电子电路与系统基础II

习题课第八讲 一阶非线性动态电路分析

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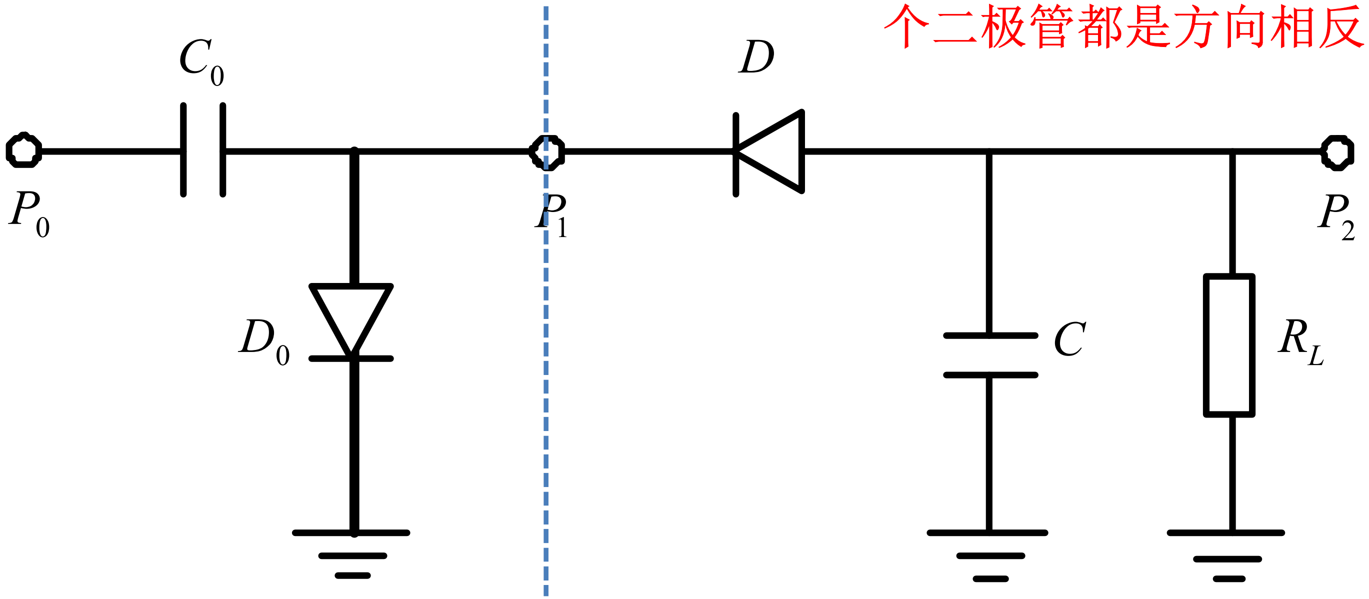
作业1 整流器电路

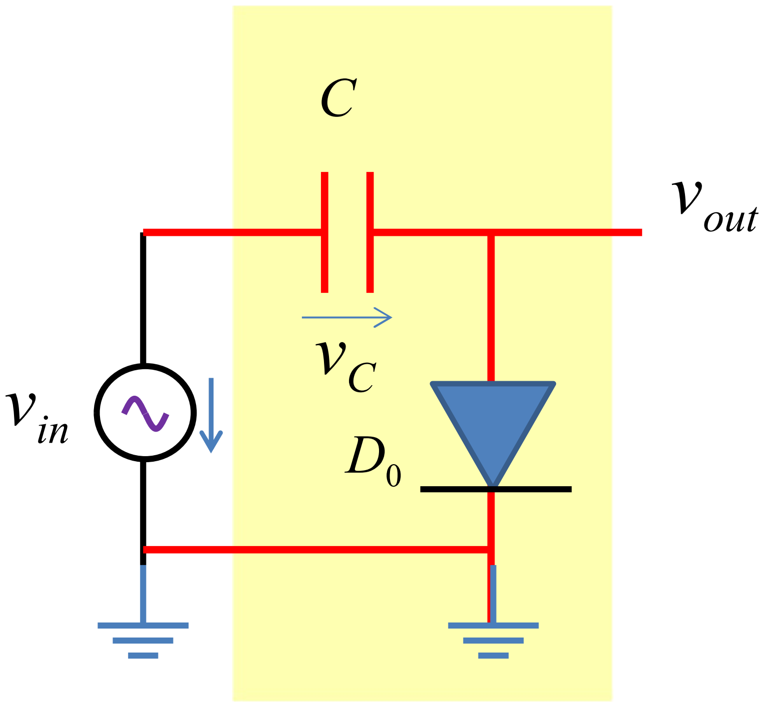
- 如图所示电路是否有错误，如果有，如何修正，修正后完成什么功能？如果没有错误，它可完成什么功能？

课堂上所讲倍压整流电路，两个二极管都是方向相反

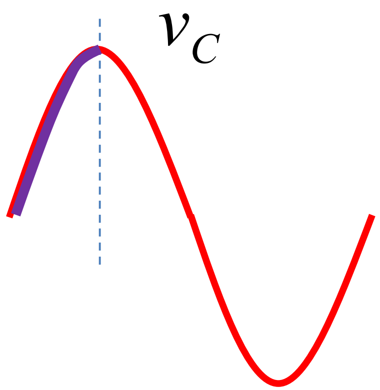


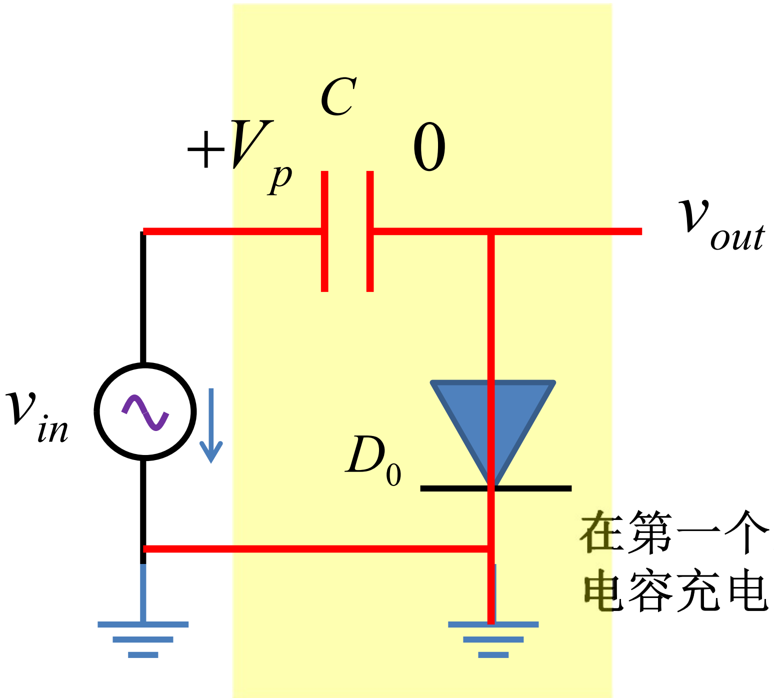
两个一阶系统的级联

嵌位器电路

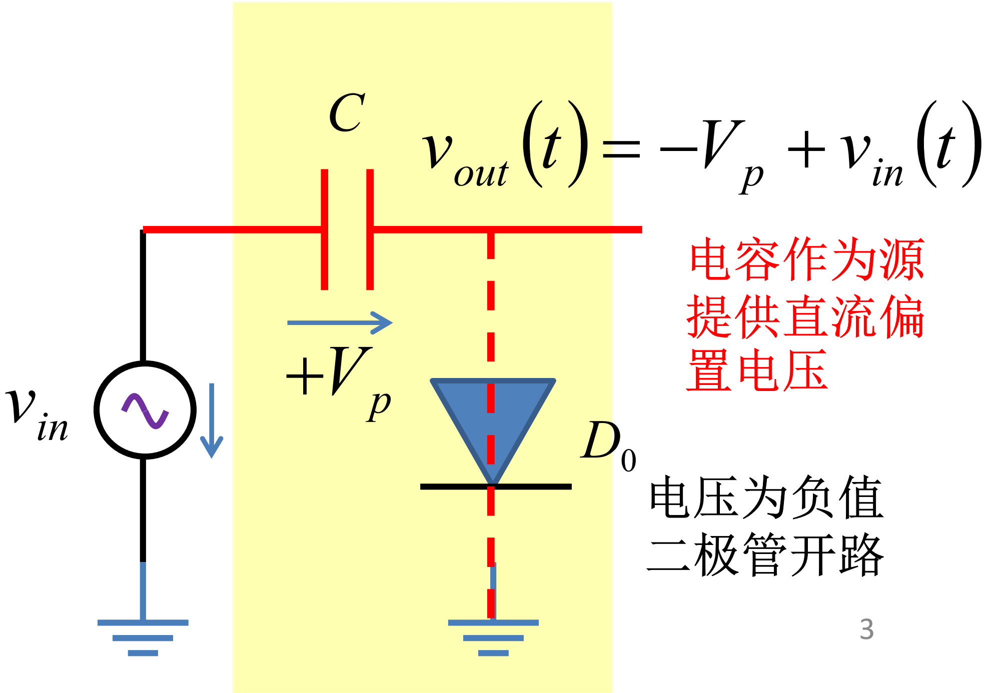


电容充电





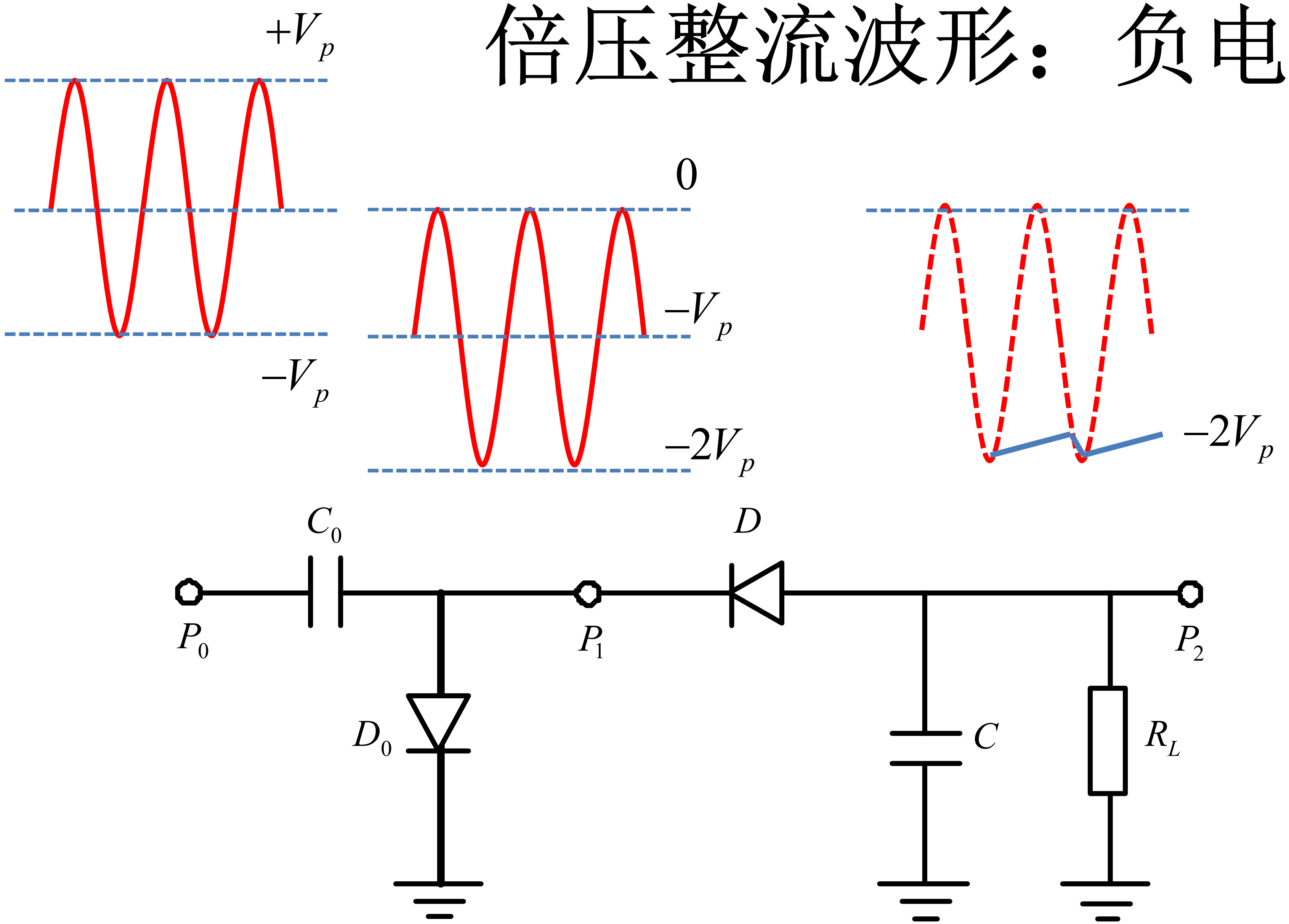
在第一个正半周
电容充电



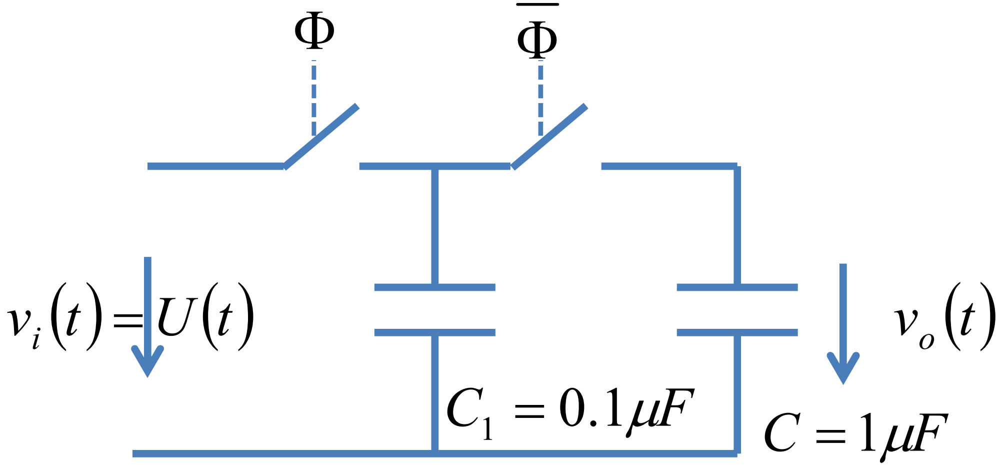
电容作为源
提供直流偏
置电压

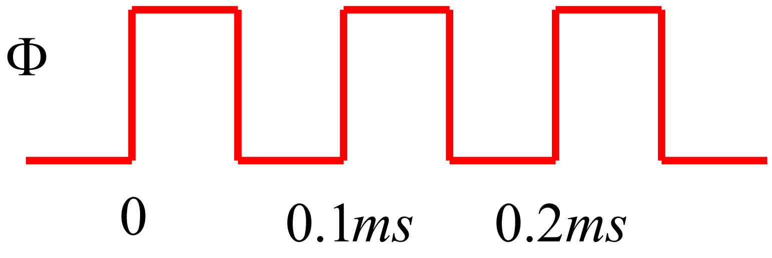
电压为负值
二极管开路

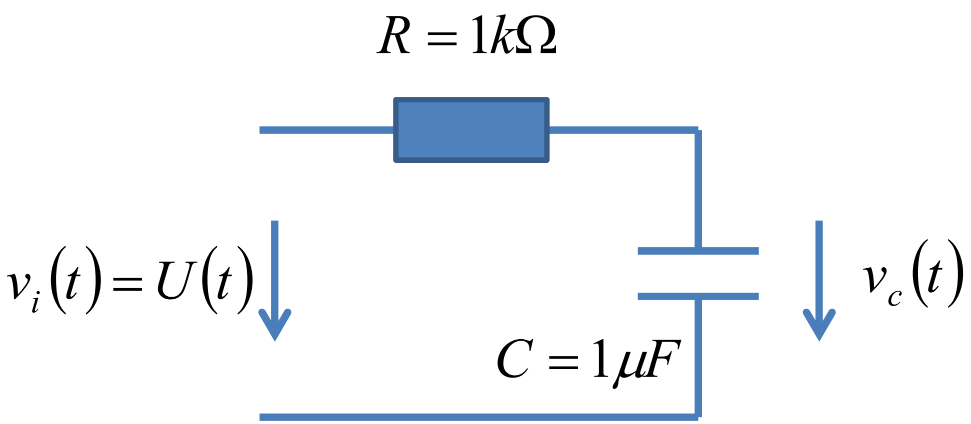
倍压整流波形：负电压



作业2 开关电容等效电阻



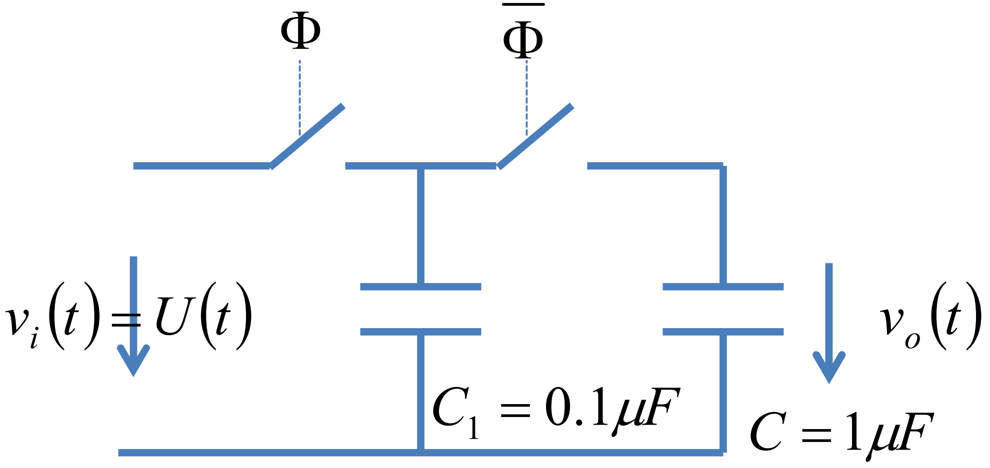


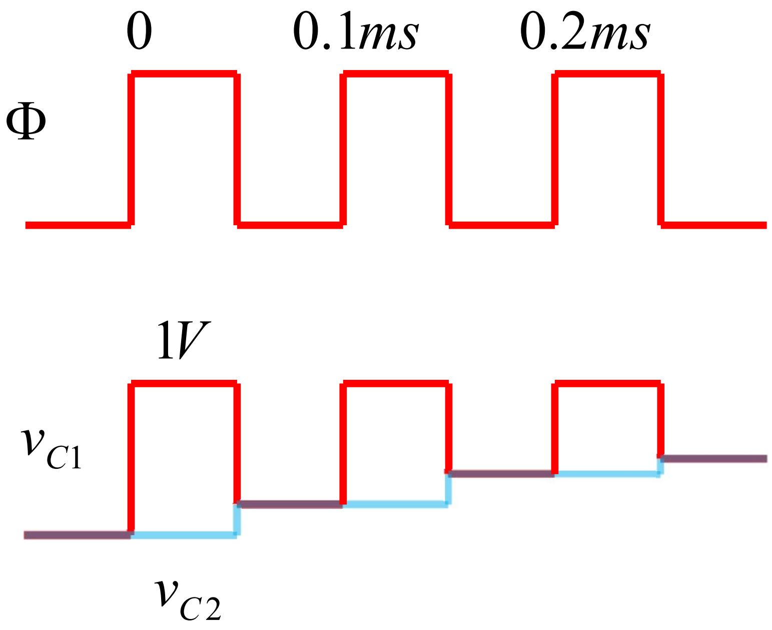


假设开关是理想开关
考察两个电路输出电压波形是否一致？

研究开关电容对电阻的可替代性？

$$R_{eff}=\frac{T}{C}$$





$t=0.05ms$

$$v_{C2}(1)=\frac{C_1\cdot 1+C_2\cdot 0}{C_1+C_2}=\frac{1}{11}(V)$$

1/电荷守恒
2/源等效

$t=0.15ms$

$$v_{C2}(2)=\frac{C_1\cdot 1+C_2\cdot v_{C2}(1)}{C_1+C_2}$$

$$=\frac{0.1+\frac{1}{11}}{1.1}=\frac{1}{11}+\frac{10}{11^2}(V)$$

$t=0.25ms$

$$v_{C2}(3)=\frac{C_1\cdot 1+C_2\cdot v_{C2}(2)}{C_1+C_2}$$

$$=\frac{1+\frac{10}{11}+\frac{100}{11^2}}{11}=\frac{1}{11}+\frac{10}{11^2}+\frac{100}{11^3}(V)$$

$t=(0.1n-0.05)ms$

电容电压变化规律

$$v_{C2}(n)=\frac{C_1\cdot 1+C_2\cdot v_{C2}(n-1)}{C_1+C_2}=\frac{C_1\cdot 1+C_2\cdot\frac{C_1\cdot 1+C_2\cdot v_{C2}(n-2)}{C_1+C_2}}{C_1+C_2}$$

$$=\frac{C_1\cdot 1+C_2\cdot\frac{C_1\cdot 1+C_2\cdot\frac{C_1\cdot 1+C_2\cdot v_{C2}(n-3)}{C_1+C_2}}{C_1+C_2}}{C_1+C_2}=\ldots$$

$$=\frac{C_1}{C_1+C_2}+\frac{C_2C_1}{(C_1+C_2)^2}+\frac{C_2^2C_1}{(C_1+C_2)^3}+\ldots.+\frac{C_2^{n-1}C_1}{(C_1+C_2)^n}$$

$$=\frac{C_1}{C_1+C_2}\left(1+\frac{C_2}{C_1+C_2}+\frac{C_2^2}{(C_1+C_2)^2}+\ldots.+\frac{C_2^{n-1}}{(C_1+C_2)^{n-1}}\right)$$

性质

$$v_{C2}(n)=\frac{C_1}{C_1+C_2}+\frac{C_2C_1}{(C_1+C_2)^2}+\frac{C_2^2C_1}{(C_1+C_2)^3}+....+\frac{C_2^{n-1}C_1}{(C_1+C_2)^n}$$

$$=\frac{C_1}{C_1+C_2}\left(1+\frac{C_2}{C_1+C_2}+\frac{C_2^2}{(C_1+C_2)^2}+....+\frac{C_2^{n-1}}{(C_1+C_2)^{n-1}}\right)=1-\left(\frac{C_2}{C_1+C_2}\right)^n$$

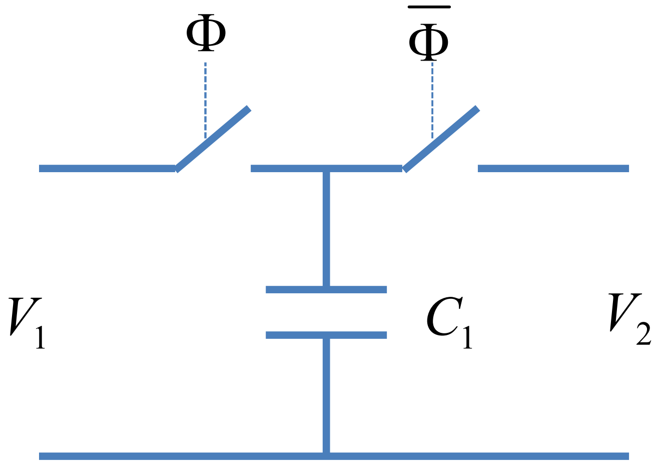
$$v_{C2}(n)=v_{C2}(n-1)+\left(\frac{C_2}{C_1+C_2}\right)^{n-1}\frac{C_1}{C_1+C_2}$$

后一个状态是前一个状态的增量
增量随时间增加是指数衰减的

$$v_{C2}(\infty)=1(V)$$

状态值在时间趋于无穷时趋于终值**1V**

开关电容等效为电阻



Φ $\quad Q_{\Phi} = C_1 V_1$

$\overline{\Phi}$ $\quad Q_{\overline{\Phi}} = C_1 V_2$

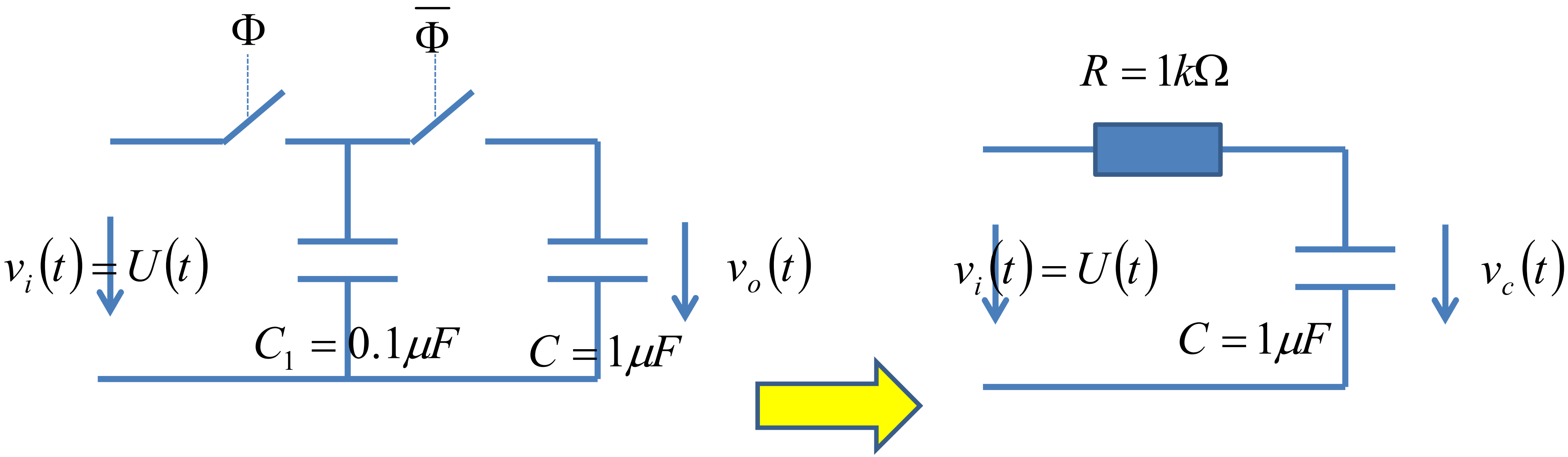
一个周期内，有ΔQ的电荷从端口**1**转移到端口**2**，相当于有电流从端口**1**流到端口**2**

$$\bar{I} = \frac{Q_{\Phi} - Q_{\overline{\Phi}}}{T} = \frac{C_1 (V_1 - V_2)}{T}$$

