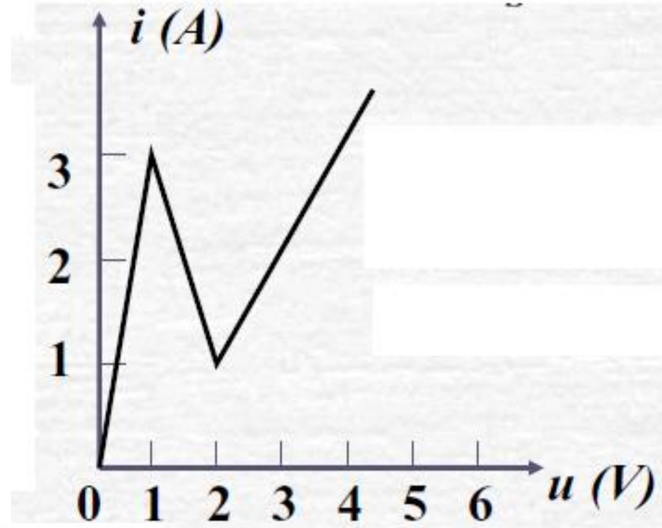
```
clc;
u=solve('7-5*u+5*abs(u-1)-3*abs(u-2)=0');
i=-1/2+2*u-5/2*abs(u-1)+3/2*abs(u-2);
disp('u=');
disp(u);
disp('i=');
disp(i)
```

```
u=
[ 8/3]
[ 4/3]
[ 6/7]
```

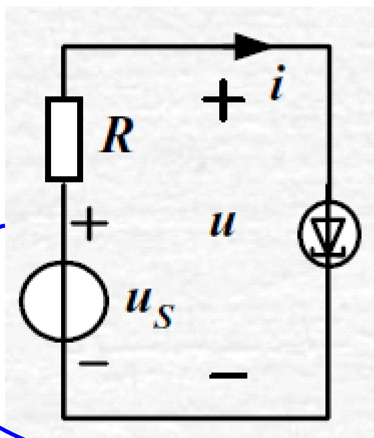
```
i=
[  5/3]
[  7/3]
[ 18/7]
```

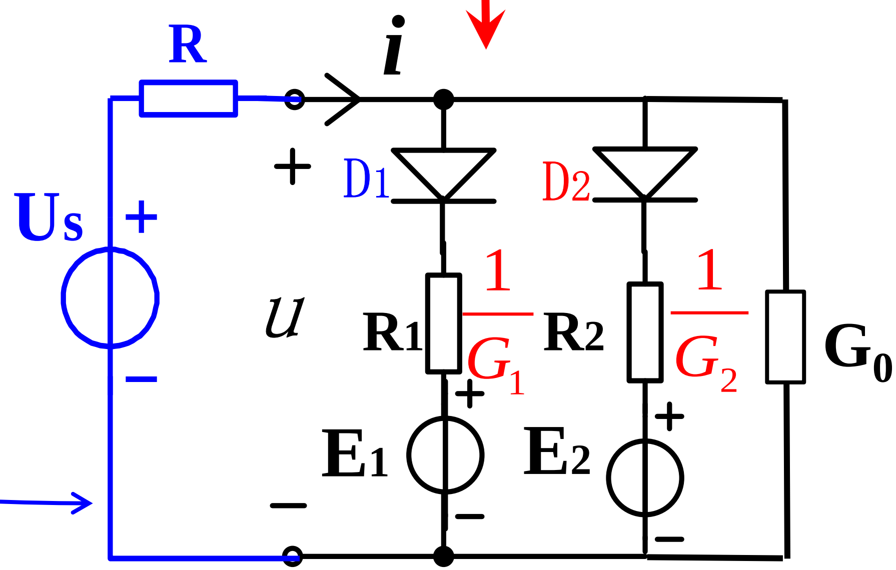
3) 等效电路法计算

非线性元件用一些理想二极管,线性电阻,电压源的并联电路来等效.



$$i = G_0 u + \frac{1}{2} G_1 \left[\left| u - E_1 \right| + (u - E_1) \right] + \frac{1}{2} G_2 \left[\left| u - E_2 \right| + (u - E_2) \right]$$

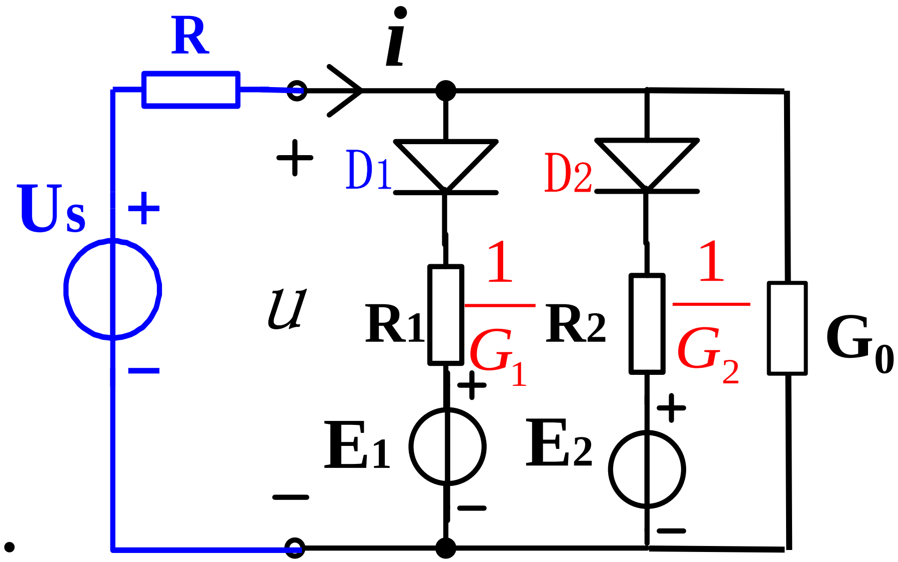




**等效电路法计算(穷举法简介)

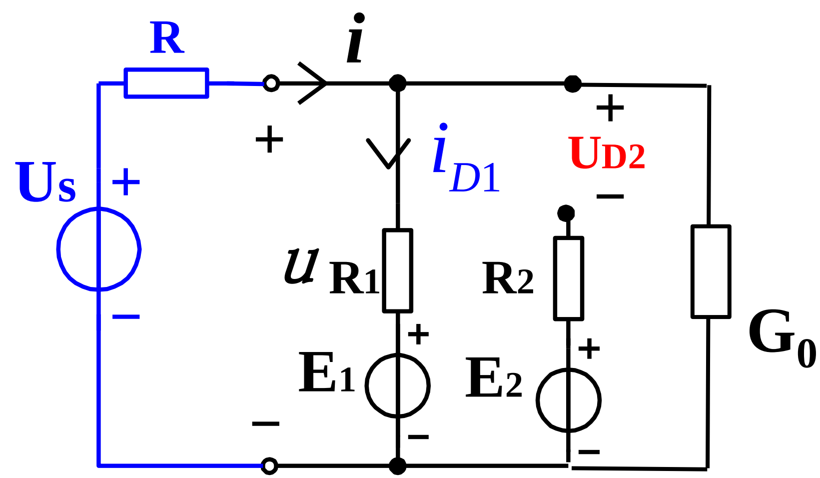
对于确定电压源 U_S 激励,

穷举法计算过程为:



1) D1导通, D2断开, 计算电路的解.

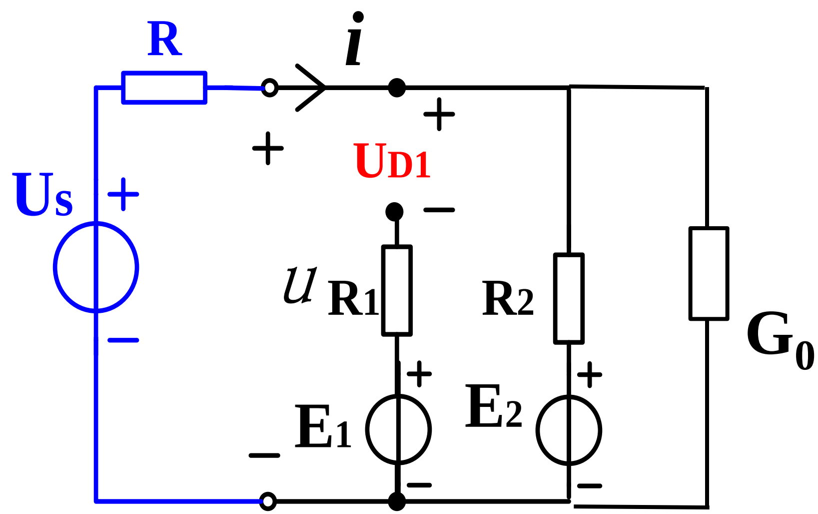
如果计算结果得到 $U_{D2}<0$ ，$i_{D1}>0$ 则为真实解; 反之为非真实解,舍去.



2) D_2导通, D_1断开, 计算电路的解.

如果计算结果使得 $U_{D1} < 0$ ，

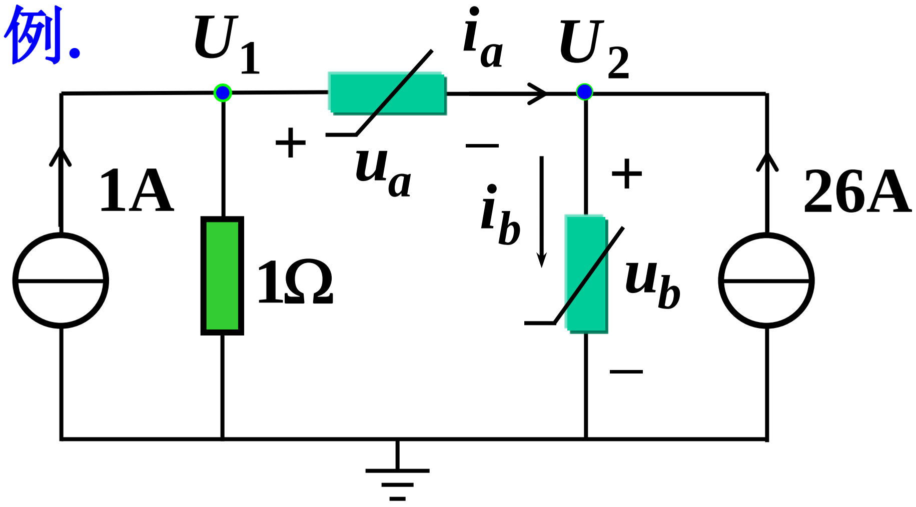
$i_{D2} > 0$ 则为真实解; 反之为非真实解,舍去.



