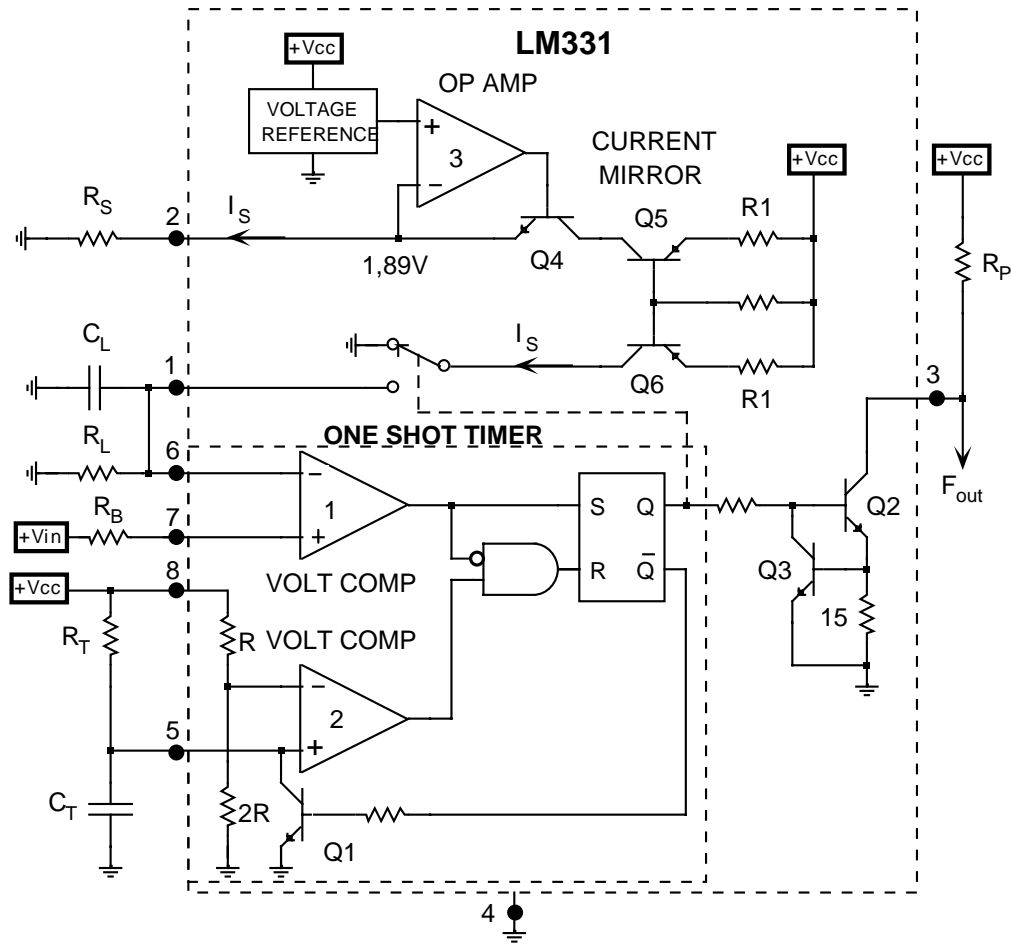
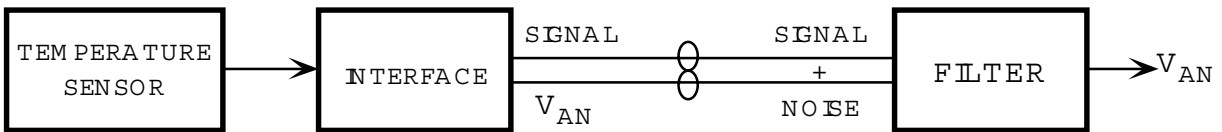