端口**1**流到端口**2**有电压差时，就有电流流过，因而可等效为一个电阻

$$R_{eq} = \frac{V_1 - V_2}{\bar{I}} = \frac{T}{C_1} = \frac{0.1ms}{0.1\mu F} = 1k\Omega$$

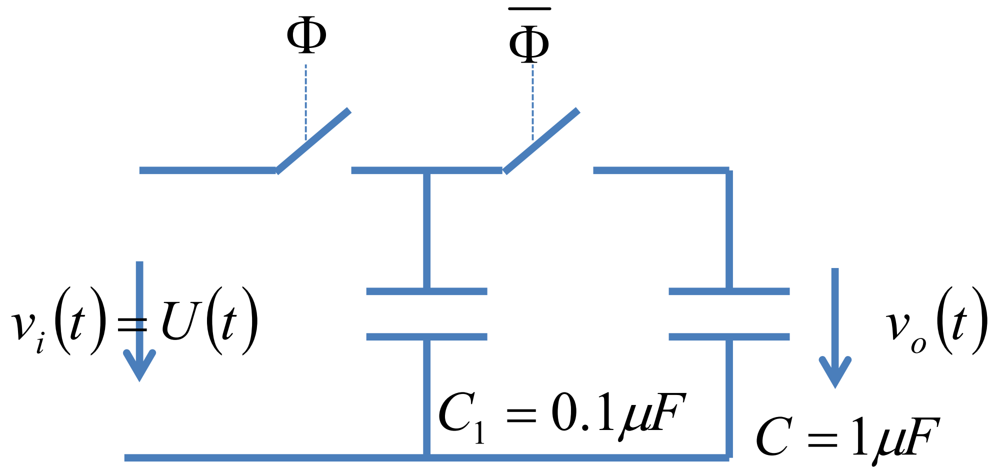
一阶RC的充电过程



$$v_{C2}(n)=\left(1-\left(\frac{C_2}{C_1+C_2}\right)^n\right)\cdot U(n)$$

$$v_c(t)=\left(1-e^{-\frac{t}{\tau}}\right)U(t)=\left(1-e^{-\frac{t}{RC}}\right)\cdot U(t)$$

两者对比
高度近似



$$v_{C2}(n)=1-\left(\frac{C_2}{C_1+C_2}\right)^n \qquad n\geq 0$$

离散时间的充电过程：一个时钟周期完成一次快速充电（瞬间充电）

$$v_c(t)=1-e^{-\frac{t}{RC}}\overset{t=nT}{=}1-e^{-\frac{nT}{RC}}=1-\left(e^{-\frac{T}{RC}}\right)^n \qquad t\geq 0$$

连续时间的充电过程：时时刻刻在充电进行中

$$\frac{C_2}{C_1+C_2}\Leftrightarrow e^{-\frac{T}{RC}}\overset{T<<RC}{\approx}\frac{1}{1+\frac{T}{RC}}=\frac{1}{1+\frac{T}{RC_2}}=\frac{C_2}{C_2+\frac{T}{R}}=\frac{C_2}{C_2+C_1} \qquad R=\frac{T}{C_1}$$

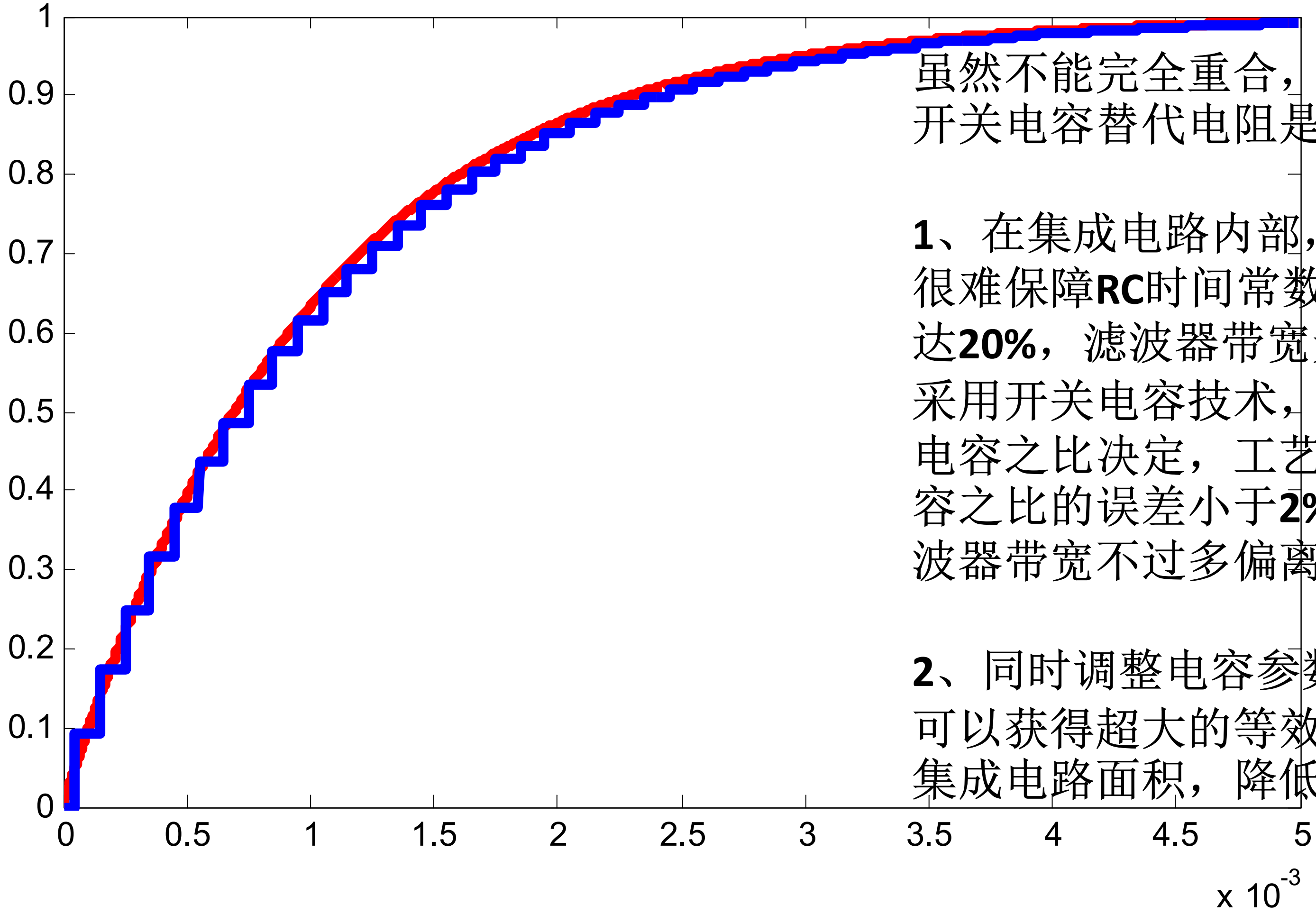
一个周期内的衰减量

$$R=\frac{T}{C_1}<<\frac{RC}{C_1} \qquad C>>C_1$$

转移电荷的开关电容越小，
用电阻等价的误差就越小

充电时域波形

$$R_{eq} = \frac{T}{C_1} \qquad \tau = R_{eq} C_2 = T\frac{C_2}{C_1}$$



虽然不能完全重合，但足够接近，用开关电容替代电阻是一种合理的选择

1、在集成电路内部，由于工艺问题，很难保障**RC**时间常数的精度，误差可达**20%**，滤波器带宽无法保证，如果采用开关电容技术，时间常数由两个电容之比决定，工艺上可保证两个电容之比的误差小于**2%**，从而可确保滤波器带宽不过多偏离设计值

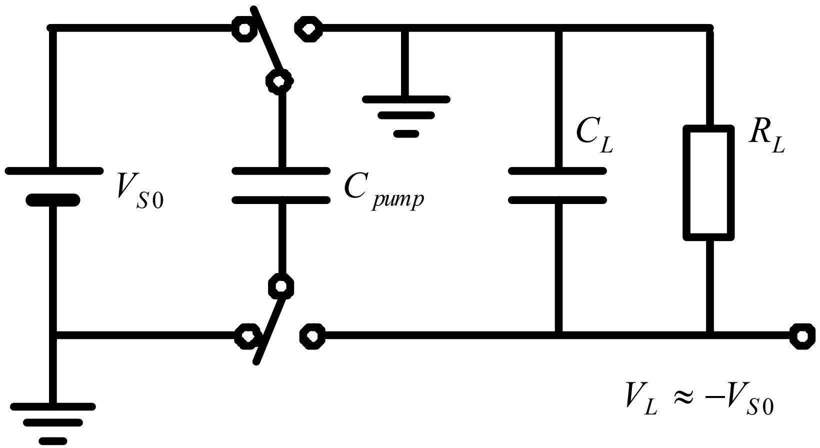
2、同时调整电容参数和时钟周期，可以获得超大的等效电阻，可以节约集成电路面积，降低系统成本

Matlab 作图程序

```
clear all

R=1E3;
C2=1E-6;
C1=0.1E-6;

tao=R*C2;
tstop=5*tao;
tnum=10000;
tstep=tstop/tnum;
t=-tstep;

for kk=1:tnum
   t=t+tstep;

   tt(kk)=t;
   v2(kk)=1-exp(-t/tao);

   n=floor(t/0.05E-3);
   if mod(n,2)==1
      v3(kk)=1-(C2/(C1+C2))^((n+1)/2);
   else
      if kk==1
         v3(kk)=0;
      else
         v3(kk)=v3(kk-1);
      end
   end
end

figure(2)
hold on
plot(tt,v2,'r')
plot(tt,v3)
```

作业3：开关电容做DC-DC转换

- 习题9.9　开关电容实现反压 两个开关在占空比为50%的时钟控制下，在前50%方波周期内使得泵电容C_{pupm}接到直流电压源V_{S0}上，从V_{S0}上获取电荷（电能），后50%方波周期内再接到负载电路上，泵电容将部分电荷转移到滤波电容C_L上，在泵电容接电源的50%周期内，滤波电容为负载提供电能。分析当电路进入稳态后，输出反相直流电压的纹波电压为多少？分析提高能量转换效率的措施？

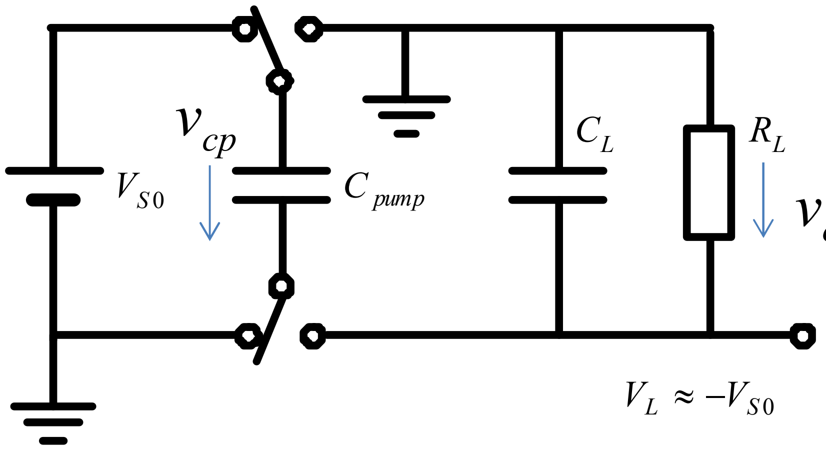


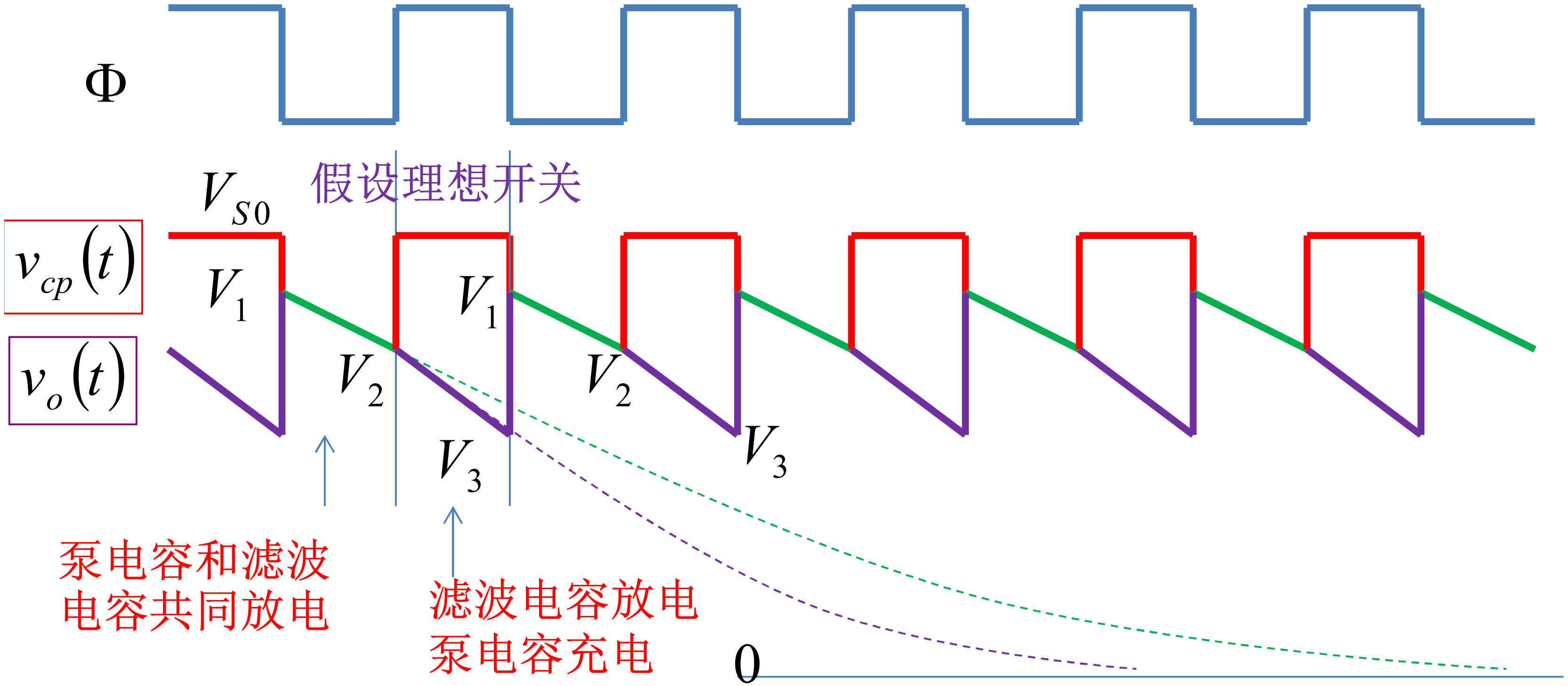
和前一个电路的区别：

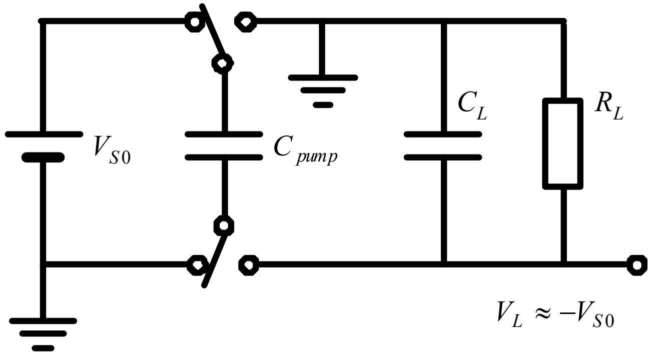
1、双掷开关使得两个电路不共地（完全隔离）

2、有负载电阻耗能

不考虑瞬态过程
只考虑稳定后的稳态响应



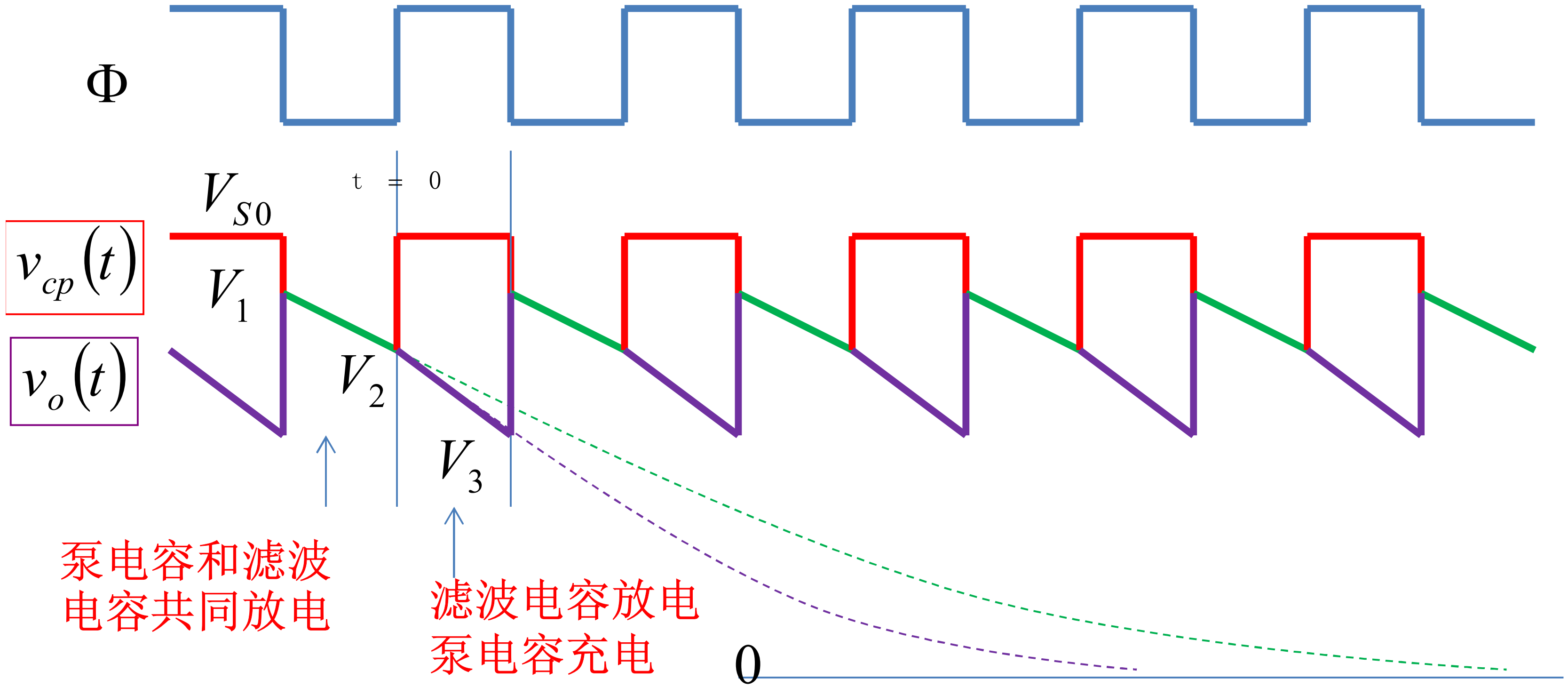


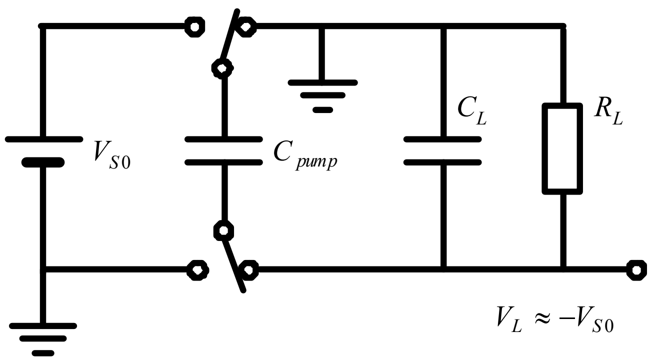


滤波电容单独放电，泵电容充电

$$v_o(t) = V_2 e^{-\frac{t}{R_L C_L}} \approx V_2\left(1 - \frac{t}{R_L C_L}\right)$$

$$V_3 \approx V_2\left(1 - \frac{0.5T}{R_L C_L}\right)$$





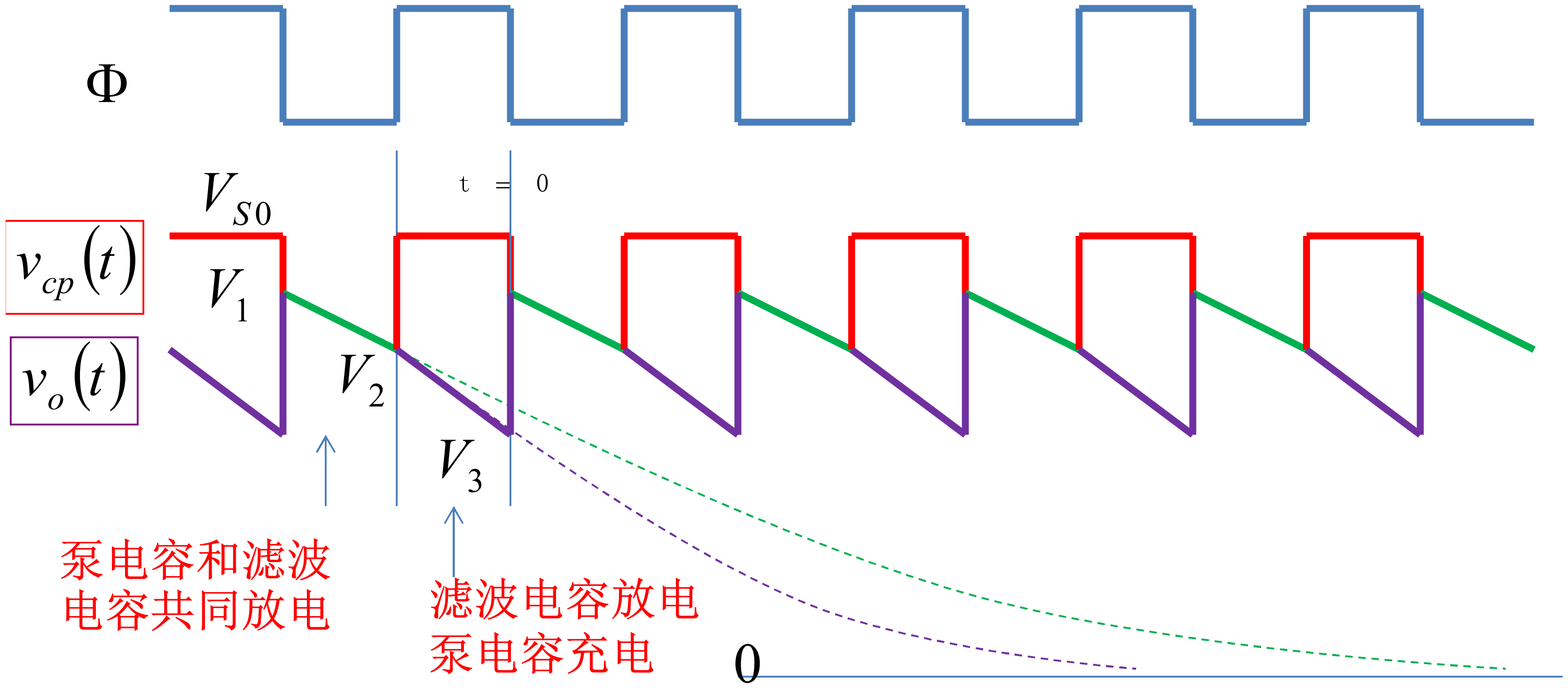
开关换向瞬间

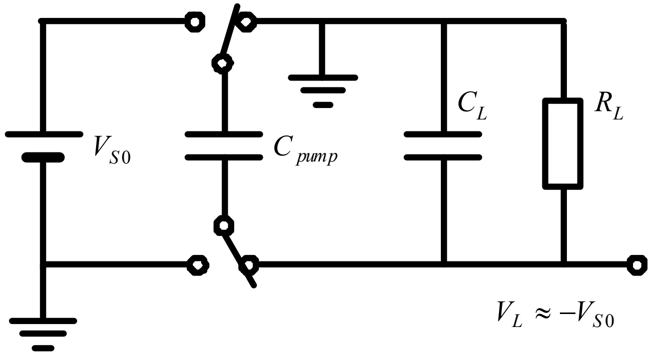
$$v_{cp}\left(0^-\right) = V_{S0} \qquad v_o\left(0^-\right) = V_3$$

$$C_L v_o\left(0^-\right) + C_p v_{cp}\left(0^-\right) = \left(C_L + C_p\right) v_o\left(0^+\right)$$

电荷守恒/源等效

$$v_o\left(0^+\right) = \frac{C_L}{C_L + C_p} V_3 + \frac{C_p}{C_L + C_p} V_{S0} = V_1$$

