V to F Converter

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

\[
I_{SW(ave)} = I_{R_i}^{(ave)} + I_{C_L}^{(ave)}
\]

\[
\frac{PW}{T} \times I_S = \frac{V_{in} + 0.5\Delta V_{C_L}}{R_L} + 0 \approx \frac{V_{in}}{R_L} \text{ if } V_{in} \gg \Delta V_{C_L}
\]

\[
F_{out} = \frac{1}{T_{out}} \approx \frac{V_{in}}{I_S R_L \times PW} = \frac{V_{in} \times R_S}{V_{ref} R_L \times Ln(3) \times R_T C_T} = \frac{V_{in} \times R_S}{2.09 \times R_L \times R_T C_T}
\]

\[
\Delta V_L = PW \times m^+ = PW \times \left( \frac{I_S - V_{in} R_L}{C_L} \right) = SW \times m^- = (T - PW) \times \left( \frac{V_{in}}{R_L C_L} \right)
\]
NOTE: To obtain good linearity at low values of $V_{in}$, the ripple voltage $\Delta V_L$ 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.

$PW = 1.1 \times RT = 1.1 \times 6800 \times 0.01 \mu = 74.8 \mu s$ fixed $\quad I_S = 1.89V/14212\Omega = 133 \mu A$

For $F = 10$ Hz to 10 kHz, duty Cycle = $74.8\mu/(0.1$ to $100\mu) \times 100 = 0.0748\%$ 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 $D/C_{out} = 99.925\%$ to 25.2\%. $V_o^+ = +15V$ and $V_o^- = 0V$

**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 determined by the time constant $R_L C_L$. For the above circuit, the rise time of $V_{thr}$ is: $\quad t_r = 0.35/(C_F) = 0.35^* 2\pi R_L C_L = 0.22s$ 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 $\Delta V_{HYS} = I_S R_{HYS} = 133\mu * 47 = 6.25 mV$ - this will impair low $V_{in}$ operation.
Choice of $R_{\text{in}}C_{\text{in}}$

The input RC low-pass filter produces a cutoff frequency of $F_c = \left(2\pi \times 100k \times 0,1\mu \right)^{-1} = 15,9 \text{ Hz}$.
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 ($V_{\text{in}}$ at pin 7) will settle to its new value in about $5R_{\text{in}}C_{\text{in}} = 5 \times 100k \times 0,1\mu = 50 \text{ ms}$. Therefore the response time of the output frequency will the compounded value of $t_r$ of $V_{\text{in}} + t_r$ of $V_{\text{thr}}$.

Choice of $R_{\text{TCT}}$

Maximum duty cycle $(PW/T) \times 100 = 1,1 R_{\text{TCT}} \times F_{\text{max}} < 95\%$ 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 $R_LC_L$

Select $R_LC_L$ for desired maximum ripple $\Delta V_L = PW \times \left(\frac{I_s - V_{\text{in}}/R_L}{C_L} \right) = (T-PW) \times \left(\frac{V_{\text{in}}}{R_LC_L} \right)$
and for desired rise time of $V_{\text{thr}}$: $t_r = 0,35 \times 2\pi R_LC_L$

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

**IMPROVED V TO F CONVERTER**

- $\text{INTEGRATOR}$
- $\text{V to F CONVERTER}$

![Diagram of an improved V to F converter](image-url)
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**

$$I_{SW} = I_s \times \frac{PW}{T} = I_E + I_{C_F \text{ ave}} = I_E = \frac{-V_{in}}{R_E}$$

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

$$F_{out} = -V_{in} \times (R_S + P_S) \times R_E \times LN(3) \times R_T C_T \times R_E \times 1.89 \times 1.1 \times R_T C_T$$

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

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.
The DC output voltage is:

\[ V_{\text{out}}(\text{ave}) = I_s R_L = I_s \left( \frac{pW}{f_{\text{in}}} \right) \times R_L = \frac{V_{\text{ref}}}{R_s} \times \frac{1}{1.1} R_T C_T F_{\text{in}} \times R_L = \frac{2.09 	imes R_T C_T F_{\text{in}} \times R_L}{R_s} \]

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

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

The output filter has the following TF:

\[ F(S) = \frac{1}{R^2 C^2 S^2 + 3RCS + 1} = \frac{\left( R^2 C^2 \right)^{-1}}{S^2 + \frac{3}{RC} S + \frac{1}{R^2 C^2}} = \left( S + \frac{0.382}{RC} \right) \times \left( S + \frac{2.618}{RC} \right) \]

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

\[ t_r \approx t_f \approx \frac{0.35}{F_{\text{Cl}}} \approx \frac{0.35}{0.382} = 5.757 \times RC \]

The internal latch SET pulsewidth (PW\text{set}) must be less than the current pulsewidth PW\text{T} = 1.1 R_T C_T, otherwise the circuit will not work properly. PW\text{set} is determined by the input coupling capacitor and the input resistance 10K || 10K.

\[ PW_{\text{set}} = R_m C_m \times \ln \left( \frac{V_1 - V_F}{V_2 - V_F} \right) = 5 \times 470 \mu s \times \ln \left( \frac{12.5 - 7.5}{9 - 7.5} \right) = 2.83 \mu s \]

\[ PW_T = 1.1 \times R_T C_T = 1.1 \times 6.8 K \times 0.01 \mu s = 74.8 \mu s \]

NOTE: PW\text{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:

\[ (10K || 10K + 3K) \times 470 \mu s \] when one of the diodes is ON

\[ (10K || 10K) \times 470 \mu s \] when the diodes are OFF.
APPENDIX 1 Derivation Of Output Ripple Voltage

\[ \Delta V_{C1}(PP) = \frac{1}{R_1 C_1} \int_{t_1}^{t_2} V_{TH(AC)} \, dt = \frac{1}{R_1 C_1} \times PW \times (I_s R_1 - V_{ave}) = \frac{1}{R_1 C_1} \times PW \times (I_s R_1 - I_s R_1 \left( \frac{PW}{T} \right)) \]

\[ \Delta V_{C1}(PP) = \frac{1}{R_1 C_1} \times PW \times I_s R_1 \left( 1 - \left( \frac{PW}{T} \right) \right) = \frac{1}{R_1 C_1} \times PW^2 \times I_s R_1 \left( \frac{1}{PW} - \frac{1}{T} \right) \]

\[ \Delta V_{C2}(PP) = \frac{1}{R_2 C_2} \int_{t_1}^{t_2} V_{C1(AC)} \, dt = \frac{1}{R_1 C_1} \times \left( \frac{T}{2} \times \Delta V_{C1(PP)} \times \frac{T}{2} \times \frac{1}{2} \right) = \frac{1}{R_1 C_1} \times \left( \Delta V_{C1(PP)} \times \frac{T}{8} \right) \]

\[ \Delta V_{C1}(PP) = \frac{1}{R_1 C_1} \times \frac{T}{8} \times \left( \frac{1}{R_1 C_1} \times PW^2 \times I_s R_1 \left( \frac{1}{PW} - \frac{1}{T} \right) \right) = \frac{1}{R_1 C_1} \times \left( \frac{PW}{R_1 C_1} \right)^2 \times \left( \frac{T}{PW} - 1 \right) \]

NOTE: \( R_1 C_1 = R_2 C_2 \)