VOLTAGE-TO-FREQUENCY CONVERTER

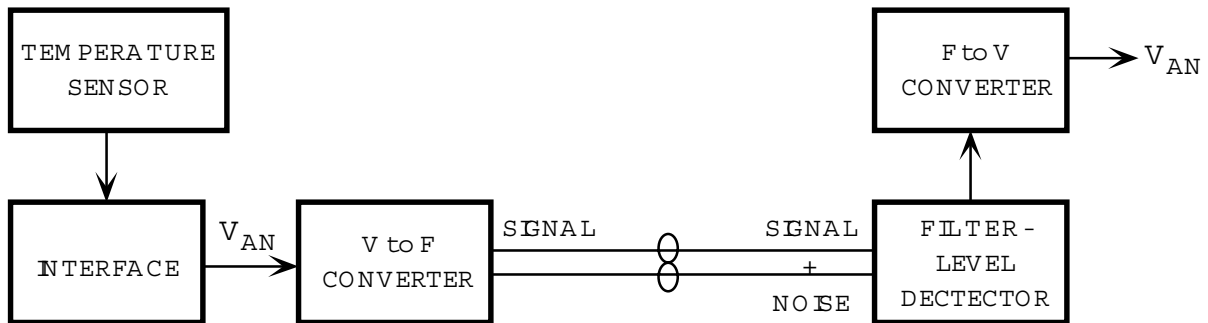
Internal circuit of LM331 IC



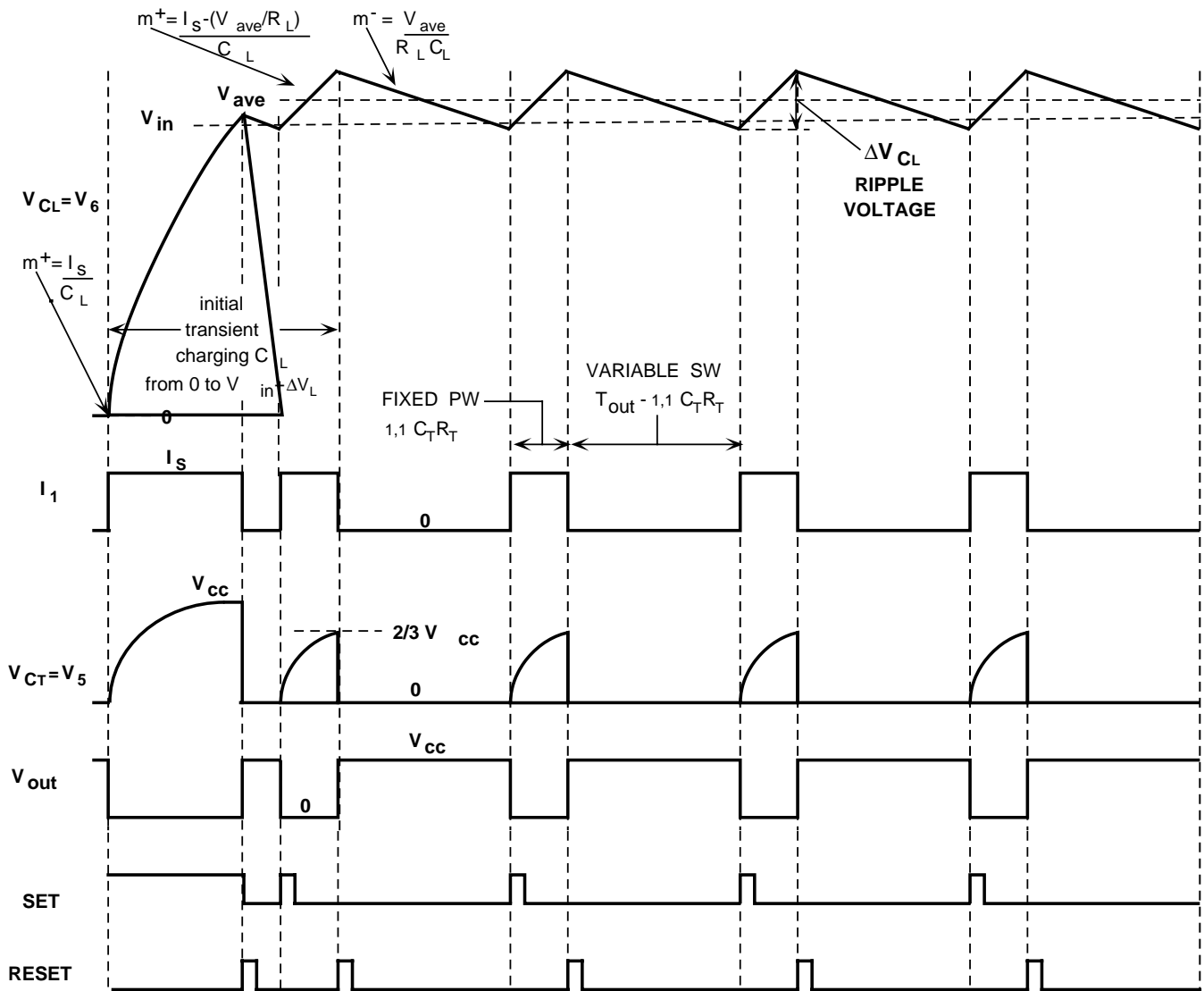
In direct transmission of an analog signal (below), V_{AN} will be more easily corrupted by noise.