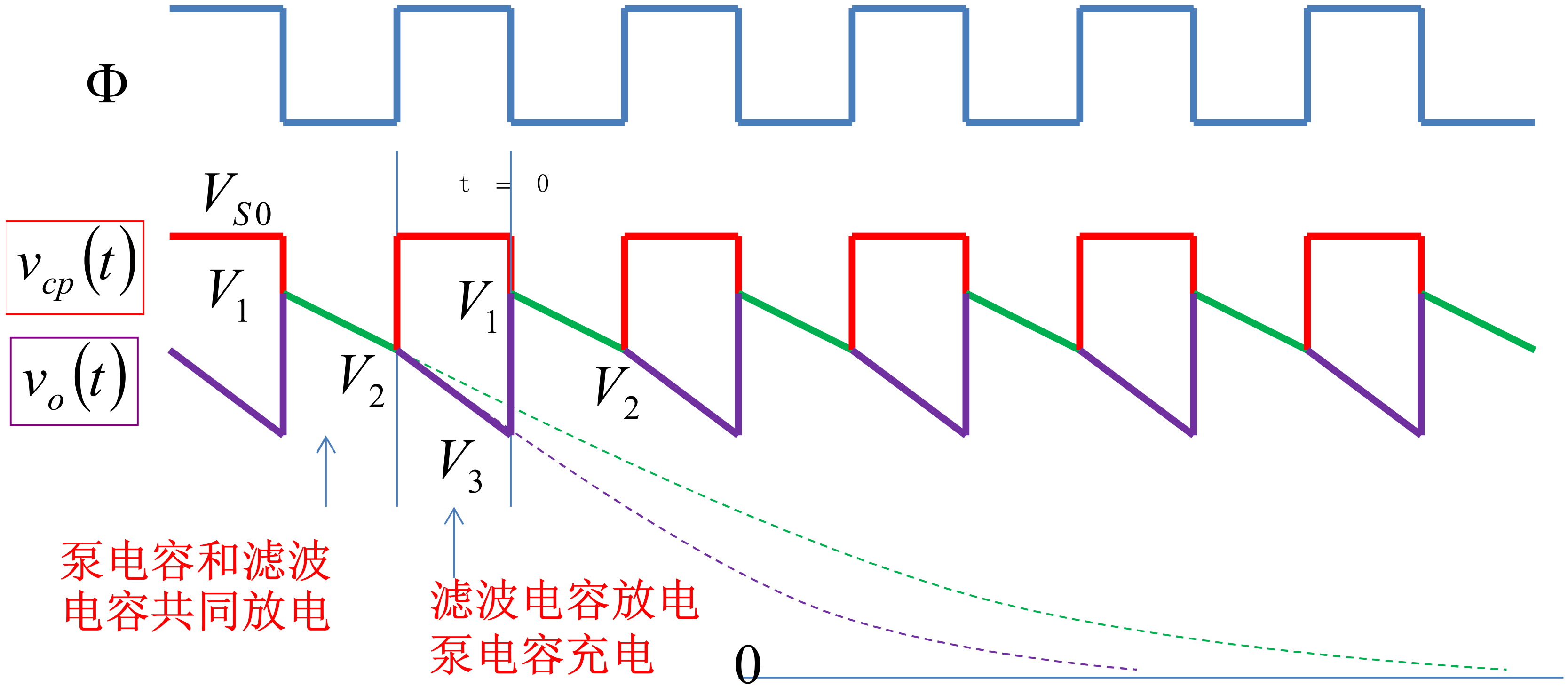


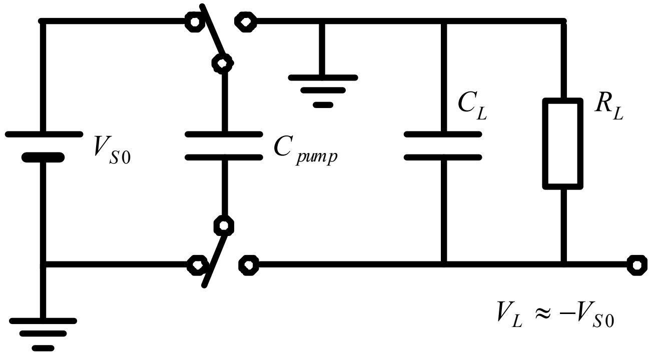


滤波电容和泵电容共同放电

$$v_o(t)=V_1 e^{-\frac{t}{R_L(C_L+C_p)}} \approx V_2\left(1-\frac{t}{R_L(C_L+C_p)}\right)$$

$$V_2 \approx V_1\left(1-\frac{0.5T}{R_L(C_L+C_p)}\right)$$

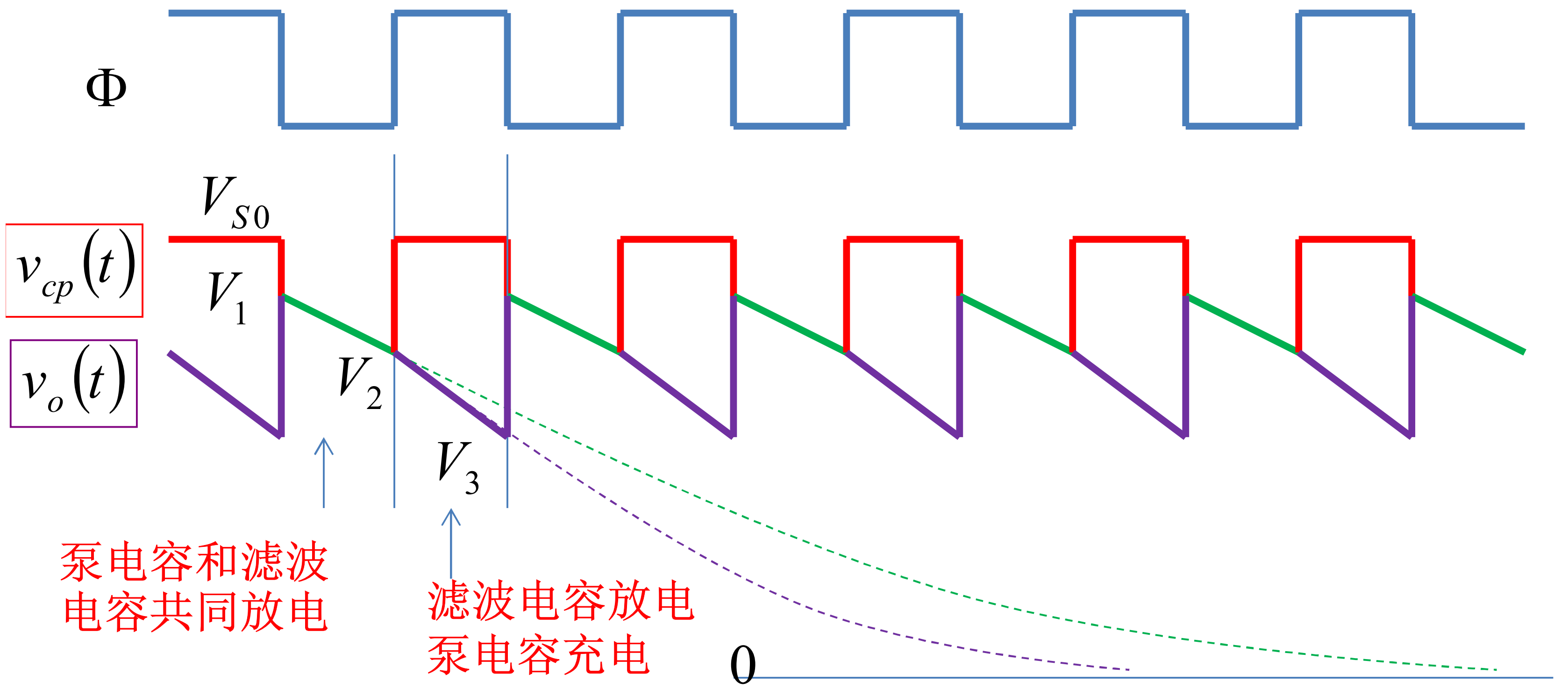




$$V_3 \approx V_2\left(1-\frac{0.5T}{R_L C_L}\right)$$

$$V_1 = \frac{C_L}{C_L + C_p}V_3 + \frac{C_p}{C_L + C_p}V_{S0}$$

$$V_2 \approx V_1\left(1-\frac{0.5T}{R_L\left(C_L + C_p\right)}\right)$$



$$V_2 \approx V_1\left(1-\frac{0.5T}{R_L\left(C_L+C_p\right)}\right)$$

$$V_3 \approx V_2\left(1-\frac{0.5T}{R_L C_L}\right)$$

$$\approx V_1\left(1-\frac{0.5T}{R_L\left(C_L+C_p\right)}\right)\left(1-\frac{0.5T}{R_L C_L}\right)$$

$$\approx V_1\left(1-\frac{0.5T}{R_L\left(C_L+C_p\right)}-\frac{0.5T}{R_L C_L}\right)$$

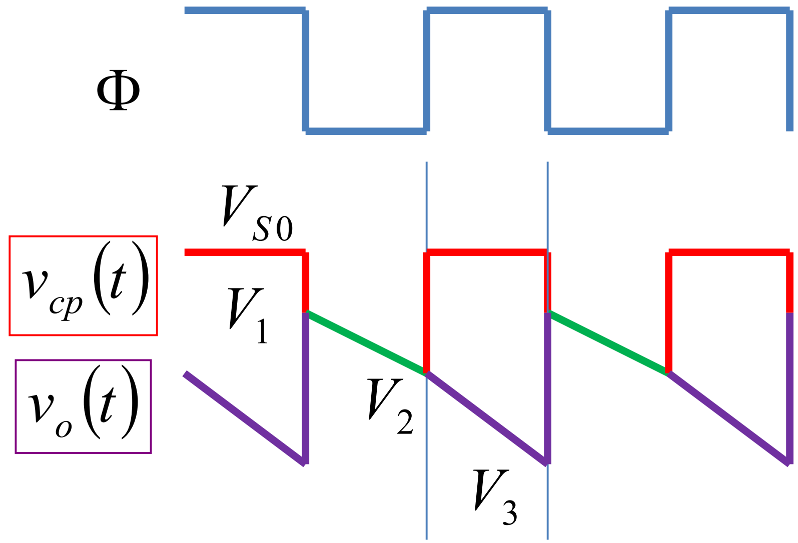
$$\approx V_1\left(1-\frac{0.5T}{R_L\left(\left(C_L+C_p\right)\text{串}C_L\right)}\right)$$

$$V_1 = \frac{C_L}{C_L+C_p}V_3+\frac{C_p}{C_L+C_p}V_{S0}$$

$$\approx \frac{C_L}{C_L+C_p}V_1\left(1-\frac{0.5T}{R_L\left(\left(C_L+C_p\right)\text{串}C_L\right)}\right)+\frac{C_p}{C_L+C_p}V_{S0}$$

$$V_1\left(\frac{C_p}{C_L+C_p}+\frac{C_L}{C_L+C_p}\frac{0.5T}{R_L\left(\left(C_L+C_p\right)\text{串}C_L\right)}\right)\approx\frac{C_p}{C_L+C_p}V_{S0}$$

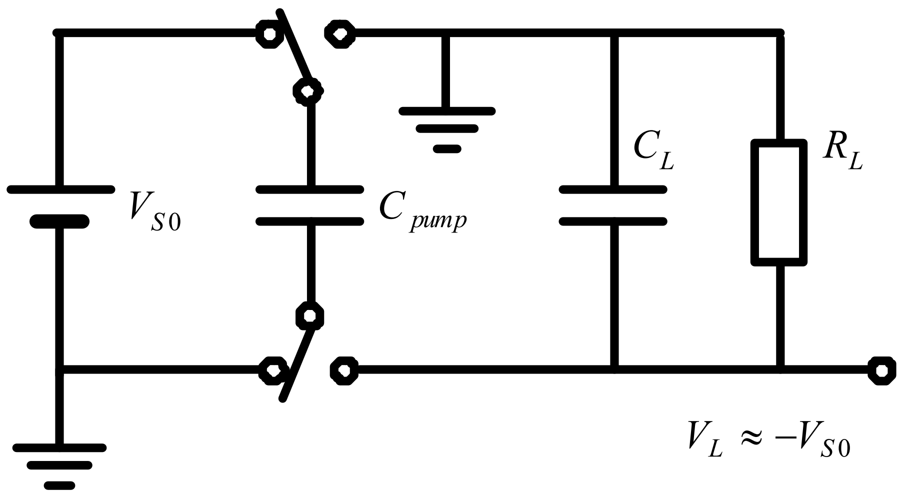
$$V_1 \approx \frac{C_p}{C_p+C_L\dfrac{0.5T}{R_L\left(\left(C_L+C_p\right)\text{串}C_L\right)}}V_{S0}$$



$$\Delta V = V_1 - V_3$$

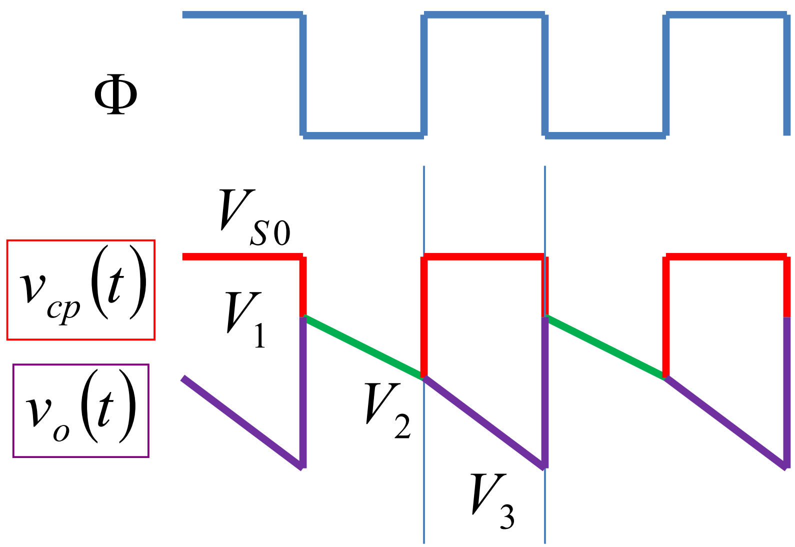
$$\approx \frac{0.5T}{R_L\left(\left(C_L+C_p\right)\text{串}C_L\right)}V_1$$

$$\approx \frac{C_p}{\dfrac{R_L\left(\left(C_L+C_p\right)\text{串}C_L\right)}{0.5T}C_p+C_L}V_{S0}$$



$$V_1 \approx \frac{C_p}{C_p + C_L \dfrac{0.5T}{R_L\left(\left(C_L + C_p\right) 串 C_L\right)}} V_{S0}$$

$$\Delta V \approx \frac{C_p}{\dfrac{R_L\left(\left(C_L + C_p\right) 串 C_L\right)}{0.5T} C_p + C_L} V_{S0}$$



$C_L \to \infty \qquad \Delta V \to 0$

滤波电容越大，纹波电压越小，降低纹波的措施是提高滤波电容C_L

$$V_1 \to \frac{C_p}{C_p + \dfrac{T}{R_L}} V_{S0} = \frac{R_L}{\dfrac{T}{C_p} + R_L} V_{S0} = \frac{R_L}{R_{pe} + R_L} V_{S0}$$

$$R_{pe} = \frac{T}{C_p}$$

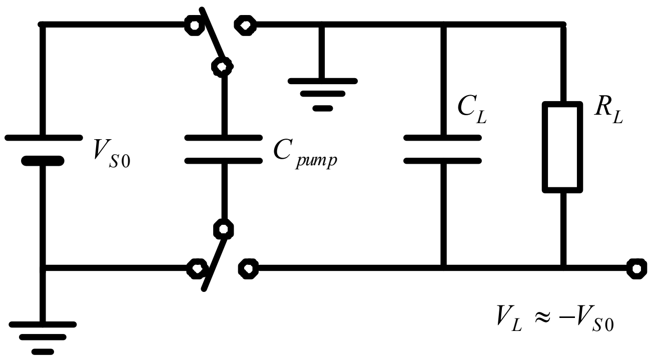
滤波电容很大时，输出电压近似为输入电压的等效分压

时钟频率越高，泵电容越大，等效电阻越小，分压越大

$$C_L >> C_p >> \frac{T}{R_L}$$

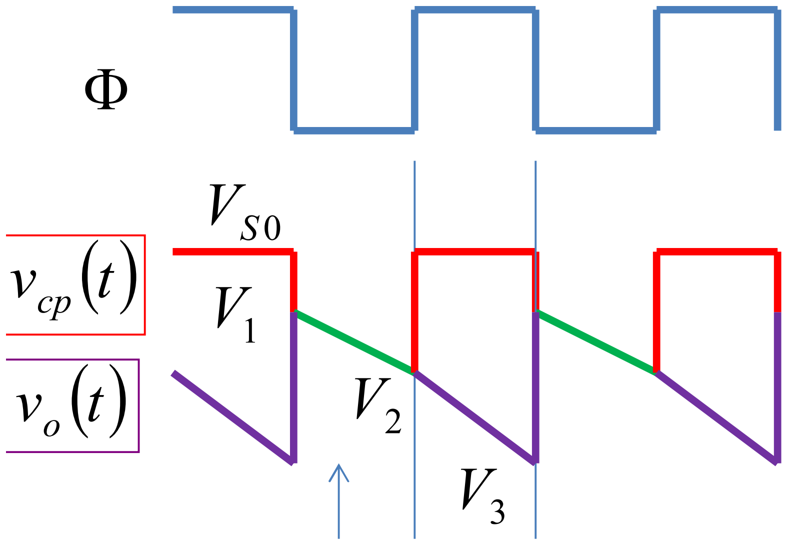
$$\Delta V \approx \frac{R_{pe}}{R_L + R_{pe}} \frac{C_p}{C_L} V_{S0}$$

非负载耗能的额外耗能分析



C_p拨向恒压源瞬间充电，冲激电流耗能

$$\Delta E_1 = \frac{1}{2} C_p (V_{S0} - V_2)^2$$



C_p拨向C_L瞬间充放电，冲激电流耗能

$$\Delta E_2 = \frac{1}{2} C_p V_{S0}^2 + \frac{1}{2} C_L V_3^2 - \frac{1}{2}(C_p + C_L) V_1^2$$

$$= \frac{1}{2} \frac{C_L C_p}{C_L + C_p} (V_{S0} - V_3)^2$$

均可理解为具有初始电压等效电容瞬间以冲激电流（电磁辐射）形式将其初始储能释放掉

$$\Delta E_1 = \frac{1}{2} C_p \left(V_{S0} - V_2\right)^2$$

$$\Delta E_2 = \frac{1}{2} \frac{C_L C_p}{C_L + C_p} \left(V_{S0} - V_3\right)^2$$

$$V_{S0} - V_2 \approx V_{S0} \left(\frac{R_{pe}}{R_L + R_{pe} \dfrac{C_L + 0.5C_p}{C_L + C_p}} \right) \overset{C_L >> C_p}{\approx} V_{S0} \frac{R_{pe}}{R_L + R_{pe}}$$

$$R_{pe} = \frac{T}{C_p}$$

$$V_{S0} - V_3 \approx V_{S0} \frac{R_{pe}}{R_L \dfrac{C_L}{C_L + 0.5C_p} + R_{pe} \dfrac{C_L}{C_L + C_p}}$$

$$\overset{C_L >> C_p}{\approx} V_{S0} \frac{R_{pe}}{R_L + R_{pe}}$$

$$\Delta E = \Delta E_1 + \Delta E_2$$

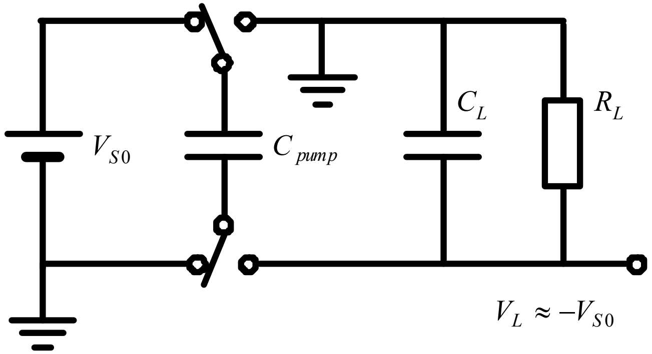
$$\overset{C_L >> C_p}{\approx} C_p V_{S0}^2 \left(\frac{R_{pe}}{R_{pe} + R_L} \right)^2$$

$$\overset{R_{pe} << R_L}{\approx} C_p V_{S0}^2 \left(\frac{R_{pe}}{R_L} \right)^2$$

$$= \frac{V_{S0}^2}{R_L^2} \frac{T^2}{C_p}$$

$$P_D = \frac{\Delta E}{T} \approx \frac{V_{S0}^2}{R_L^2} \frac{T}{C_p} \approx I_L^2 R_{pe}$$

提高效率的措施是提高C_p

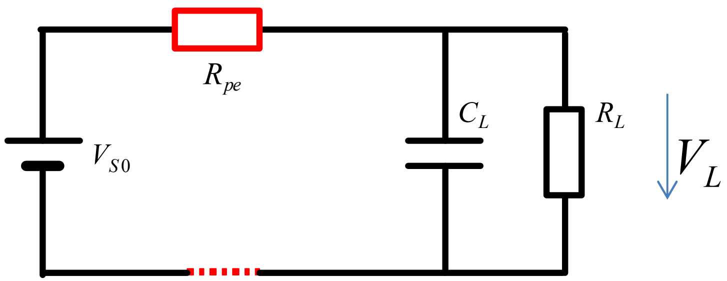


输出直流电压：为R_L分压

$$V_1 \approx \frac{C_p}{C_p + C_L \dfrac{0.5T}{R_L\left(\left(C_L + C_p\right)\text{串}\, C_L\right)}} V_{S0}$$

$$\overset{C_L >> C_p}{\approx} \frac{R_L}{R_L + R_{pe}} V_{S0} \overset{R_{pe} << R_L}{\approx} V_{S0}$$

C_L>>C_p：分析可以用如下等效电路简化分析



$$R_{pe} = \frac{T}{C_p}$$

$$P_D \underset{R_{pe} << R_L}{\overset{C_L >> C_p}{\approx}} I_L^2 R_{pe}$$

开关损耗为开关电容等效电阻消耗电能

C_p越大，开关电容等效电阻越小，等效电阻损耗越小，效率越高

波纹由电荷转移导致：

$$\Delta V \overset{C_L >.> C_p}{\approx} \frac{C_p}{C_L} \frac{R_{pe}}{R_{pe} + R_L} V_{S0}$$

$$\approx \frac{T}{R_L C_L} V_{S0} = \frac{I_L}{f C_L}$$

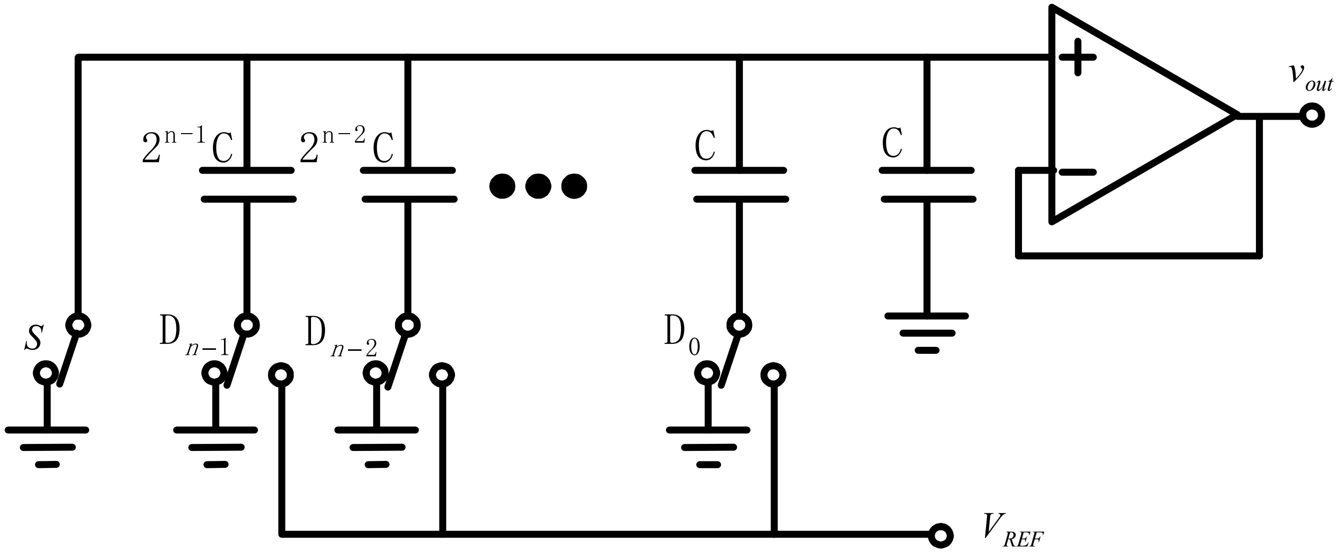
$$C_L >> C_p >> \frac{T}{R_L}$$

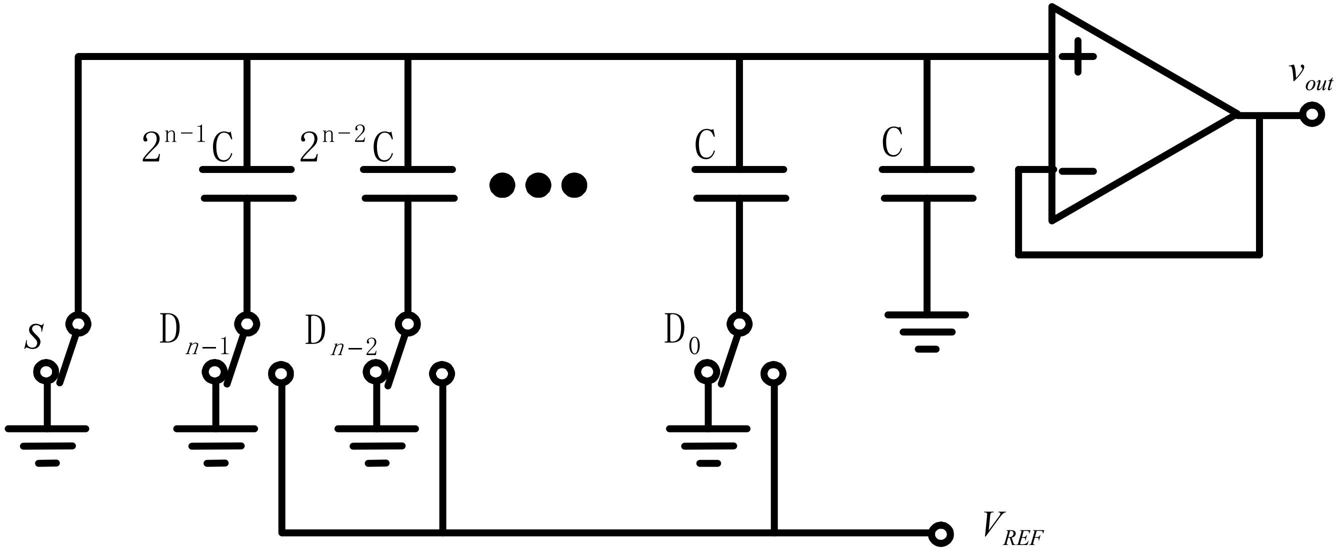
C_L越大，纹波越小，输出越接近理想直流

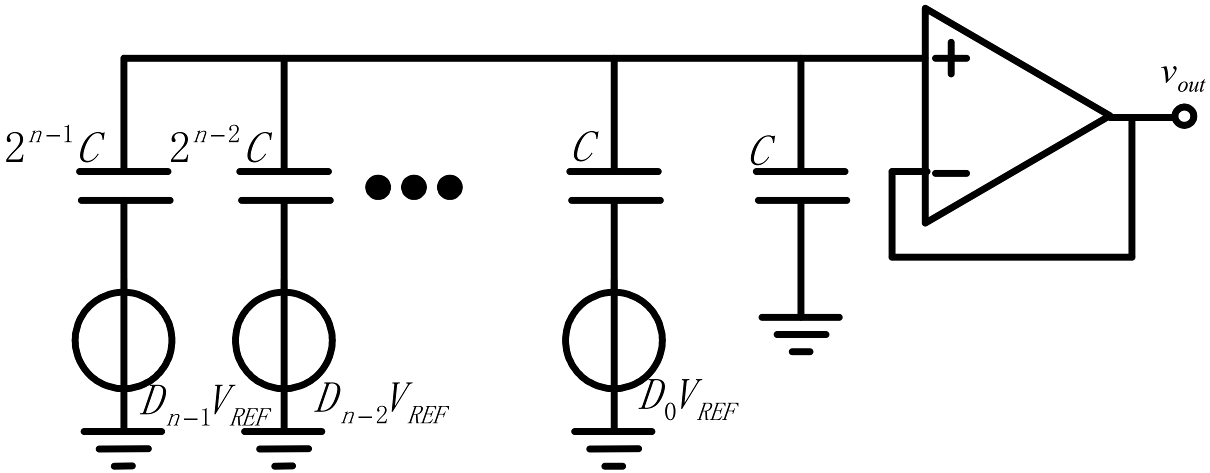
C_p越大，损耗越小，输出电压越接近输入

作业4 开关电容做DA转换

- **习题9.6 加权电容DAC** 如图**E9.4.14**所示，这是加权电容**DAC**电路，请证明它完成了**n-bit**的**DA**转换。其工作顺序为：在复位相，所有开关全部接到地上，如图所示。在采样相，开关**S**断开，开关D_0到D_{n-1}则依数字输入而定，如果输入$D_i=1$，相应开关则拨向V_{REF}，如果$D_i=0$，相应开关则仍然保持和地连通。