依此类推, 通过对所有的理想二极管所有通断可能性的组合分析,分别计算出每次每个开断二极管的正向电压和导通二极管的正向电流, 如果所有的正向电压和正向电流均大于零,其电路解为一个真实解,否则为非真实解.据此可计算所有的真实解.

方程法：以u_a, u_b为变量

例.



$$i_a = 2u_a^3 \ , \ i_b = u_b^3 + 10u_b$$

计算： u_a, i_a, u_b, i_b

列节点方程：

$$\begin{cases} U_1 + 2u_a^3 = 1 \\ -2u_a^3 + u_b^3 + 10u_b = 26 \end{cases}$$

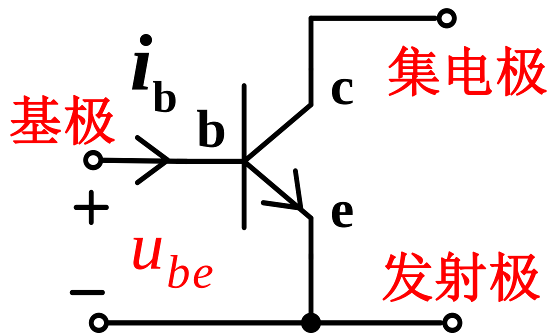
$$\begin{cases} u_a + u_b + 2u_a^3 - 1 = 0 \\ 2u_a^3 - u_b^3 - 10u_b + 26 = 0 \end{cases}$$