By converting V_{AN} to a large signal whose frequency is proportional to V_{AN} , the transmission of the signal becomes much less corruptible by external noise.



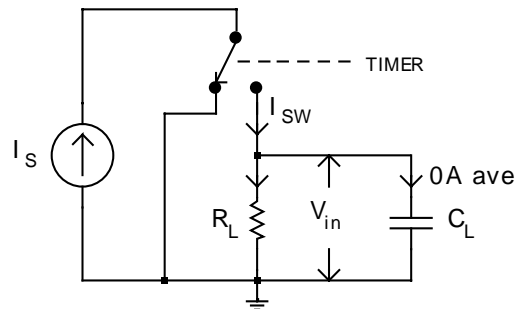
Timing Diagram



The DC current, or average current, through capacitor C_L is 0A once the V_{CL} waveform has settled.

$$I_{SW(ave)} = I_{R_L(ave)} + I_{C_L(ave)}$$

$$\frac{PW}{T} \times I_S = \frac{V_{in} + 0,5 \Delta V_{C_L}}{R_L} + 0 \approx \frac{V_{in}}{R_L} \quad \text{if } V_{in} \gg \Delta V_{C_L}$$



$$F_{out} = \frac{1}{T_{out}} \approx \frac{V_{in}}{I_S R_L \times PW} = \frac{V_{in} \times R_S}{V_{ref} R_L \times \ln(3) \times R_T C_T} = \frac{V_{in} \times R_S}{2,09 \times R_L \times R_T C_T}$$

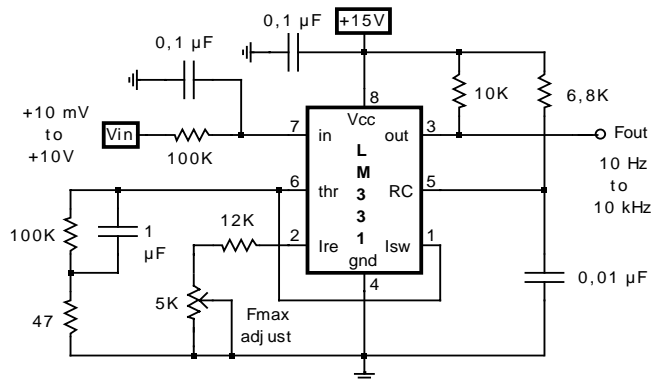
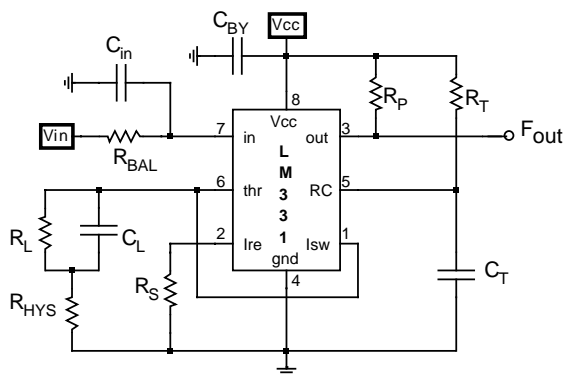
$$\Delta V_L = PW \times m^+ = PW \times \left(\frac{I_S - V_{in}/R_L}{C_L} \right) = SW \times m^- = (T - PW) \times \left(\frac{V_{in}}{R_L C_L} \right)$$

V to F Converter

NOTE: To obtain good linearity at low values of V_{in} , the ripple voltage ΔV_L must be very small which means that the time constant $R_L C_L$ must be very large and this makes the converter very slow to react to changes of V_{in} . When ripple is very small, the frequency of the V to F depends on a very small signal easily corruptible with noise or spurious signals which may result in an erratic O/P frequency.

For small values of V_{in} , the equation derived for F_{out} is not accurate because ripple must be factored in and F_{out} becomes a non-linear function of V_{in} .

Basic V-F Converter



From $F_{out} = \frac{V_{in} \times R_S}{2,09 \times R_L \times R_T C_T}$ we find that $R_S = 14212$ will produce a 10 kHz full scale output given the

standard values on the diagram. The 5k pot will have to be adjusted to some other value because of component tolerance.