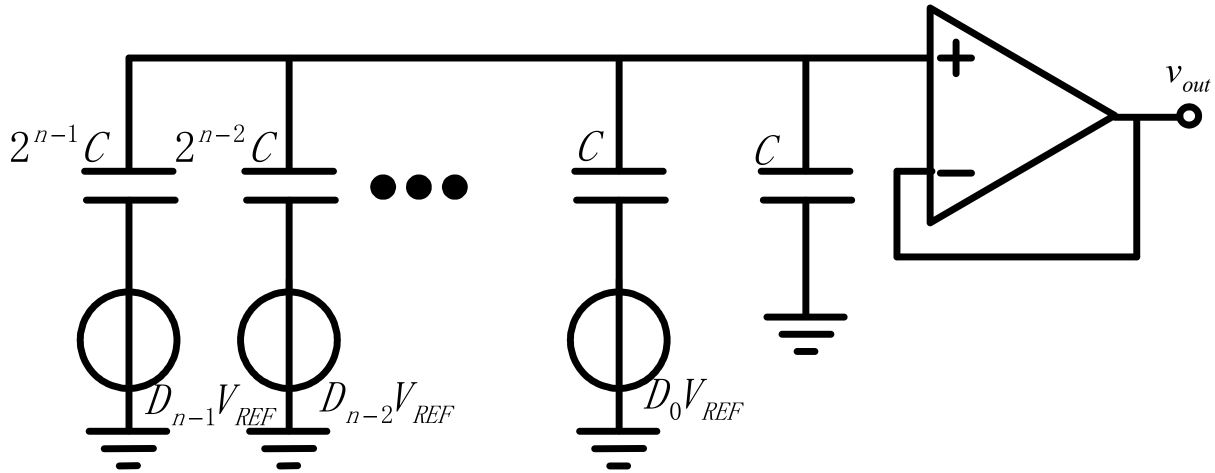




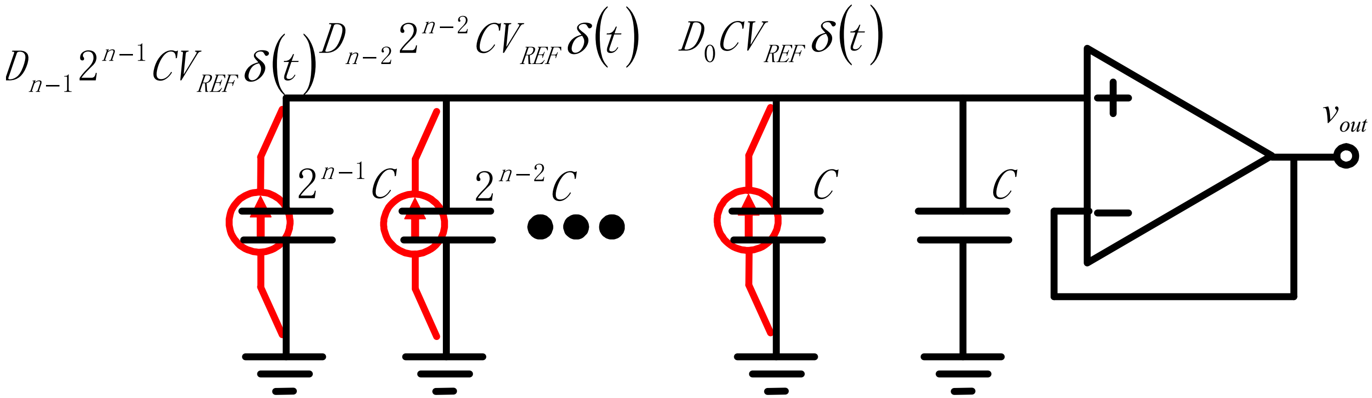


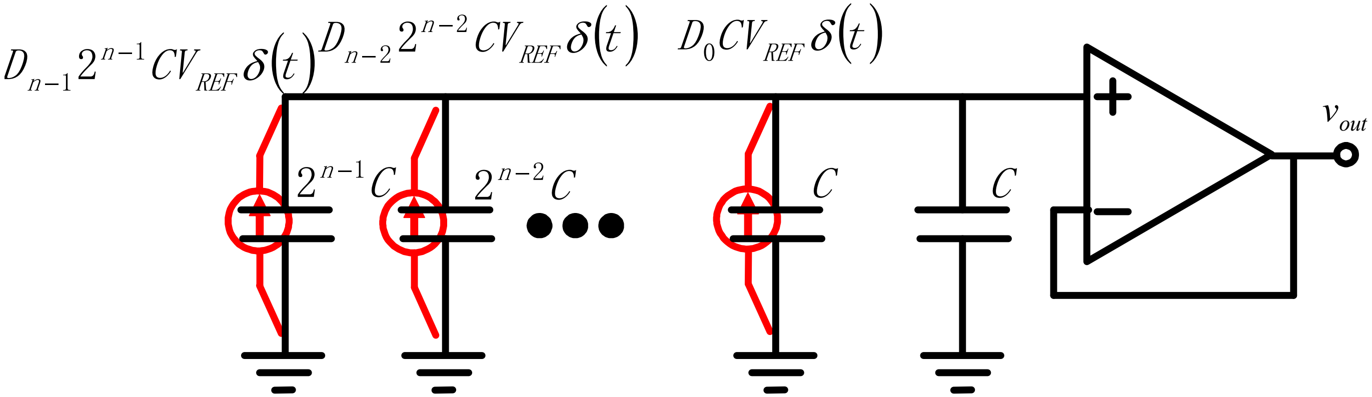
戴维南源表述

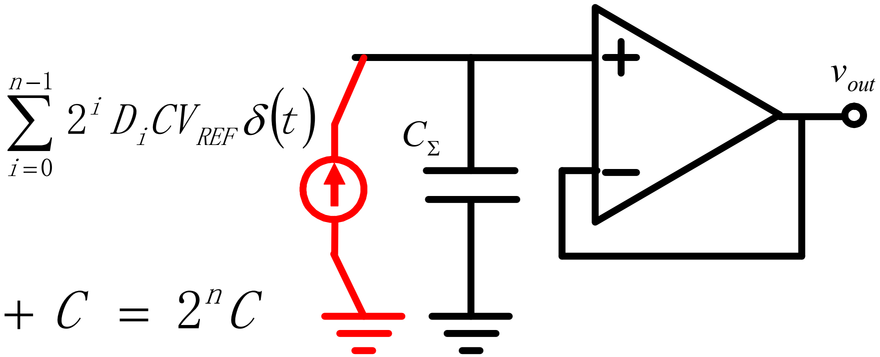
也可用电容分压，电荷重分配分析，不如源等效简洁



并联用诺顿等效表述最为简单



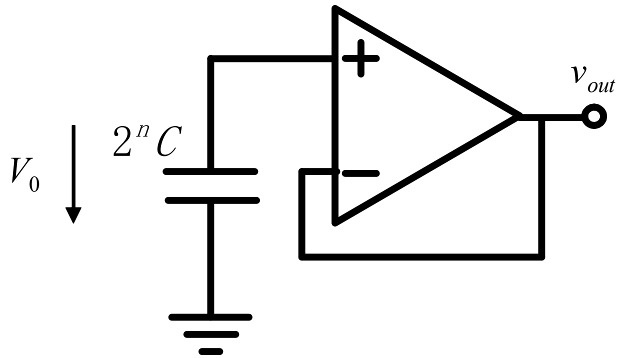


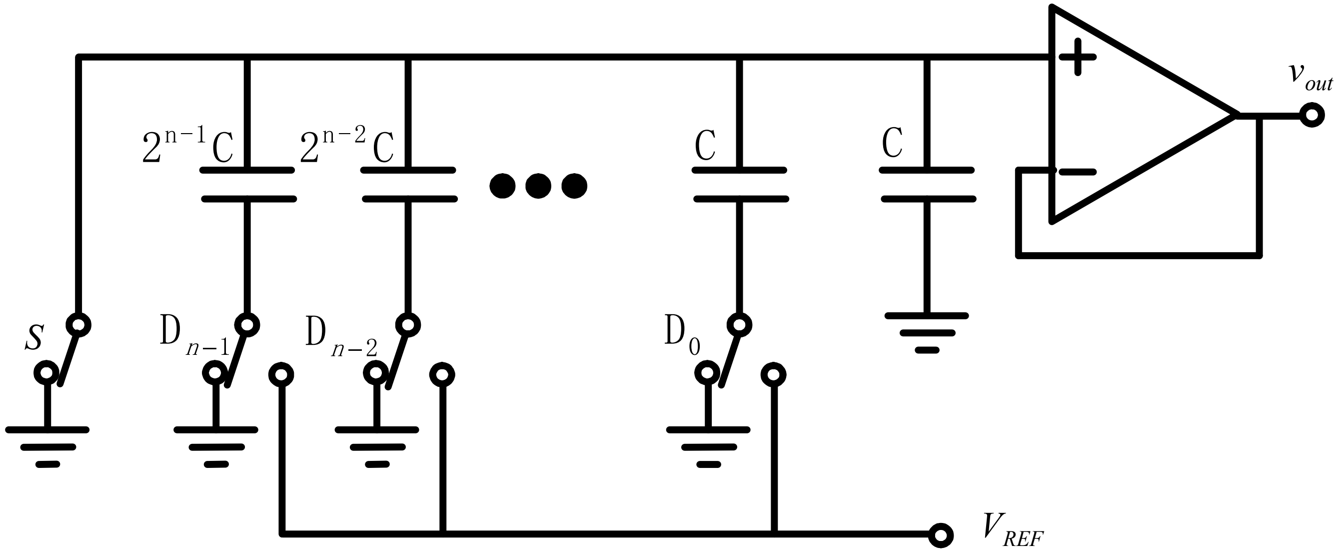


$$C_\Sigma = 2^{n-1}C + 2^{n-2}C + ... + C + C = 2^nC$$

$$V_{out} = V_0 = \frac{\sum_{i=0}^{n-1}2^iD_iCV_{REF}}{2^nC} = \frac{1}{2^n}\sum_{i=0}^{n-1}2^iD_iV_{REF}$$

$$= \left(2^{n-1}D_{n-1} + ... + 2D_1 + D_0\right)\frac{V_{REF}}{2^n}$$





$$v_{out} = V_0 = \frac{\sum_{i=0}^{n-1} 2^i D_i C V_{REF}}{2^n C} = \frac{1}{2^n}\sum_{i=0}^{n-1} 2^i D_i V_{REF}$$

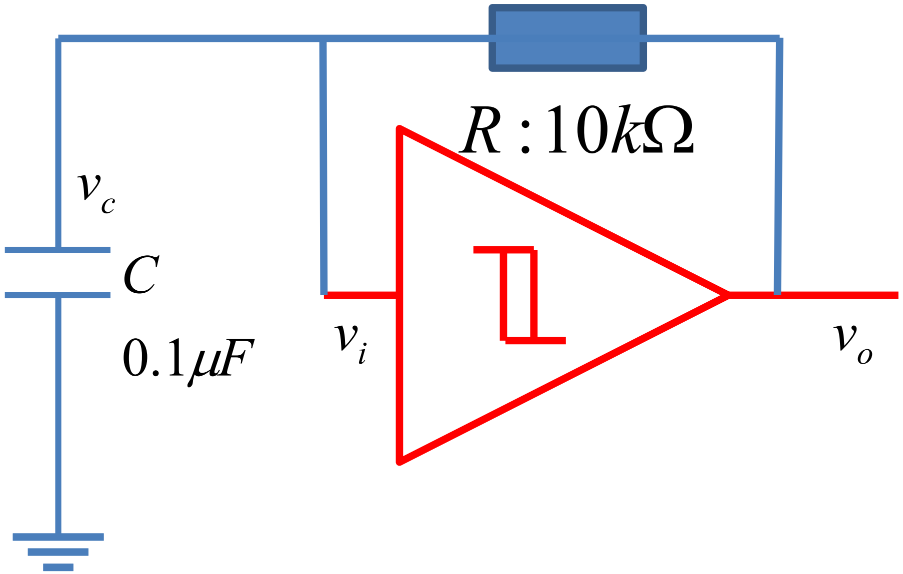
$$= \left(2^{n-1} D_{n-1} + \ldots + 2D_1 + D_0\right)\frac{V_{REF}}{2^n}$$

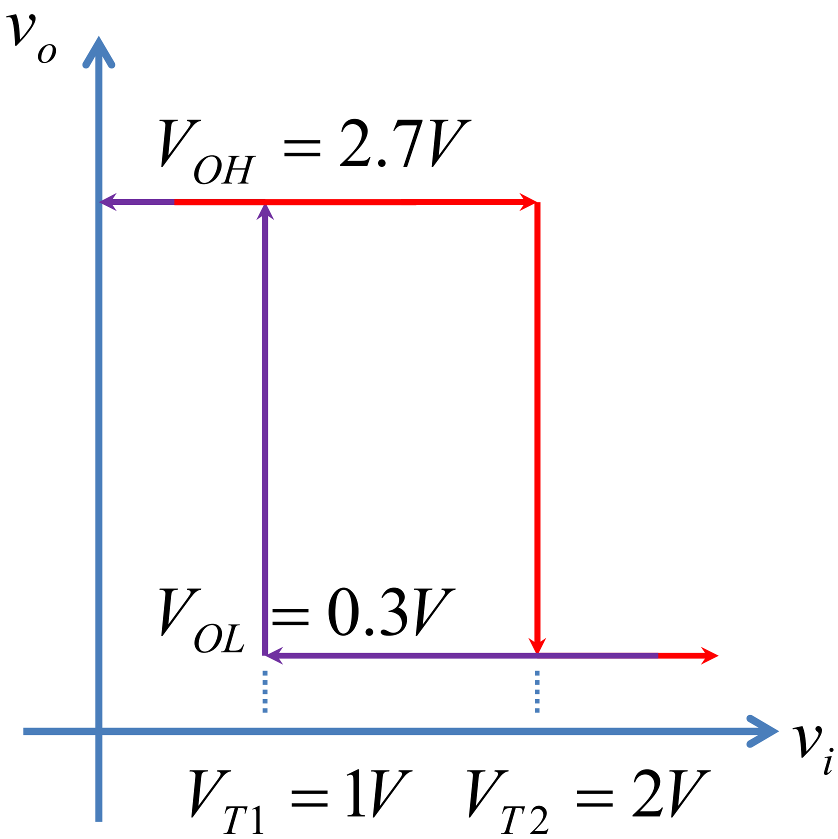
$D_3D_2D_1D_0$

1111

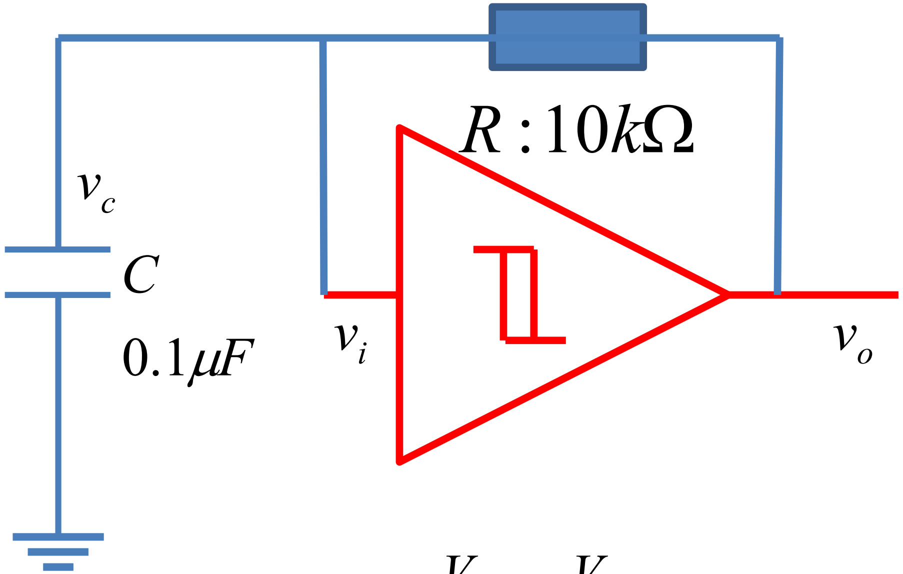
$$v_{out} = \left(8 + 4 + 2 + 1\right)\frac{V_{REF}}{16} = \frac{15}{16}V_{REF}$$

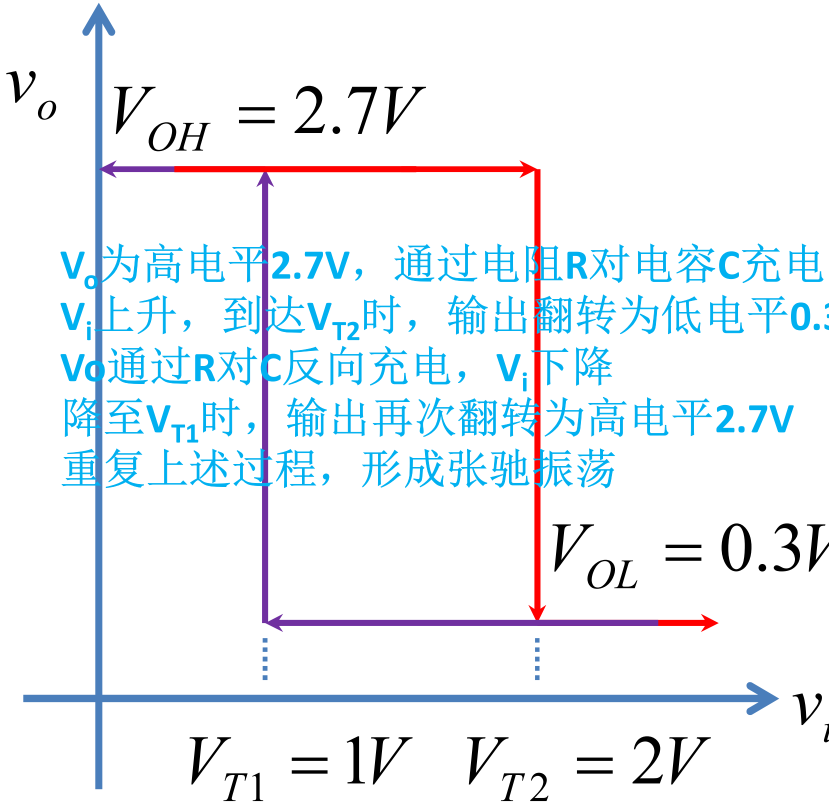
作业5
反相施密特触发器RC方波振荡器





- 已知施密特触发器的滞回曲线如图所示
- 画出电容电压和触发器输出电压波形，根据波形对其工作原理进行描述，并给出振荡频率，请用**R, C, V_{OH}, V_{OL}, V_{T1}, V_{T2}**参量表述振荡频率

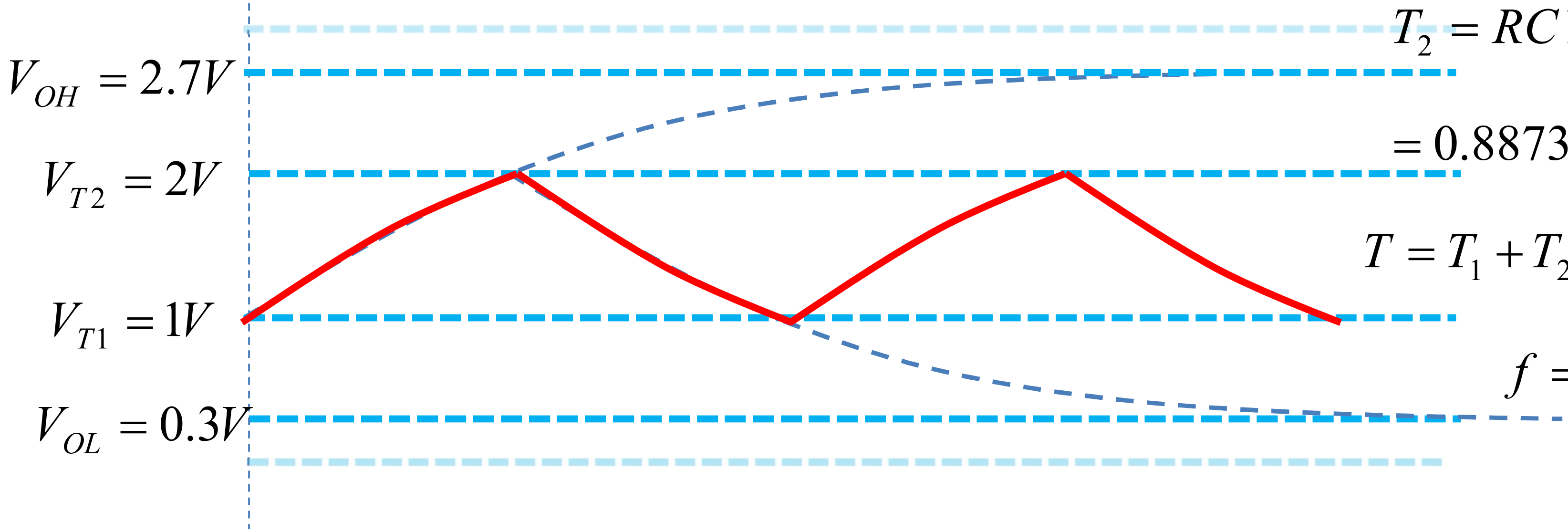




1. V_o为高电平2.7V，通过电阻R对电容C充电
2. V_i上升，到达V_{T2}时，输出翻转为低电平0.3V
3. Vo通过R对C反向充电，V_i下降
4. 降至V_{T1}时，输出再次翻转为高电平2.7V
5. 重复上述过程，形成张驰振荡

