Designing Square-Wave Generators

The theory and practice of designing square-wave generators that can stand alone or be integrated into circuit systems

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Square wave generators are commonly used to test a wide variety of electronic circuits, particularly in the digital area. The general utility of the square wave is the result of its rich harmonic content. A pure sine wave is composed of a single (fundamental) frequency. A square wave, on the other hand, contains a fundamental frequency (like the sine wave) and theoretically an infinite number of odd harmonics. As a general rule, the sharper the rise time, the greater the harmonic content of the square wave.

In this article, we focus on how to design and build custom square-wave generator circuits that can be used as part of a complex circuit or as a stand-alone signal source for bench testing. In designing such a circuit, be prepared to deal with a fair amount of arithmetic, though nothing more complex than simple algebra, to determine the values of resistors and capacitors to use.

The Square Wave

Depicted in Fig. 1 is a graphic representation of the symmetrical square wave. Each time interval of the wave is quasi-stable. Therefore, you might conclude that the square-wave generator has no permanent stable states and, hence, is astable. The waveform snaps back and forth between −V and +V, dwelling on each level for a period of time given as t_a or t_b. Period T is calculated using the formula:

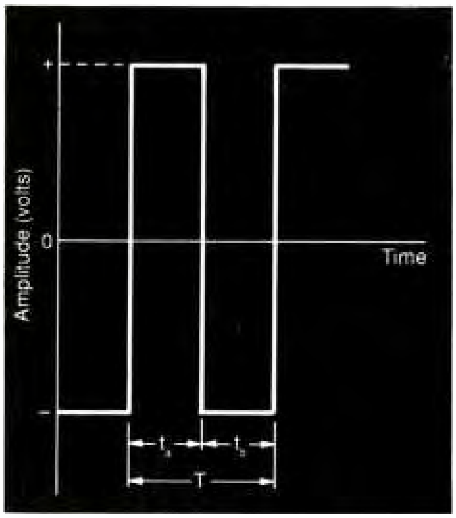

Fig. 1. Perfect square wave is symmetrical across 0-volt baseline and also between right and left halves. Time T is period; frequency is reciprocal of T, or 1/T.

$$T = t_a + t_b \quad [1]$$

where *T* is the period of the square wave (t1 to t3), t_a is interval t1 to t2 and t_b is interval t2 to t3.

Frequency of oscillation F is the reciprocal of T:

$$F = 1/T \quad [2]$$

The ideal square wave is both base- and time-line symmetrical, which means that the absolute value of +V is equal to the absolute value of −V and $t_a = t_b$. Under time-line symmetry $t_a = t_b = t$. Hence, T = 2t and f = (1/2t).

The schematic diagram for an operational-amplifier square-wave generator is shown in Fig. 2(A). The basic circuit configuration is similar to the simple voltage comparator. Operation depends upon the relationship between V(−IN) and V(+IN). The voltage applied to the noninverting (+) input [V(+IN)] is determined by the resistive voltage divider composed of *R2* and *R3*. This voltage is shown as V1 in Fig. 1(A) and is calculated as follows:

$$V1 = (V_oR3)/(R2 + R3) \quad [3]$$

When V_o is saturated, the formula is rewritten as follows:

$$V1 = (V_{sat} \times R3)/(R2 + R3) \quad [4]$$

Once again, the factor R3/(R2 + R3) is often designated B:

$$B = R3/(R2 + R3) \quad [5]$$

Because Equation [5] is always a fraction, V1 is less than V_{sat} and is of the same polarity as V_{sat}.

Voltage V(−IN) applied to the inverting (−) input is the potential that appears across *C1*, or V_{C1}, and is created when *C1* charges under the influence of current I that, in turn, is a function of V_o and the R1C1 time constant. Timing of the circuit is shown graphically in Fig. 2(B).