$PW = 1,1 R_T C_T = 1,1 * 6800 * 0,01 \mu = 74,8 \mu s$ fixed $I_S = 1,89V / 14212 \Omega = 133 \mu A$
 For $F = 10 \text{ Hz to } 10 \text{ kHz}$, duty Cycle = $74,8 \mu / (0,1 \text{ to } 100 \mu) * 100 = 0,0748\% \text{ to } 74,8\%$

NOTE: PW and duty cycle refer to the switched current source I_{sw} (pin#1). The duty cycle of the output waveform is inverted, that is $D/C_{out} = 99,925\% \text{ to } 25,2\%$. $V_{O^+} \approx +15V$ and $V_{O^-} \approx 0V$

Ripple Voltage

$$\Delta V_L = PW \times m^+ = PW \times \frac{I_C}{C_L} = 74,8 \mu \times \left(\frac{133 \mu - (10m \rightarrow 10) / 100k}{1 \mu} \right) = 9,94m \rightarrow 2,47mV_{pp}$$

NOTE: Those small ripple values make the V to F vulnerable to noise and unreliable operation may result.

At 10 Hz the discharge of C_L is not linear (it is exponential) because $R_L C_L = 0,1s = T \approx SW$.

The speed of the V-F converter is determine by the time constant $R_L C_L$. For the above circuit, the rise time of V_{thr} is : $t_r = 0,35 / (F_c) = 0,35 * 2\pi * R_L C_L = 0,22s$ which is rather slow.

For a faster response of V_{thr} (and F_{out}) $R_L C_L$ should be made smaller but this will entail more ripple voltage across C_L and therefore less accuracy at low V_{in} and F_{out} values.

Hysteresis

The amount of hysteresis of the input comparator, for clean and faster switching (no crossover oscillations), is $\Delta V_{HYS} = I_S R_{HYS} = 133 \mu * 47 = 6,25 \text{ mV}$ - this will impair low V_{in} operation.

Choice of $R_{in}C_{in}$

The input RC low-pass filter produces a cutoff frequency of $F_c = (2\pi \cdot 100k \cdot 0,1\mu)^{-1} = 15,9$ Hz.

It is used to filter down any HF noise that contaminates the DC input voltage. If the input DC voltage is changed abruptly to a new value, the LM331 input (V_{in} at pin 7) will settle to its new value in about $5R_{in}C_{in} = 5 \cdot 100K \cdot 0,1\mu = 50$ ms. Therefore the response time of the output frequency will be the compounded value of t_r of V_{in} + t_r of V_{thr} .

Choice of $R_T C_T$

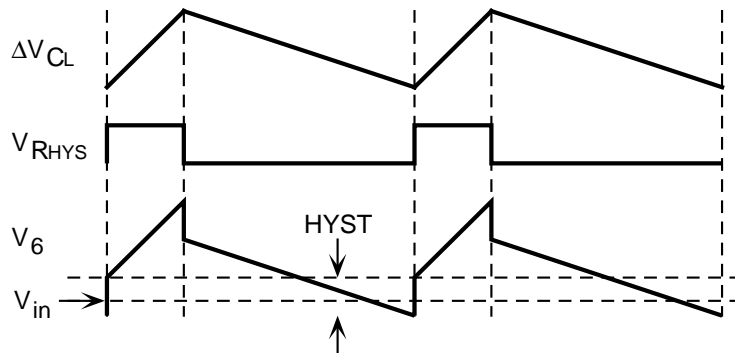
Maximum duty cycle $(PW/T) \cdot 100 = 1,1 R_T C_T \cdot F_{max} < 95\%$ and should leave enough time for the internal circuit to reset when $SW = T - PW$ becomes very small. PW should not be too small either.

Choice of $R_L C_L$

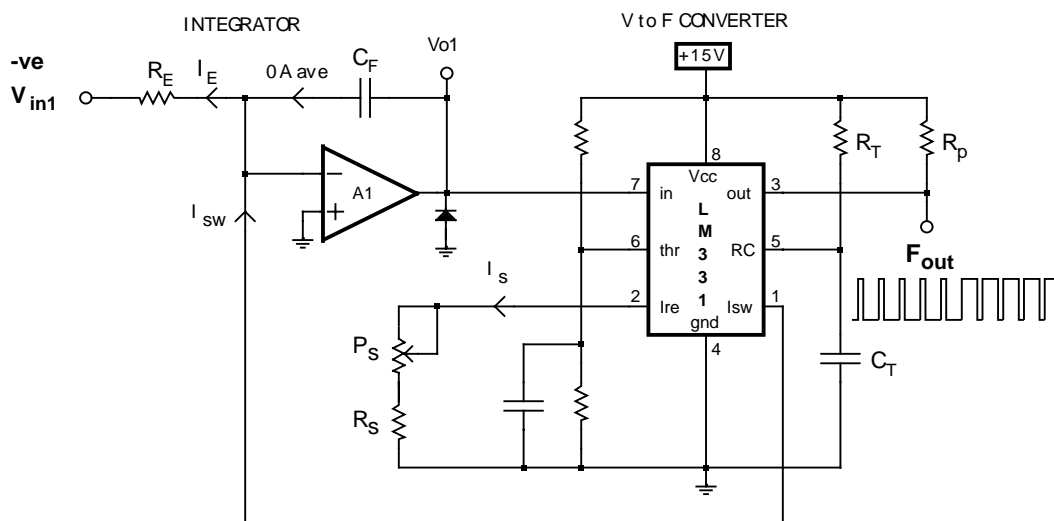
Select $R_L C_L$ for desired maximum ripple $\Delta V_L = PW \times \left(\frac{I_s - V_{in}/R_L}{C_L} \right) = (T - PW) \times \left(\frac{V_{in}}{R_L C_L} \right)$