$$T_1 = RC\ln\frac{V_{OH}-V_{T1}}{V_{OH}-V_{T2}}$$

$$=10k\times 0.1\mu\times\ln\frac{1.7}{0.7}=0.8873ms$$



$$T_2 = RC\ln\frac{V_{OL}-V_{T2}}{V_{OL}-V_{T1}}$$

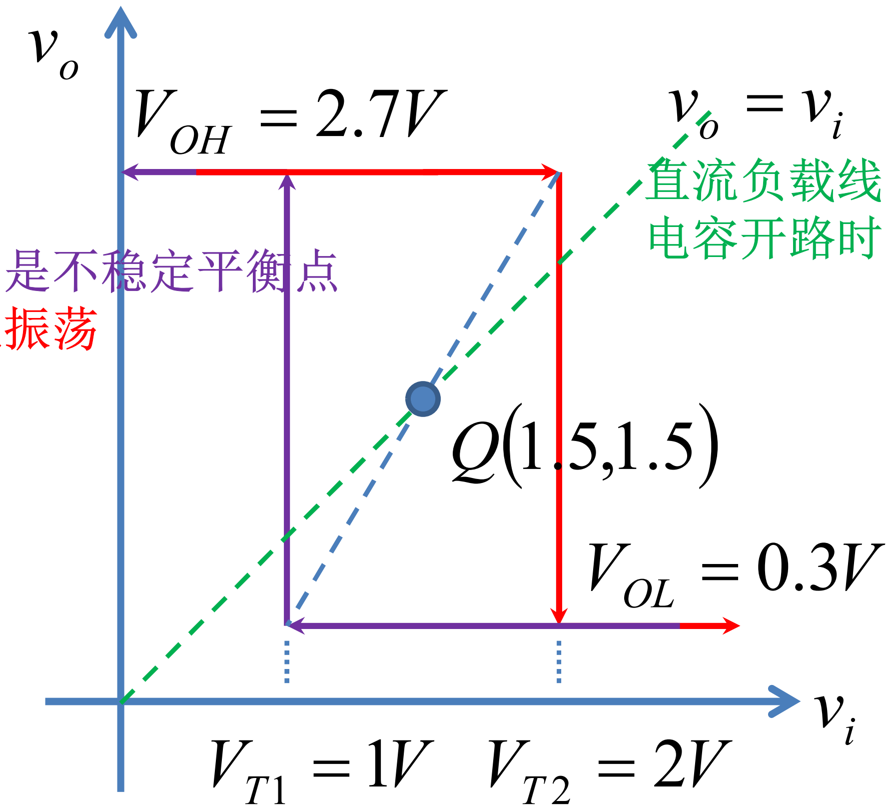
$$=0.8873ms$$

$$T=T_1+T_2=1.7746ms$$

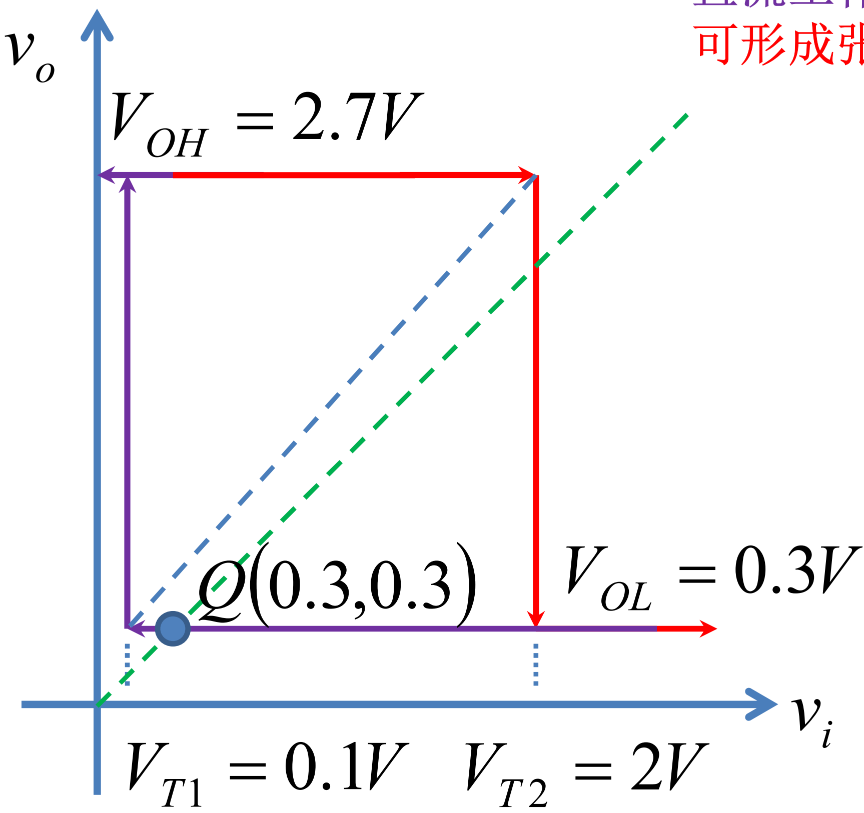
$$f=\frac{1}{T}=564Hz$$

形成张弛振荡？

条件：直流工作点偏置在负阻区，偏置点为不稳定平衡点

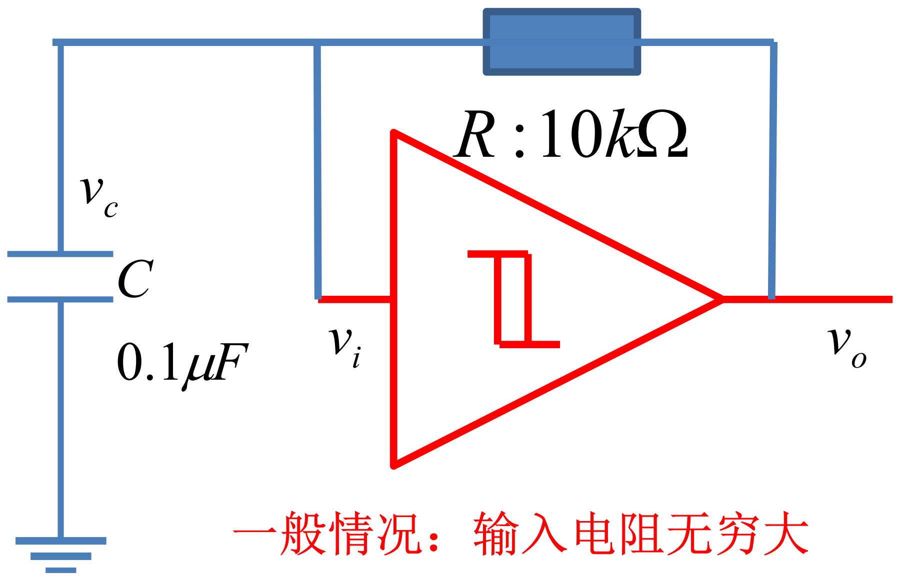


直流工作点是不稳定平衡点
可形成张弛振荡



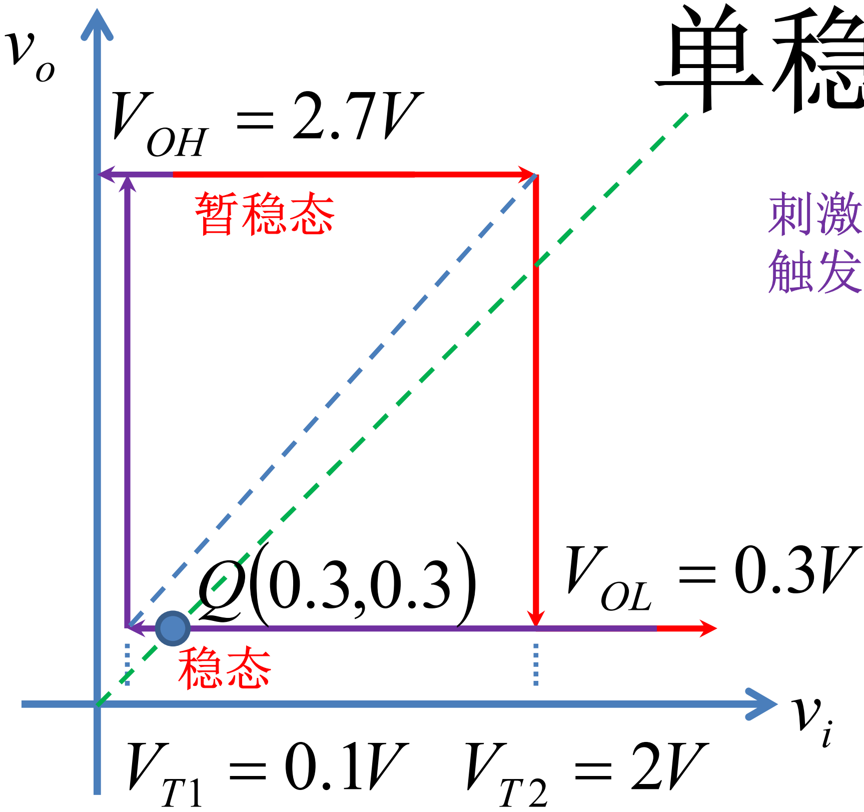
无法形成张弛振荡
最终稳定在**0.3V**电压上
直流工作点是稳定平衡点

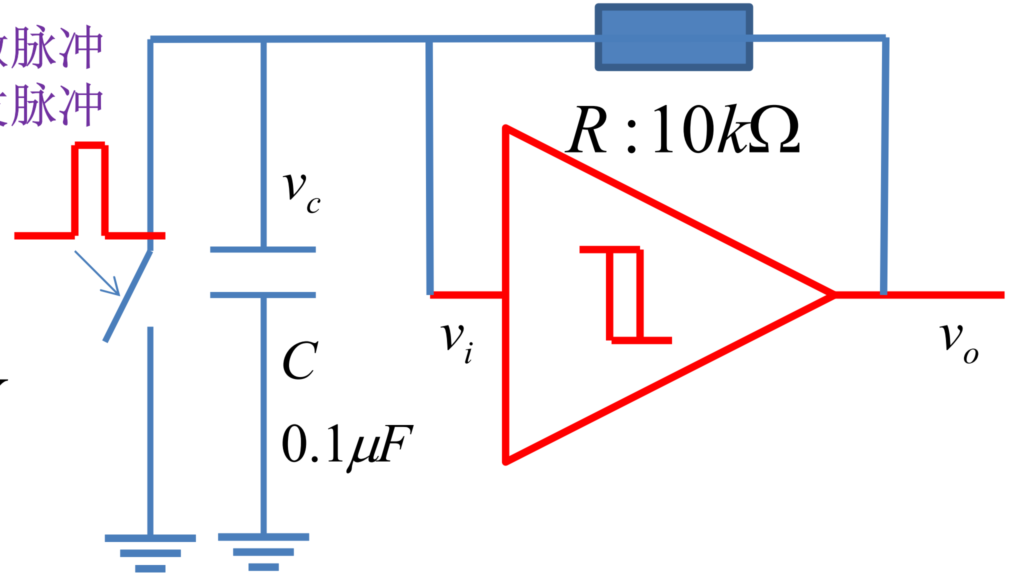
如果设计的振荡不振荡，原因？

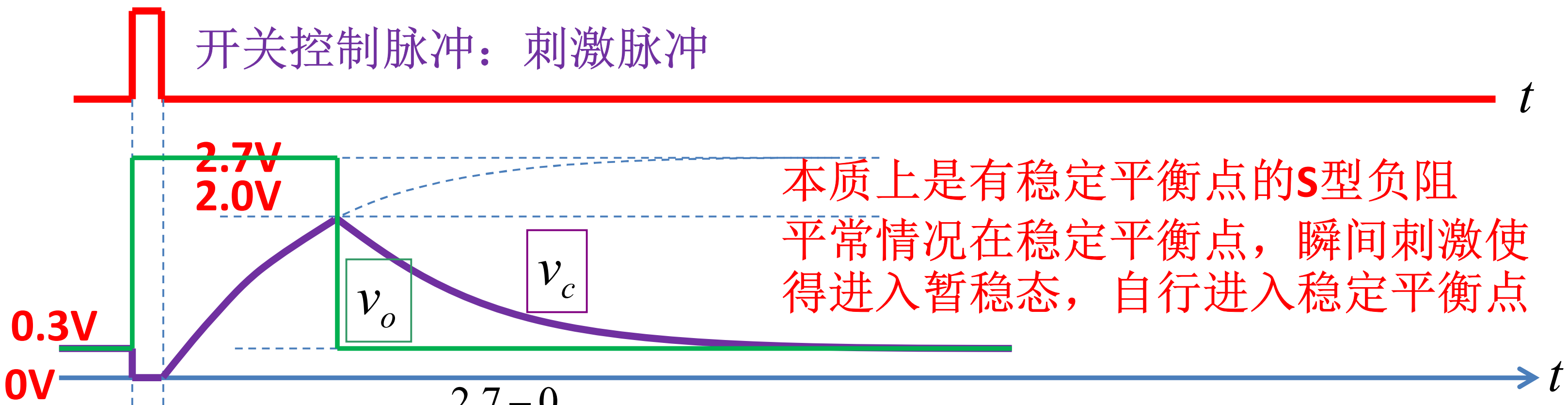


一般情况：输入电阻无穷大

单稳电路





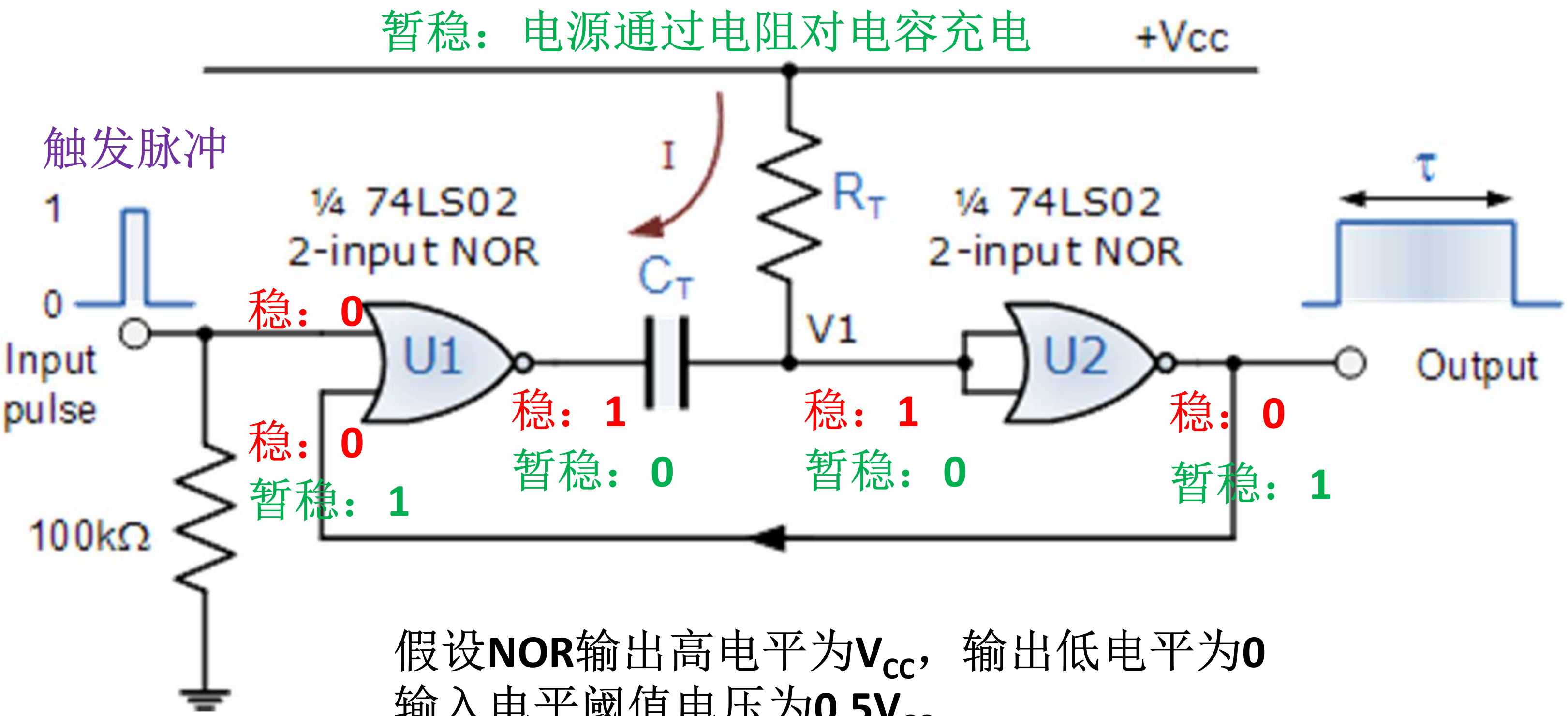


本质上是有稳定平衡点的S型负阻
平常情况在稳定平衡点，瞬间刺激使得进入暂稳态，自行进入稳定平衡点

$$T_W = T_t + RC\ln\frac{2.7-0}{2.7-2.0} = T_t + 1.35RC$$ 输出脉冲宽度

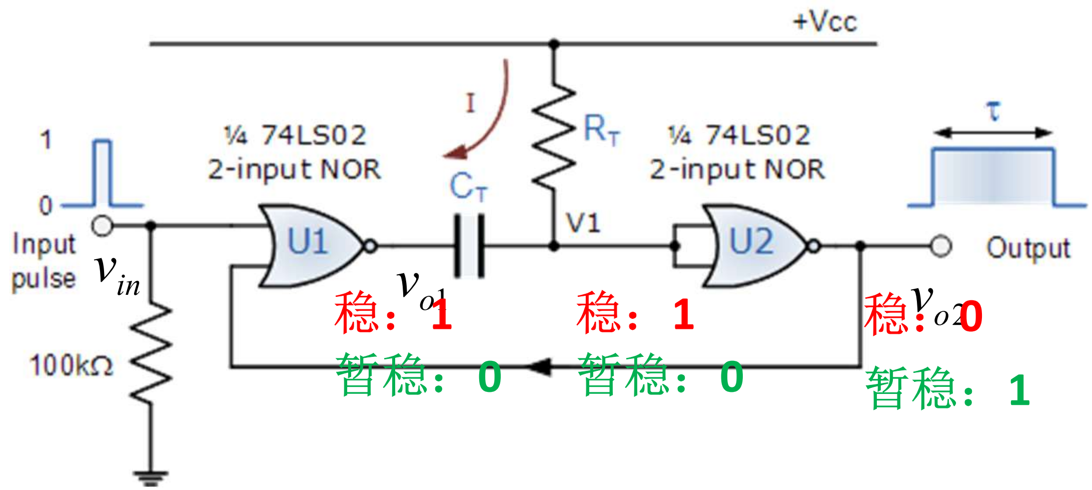
作业6 NOR gate monostable multivibrator

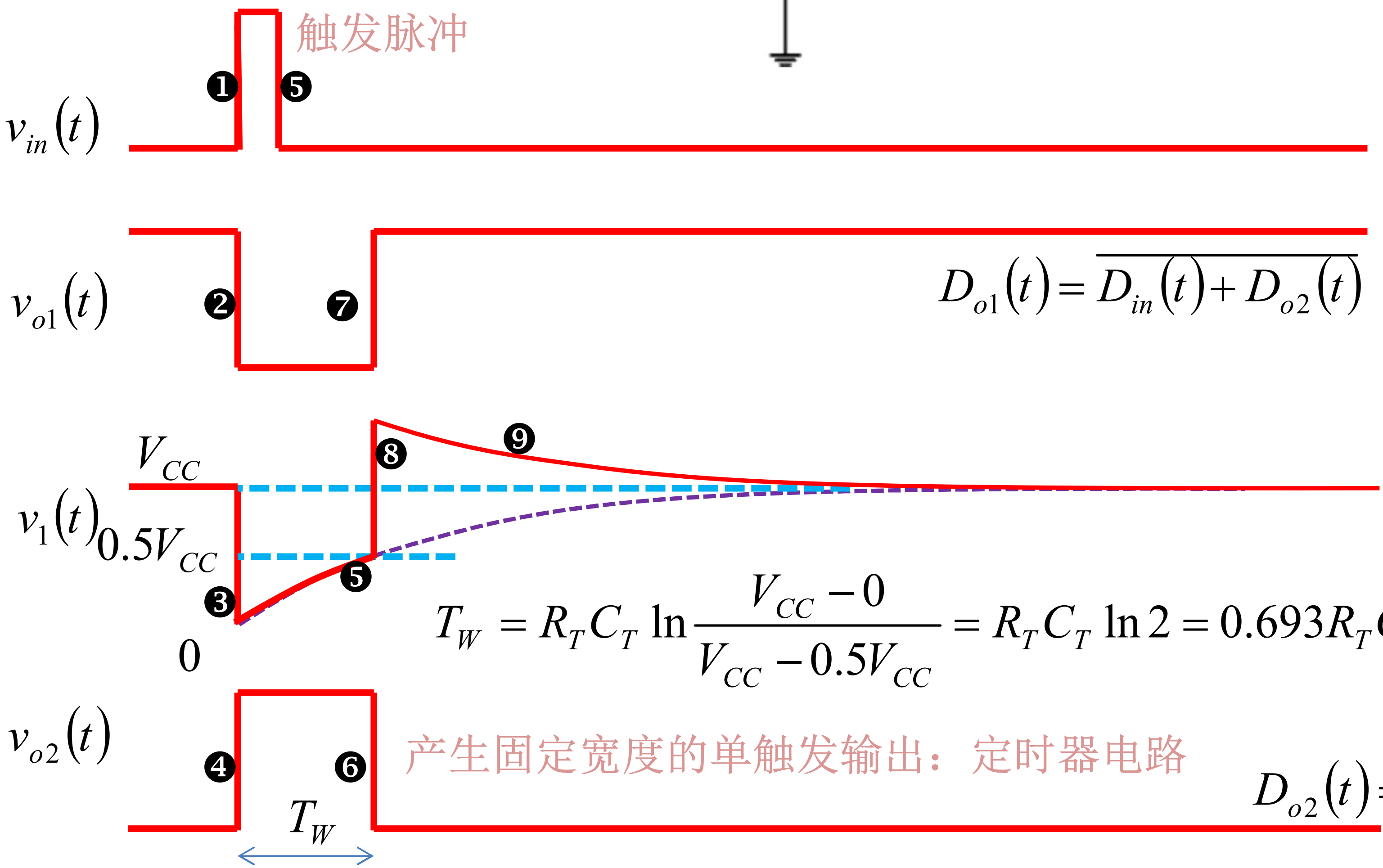
单稳态
单脉冲产生



假设NOR输出高电平为V_{CC}，输出低电平为0
输入电平阈值电压为$0.5V_{CC}$
1、画出各个结点的波形
2、求单脉冲输出脉宽

本质上是有稳定平衡点的S型负阻
平常情况在稳定平衡点，瞬间刺激使得进入暂稳态，自行进入稳定平衡点





$$D_{o1}(t) = \overline{D_{in}(t) + D_{o2}(t)}$$

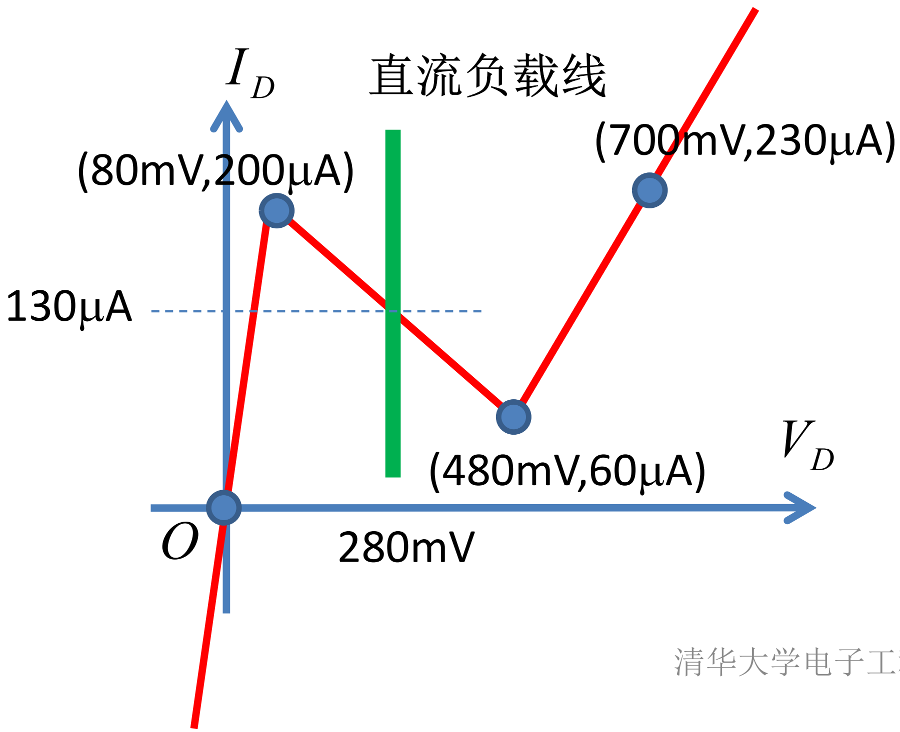
$$T_W = R_T C_T \ln \frac{V_{CC} - 0}{V_{CC} - 0.5V_{CC}} = R_T C_T \ln 2 = 0.693 R_T C_T$$