非线性代数方程组的求解

——牛顿拉夫逊法

9.6　三端非线性电阻元件

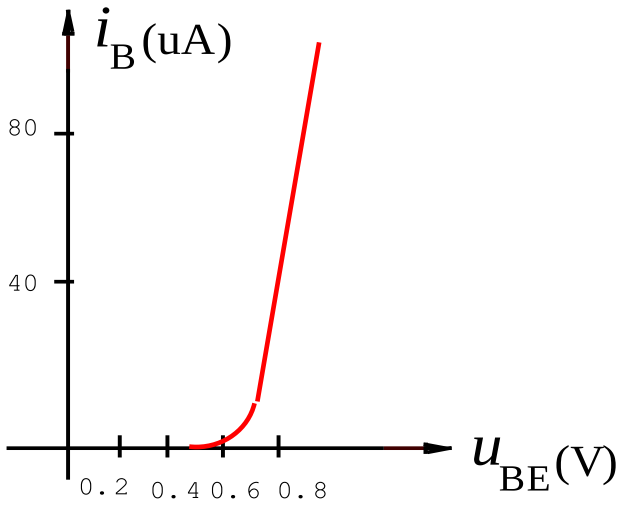
晶体管伏安特性



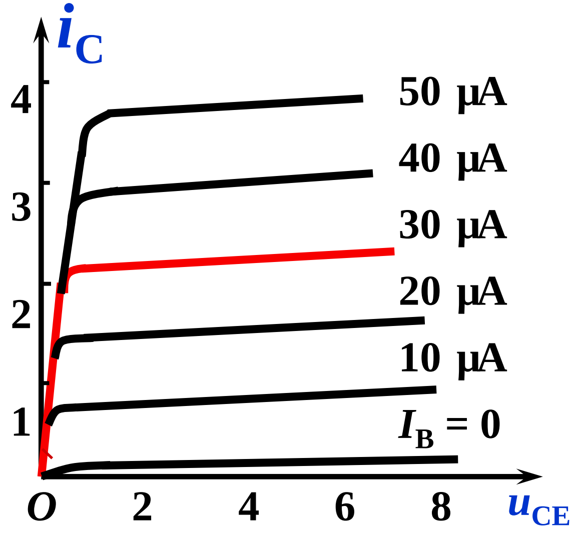
NPN管

$$i_B = f(u_{BE})\Big|_{u_{CE}=常数}$$

$$i_C = f(u_{CE})\Big|_{i_B=常数}$$

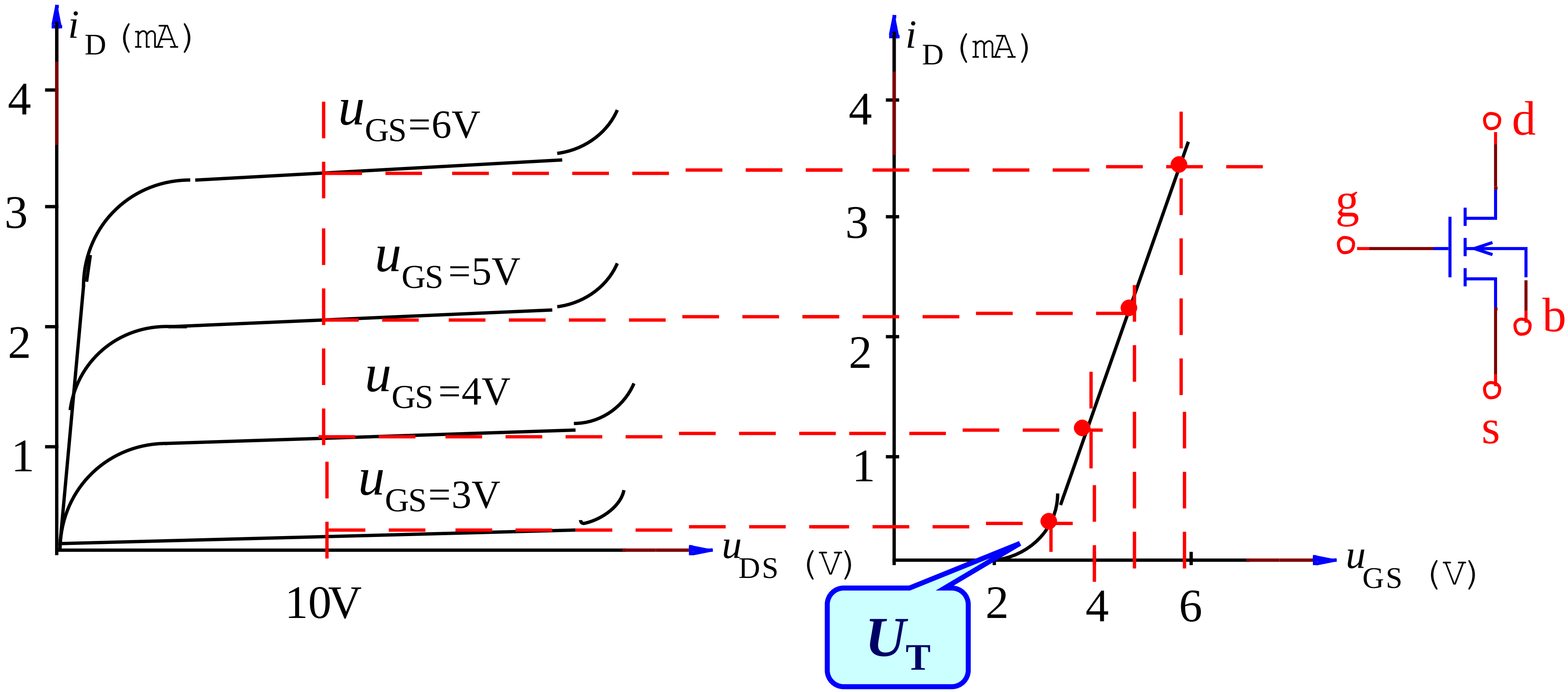


输入特性



输出特性

场效应管伏安特性



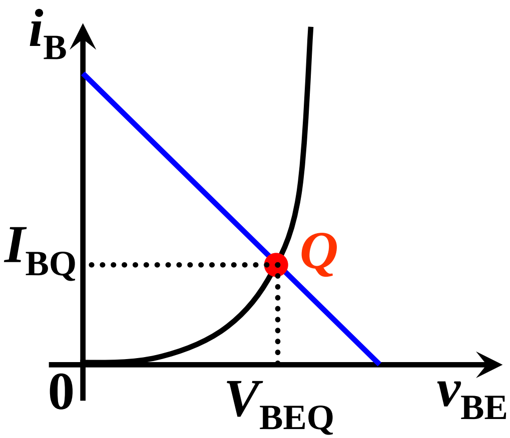
输出特性曲线

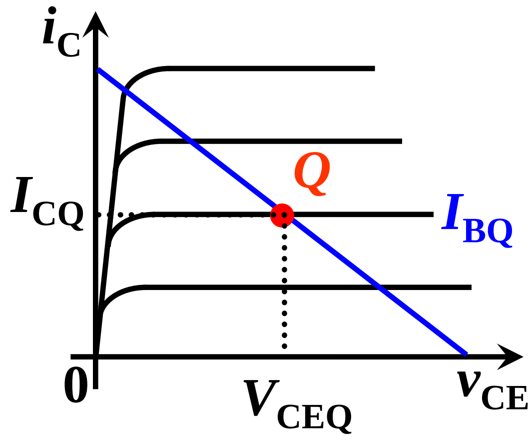
$$i_D=f(u_{DS})\big|_{u_{GS}=const}$$

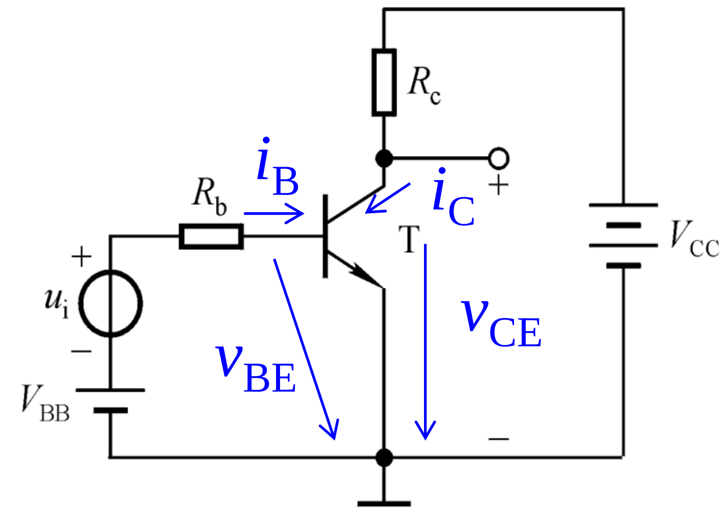
转移特性曲线 （电压控制电流源）

$$i_D=f(u_{GS})\big|_{u_{DS}=const}$$

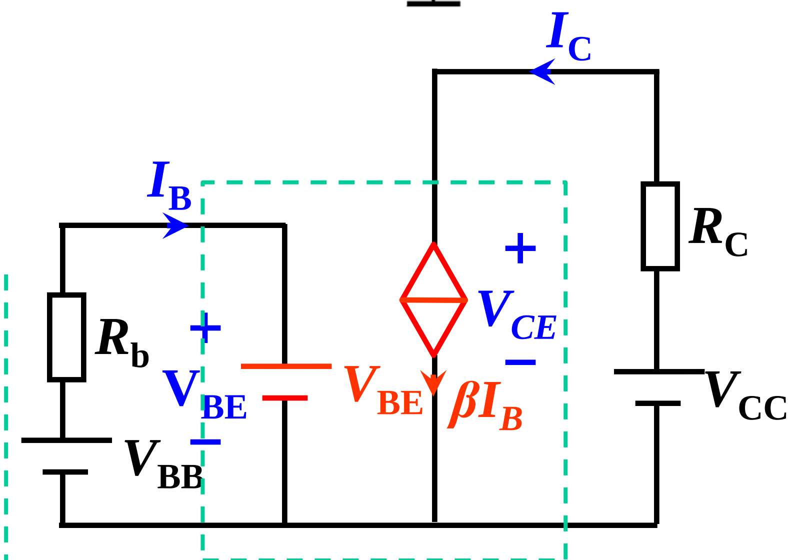
静态分析



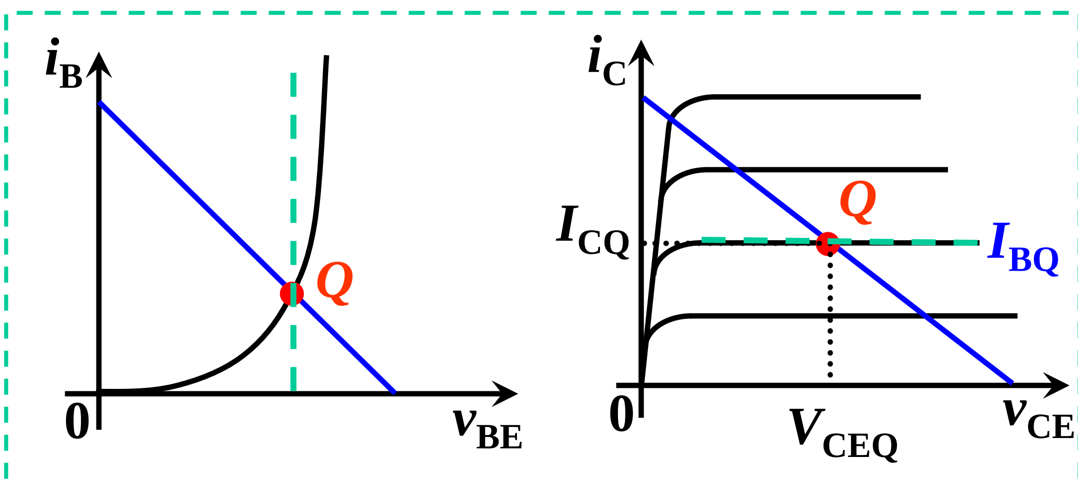




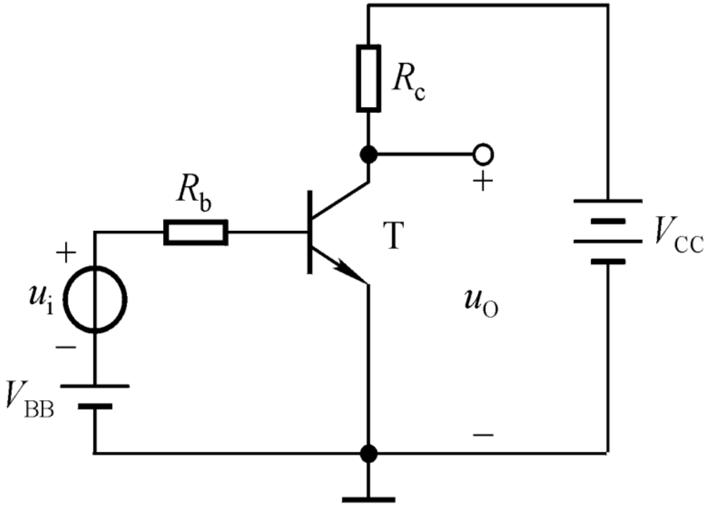
方法1：图解法