and for desired rise time of V_{thr} : $t_r = 0,35 \cdot 2\pi \cdot R_L C_L$

Waveforms showing effect of hysteresis provided by R_{HYS} on V_6 waveform. When V_{in} is detected by the comparator, V_6 pulls up abruptly to prevent oscillations (chattering) at the internal comparator output.



IMPROVED V to F CONVERTER



V to F Converter

The above converter has a very linear V to F characteristic because its output frequency is totally independent of the ripple voltage present at V_{in} (pin 7) of the LM331. For fast and reliable operation of the V to F converter, C_F can be made very small in order to get substantial ripple - $1V_{pp}$ recommended

Converter equations

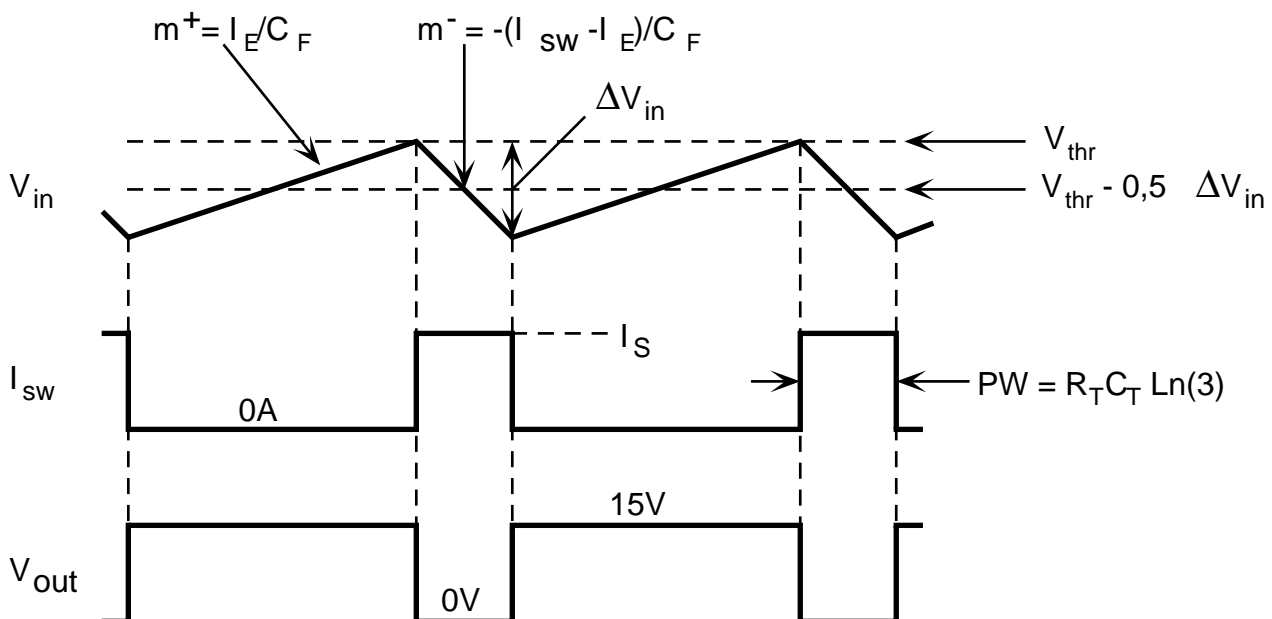
$$I_{sw} = I_S \times \frac{PW}{T} = I_E + I_{C_F ave} = I_E = \frac{-V_{in}}{R_E}$$

$$I_S \times \frac{PW}{T} = \frac{-V_{in}}{R_E} \Rightarrow \frac{V_{ref}}{R_S + P_S} \times \ln(3) \times R_T C_T \times F_{out} = \frac{-V_{in}}{R_E}$$

$$F_{out} = \frac{1}{T} = \frac{-V_{in} \times (R_S + P_S)}{V_{ref} R_E \times \ln(3) \times R_T C_T} = \frac{-V_{in} \times (R_S + P_S)}{R_E \times 1.89 \times 1.1 \times R_T C_T}$$