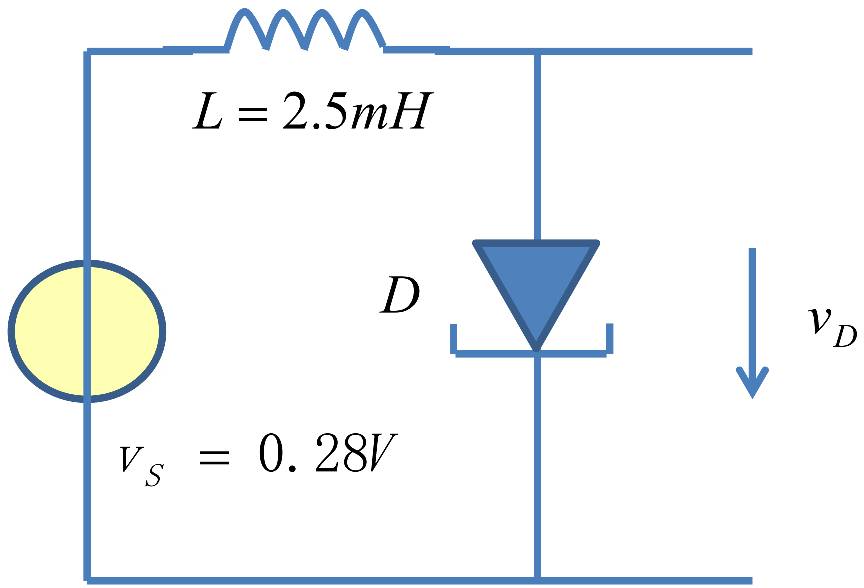
产生固定宽度的单触发输出：定时器电路

$$D_{o2}(t) = \overline{D_1(t)}$$

作业7 L和N型负阻：张弛振荡？

- 相图分析后，给出张弛振荡器振荡频率，画出v_D振荡时域波形图

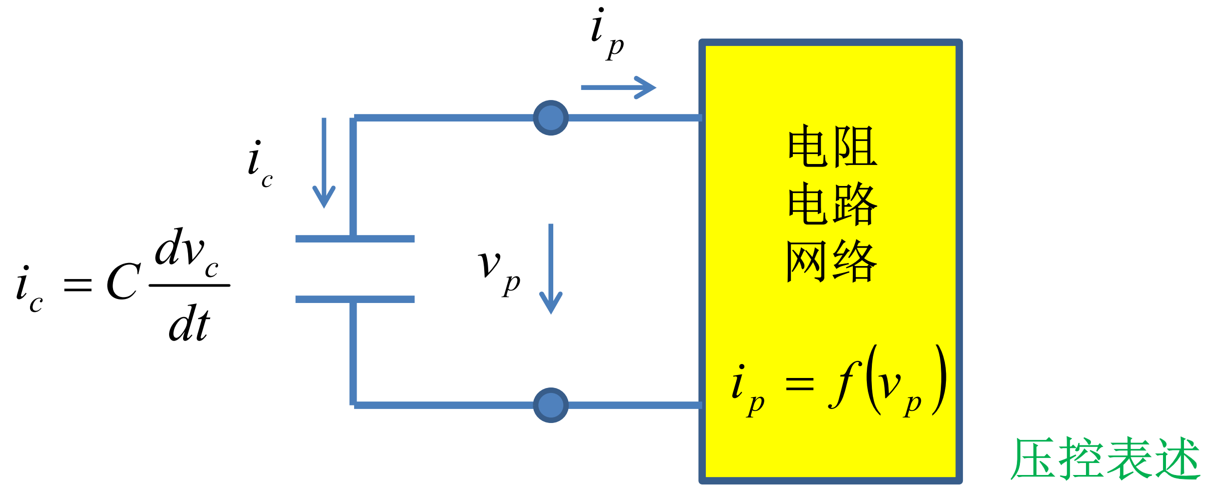




1、如果分析不清楚，请先PSPICE仿真，根据仿真结果分析（选作）

2、用PSPICE仿真确认你的分析结果（选作）

课堂讨论内容：非线性加单电容



$$C\frac{dv_c}{dt} = i_c = -i_p = -f(v_p) = -f(v_c)$$

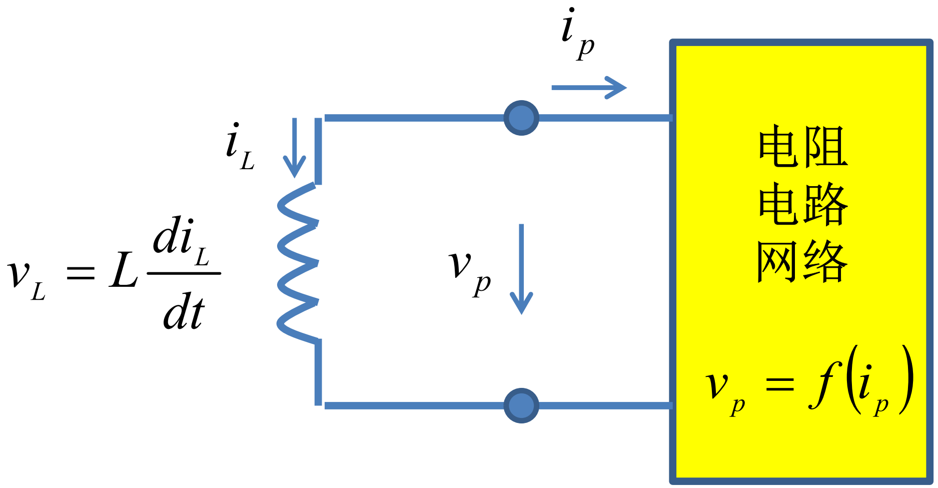
$$x = v_c$$

$$y = \frac{dv_c}{dt} = \frac{dx}{dt}$$

相图研究

$$y = -\frac{1}{C}f(x)$$

对偶研究：非线性加单电感



流控表述

$$L\frac{di_L}{dt} = v_L = v_p = f(i_p) = f(-i_L)$$

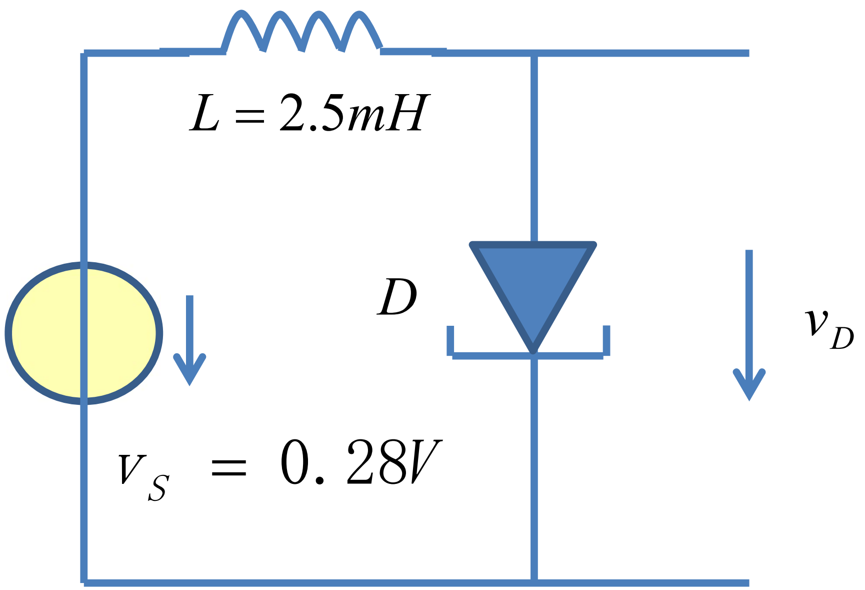
$$x = i_L$$

相图研究

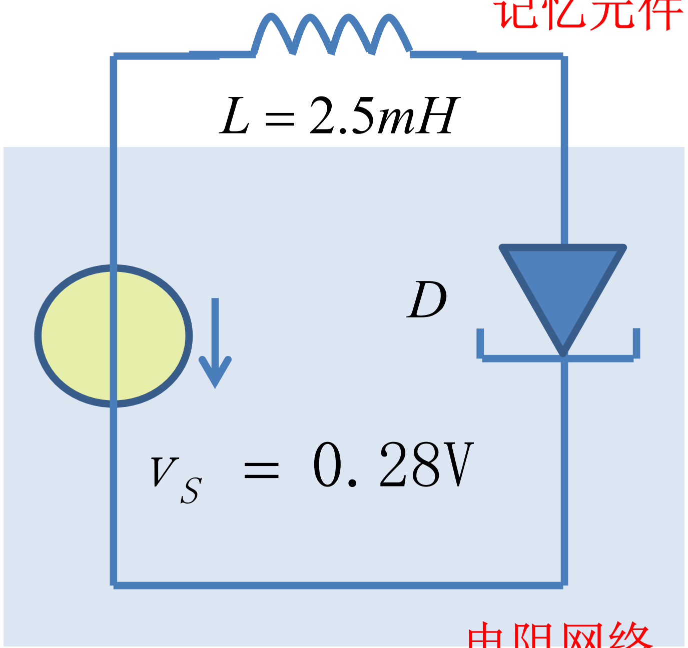
$$y = \frac{1}{L} f(-x)$$

$$y = \frac{di_L}{dt} = \frac{dx}{dt}$$

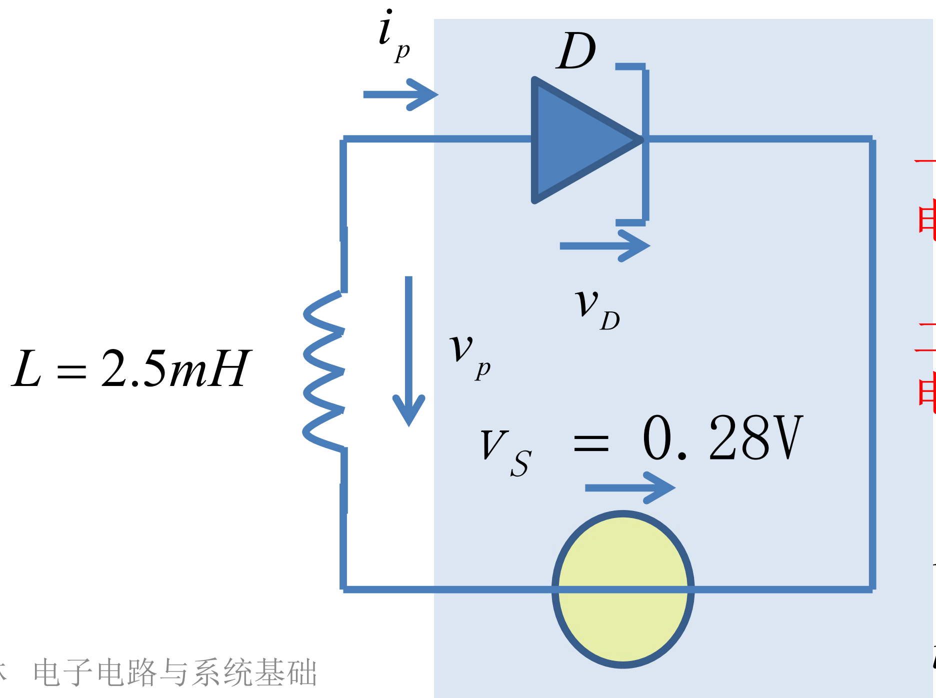
电阻电路重新封装为单端口网络



记忆元件



电阻网络分离



一阶系统
电阻网络抽象为单端口网络

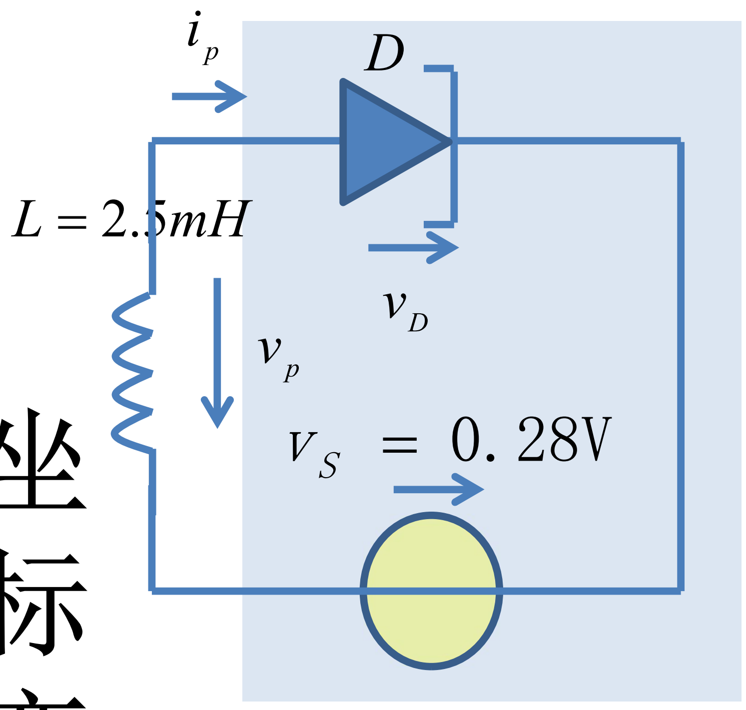
二阶系统
电阻网络抽象为二端口网络

单端口网络元件约束

$$v_p = v_D - v_S = v_D - 0.28V$$

$i_p = i_D$ **v_D，i_D已知**

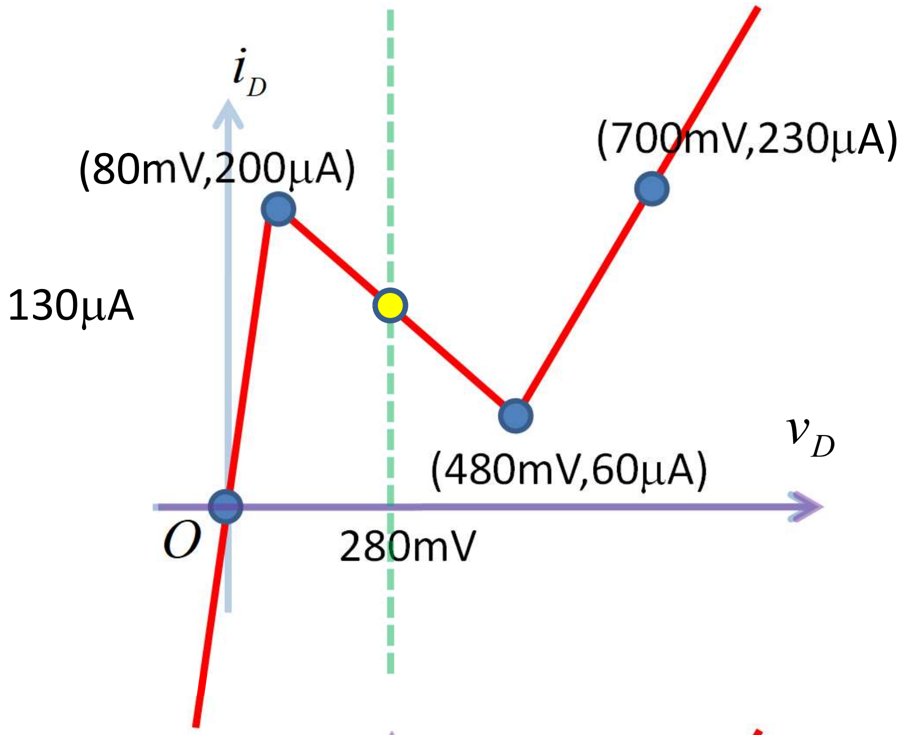
坐标变换

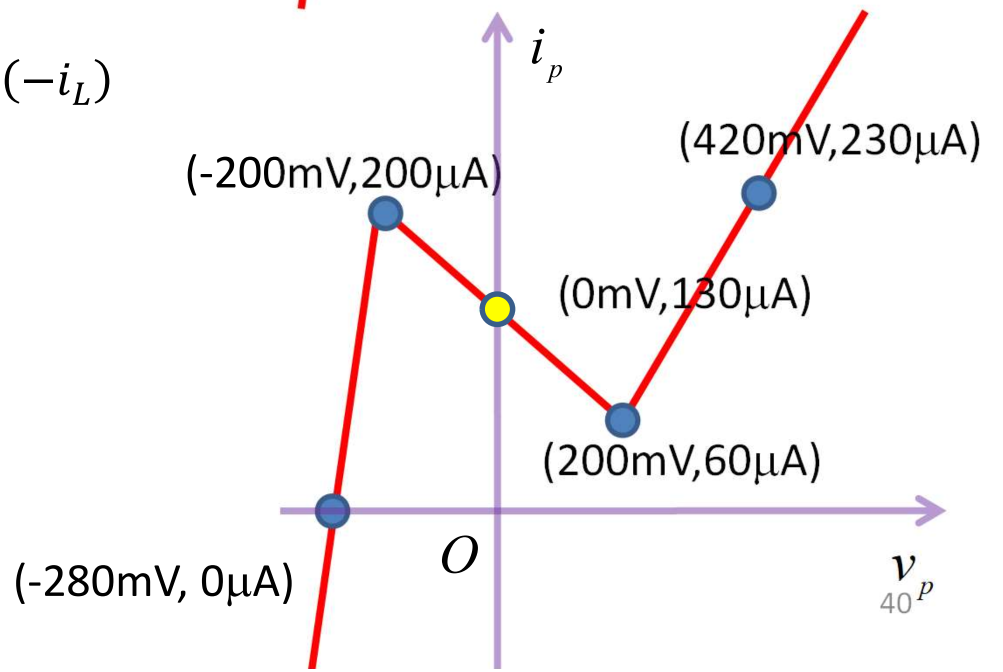


$$\frac{di_L}{dt} = \frac{1}{L} v_L = \frac{1}{L} v_p = \frac{1}{L} f(i_p) = \frac{1}{L} f(-i_L)$$

