SQUARE-WAVE GENERATOR

by M. Clarkson

Many circuits nowadays require a square-wave generator for which invariably a separate NE555 is used. Since many of such circuits frequently have an unused opamp or voltage comparator available, why not use that to build the square-wave generator?

If the circuit that requires a square-wave generator has a spare opamp or voltage comparator, the diagram in Fig. 1 may be used to realize the generator.

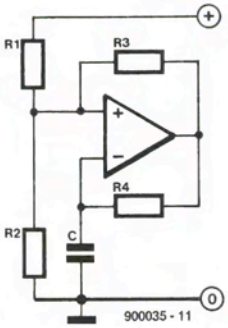

Fig. 1. Basic circuit of proposed square-wave generator.

The circuit works by capacitor C being charged and discharged to two different potentials created by R_1, R_2 and R_3. The time taken by C to reach the higher potential is the high period of the output, while that taken by C to discharge to the lower potential is the low period of the output.

To calculate the values of the circuit elements, we must simplify the circuit. Firstly, R_1 and R_2 can be reduced to their Thévenin equivalent as shown in Fig. 2.

When V_{out} is low, R_3 pulls V_{sense} to a lower voltage, V_{T-}. Capacitor C is then discharged via R_4 to the level of V_{T-}. When the potential across C, V_c, reaches V_{T-}, the output swings high. When V_{out} is high, R_3 pulls V_{sense} from V_{T-} to V_{T+}. Capacitor C then charges via R_4. As soon as V_c reaches V_{T+}, the output swings low and the cycle is completed.

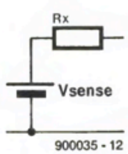

Fig. 2. Thévenin equivalent of R_1 and R_2.

If a spare opamp is used, the output frequency is limited to a range of 10 Hz to about 10 kHz, but this is sufficient for the majority of applications.

The two states of the circuit, ignoring R_4 and C, are shown in Fig. 3. The circuits in Fig. 3 enable us to calculate V_{T-} and V_{T+}:

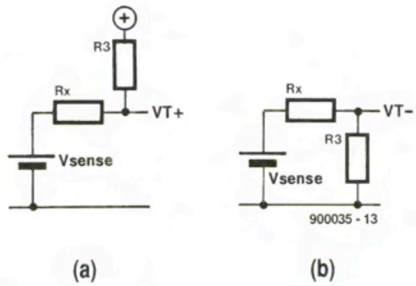

Fig. 3. The two equivalent states of the circuit: (a) ON state (C charges) and (b) OFF state (C discharges).

$$V_{T-} = V_s \times R_3 / (R_3 + R_x) \quad [1]$$

$$V_{T+} = (V+ - V_s) \times R_x(R_x + R_3) + V_s. \quad [2]$$

So far I have assumed that the opamp requires no bias current—see Fig. 4. This is not true and, although the current is generally small, it can affect the circuit to quite an extent if R_1 and R_2 are too large. It is necessary that the current flowing through R_1 and R_2, that is, $V_c / (R_1 + R_2)$, is large compared with the bias current of the opamp.

I have also assumed that the output of the opamp swings between 0 V and $V+$. However, most opamps have a limited swing: if the one you use can not swing to within 10% of the supply voltage, you must take that into account in the calculations.

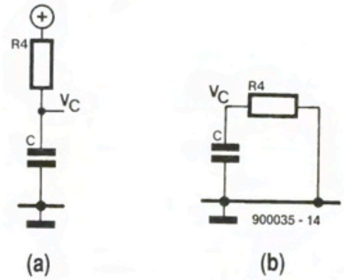

Fig. 4. The two states of R_4 and C: (a) ON state; (b) OFF state.

If, in Fig. 4., we make the difference between V_{T+} and V_{T-} small compared with $V+$, we may assume that C is charged and discharged at constant currents. The time, t, taken by a capacitor to charge at constant current is:

$$t = dVC / i, \quad [3]$$

where dV is the voltage C has to charge to and i is the charging current.

The charging current is $(V+ - V_c) / R_4$ and the discharge current is V_c / R_4.

If we want C to charge to V_{T+} and to discharge to V_{T-} in equal times, the charging and discharge currents must be equal, that is,

$$(V+ - V_c) / R_4 = V_c / R_4, \quad [4]$$

so that

$$V_c = V+ / 2 \qquad [5]$$

Voltage V_c is also equivalent to V_{sense}, that is, the mid-point between V_{T-} and V_{T+}.

To recap, I have said that the difference between V_{T-} and V_{T+} must be small compared with $V+$. This allows us to assume that a constant current flows through C.

Also, V_c must be equal to $V+/2$ to ensure that C is charged and discharged at the same rate.

Then, I have assumed that the output swings between 0 V and $V+$.

Furthermore, I have not taken into account the output resistance of the opamp. This is all right as long as R_3 and R_4 are sufficiently large.

Another aspect that must be borne in mind is the common-mode voltage, V_{cm}, of the opamp. As said, V_{sense} must be $V_c / 2$, which may be higher than V_{cm}.