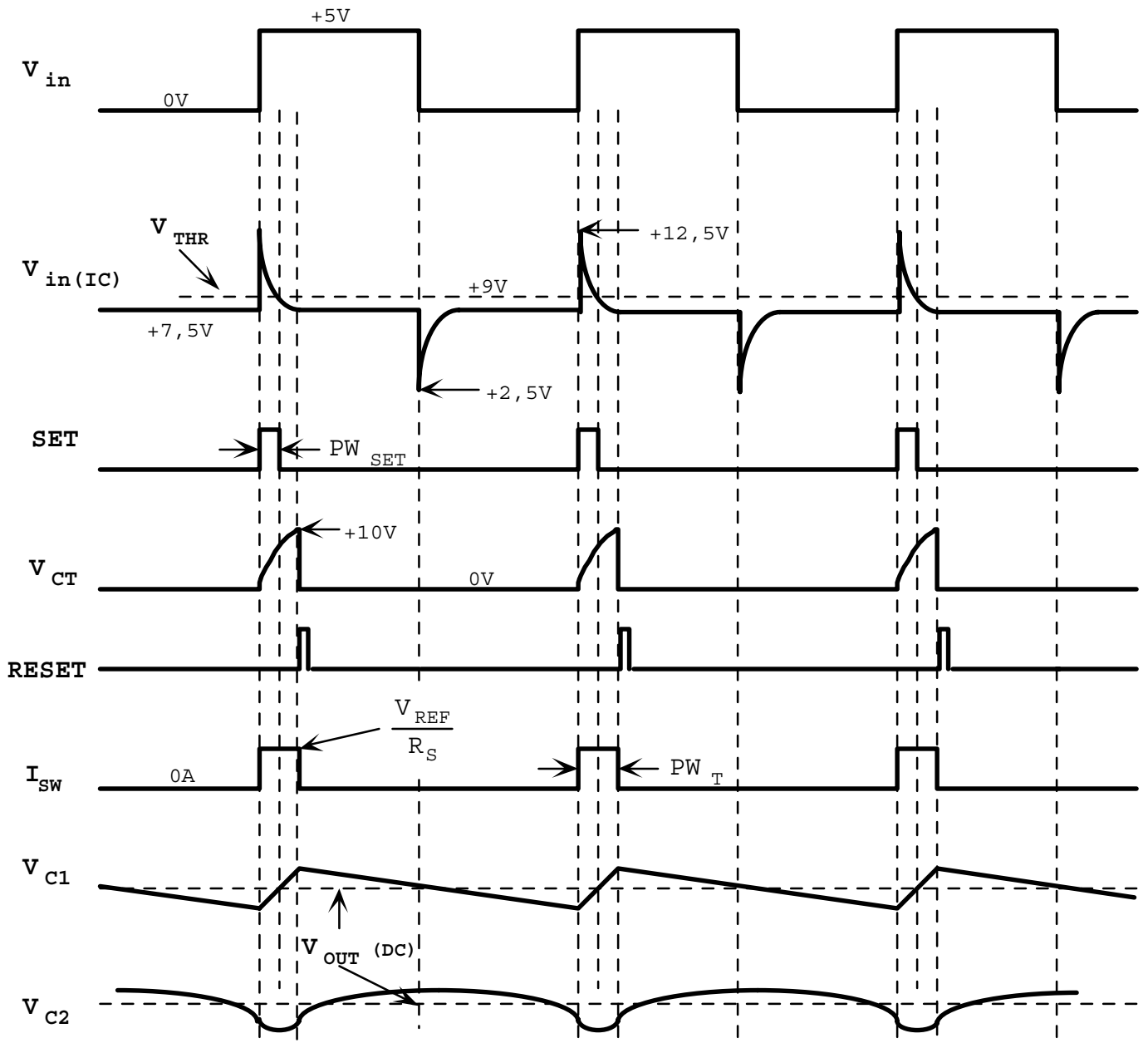
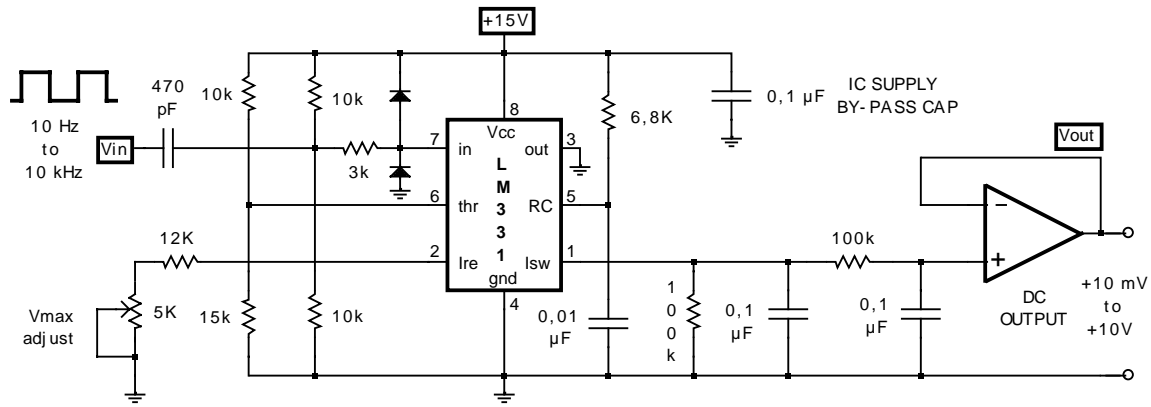
$$\Delta V_{in} = \frac{I_E}{C_F} \times (T - PW) = \frac{(I_{sw} - I_E)}{C_F} \times PW$$