$$v_p = v_D - v_S = v_D - 0.28V$$

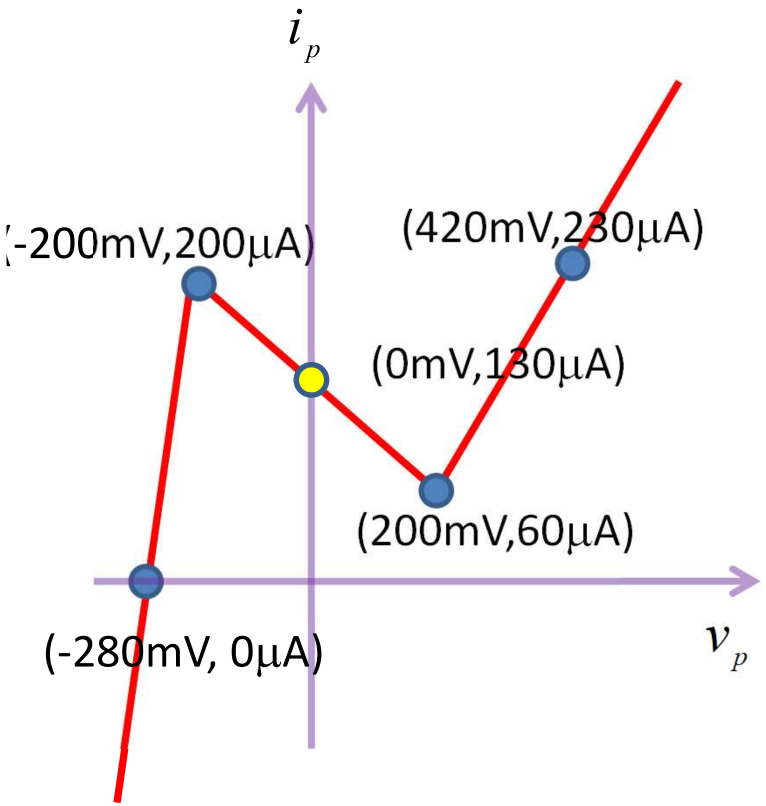
$$i_p = i_D$$





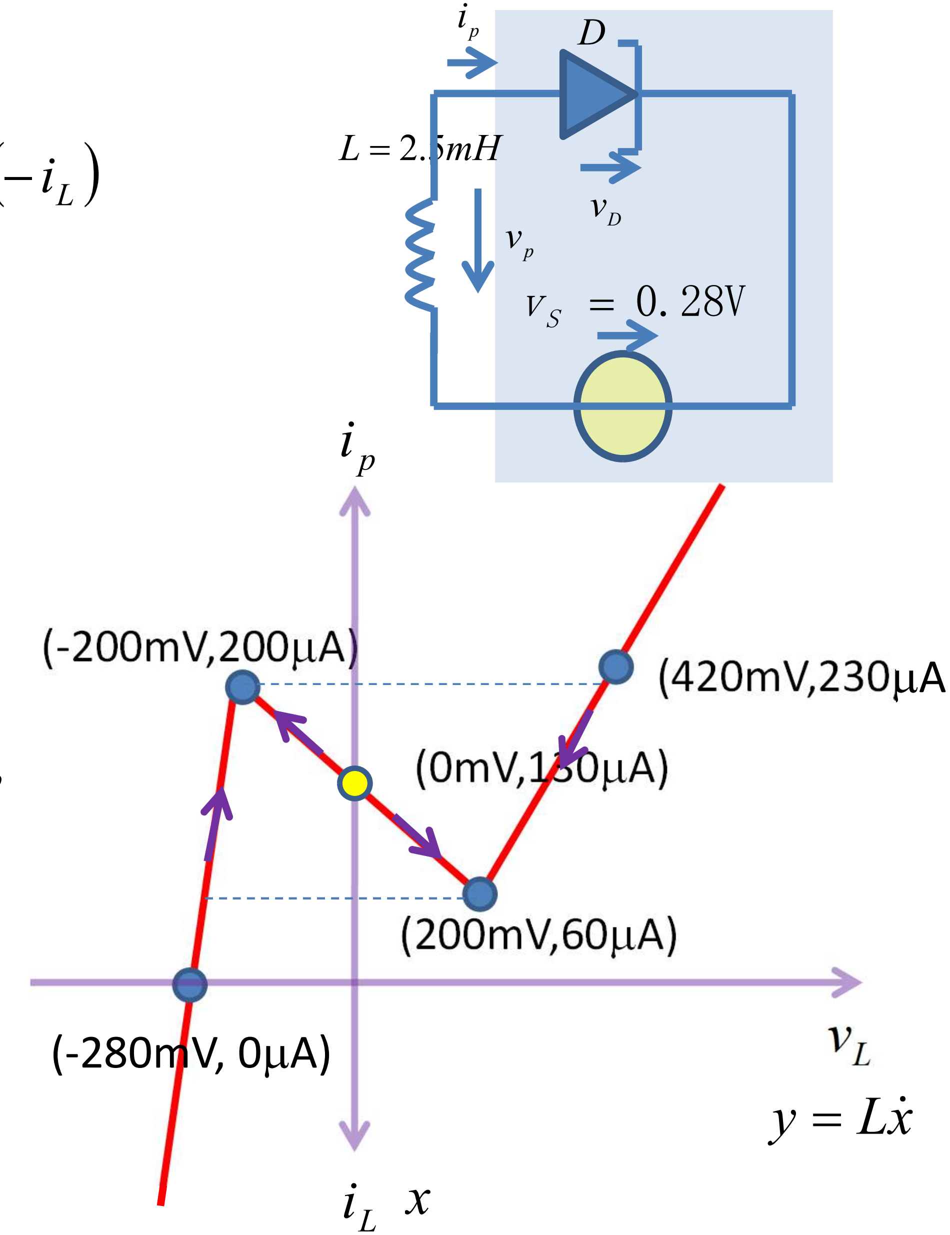
相图分析

$$\frac{di_L}{dt}=\frac{1}{L}f(-i_L)$$

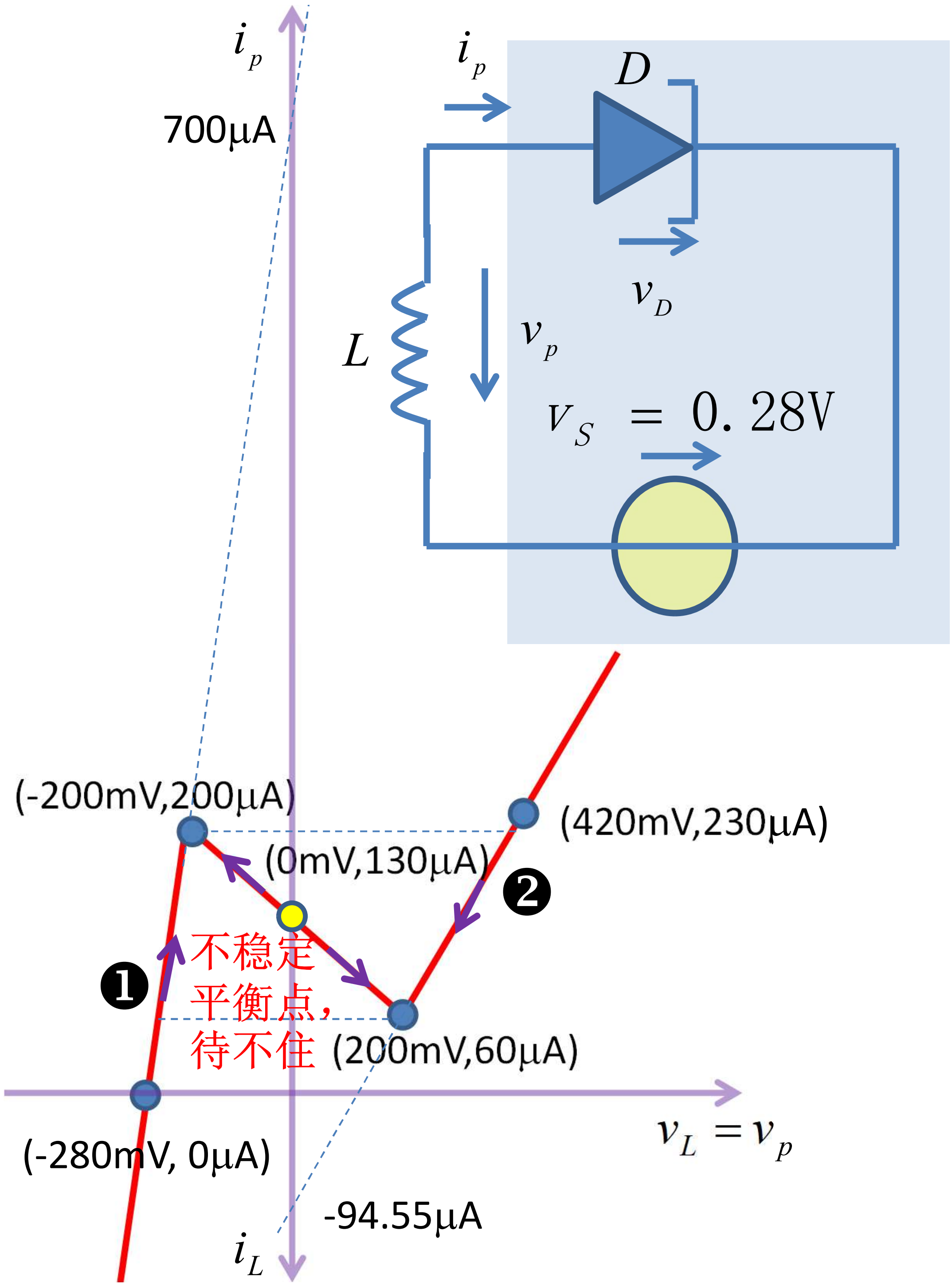


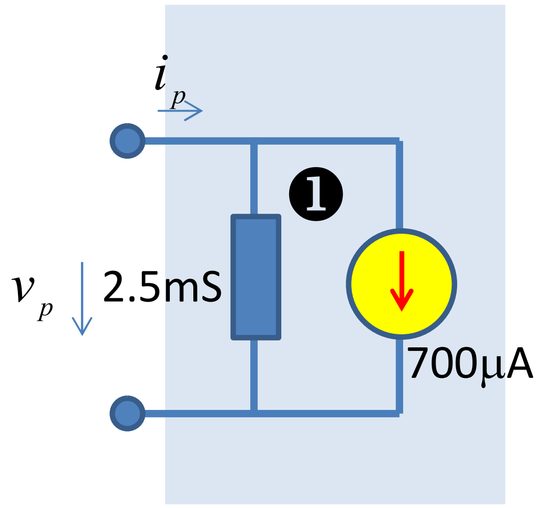
$i_L=-i_p$

$v_L=v_p$

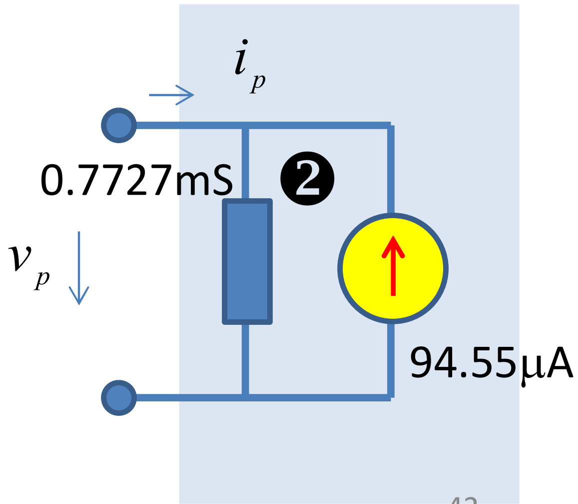


正阻区诺顿等效

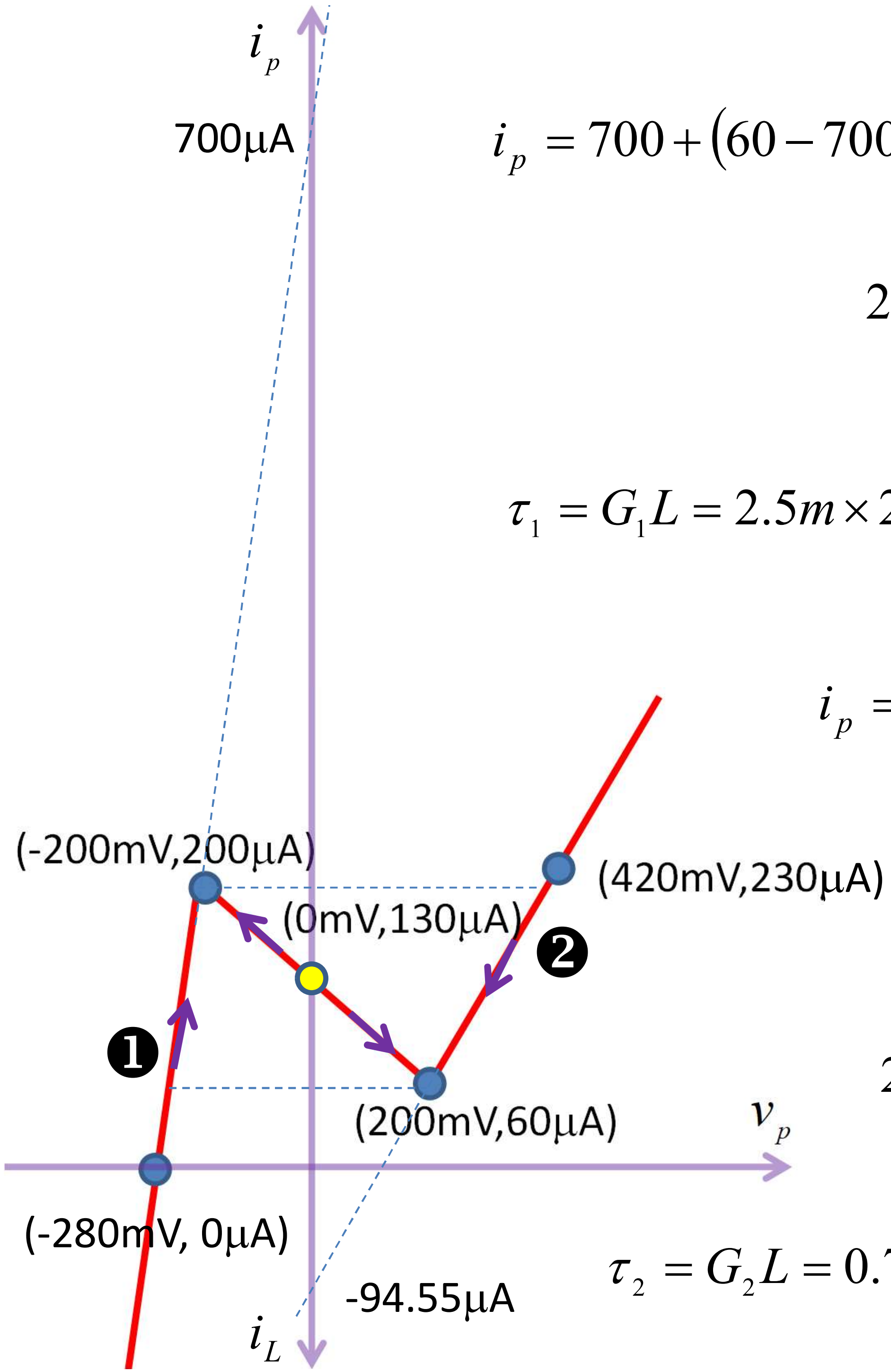




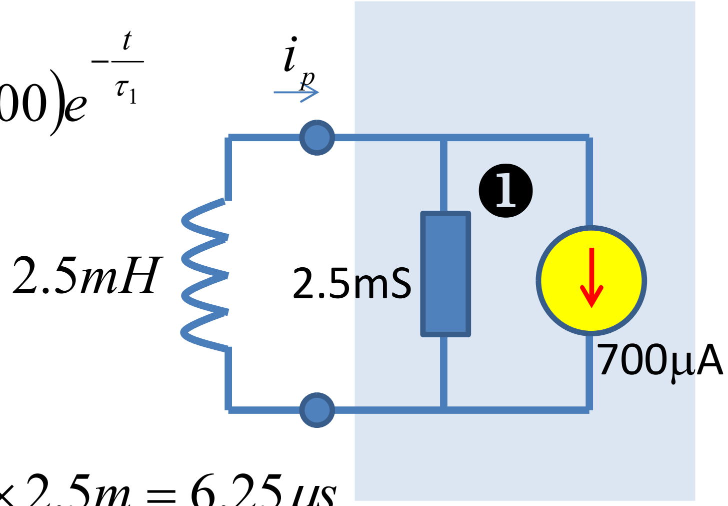
针对v_p，i_p进行建模



诺顿源为电感充磁

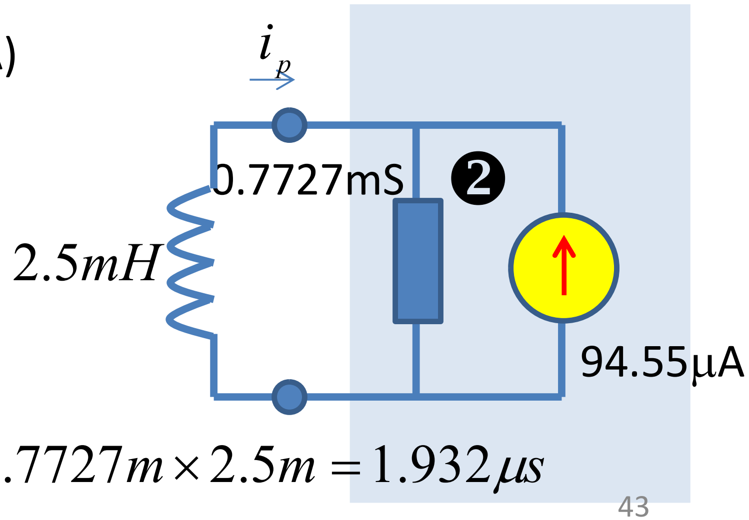


$$i_p = 700 + (60-700)e^{-\frac{t}{\tau_1}}$$



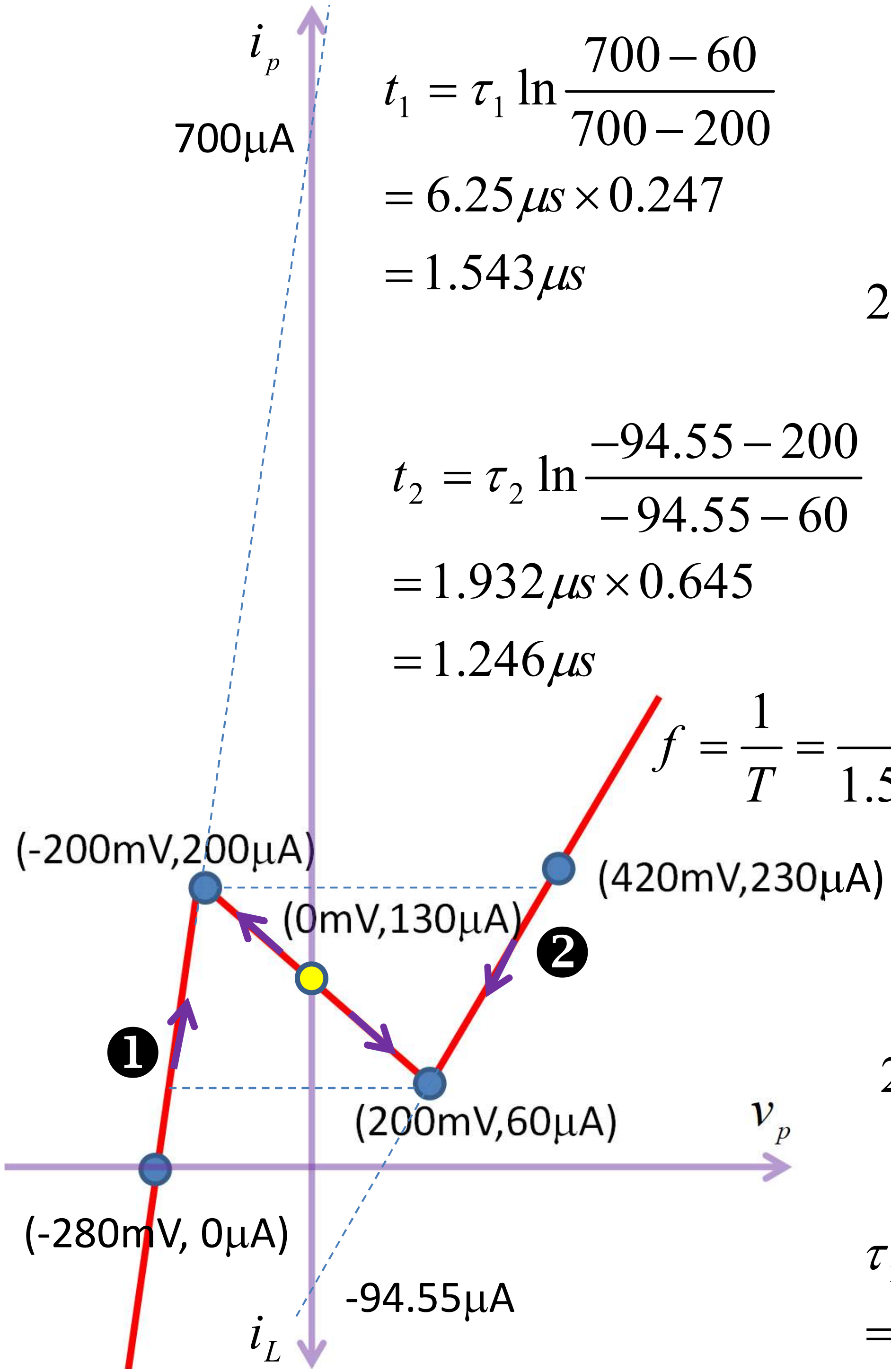
$$\tau_1 = G_1 L = 2.5m \times 2.5m = 6.25\mu s$$

$$i_p = -94.55 + (200+94.55)e^{-\frac{t}{\tau_2}}$$



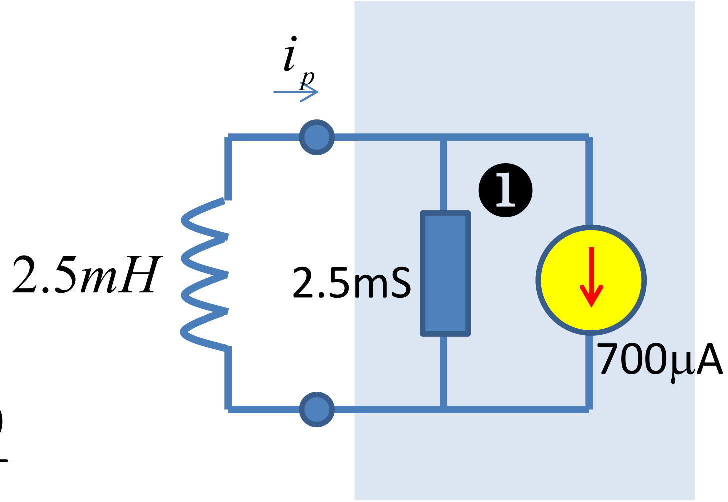
$$\tau_2 = G_2 L = 0.7727m \times 2.5m = 1.932\mu s$$

待在两个暂稳态的时间与振荡频率



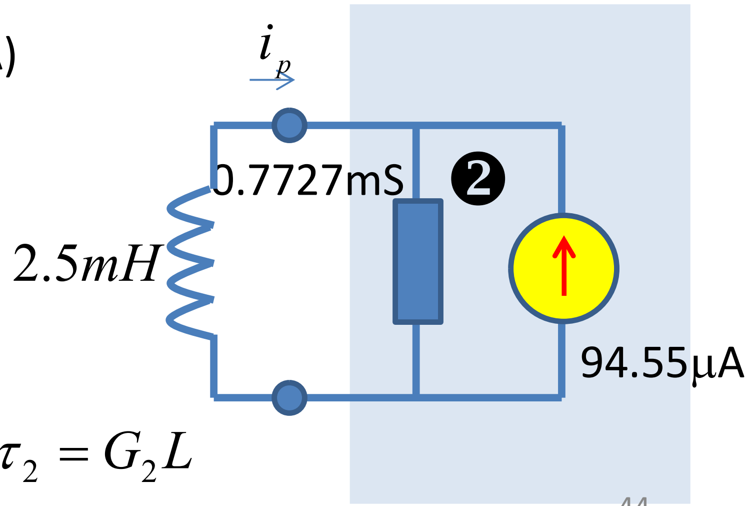
$$t_1 = \tau_1 \ln \frac{700-60}{700-200} = 6.25\mu s \times 0.247 = 1.543\mu s$$

$$t_2 = \tau_2 \ln \frac{-94.55-200}{-94.55-60} = 1.932\mu s \times 0.645 = 1.246\mu s$$