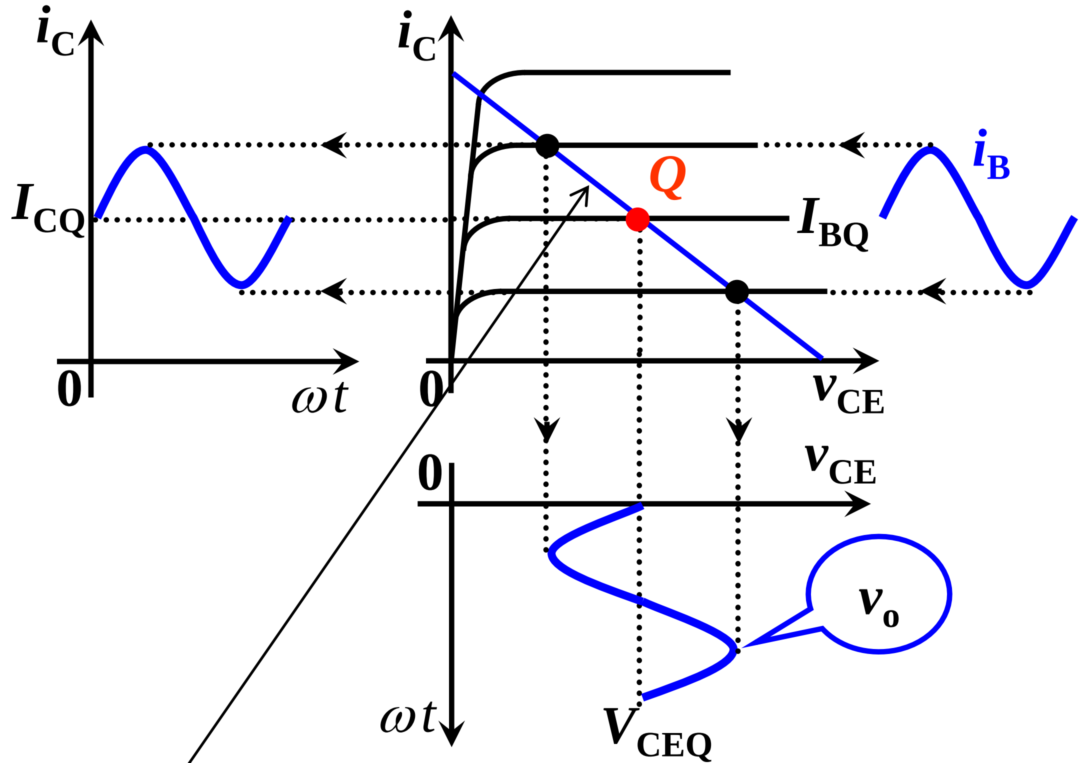


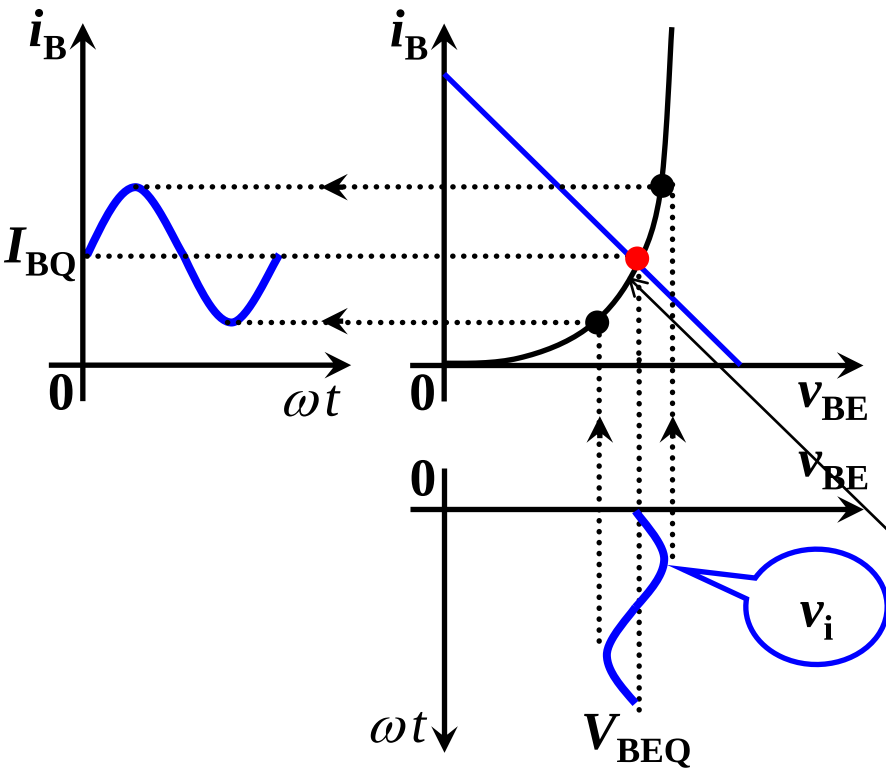
方法2：等效电路法



工作在放大区的
晶体管等效电路





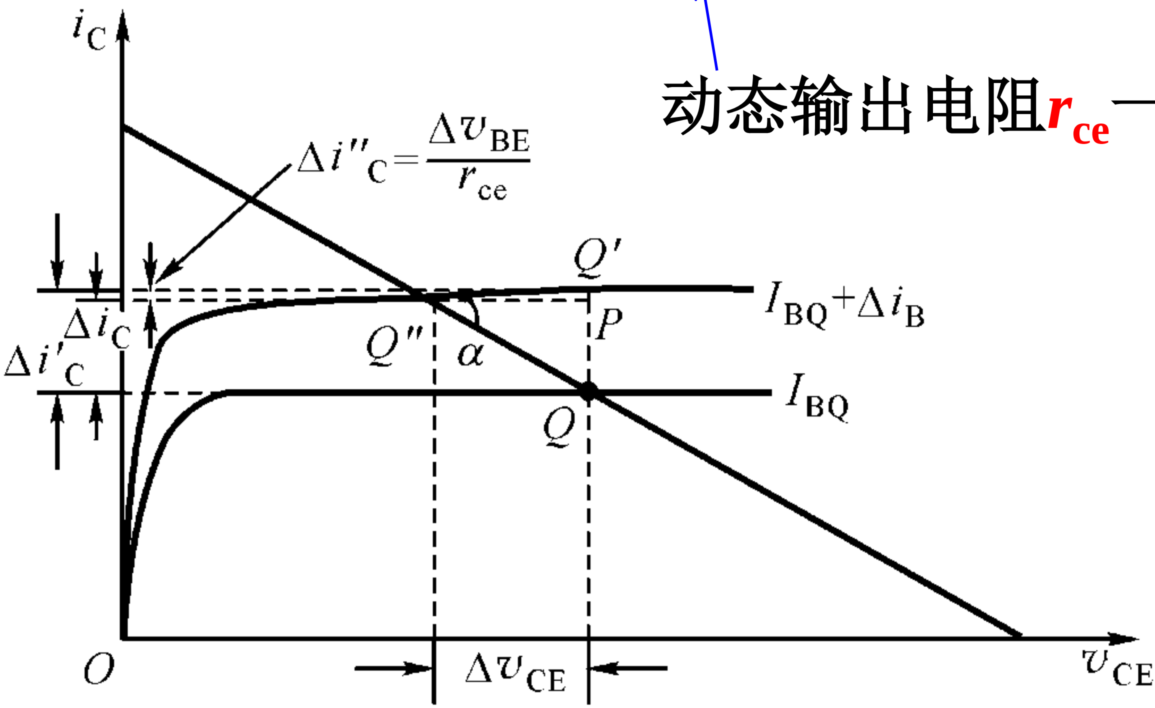


从输出口ce看，小信号模型为？
$\Delta i_c = f(\Delta v_{ce}, \Delta i_b)$

从输入口be看，小信号模型为动态电阻 $\Delta v_{be} = r_{be} \Delta i_b$

$$\Delta v_{BE} = r_{be} . \Delta i_B$$

$$\Delta i_C = \beta \Delta i_B + \frac{\Delta v_{CE}}{r_{ce}}$$

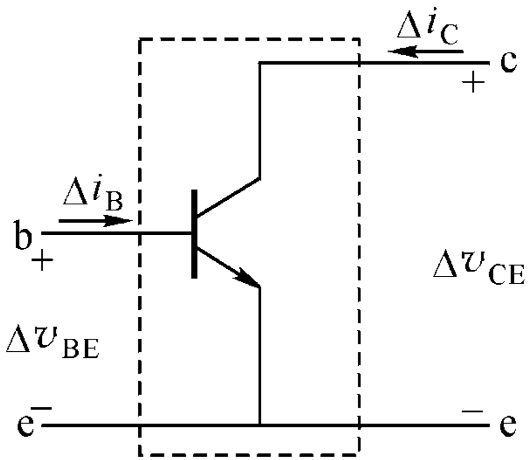


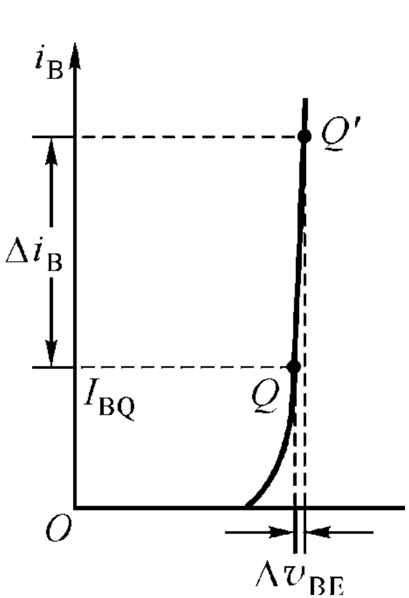
动态输出电阻r_{ce}一般很大，通常忽略。

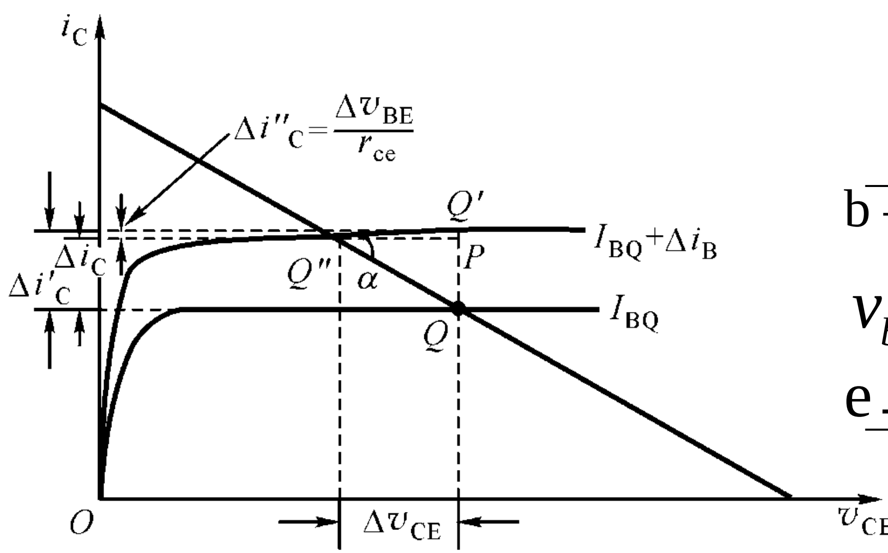
$$\Delta v_{BE} = r_{be} . \Delta i_B$$

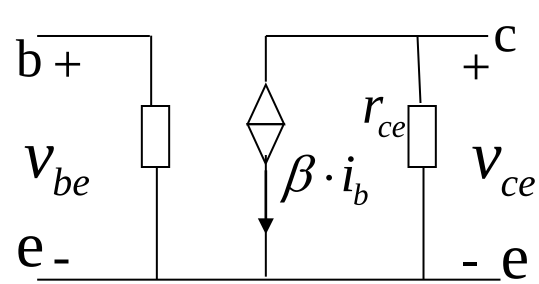
$$\Delta i_C = \beta \Delta i_B + \frac{\Delta v_{CE}}{r_{ce}}$$