The basic waveforms are shown below.



The output frequency can be made to respond very rapidly to an abrupt change in V_{in} by selecting a small value for C_F which entails a large ripple voltage for V_{in} of LM331.

BASIC F TO V CONVERTER



The DC output voltage is :

$$V_{out(ave)} = I_{SW(ave)} \times R_L = I_S \left(\frac{PW}{T_{in}} \right) \times R_L = \frac{V_{ref}}{R_S} \times 1,1 R_T C_T F_{in} \times R_L = \frac{2,09 \times R_T C_T F_{in} \times R_L}{R_S}$$

The output ripple voltage is given by - see appendix for derivation:

$$\Delta V_{out(pp)} = \frac{I_S R_L}{8} \times \left(\frac{PW}{R_L C_L} \right)^2 \times \left(\frac{1}{F \times PW} - 1 \right) \text{ for } F > (10\pi R_L C_L)^{-1}$$

The output filter has the following TF:

$$F(S) = \frac{1}{R^2 C^2 S^2 + 3RCS + 1} = \frac{(R^2 C^2)^{-1}}{S^2 + \frac{3}{RC} S + \frac{1}{R^2 C^2}} = \frac{(R^2 C^2)^{-1}}{\left(S + \frac{0,382}{RC} \right) \times \left(S + \frac{2,618}{RC} \right)}$$

The above TF allows us to determine the rise and fall times of V_{out} in response to an input frequency jump. The approximate value can be determined from the first cutoff frequency:

$$t_r = t_f \approx \frac{0.35}{F_{c1}} = \frac{0.35}{\left(\frac{0.382}{2\pi RC} \right)} = 5.757 \times RC$$

The internal latch SET pulsewidth (PW_{set}) must be less than the current pulsewidth $PW_T = 1,1 R_T C_T$, otherwise the circuit will not work properly. PW_{set} is determined by the input coupling capacitor and the input resistance $10K \parallel 10K$.

$$PW_{SET} = R_{in} C_{in} \times Ln \left(\frac{V_1 - V_F}{V_2 - V_F} \right) = 5K \times 470p \times Ln \left(\frac{12.5 - 7.5}{9 - 7.5} \right) = 2.83 \mu s$$

