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$$V = V_-$$

$$V_+ = V_x \frac{R_2}{R_1 R_2}$$

$$V_0 = V_x \frac{R_4}{R_3 R_4}$$

$$C = 1 \mu F$$

$$R_f = 0.5 k\Omega$$

$$R_1 = 2.2 k\Omega$$

$$R_3 = 1 k\Omega$$

$R_2, R_4 \rightarrow$  variable

if  $V_+ > V_-$   $V_x = 12$

$$V_+ = V_x \frac{R_2}{R_1 + R_2} = 12 \frac{R_2}{R_1 + R_2}$$

limit values for  $V_+$

if  $V_- > V_+$   $V_x = -12$

$$V_+ = V_x \frac{R_2}{R_1 + R_2} = -12 \frac{R_2}{R_1 + R_2}$$

$$I_c = -I_x$$

$$C \frac{dV}{dt} = - \left[ \frac{V - V_x}{R_f} \right]$$

$$\Rightarrow C \frac{dV}{dt} + \frac{V}{R_f} = \frac{V_x}{R_f}$$

$$\frac{dV}{dt} + \frac{V}{CR_f} = \frac{V_x}{CR_f}$$

differential equation

\* Assume,  $V = V_- = -12 \frac{R_2}{R_1 + R_2}$  and  $V_+ = 12 \frac{R_2}{R_1 + R_2} \Rightarrow V_+ > V_- \Rightarrow V_x = 12$   
 $t=0$

then  $\frac{dV}{dt} + \frac{V}{CR_f} = \frac{12}{CR_f}$   
 $V(0) = -12 \frac{R_2}{R_1 + R_2}$

solution  $V = -12 \frac{R_2}{R_1 + R_2} e^{-\frac{t}{CR_f}} + 12 \left( 1 - e^{-\frac{t}{CR_f}} \right)$

for  $0 < t < t_1$

let at  $V(t_1) = 12 \frac{R_2}{R_1 + R_2} = V_+ \Rightarrow$

$$V(t) = 12 \frac{R_2}{R_1 + R_2} = -12 \frac{R_2}{R_1 + R_2} e^{-\frac{t_1}{CR_f}} + 12 \left[ 1 - e^{-\frac{t_1}{CR_f}} \right]$$

$$12 e^{-\frac{t_1}{CR_f}} \left[ 1 + \frac{R_2}{R_1 + R_2} \right] = 12 \frac{R_1}{R_1 + R_2} \Rightarrow e^{-\frac{t_1}{CR_f}} = \frac{R_1}{R_1 + 2R_2}$$

$$-\frac{t_1}{CR_F} = \ln \frac{R_1}{R_1 + 2R_2}$$

$$\frac{t_1}{CR_F} = \ln \frac{R_1 + 2R_2}{R_1}$$

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$$t_1 = CR_F \ln \frac{2R_2 + R_1}{R_1}$$

\*\*\* at  $t = t_1$   $V_- = 12 \frac{R_1}{R_1 + R_2} \geq V_T$  hence  $V_x$  becomes  $-12$  Volt ( $V_x = -12$  Volt)  
if  $V_x = -12 \Rightarrow V_T = -12 \frac{R_2}{R_1 + R_2}$

then

$$\frac{dV}{dt} + \frac{V}{CR_F} = \frac{-12}{CR_F}$$

$$V(t_1) = 12 \frac{R_2}{R_1 + R_2}$$

solution  $\Rightarrow$

$$V = 12 \frac{R_2}{R_1 + R_2} e^{-\frac{(t-t_1)}{CR_F}} - 12 \left[ 1 - e^{-\frac{(t-t_1)}{CR_F}} \right]$$

for  $t_1 \leq t < t_2$

Let at  $V(t_2) = -12 \frac{R_2}{R_1 + R_2} = V_T$

$$V(t_2) = -12 \frac{R_2}{R_1 + R_2} = 12 \frac{R_2}{R_1 + R_2} e^{-\frac{(t_2-t_1)}{CR_F}} - 12 \left[ 1 - e^{-\frac{(t_2-t_1)}{CR_F}} \right]$$