动态输出电阻r_{ce}一般很大，通常忽略。

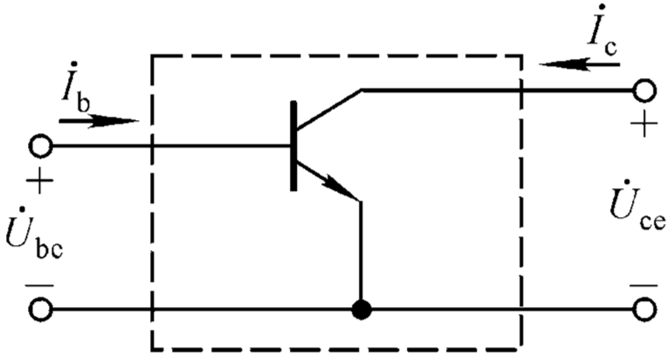


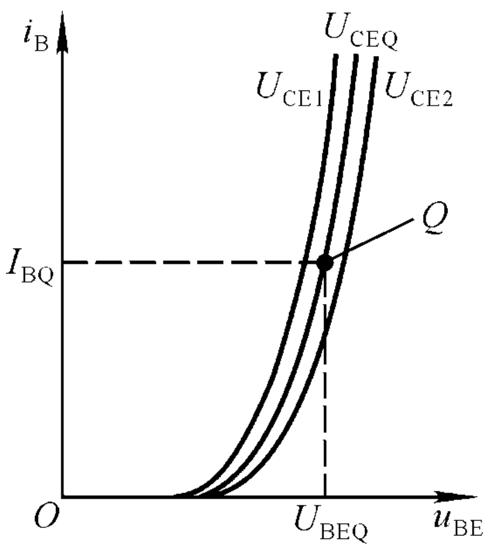


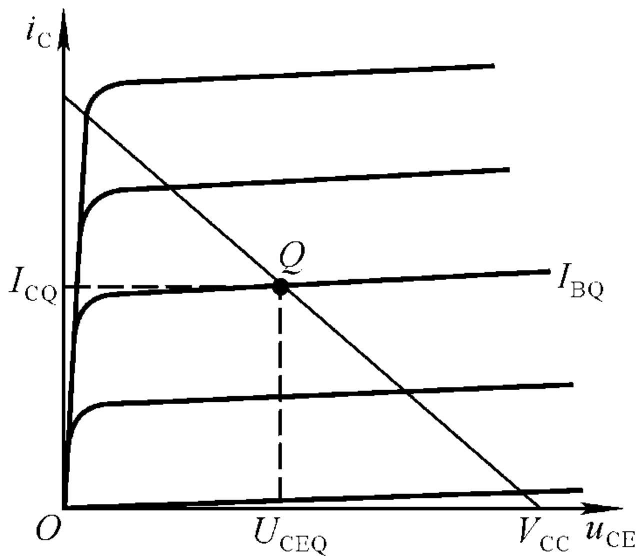




小信号模型







$$\begin{cases} u_{BE} = f(i_B, u_{CE}) \\ i_C = f(i_B, u_{CE}) \end{cases}$$

小信号作用下的关系式

$$
\begin{cases}
\mathrm{d}u_{\mathrm{BE}} = \dfrac{\partial u_{\mathrm{BE}}}{\partial i_{\mathrm{B}}}\Big|_{U_{\mathrm{CE}}} \mathrm{d}i_{\mathrm{B}} + \dfrac{\partial u_{\mathrm{BE}}}{\partial u_{\mathrm{CE}}}\Big|_{I_{\mathrm{B}}} \mathrm{d}u_{\mathrm{CE}} \\[2ex]
\mathrm{d}i_{\mathrm{C}} = \dfrac{\partial i_{\mathrm{C}}}{\partial i_{\mathrm{B}}}\Big|_{U_{\mathrm{CE}}} \mathrm{d}i_{\mathrm{B}} + \dfrac{\partial i_{\mathrm{C}}}{\partial u_{\mathrm{CE}}}\Big|_{I_{\mathrm{B}}} \mathrm{d}u_{\mathrm{CE}}
\end{cases}
\Rightarrow
\begin{cases}
\dot{U}_{\mathrm{be}} = h_{11}\dot{I}_{\mathrm{b}} + h_{12}\dot{U}_{\mathrm{ce}} \\
\dot{I}_{\mathrm{c}} = h_{21}\dot{I}_{\mathrm{b}} + h_{22}\dot{U}_{\mathrm{ce}}
\end{cases}
$$

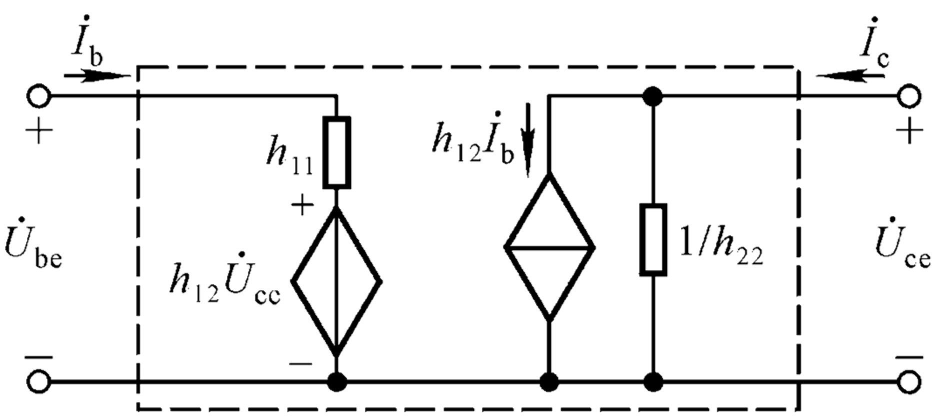
电阻

无量纲

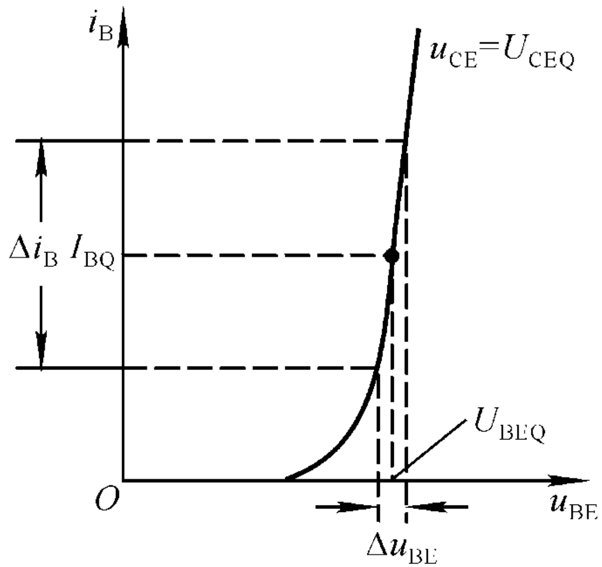
无量纲

电导

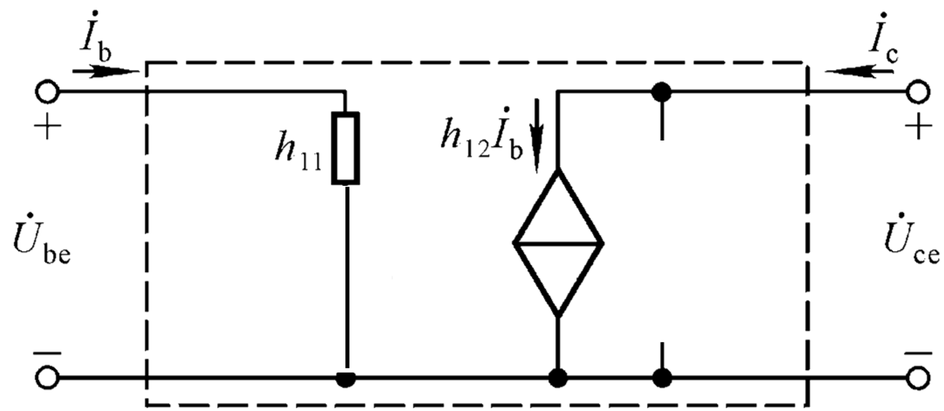
小信号等效电路模型



动态输入电阻



$$\begin{cases}\dot{U}_{be} = h_{11}\dot{I}_b + \cancel{h_{12}\dot{U}_{ce}} \\ \dot{I}_c = h_{21}\dot{I}_b + \cancel{h_{22}\dot{U}_{ce}}\end{cases}$$



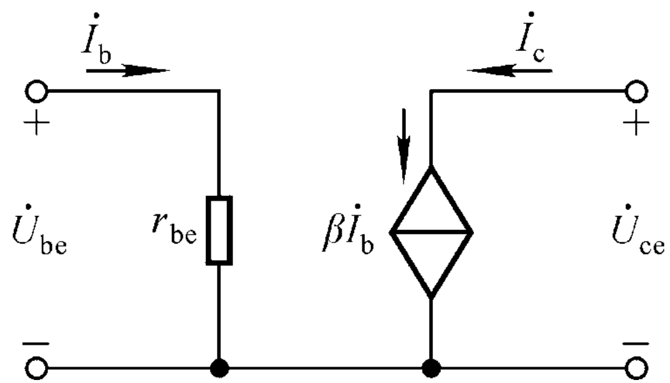
$$\boxed{i_B = I_S(e^{\frac{u_{BE}}{V_T}} - 1)}$$

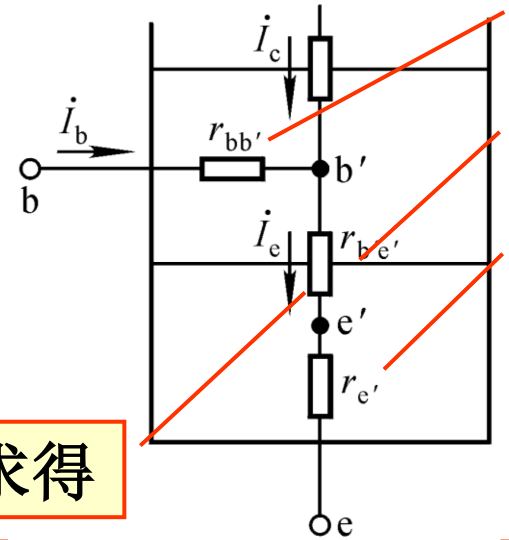
$$\boxed{g_{be} \approx \frac{I_{BQ}}{V_T}}$$

$$\boxed{h_{11} = r_{be} \approx \frac{V_T}{I_{BQ}} = \frac{26mV}{I_{BQ}}}$$

$$\boxed{h_{21} = \beta = \frac{\Delta i_C}{\Delta i_B} \approx \bar{\beta} = \frac{I_C}{I_B}}$$

简化的h参数等效电路－小信号（交流）等效模型





基区体电阻

发射结电阻

发射区体电阻
数值小可忽略

利用PN结的电流方程可求得

$$g_{be} \approx \frac{I_{BQ}}{V_T}$$

$$r_{be} = \frac{U_{be}}{I_b} = r_{bb'} + r_{b'e} \approx r_{bb'} + (1+\beta)\frac{U_T}{I_{EQ}}$$