$$PW_T = 1,1 \times R_T C_T = 1,1 \times 6.8K \times 0.01\mu = 74.8 \mu s$$

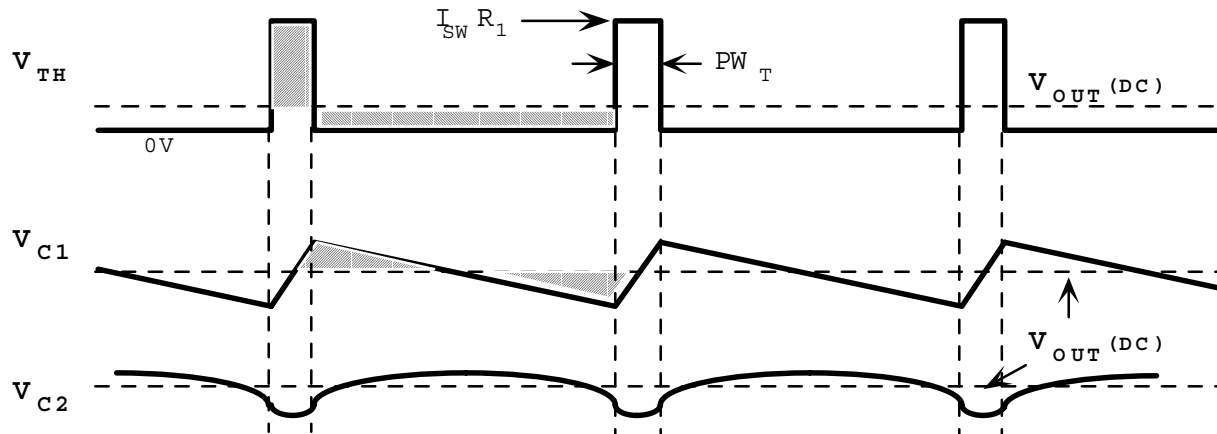
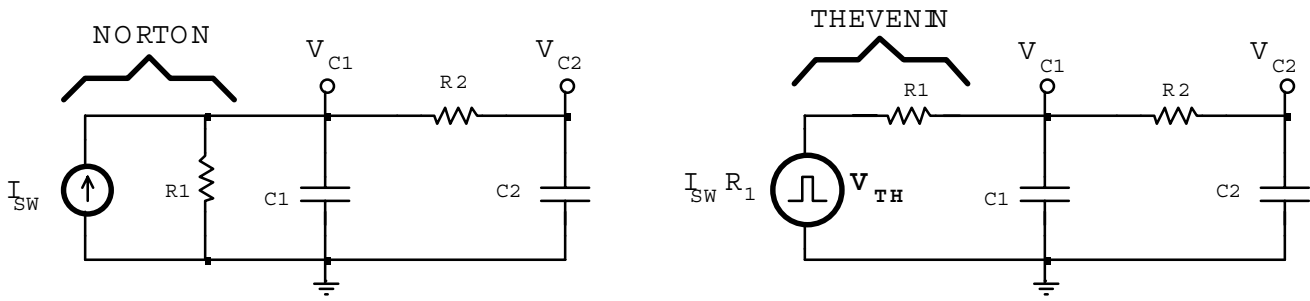
NOTE: $PW_{set} = 2.83 \mu s$ may not be long enough to set the internal RS latch - minimum time not specified.

NOTE: If the input square wave has a large amplitude, the protection diodes will turn on and the exponential pulses at the junction of the two 10K resistors will have two time constants, that is:

$$(10K \parallel 10K + 3K) \times 470p \quad \text{when one of the diodes is ON}$$

$$(10K \parallel 10K) \times 470p \quad \text{when the diodes are OFF.}$$

APPENDIX 1 Derivation Of Output Ripple Voltage



$$\Delta V_{C_1 (PP)} = \frac{1}{R_1 C_1} \int_{t_1}^{t_2} V_{TH(AC)} dt = \frac{1}{R_1 C_1} \times PW \times (I_S R_1 - V_{ave}) = \frac{1}{R_1 C_1} \times PW \times \left(I_S R_1 - I_S R_1 \left(\frac{PW}{T} \right) \right)$$

$$\Delta V_{C_1 (PP)} = \frac{1}{R_1 C_1} \times PW \times I_S R_1 \left(1 - \left(\frac{PW}{T} \right) \right) = \frac{1}{R_1 C_1} \times PW^2 \times I_S R_1 \left(\frac{1}{PW} - \frac{1}{T} \right)$$

$$\Delta V_{C_2 (PP)} = \frac{1}{R_2 C_2} \int_{t_1}^{t_2} V_{C_1 (AC)} dt = \frac{1}{R_1 C_1} \times \left(\frac{1}{2} \times \Delta V_{C_1 (PP)} \times \frac{T}{2} \times \frac{1}{2} \right) = \frac{1}{R_1 C_1} \times \left(\Delta V_{C_1 (PP)} \times \frac{T}{8} \right)$$

$$\Delta V_{C_2 (PP)} = \frac{1}{R_1 C_1} \times \frac{T}{8} \times \left(\frac{1}{R_1 C_1} \times PW^2 \times I_S R_1 \left(\frac{1}{PW} - \frac{1}{T} \right) \right) = \frac{I_S R_1}{8} \times \left(\frac{PW}{R_1 C_1} \right)^2 \times \left(\frac{T}{PW} - 1 \right)$$

NOTE: $R_1 C_1 = R_2 C_2$