At turn-on $V_{C1} = 0$ volts and $V_o = +V_{sat}$. Therefore, $V1 = +V1 = B(+V_{sat})$. Because V_{C1} is less than V1, the op amp sees a negative differential input voltage; hence, the output remains at $+V_{sat}$. During this

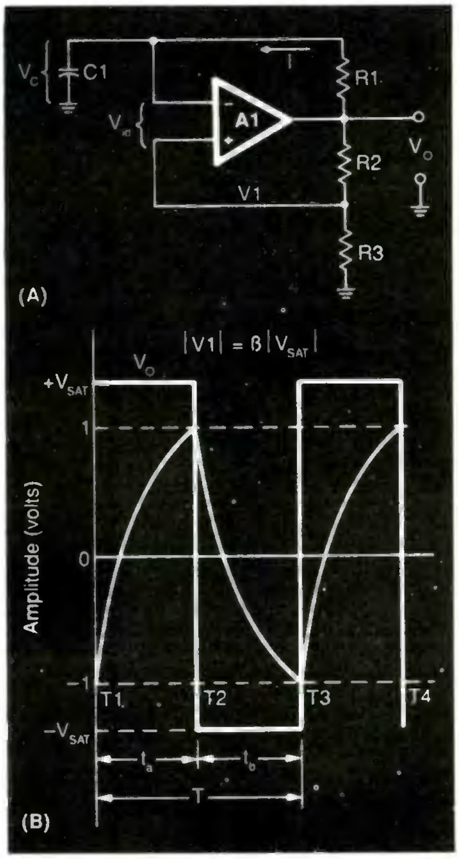

Fig. 2. (A) Circuit details for a simple op-amp square wave generator and (B) timing waveforms.

time, however, V_{C1} is charging towards $+V_{sat}$ at a rate of:

$$V_{C1} = V_{sat}[1 - e(-t2/R1C1)] \quad [6]$$

When V_{C1} reaches +V1, however, the op amp sees V_{C1} as being equal to V1; so $V_{id} = 0$. The output now snaps from $+V_{sat}$ to $-V_{sat}$, which is time t2 in Fig. 2(B). The capacitor now begins to discharge from +V1 towards zero, and then recharges towards $-V_{sat}$. When it reaches −V1, the inputs are once again zero; so the output again snaps to $+V_{sat}$. The output continuously snaps back and forth between $-V_{sat}$ and $+V_{sat}$, thereby producing a square wave output signal.

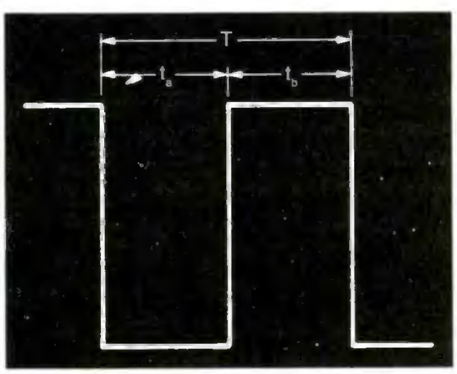

Fig. 3. Square wave train.

Time constant required to charge from an initial V_{C1} voltage to a V_{C2} end voltage time t is defined by the formula:

$$RC = -T/\{[(V - V_{C2})]/Ln \times [(V - V_{C2})/(V - V_{C1})]\} \quad [7]$$

In Fig. 2(A), the RC time constant is calculated for the R1C1 values. From Fig. 2(B), it should be apparent that for interval t_a $V_{C1} = -BV_{sat}$, $V_{C2} = +BV_{sat}$ and $V = V_{sat}$. To calculate period T, use the formula:

$$2R1C1 = -T/\{Ln[(V_{sat} - BV_{sat})/(V_{sat} - (-BV_{sat})]\} \quad [8]$$

By rearranging Equation [8], we obtain:

$$-T = 2R1C1 \times Ln \times [(V_{sat} - BV_{sat})/(V_{sat} - (-BV_{sat}] \quad [9]$$

$$-T = 2R1C1 \times Ln[(1 - B)/(1 + B)] \quad [10]$$

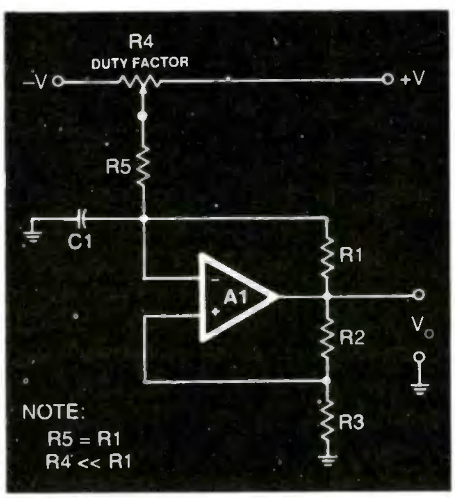

Fig. 4. Potentiometer provides variable duty cycle square wave.