查阅手册

由I_{EQ}算出

在输入特性曲线上，Q点越高，r_{be}越小！

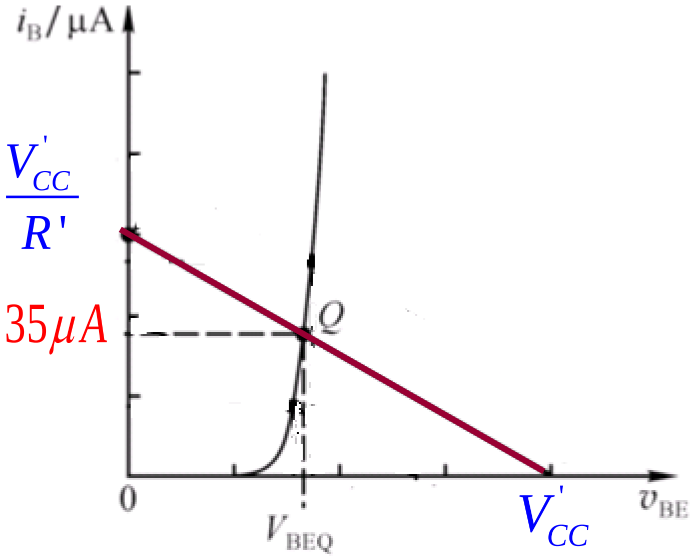
$r_{bb'}$为晶体三极管的基区体电阻，约为100～300Ω；

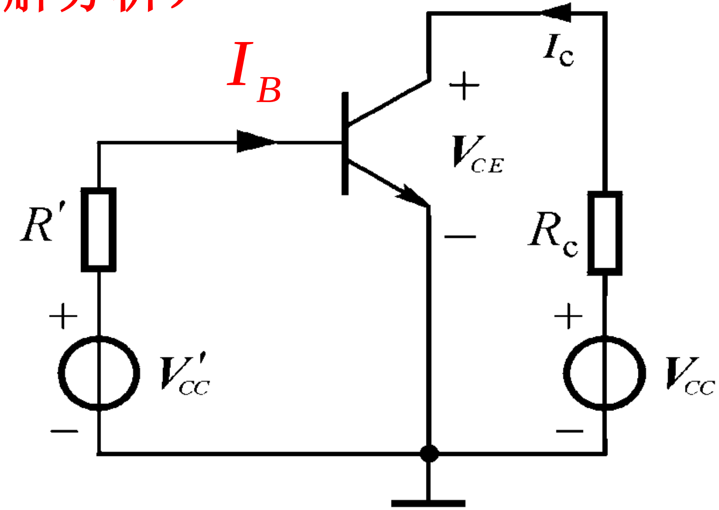
V_T＝26mV（室温下，是电压的温度档量）；

I_{EQ}为发射极静态电流。

六*、三极管放大的基本原理（图解分析）

基极电流（输入电压变化时）





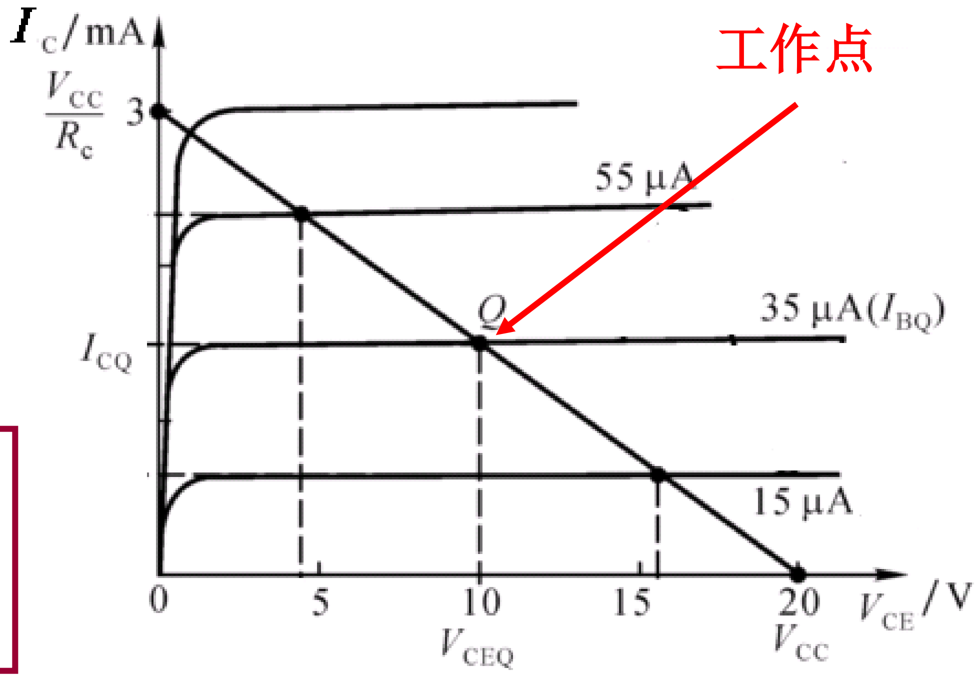
当 $i_b = 0 \rightarrow i_C \approx 0$

三极管输出回路截止

当 $V_{CC}\downarrow$ 或 $i_B\uparrow \rightarrow u_{CE} \approx 0.3V$

三极管输出回路饱和

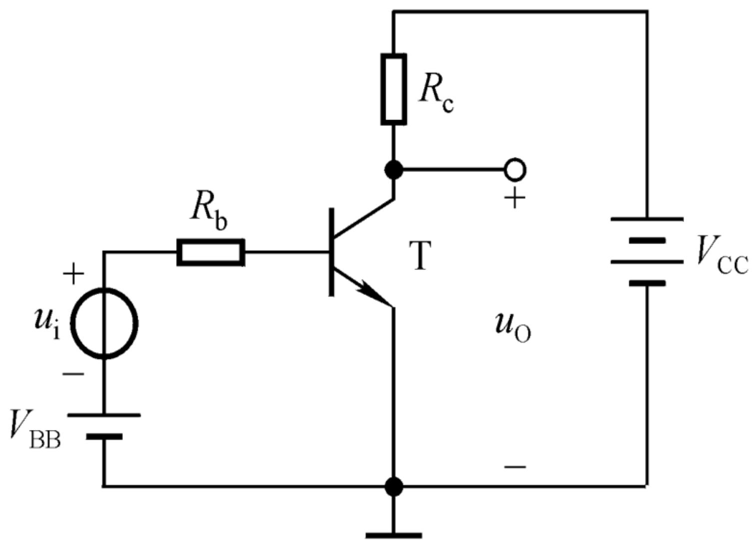
集电极电流（输入电压变化时）

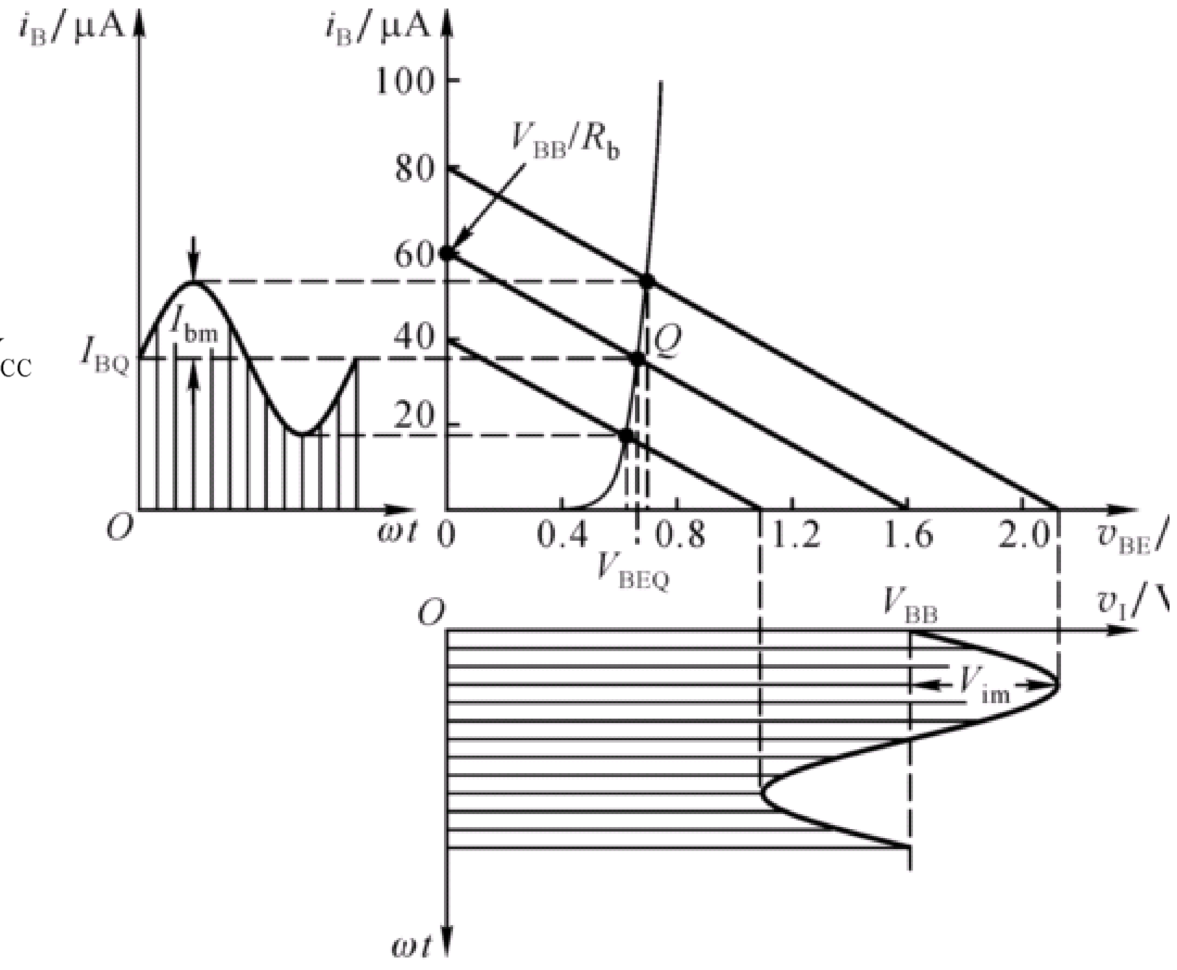


输入端电压电流关系

$$i_B = I_B + \Delta i_b$$

若 $I_B=0$，则 Δi_b 的波形如何？（输入失真）



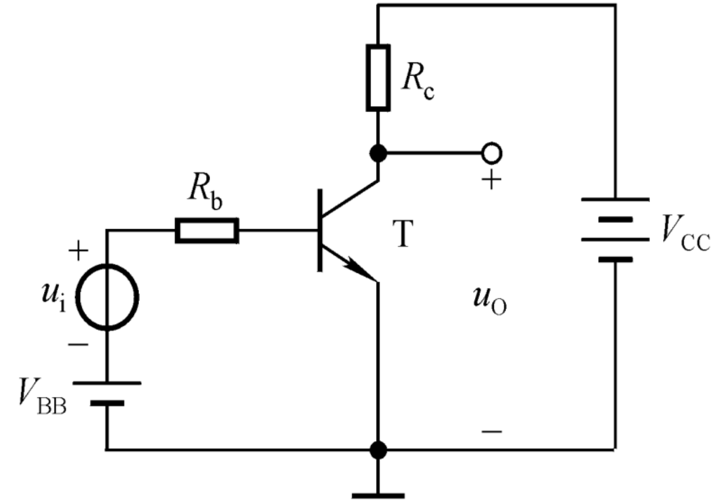


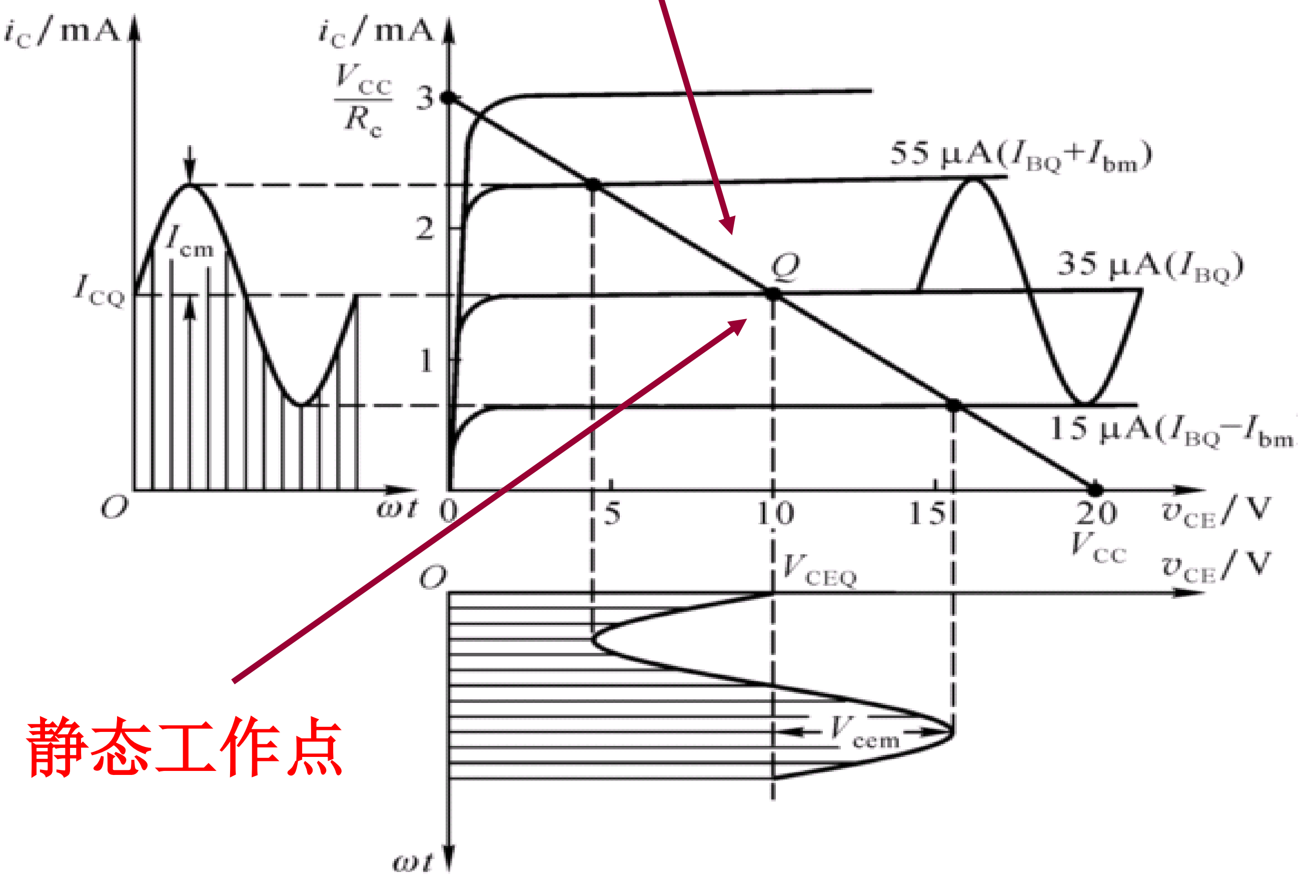
输出端电压电流关系

$$i_C = f(v_{CE})\Big|_{I_B}$$