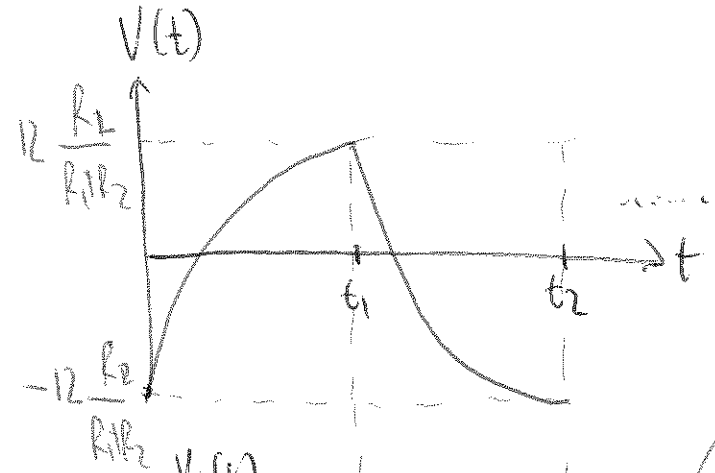
$$12 \left[ 1 - \frac{R_2}{R_1 + R_2} \right] = 12 e^{-\frac{(t_2-t_1)}{CR_F}} \left[ \frac{R_2}{R_1 + R_2} + 1 \right]$$

$$\frac{R_1}{R_1 + R_2} = e^{-\frac{(t_2-t_1)}{CR_F}} \frac{2R_2 + R_1}{R_1 + R_2}$$

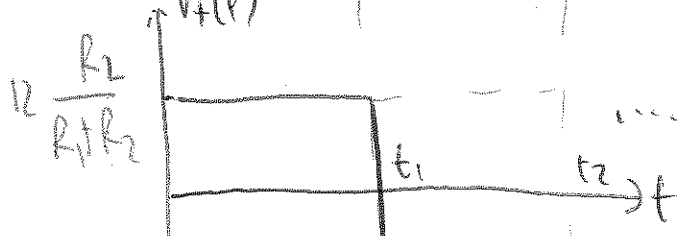
$$-\frac{(t_2-t_1)}{CR_F} = \ln \frac{R_1}{R_1 + R_2} \quad \frac{t_2-t_1}{CR_F} = \ln \frac{R_1 + 2R_2}{R_1}$$

$$t_2 = t_1 + CR_F \ln \frac{R_1 + 2R_2}{R_1} \Rightarrow t_2 = 2t_1$$

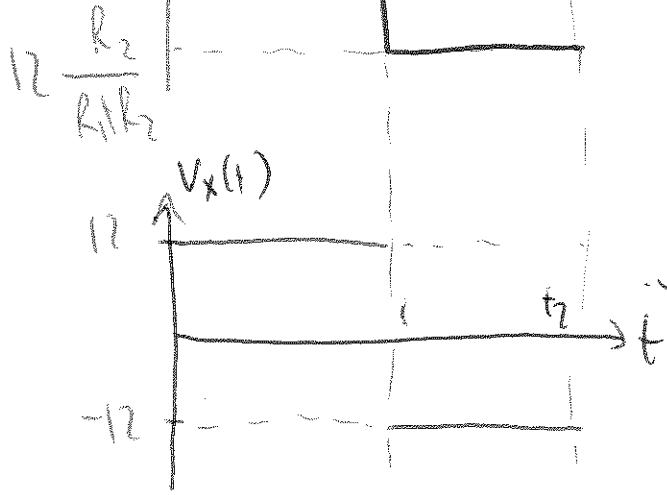
Let's draw  $V$ ,  $V_+$ ,  $V_x$  and  $V_o$  when  $0 < t < t_2$ ; then these signals will continue periodically with period  $t_2$



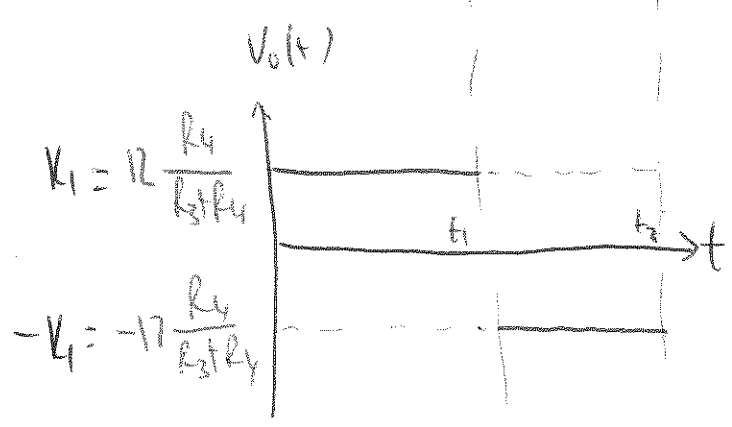
As seen  $V_+$  is a square wave (oscillator)



$V_x(t)$  is a square wave (oscillator)