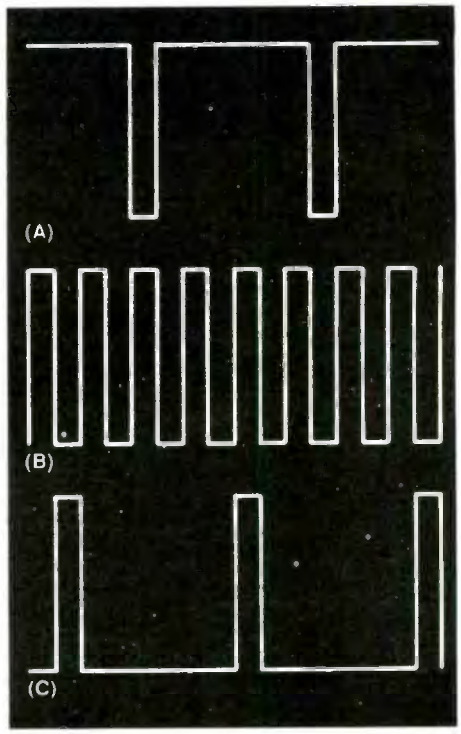

Fig. 5. Output waveforms for three different settings of the potentiometer (see text).

$$T = 2R1C1 \times Ln[(1 + B)/(1 - B)] \quad [11]$$

Because B = R3/(R2 + R3),

$$T = 2R1C1 \times Ln \{\{1 + [R3/(R2 + R3)]/\}/\{1 - [R3/(R2 + R3)]\}\} \quad [12]$$

which reduces to:

$$T = 2R1C1 \times Ln (2R2/R3) \quad [13]$$

Equation [13] defines the frequency of oscillation for any combination of *R1*, *R2*, *R3* and *C1*. In the special case where R2 = R3 and B = 0.5,

$$T = 2R1C1 \times Ln[(1 + 0.5)/(1 - 0.5)] \quad [14]$$

$$T = 2R1C1 \times Ln (1.5/0.5) \quad [15]$$

$$T = 2R1C1 \quad [16]$$

Equations [13] and [16] should be remembered because they are the basic

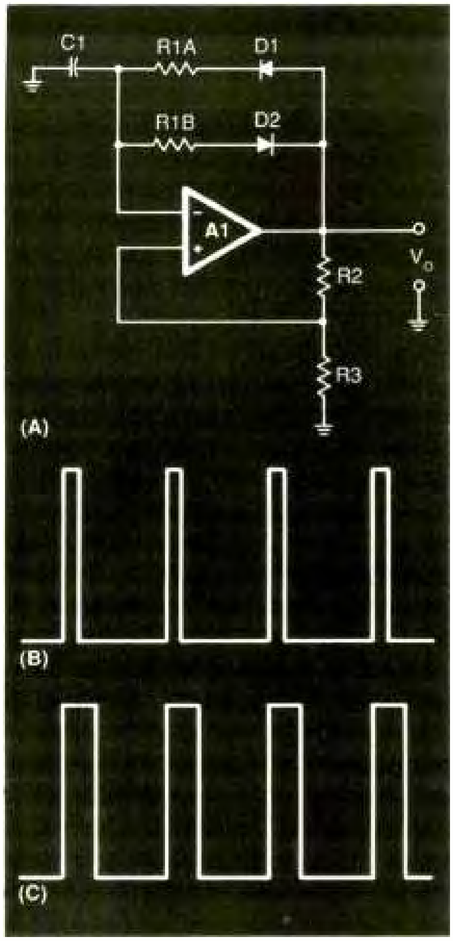

Fig. 6. (A) Diode circuit for producing asymmetrical, but fixed, duty-cycle square wave. (B) Two different ratios of feedback resistors.

design formulas for the general and special cases, respectively.