$$i_C = \frac{V_{CC} - v_{CE}}{R_C}$$

直流负载线





静态工作点

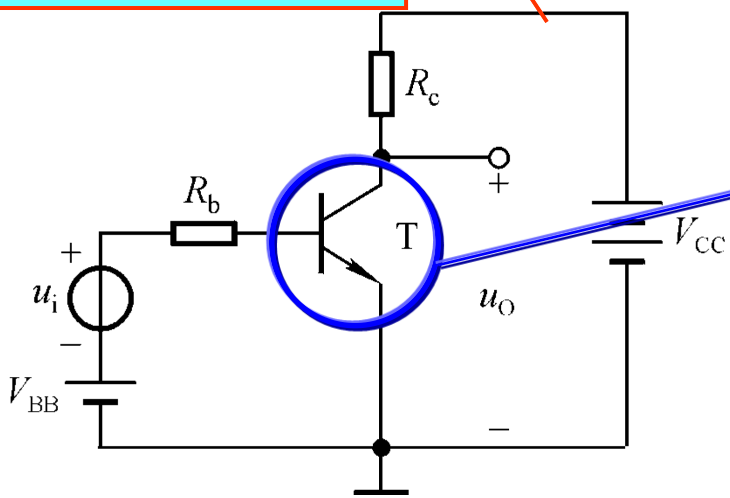
$$i_C = I_C + \Delta i_c$$

讨论：静态工作点变化对电流 i_C 波形的影响？

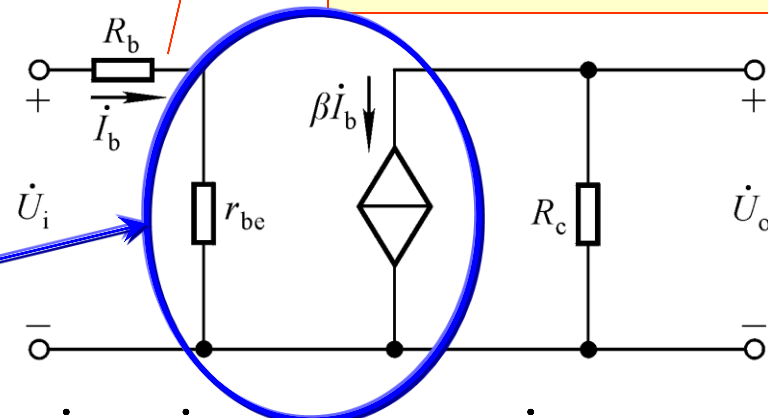
（输出失真）

放大电路的动态分析

直接耦合共射电路

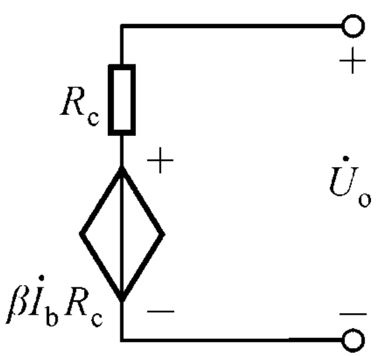


放大电路的
微变（交流）等效电路



$$\dot{U}_i = \dot{I}_i(R_b + r_{be}) = \dot{I}_b(R_b + r_{be})$$

$$\dot{U}_o = -\dot{I}_c R_c$$

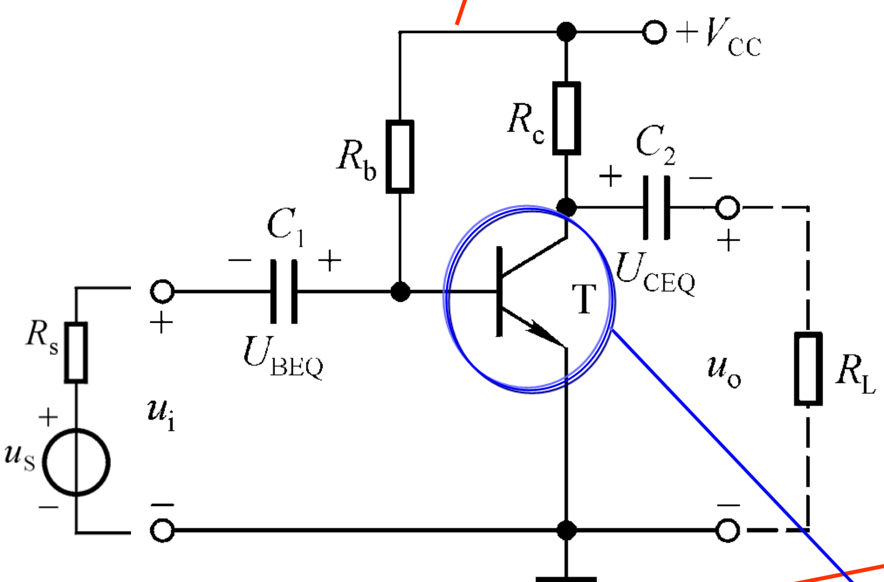


$$R_o = R_c$$

$$\dot{A}_u = \frac{\dot{U}_o}{\dot{U}_i} = -\frac{\beta R_c}{R_b + r_{be}}$$

$$R_i = \frac{U_i}{I_i} = R_b + r_{be}$$

阻容耦合共射放大电路



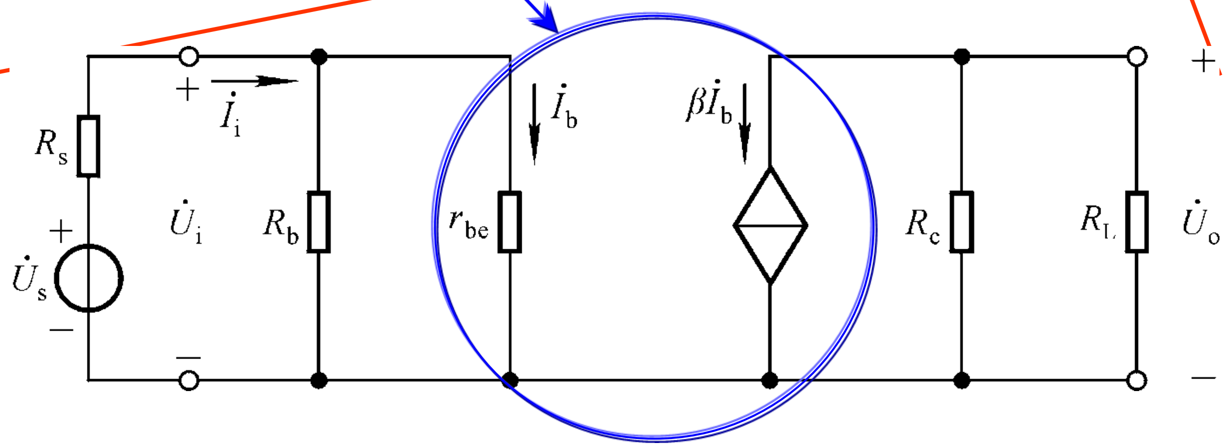
$$\dot{A}_u = \frac{\dot{U}_o}{\dot{U}_i} = \frac{-\dot{I}_c(R_c \,//\, R_L)}{\dot{I}_b r_{be}} = -\frac{\beta R_L'}{r_{be}}$$