$$\tau_1 = G_1 L = 2.5m \times 2.5m = 6.25\mu s$$

$$f = \frac{1}{T} = \frac{1}{1.543\mu + 1.246\mu} = 359kHz$$



$$\tau_2 = G_2 L = 0.7727m \times 2.5m = 1.932\mu s$$

振荡波形分析

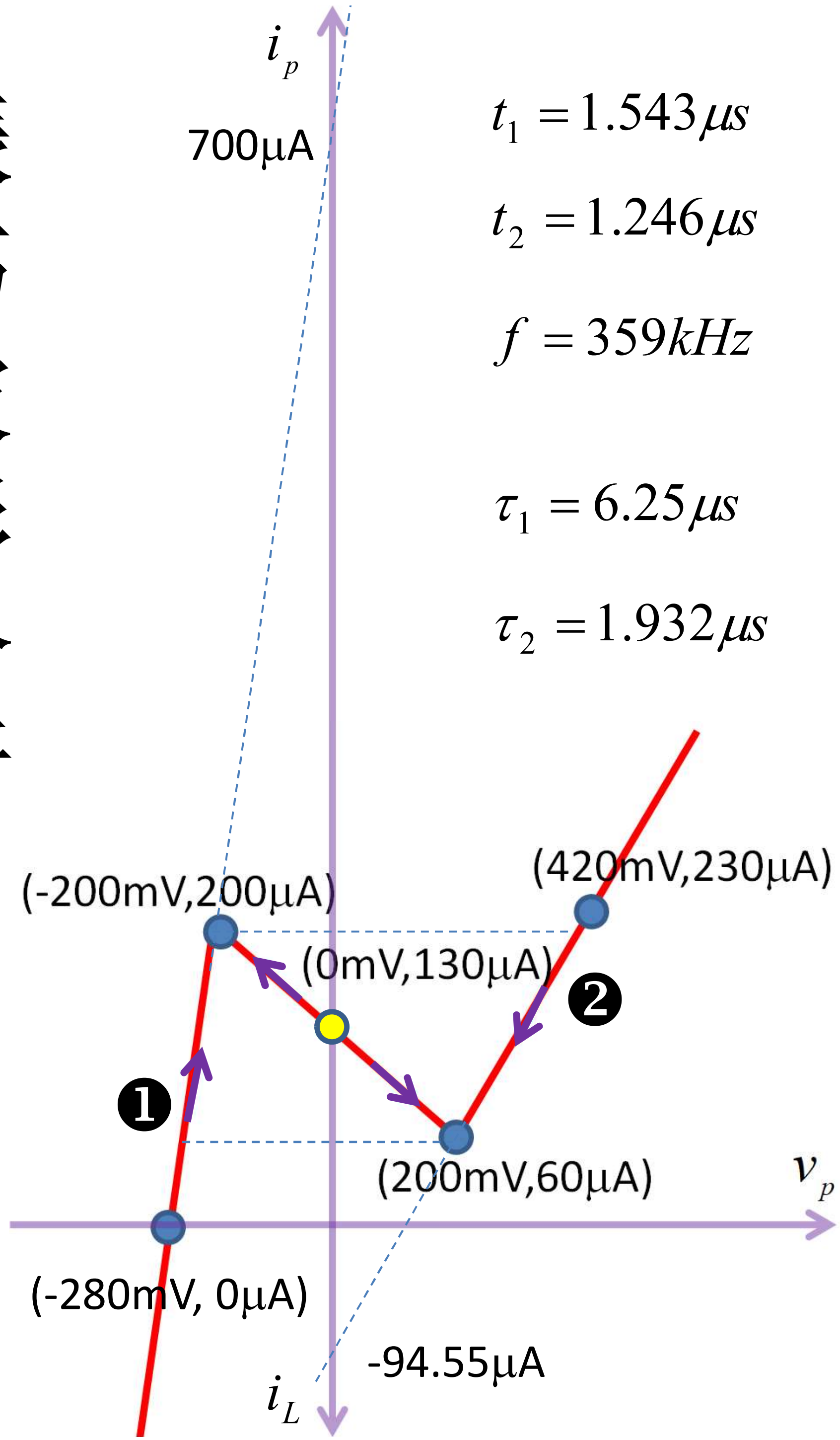
$t_1 = 1.543\mu s$

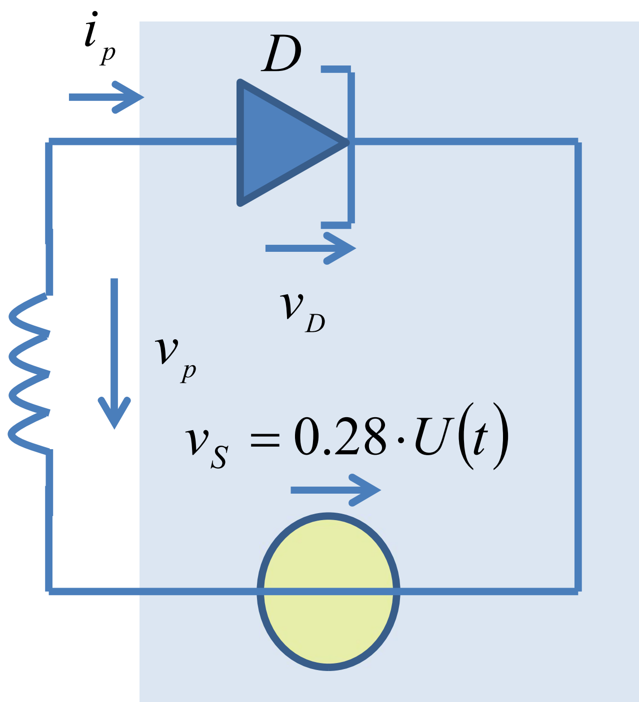
$t_2 = 1.246\mu s$

$f = 359kHz$

$\tau_1 = 6.25\mu s$

$\tau_2 = 1.932\mu s$





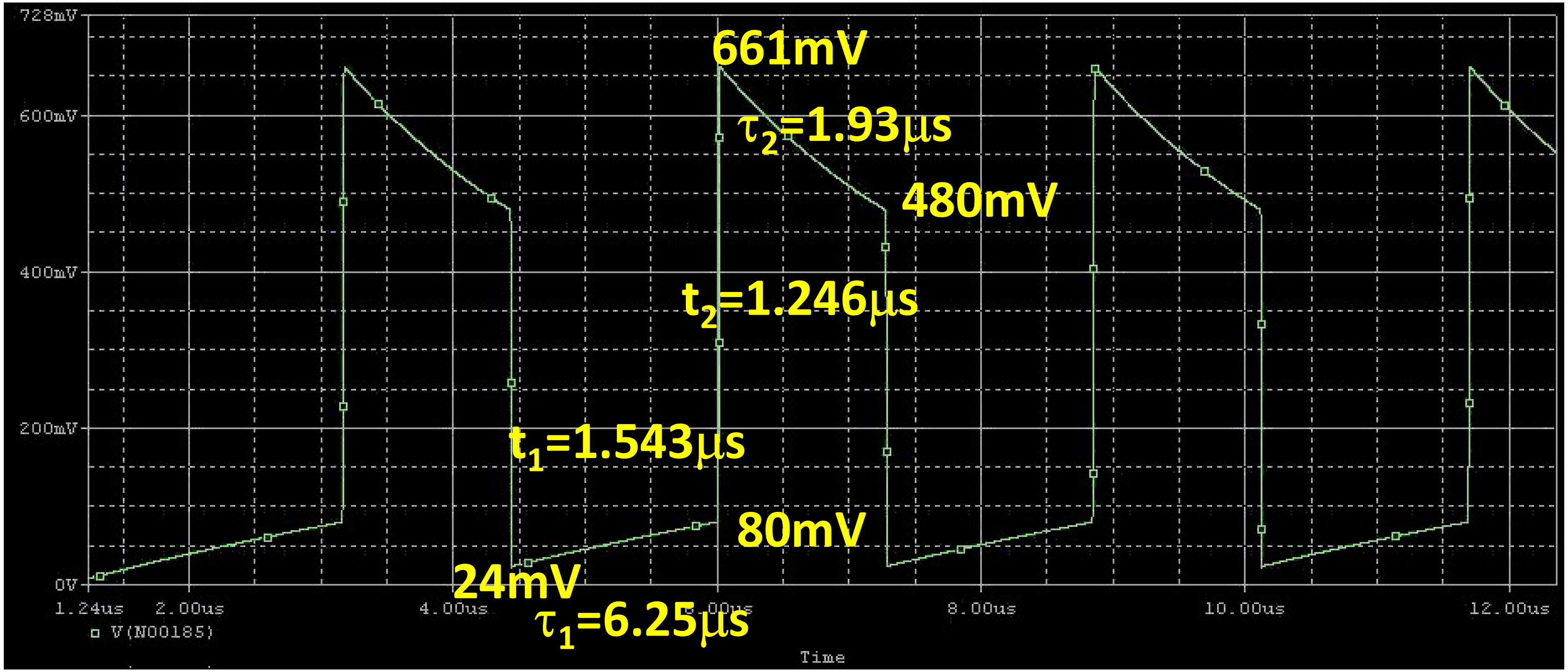
$i_p(\mu A)$
❶:60μA→200μA
❷: 200μA→60μA

$v_p(mV)$
❶:-256mV→-200mV
❷: 381mV→200mV

$v_D(mV)$
❶:24mV→80mV
❷: 661mV→480mV

考试画波形图时，需要标注清楚转折点电压电流/时间点，时间常数等关键参量

振荡波形仿真结果



$v_D(mV) \sim t(\mu s)$

$\tau_1 = 6.25\mu s$

$\tau_2 = 1.932\mu s$

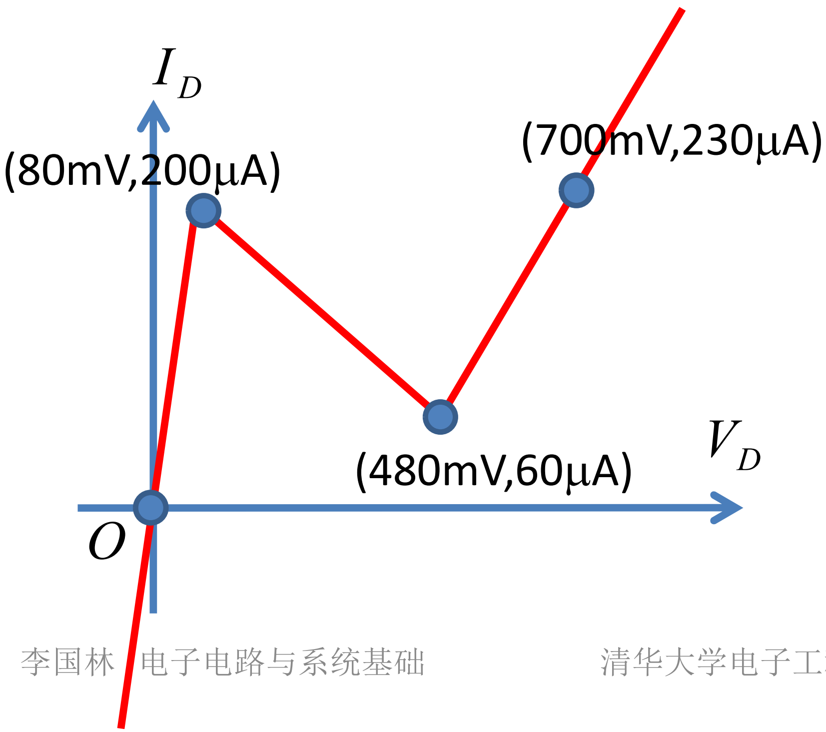
$v_D(mV)$

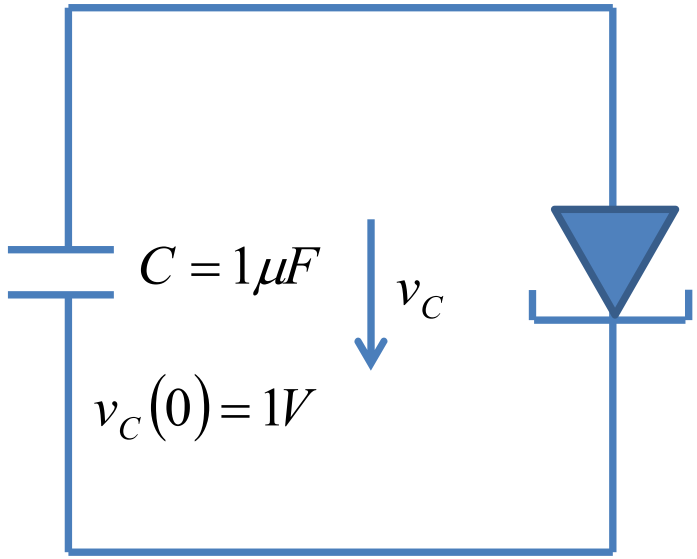
❶:24mV→80mV

❷: 661mV→480mV

作业8 C和N型负阻：电容放电

- 相图分析后，给出电容电压时域表达式和时域波形图



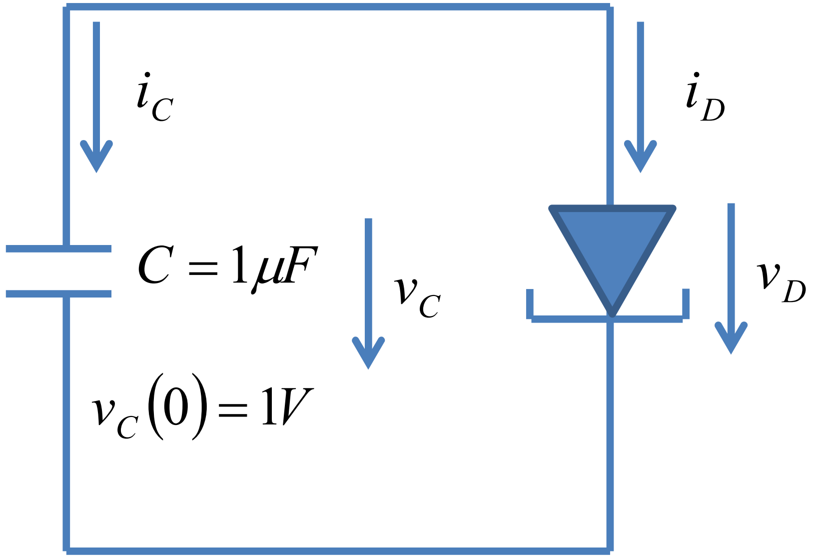


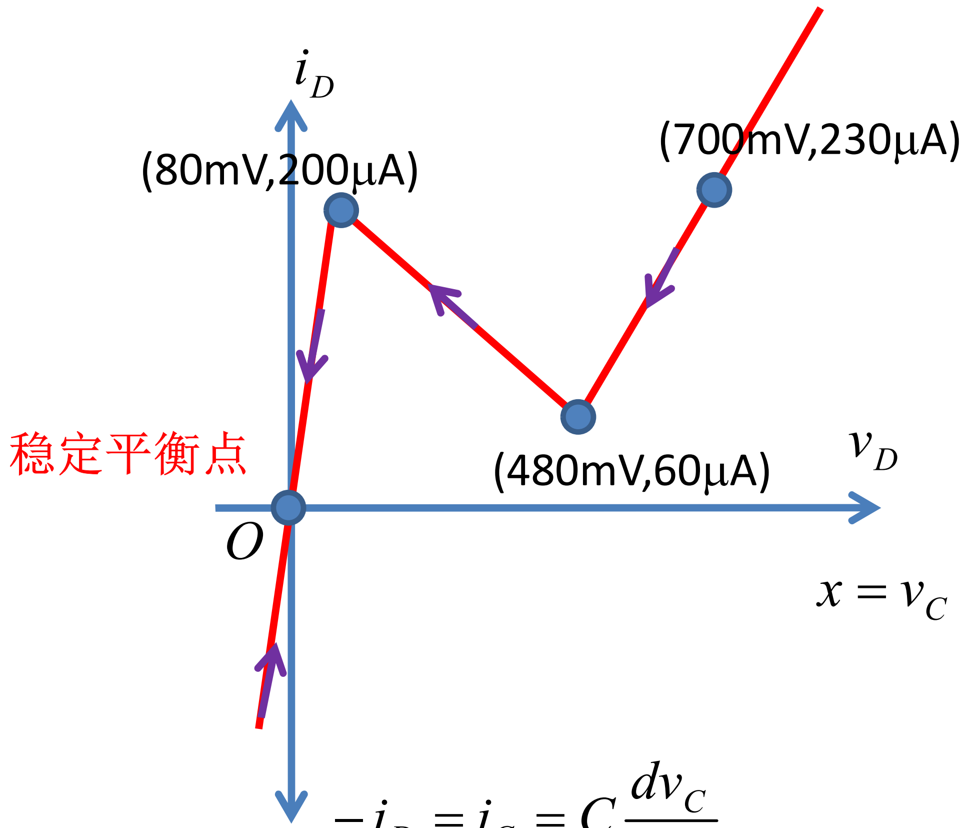
1、如果分析不清楚，请先**PSPICE**仿真，根据仿真结果分析（选作）

2、用**PSPICE**仿真确认你的分析结果（选作）

相图分析

$$C\frac{dv_C}{dt}=i_C=-i_D=-f(v_D)$$

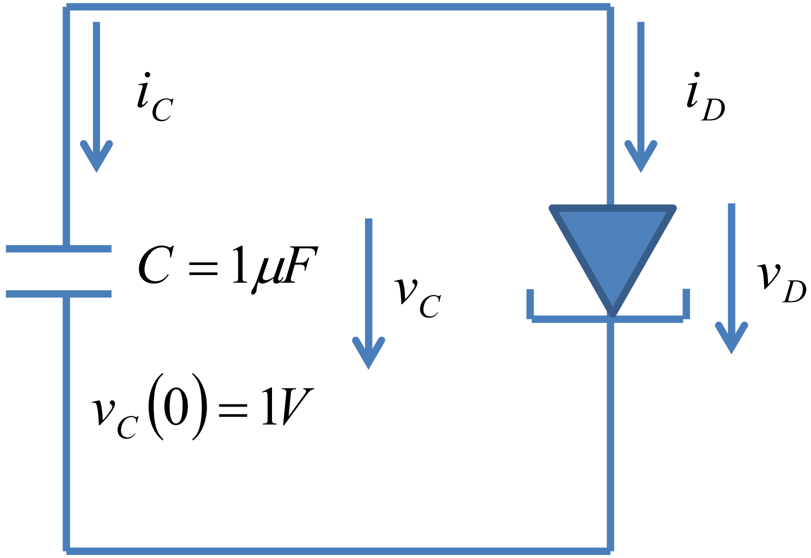


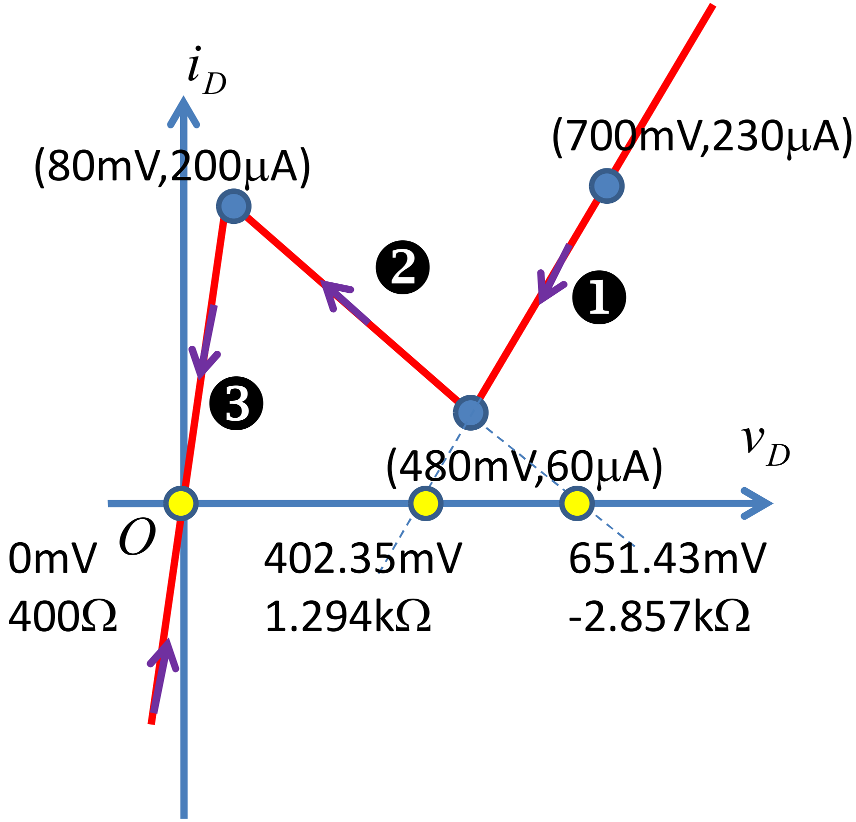


$$-i_D=i_C=C\frac{dv_C}{dt}$$

$$y=C\dot{x}$$

等效电路分析





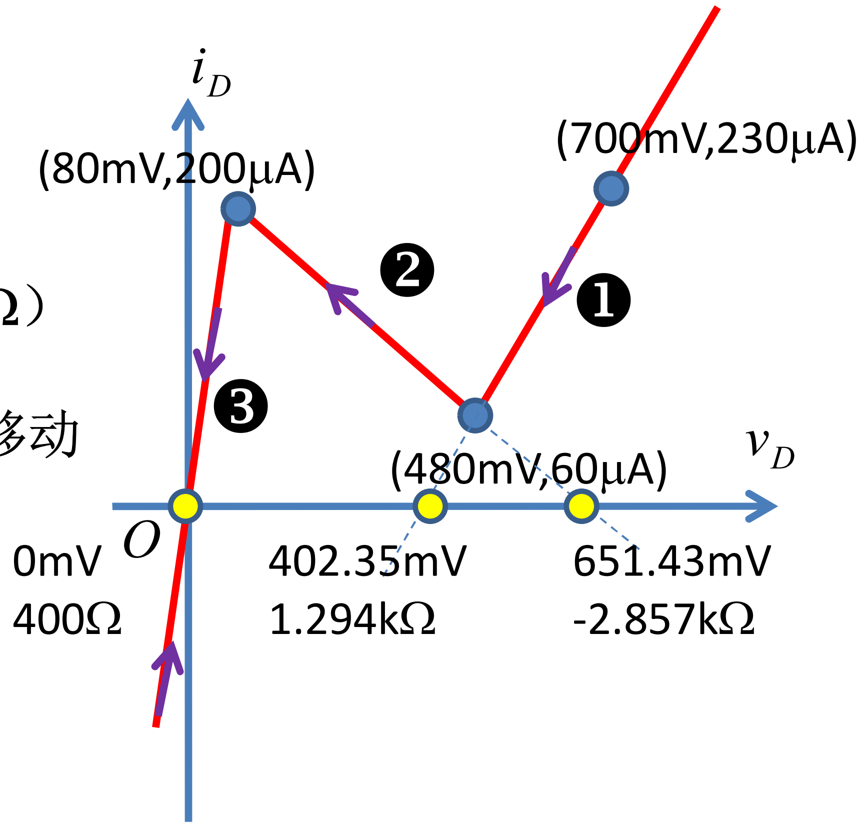
❶区：戴维南电压源（**402.35mV**，**1.294kΩ**）对电容充电：从**1V**到**480mV**
正内阻：朝稳定平衡点**402.35mV**移动

❷区：戴维南电压源（**651.43mV**，**-2.857kΩ**）对电容充电：从**480mV**到**80mV**
负内阻：背离不稳定平衡点**651.43mV**移动

❸区：戴维南电压源（**0mV**，**400Ω**）对电容充电：从**80mV**到**0mV**
正内阻：朝稳定平衡点**0mV**移动

❶区
指数衰减规律

❶区：戴维南电压源（**402.35mV**，**1.294kΩ**）
对电容充电：从**1V**到**480mV**
正内阻：朝稳定平衡点**402.35mV**移动



$$v_{C1}(t)=v_{C\infty1}(t)+\left(v_{C1}(0)-v_{C\infty1}(0)\right)e^{-\frac{t}{\tau_1}}$$

$$=402.35+(1000-402.35)e^{-\frac{t}{1.294ms}}$$

$$=402.35+597.65e^{-\frac{t}{1.294ms}} \qquad t\ge0 \qquad 2.641ms\ge t\ge0$$

$$\Delta t_1=\tau_1\ln\frac{V_{S01}-V_{00}}{V_{S01}-V_{01}}=1.294ms\times\ln\frac{402.35-1000}{402.35-480}=2.641ms$$

❷区
指数增长规律

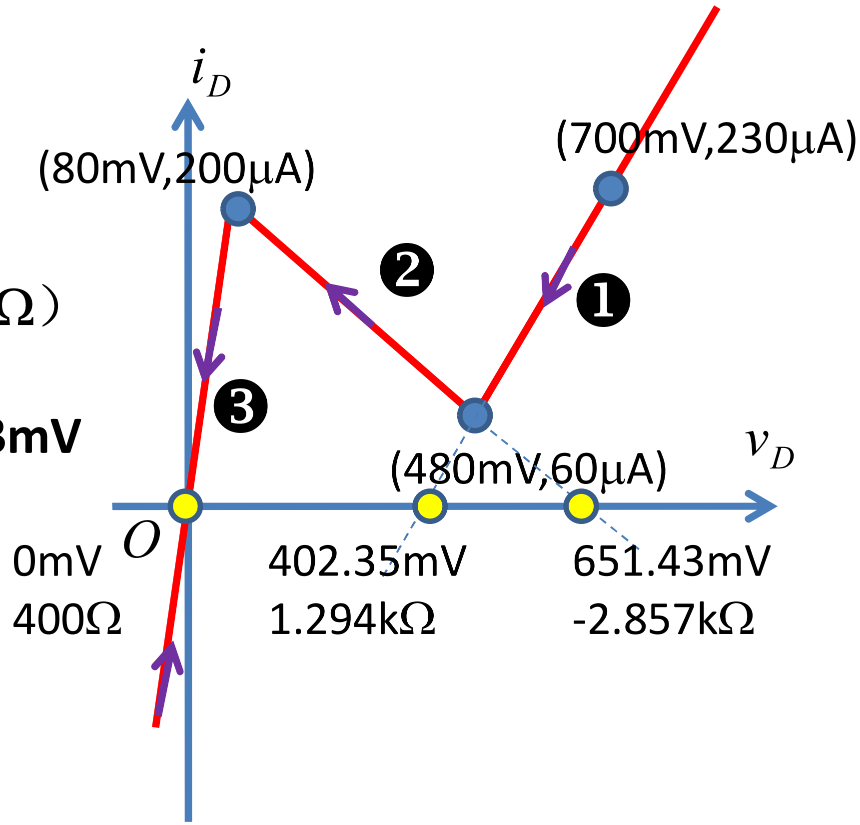
❷区：戴维南电压源（**651.43mV**，**-2.857kΩ**）
对电容充电：从**480mV**到**80mV**
负内阻：背离不稳定平衡点**651.43mV**移动

不稳定平衡：负无穷时间点对应点

$$v_{C2}(t)=v_{C\infty 2}(t)+\left(v_{C2}(t_1)-v_{C\infty 2}(t_1)\right)e^{-\frac{t-t_1}{\tau_2}}$$

$$=651.43+(480-651.43)e^{\frac{t-t_1}{2.857ms}}$$

$$=651.43-171.43e^{\frac{t-2.641ms}{2.857ms}} \qquad 6.081ms\ge t\ge 2.641ms$$

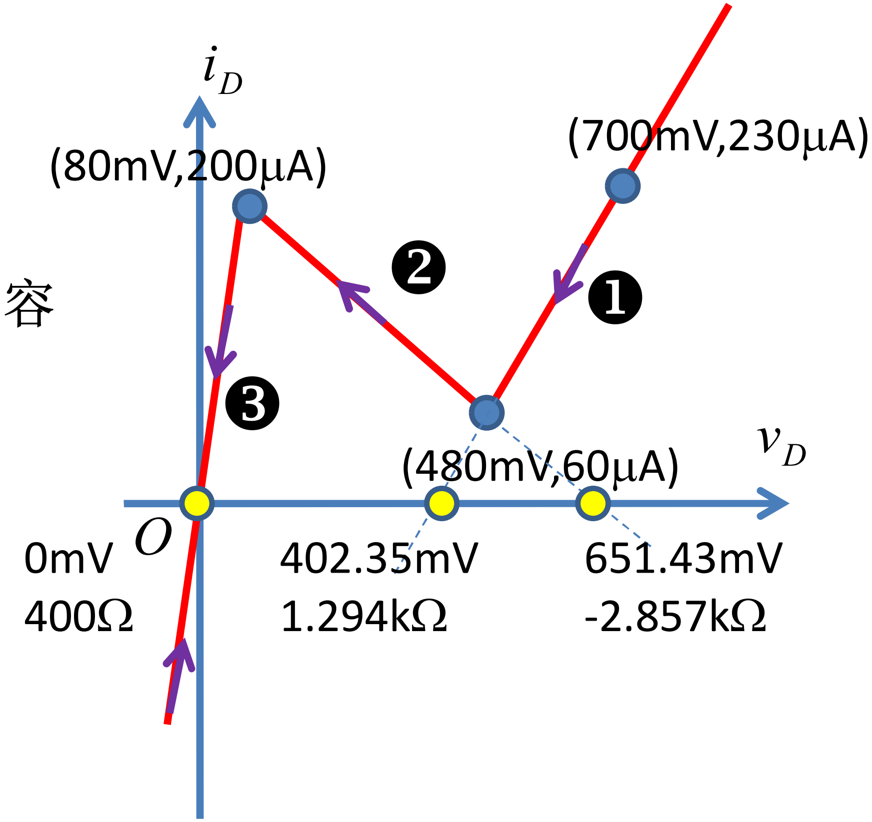


$$\Delta t_2=\tau_2\ln\frac{V_{S02}-V_{01}}{V_{S02}-V_{02}}=-2.857ms\times\ln\frac{651.43-480}{651.43-80}=3.440ms$$

❸区
指数衰减规律

❸区：戴维南电压源（**0mV**，**400Ω**）对电容充电：从**80mV**到**0mV**

正内阻：朝稳定平衡点**0mV**移动



$$v_{C3}(t)=v_{C\infty3}(t)+\left(v_{C3}(0)-v_{C\infty3}(0)\right)e^{-\frac{t-t_2}{\tau_3}}$$

$$=0+(80-0)e^{-\frac{t-6.081ms}{0.4ms}}$$

$$=80e^{-\frac{t-6.081ms}{0.4ms}} \qquad t\geq 6.081ms$$

$$5\tau_3=5\times0.4ms=2ms$$ **2ms**后可视为进入稳态（**t>8ms**）

波形图

$$v_{C1}(t) = 402.35 + 597.65e^{-\frac{t}{1.294ms}}$$

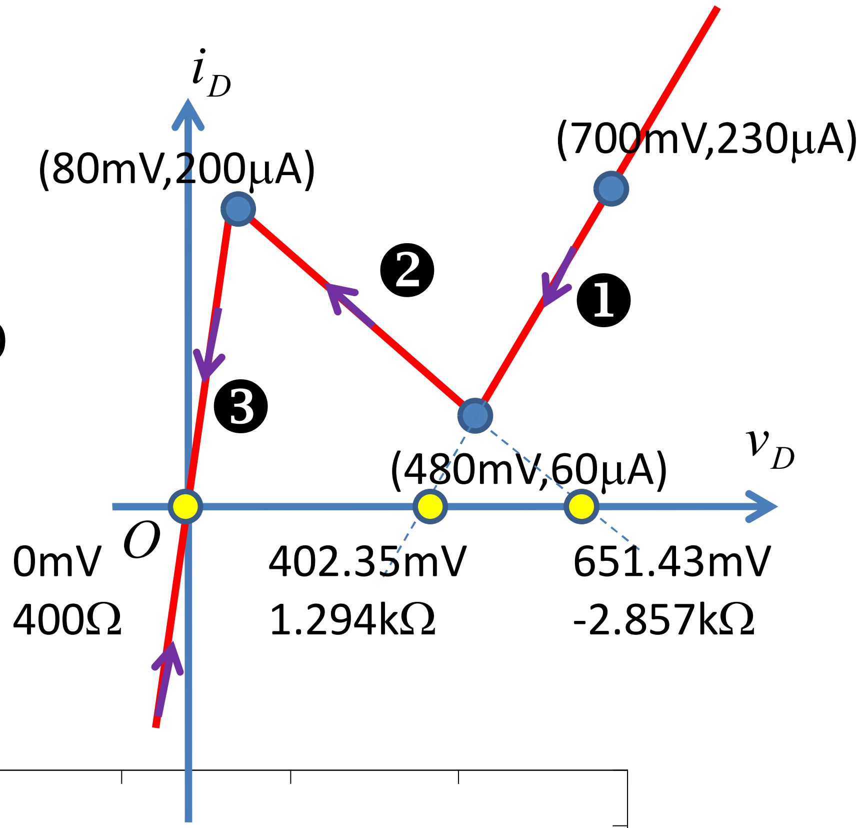
$$2.641ms \ge t \ge 0$$

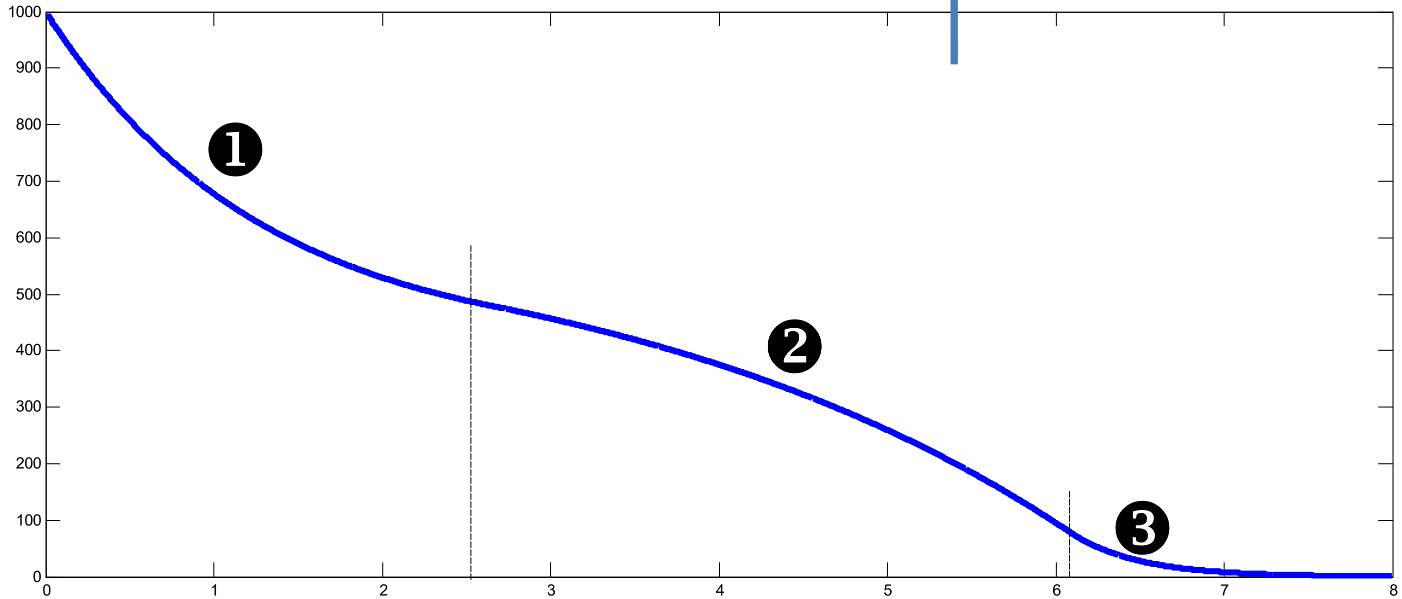
$$v_{C2}(t) = 651.43 - 171.43e^{\frac{t-2.641ms}{2.857ms}}$$

$$6.081ms \ge t \ge 2.641ms$$

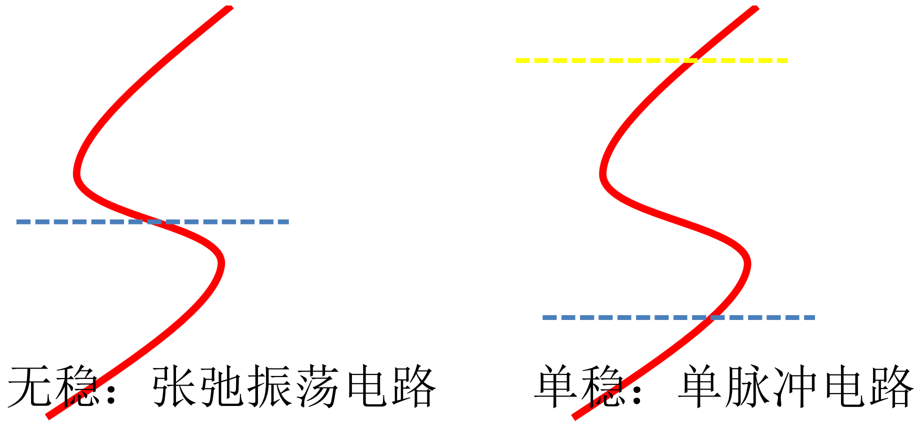
$$v_{C3}(t) = 80e^{-\frac{t-6.081ms}{0.4ms}}$$

$$t \ge 6.081ms$$

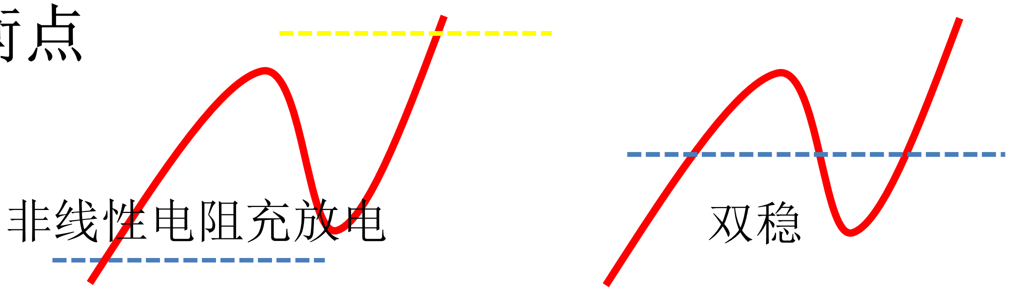




结论



- **S型负阻+电容**
  - 直流工作点在负阻区，张弛振荡：无稳
    - 只有一个不稳定平衡点
  - 直流工作点在正阻区：单稳
    - 只有一个稳定平衡点



- **N型负阻+电容**
  - 有一个稳定平衡点：非线性电阻的充放电
  - 有一个不稳平衡点，两个稳定平衡点：双稳