$V_o(t) = V_x(t) \frac{R_4}{R_3 + R_4}$   
 ↓  
 another square wave (oscillator)



$$t_2 = 2t_1 = 2CR_F \ln \frac{R_1 + 2R_2}{R_1} = T$$

$T = \text{period of } V_o(t) = t_2$   
 $K_1 = 12 \frac{R_4}{R_3 + R_4} = \text{amplitude of } V_o(t)$

$V_o(t)$  is a square oscillator

assume  $K_1 = 2$  Volt [amplitude of square wave]  
 Volt

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$$K_1 = 12 \frac{R_4}{R_3 + R_4} = 2$$

$$\frac{R_4}{R_3 + R_4} = \frac{1}{6}$$

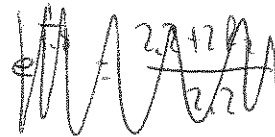
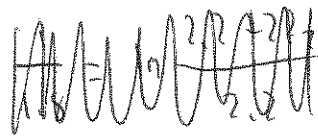
$$6R_4 = R_3 + R_4 \rightarrow R_4 = \frac{R_3}{5}$$

$$R_4 = \frac{1k\Omega}{5} = 200\Omega \quad (R_4 \text{ should be adjusted such that } R_4 \approx 200\Omega)$$

(use 1k pot for  $R_4$ )

assume  $f = 500$  Hertz  $T = \frac{1}{f} = \frac{1}{500} = t_2 = 2CR_f \ln \frac{R_1 + 2R_2}{R_1}$

$$\frac{1}{500} = 2 \times 10^{-6} \times 0.5 \times 10^3 \times \ln \frac{2.2 + 2R_2}{2.2}$$



$$2 = \ln \frac{2.2 + 2R_2}{2.2}$$

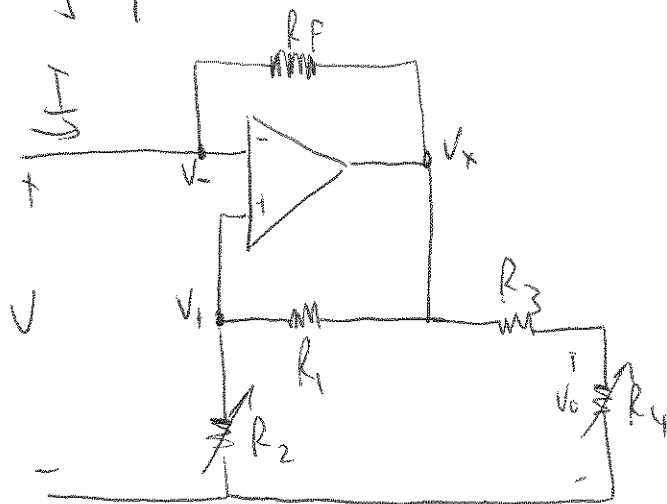
$$e^2 = \frac{2.2 + 2R_2}{2.2}$$

$$2.2e^2 - 2.2 = 2R_2$$

$$R_2 = \frac{2.2[e^2 - 1]}{2} = 1.1[e^2 - 1] \text{ k}\Omega = 7.026 \text{ k}\Omega$$

(For  $R_2$  use 10k pot)

Driving point characteristics



\* if  $V_x = 12$   $V_+ = 12 \frac{R_2}{R_1 + R_2}$  assume  $V = V_- < V_+$  but increase  $[V = V_-]$

$$I = \frac{V - V_x}{R_f} = \frac{V - 12}{R_f}$$

The current value when  $V = V_- = 12 \frac{R_2}{R_1 + R_2}$

$$I = \frac{12 \frac{R_2}{R_1 + R_2} - 12}{R_f} = -12 \frac{R_1}{R_f (R_1 + R_2)} \text{ Ampere}$$

when  $V > 12 \frac{R_2}{R_1 + R_2}$   $V_- > V_+$  and hence  $V_x = -12 \Rightarrow V_+ = -12 \frac{R_2}{R_1 + R_2}$

then  $I = \frac{V - V_x}{R_f} = \frac{V - (-12)}{R_f} = \frac{V + 12}{R_f}$

\*\* if  $V_x = -12$   $V_+ = -12 \frac{R_2}{R_1 + R_2}$  assume  $V = V_- > V_+$  but decrease  $[V = V_-]$