Let us now calculate some circuit values: R_4 and C may be determined by deciding on the frequency, f, and the allowable charging current, i_c: $R_4 = V_c / 2i_c$, $f = 1 / T$, where $T = 2t$.

From [3] we obtain

$$C = it / dV.$$

In terms of frequency,

$$C = i / dV \times 2f, \qquad [6]$$

where dV is the difference between V_{T+} and V_{T-} and this must be small compared with $V+$. At the same time, it must be large compared with the offset voltage of the opamp. Since the offset voltage is usually about 5 mV, dV should be not less than 200 mV. It is calculated by subtracting [1] from [2], which yields:

$$dV = V+ \times R_x / (R_x + R_3). \qquad [7]$$

Since $V_{sense} = V_c = V+ / 2$, R_1 must be equal to R_2, so that $R_x = R_1 / 2$. From this it follows that

$$dV = V+ \times R_1 / (R_1 + 2R_3). \qquad [8]$$

The value of R_3 is then given by

$$R_3 = R_1 / 2\,(V+ / dV - 1) \qquad [9]$$

Resistor R_1 must be small enough to ensure that the current through R_1 and R_2 is large compared with the bias current, I_b, for the opamp, that is, $V+ / 2R_1 >> I_b$.

Let us now use a quarter of a Type LM339 voltage comparator as a practical example—see Fig. 5. The first thing to note is its open-collector output, which means that a pull-up resistor is required at the output. This resistor must be sufficiently small not to introduce any errors in our calculations.

The V_{cm} of the LM339 is greater than $V+ / 2$, assuming that $V+ = 5$ V. The bias current is around 0.25 µA, so that the current, i_c, through R_1 and R_2 may be set to 25 µA. We then obtain the folowing values:

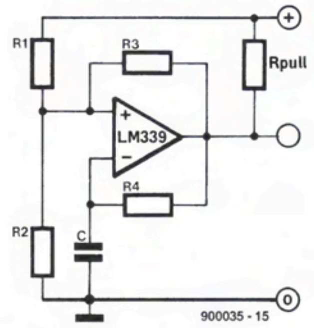

Fig. 5. Square-wave generator based on 1/4 Type LM339 voltage comparator

$$R_1 = V+ / 2i_c = 100\ \text{k}\Omega$$

$$R_2 = R_1 = 100\ \text{k}\Omega$$

Since the offset of the LM339 is <5 mV, we may take $dV = 200$ mV. Then, from [9],

$$R_3 = 1.2\ \text{M}\Omega$$

Assuming we want $f = 5$ kHz and a charging current, $i = 25$ µA, then, using [7],we obtain a value for C of 12.5 nF.

The value of R_4 is

$$R_4 = V_c / 2i_c = 50\ \text{k}\Omega.$$

When the output of the LM339 is high, the circuit in Fig. 6 may be used to calculate the optimum value of the pull-up resistor, R_{pull}.

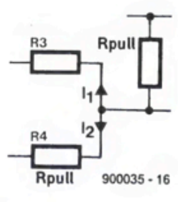

Fig. 6. Simplified circuit to calculate the voltage drop across R_{pull}.

If we allow a drop of 200 mV across R_{pull}, and taking into account that

$$i_1 = (V+ - V_c) / R_3 = 2\ \mu\text{A and}$$

$$i_2 = (V+ - V_c) / R_4 = 50\ \mu\text{A},$$

we obtain a value for R_{pull} of

$$R_{pull} = 200\ \text{mV} / (i_1 + i_2) = 200 / 52 = 3.8\ \text{k}\Omega.$$

In practice, the value may be reduced to, say, 2.2 kΩ and even further for low-impedance loads, but take care as the low output voltage of the LM339 may suffer.

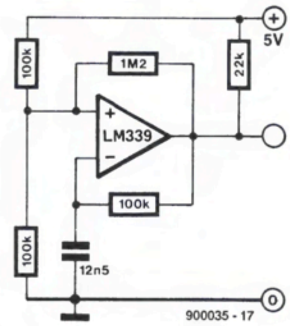

Fig. 7. Diagram of the final circuit of a 5 kHz square-wave generator.

The completed circuit is shown in Fig. 7. The prototype under test yielded a high period of 94 µs and a low period of 96 µs. The final frequency was 5263 Hz. It was calculated that the capacitor value should be 12.5 nF to give a frequency of 5208 Hz. Since a 12 nF type was used in the prototype, the actual frequency was rather higher, but well within satisfactory tolerance.

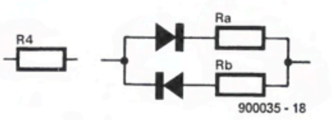

Fig. 8. Replacing R_4 by a resistor-diode network as shown enables the mark-to-space ratio of the output to be altered as required.

The high and low periods, that is, the mark-to-space ratio of the output voltage, may be varied by replacing R_4 by two resistors and two diodes as shown in Fig. 8. I shall leave the derivation to you. ■