The circuit shown in Fig. 2(A) produces time-line symmetrical square waves ($t_a = t_b$), such as Fig. 3. If time-line asymmetrical square waves are required, a circuit like those shown in Fig. 4 or Fig. 6(A) is required.

The Fig. 4 circuit utilizes potentiometer *R4* and a fixed resistor *R5* to establish a variable duty cycle asymmetry. This circuit is similar to the one shown in Fig. 2(A), except offset circuit *R4/R5* has been added. Assumptions here are that R5 = R1 and R4 is much less than R1. If V_a is the potentiometer output voltage, *C1* charges at a rate equal to (R1/2)C1 towards a potential of $V_a + V_{sat}$. After output transition, however, the capacitor discharges at the same (R1/2)C1 rate towards $(V_a - V_{sat})$. Therefore, the two interval times are different so that t_a and t_b are no longer equal.

Shown in Fig. 5 are three extremes of V_a: (A) $V_a = +V$, (B) $V_a = 0$ and (C) $V_a = -V$. These traces represent very long, equal and very short duty cycles, respectively.

The circuit shown in Fig. 6(A) also produces asymmetrical square waves, but the duty cycle is fixed instead of being variable. Once again, the basic circuit here is like that shown in Fig. 2(A), except that it has added components. In Fig. 6(A), the RC timing network is altered in such a manner that the resistors are different on each swing of the output signal. During t_a, $V_a = +V_{sat}$; so *D1* is forward biased and *D2* is reverse biased. For this interval:

$$t_a = R1A \times C1 \times Ln[1 + (2R2/R3)] \quad [17]$$

During the alternate t_b half cycle, output voltage V_o is at $-V_{sat}$. Hence, *D1* is reverse biased and *D2* is forward biased. During this interval, *R1B* is the timing resistor, while *R1A* is effectively out of the circuit. The timing equation is now:

$$t_b = R1B \times C1 \times Ln[1 + (2R2/R3) \quad [18]$$

Total period T is $t_a + t_b$; so

$$T = R1A \times C1 \times Ln[1 + (2R2/R3) + R1B \times C1] \times Ln[1 + (2R2/R3)] \quad [19]$$

Collecting terms, we obtain:

$$T = (R1A + R1B) \times C1 \times Ln[1 + (2R2/R3)] \quad [20]$$

Equation [20] defines the oscillation frequency of the Fig. 6(A) circuit. Figures 6 shows the effects of two

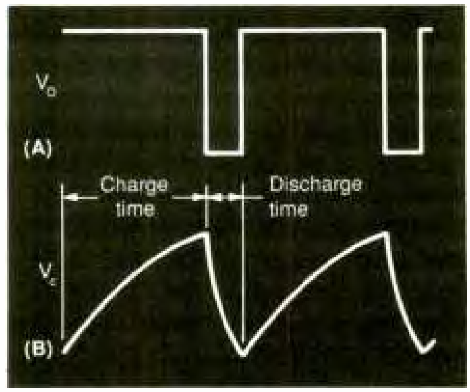

Fig. 7. Relationship between output voltage V_o and capacitor voltage, V_c.

values of R1A/R1B ratio. In (B), the ratio of R1A/R1B is 3:1, while in (C), the ratio of R1A/R1B is 10:1.

The effect of this circuit on capacitor charging can be seen in Fig. 7. Notice here in the lower lower trace that the capacitor charge time is long compared with the discharge time.

The standard op-amp circuit sometimes produces a relatively sloppy square output waveform. By adding a pair of back-to-back zener diodes across the output, as in Fig. 7(A), the signal can be cleaned up. By doing this, though, you pay a penalty in reduced output signal amplitude. For each polarity the output signal sees one forward-biased and one reverse-biased zener diode. On the positive swing, the output voltage is clamped at V_{Z1} + 0.7 volt. The 0.7-volt factor represents the normal junction potential across the forward biased diode (*D2*). On negative

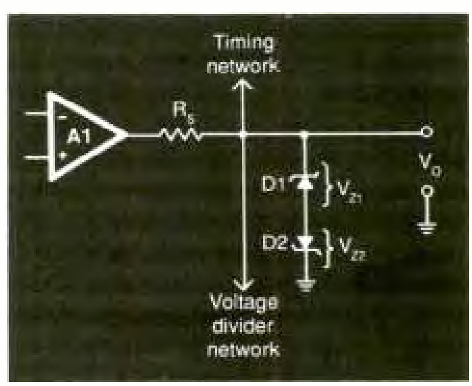

Fig. 8. Output limiting circuit.