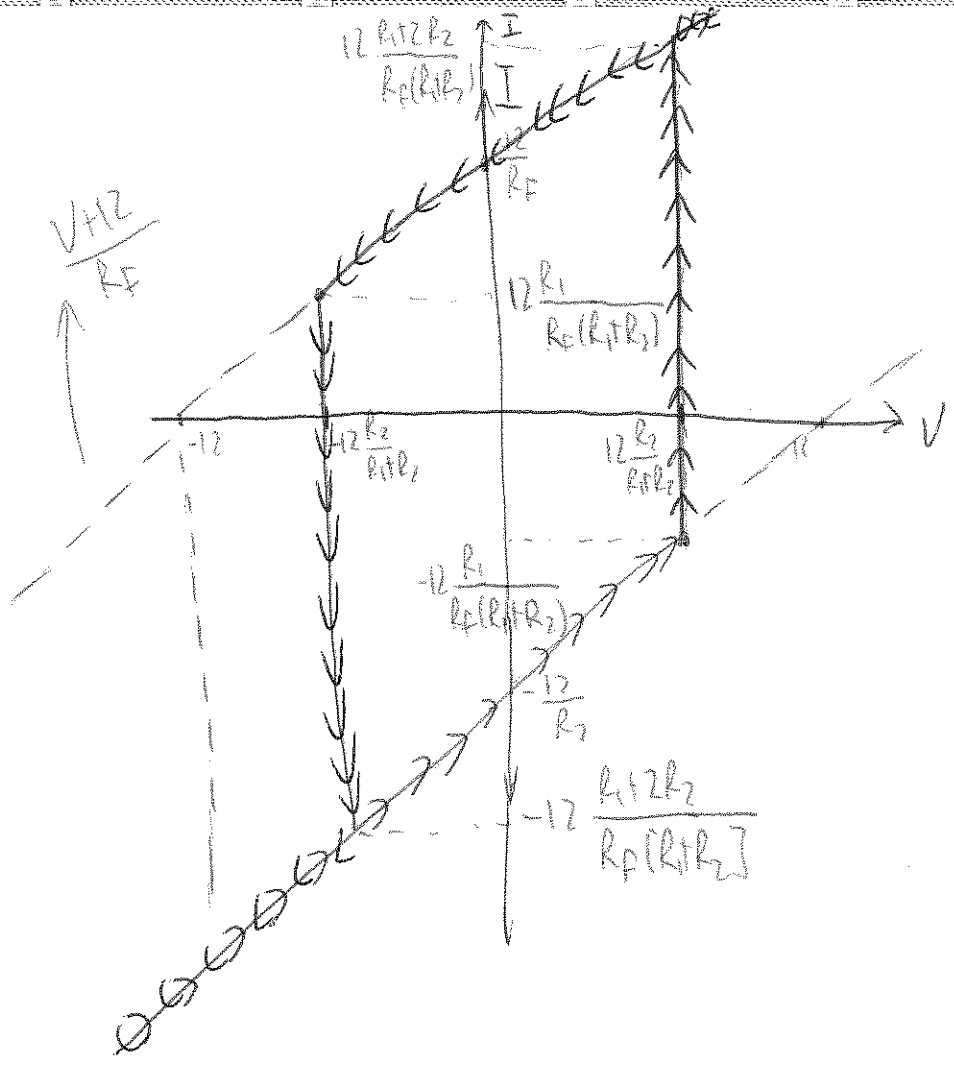
$$I = \frac{V - V_x}{R_f} = \frac{V - (-12)}{R_f} = \frac{V + 12}{R_f}$$

The current value  $V = V_- = -12 \frac{R_2}{R_1 + R_2}$

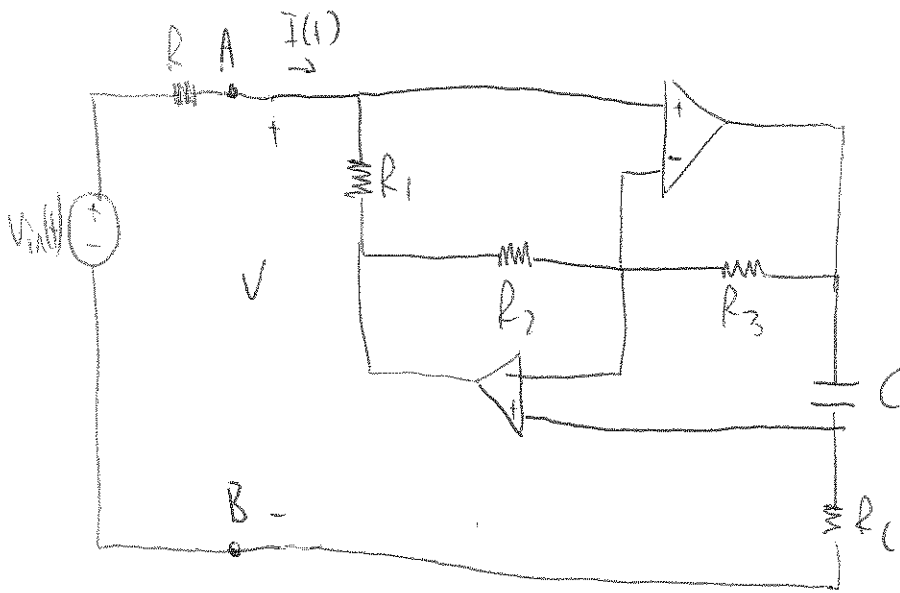
$$I = \frac{-12 \frac{R_2}{R_1 + R_2} + 12}{R_f} = \frac{12 R_1}{R_f (R_1 + R_2)} \text{ Ampere}$$