$$\dot{A}_{us} = \frac{\dot{U}_o}{\dot{U}_s} = \frac{\dot{U}_i}{\dot{U}_s} \cdot \frac{\dot{U}_o}{\dot{U}_i} = \frac{R_i}{R_s + R_i} \cdot \dot{A}_u$$

$$R_i = R_b \,//\, r_{be} \approx r_{be}$$

$$R_o = R_c$$

输入电阻中不应含有 R_s!



输出电阻中不应含有 R_L!

场效应管的小信号（交流）等效模型

$$\begin{cases} i_G = f(u_{GS}, u_{DS}) \\ i_D = f(u_{GS}, u_{DS}) \end{cases}$$

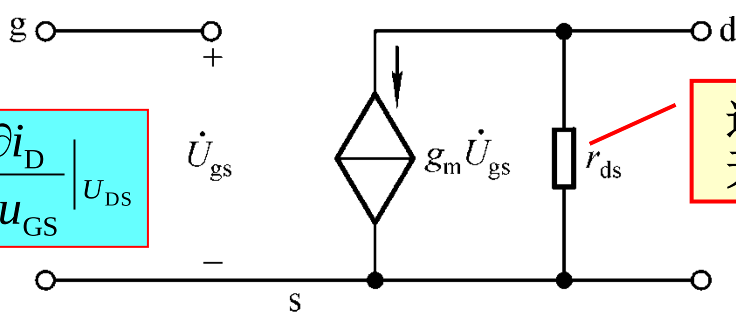
$$\begin{cases} u_{BE} = f(i_B, u_{CE}) \\ i_C = f(i_B, u_{CE}) \end{cases}$$

$$0 \longleftarrow \begin{cases} \dot{I}_g = g_{11}\dot{U}_{gs} + g_{12}\dot{U}_{ds} \\ \dot{I}_d = g_{21}\dot{U}_{gs} + g_{22}\dot{U}_{ds} \end{cases}$$

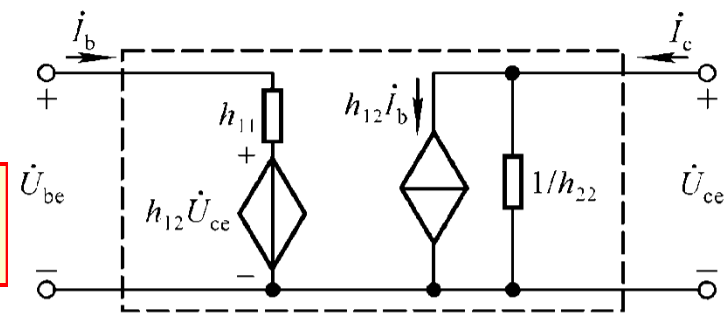
$$\begin{cases} \dot{U}_{be} = h_{11}\dot{I}_b + h_{12}\dot{U}_{ce} \\ \dot{I}_c = h_{21}\dot{I}_b + h_{22}\dot{U}_{ce} \end{cases}$$

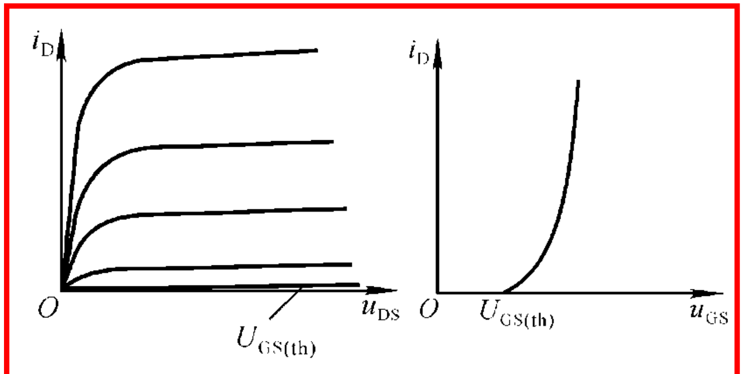
与晶体管的*h*参数等效模型类比：

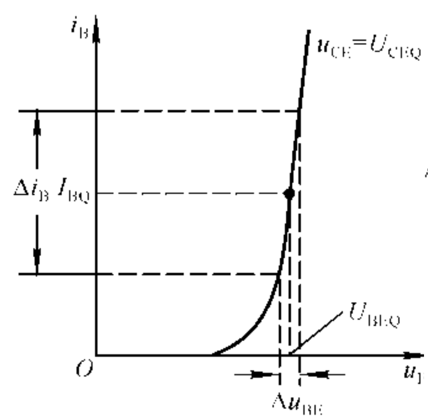
$$g_m = \frac{\partial i_D}{\partial u_{GS}}\bigg|_{U_{DS}}$$

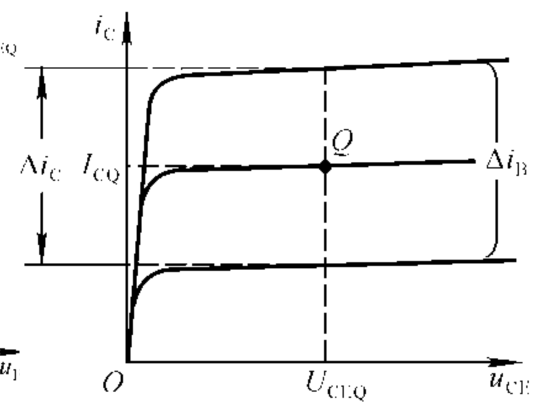


近似为无穷大

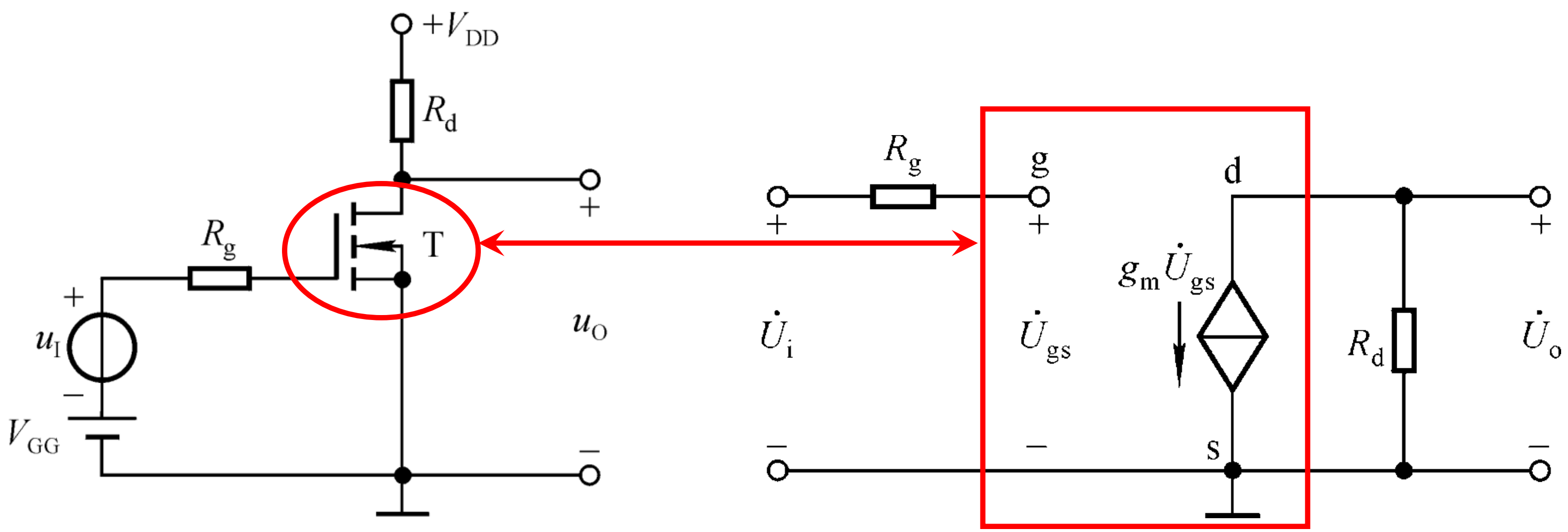








例．场效应管的动态分析



$$\dot{A}_u = \frac{\dot{U}_o}{\dot{U}_i} = \frac{-\dot{I}_d R_d}{\dot{U}_{gs}} = -g_m R_d$$

$$R_i = \infty$$

$$R_o = R_d$$

若R_d=3kΩ， R_g=5kΩ，g_m=2mS，则 $\dot{A}_u = ?$

输入与输出电阻，与共射电路比较。

作业

- **9.7，8，10** 静态工作点
- **9.14, 15*** 方程法
- **9.16，17，18*** 小信号分析，折线法
- **9.24，25** 基本放大电路分析