when  $V < -12 \frac{R_2}{R_1 + R_2}$   $V_- < V_+$  and hence  $V_x = +12 \Rightarrow V_+ = 12 \frac{R_2}{R_1 + R_2}$

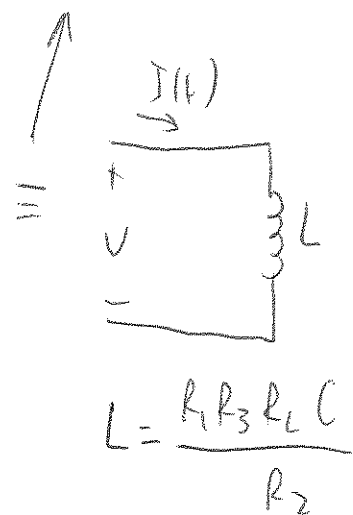
then  $I = \frac{V - V_x}{R_f} = \frac{V - 12}{R_f}$



$\frac{V-I_2}{R_F}$



equivalence

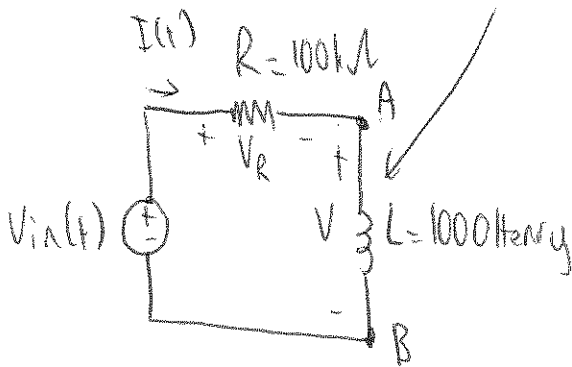


$$V = L \frac{dI}{dt}$$

$$R_1 = R_2 = R_3 = R_L = 10 \text{ k}\Omega$$

$$C = 10 \text{ nF}$$

$$L = \frac{10 \times 10^3 \times 10 \times 10^3 \times 10 \times 10^3 \times 10 \times 10^{-6}}{10 \times 10^3} = 1000 \text{ Henry}$$



$$V_{in} = V_R + V$$

$$V_{in} = 10^5 \times I + 10^3 \frac{dI}{dt}$$

$$\frac{dI}{dt} + 100I = \frac{V_{in}}{1000}$$

$$\Rightarrow \tau = \frac{L}{R} = \frac{1000}{10^5} = 0.01$$

time constant

$V_{in}(t) \Rightarrow$  Square wave with 2 Volt peak-to-peak value and 1 volt DC offset with frequency = 10 Hertz

$$f = 10 \text{ Hertz} \quad T = 0.1 \text{ sec}$$

$T \gg \tau$  (hence system goes to steady-state)

$\downarrow$  period of square wave  
 $\downarrow$  time constant

$0 < t < \frac{T}{2}$ ,  $V_{in}(t) = 2 \text{ Volt}$  [  $1 + 1 \rightarrow$  <sup>peak value</sup> DC offset ],  $I_0 = \frac{0}{10^3} = 0 \text{ Amper}$   
 $I(t) = -\frac{2}{10^3} e^{-\frac{t}{\tau}} + \frac{2}{10^3} [1 - e^{-\frac{t}{\tau}}]$   $I_f = \frac{2}{10^3} \text{ Amper}$

$\frac{T}{2} < t < T$ ,  $V_{in}(t) = -2 \text{ Volt}$  [  $-1 + 1 \rightarrow$  <sup>negative-peak</sup> DC offset ],  $I_0 = \frac{2}{10^3} \text{ Amper}$   
 $I(t) = \frac{2}{10^3} e^{-\frac{(t - \frac{T}{2})}{\tau}} + 0 [1 - e^{-\frac{t}{\tau}}]$   $I_f = 0 \text{ Amper}$

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