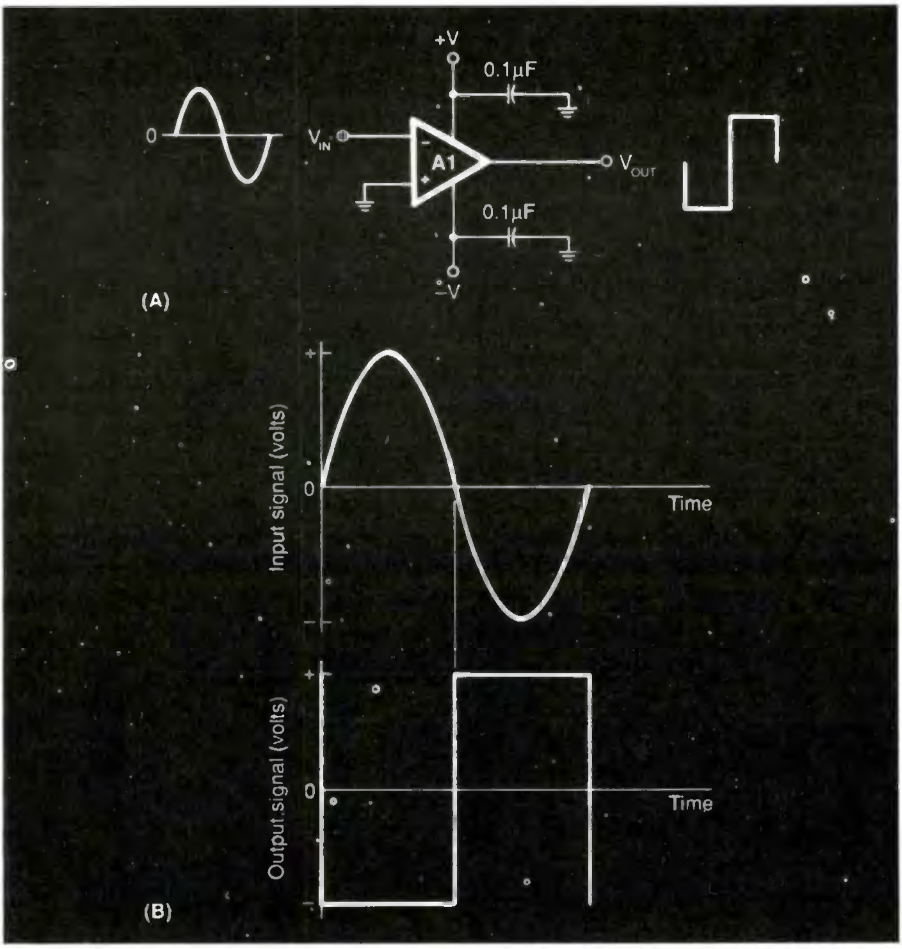

Fig. 9. (A) Voltage comparator used to make square waves from sine-wave input. (B) timing diagram waves.

swings, the situation reverses, and the output signal is clamped to $-V_{Z2} + 0.7$ volt.

Square From Sine Waves

Figure 9 shows a method for converting sine waves to square waves. The circuit configuration is shown in (A), while the waveforms are shown (B). The circuit uses an op amp connected as a comparator. Because the op amp has no negative feedback path, the gain is very high (A_{vol}). In op amps gains of 20,000 to 2,000,000 (250,000 typical) are frequently found. Thus, a voltage difference across the inputs of only a few millivolts will saturate the output of the op amp, which is illustrated in Fig. 9(B).

The input waveform to the Fig. 9(A) circuit is a sine wave. Because the noninverting input is grounded, the output of the op amp is zero only when the input signal voltage is also zero. When the sine wave is positive, the output signal will be at $-V_o$; and when the sine wave is negative, the output signal will be at $+V_o$. The output signal will, thus, be a square wave at the sine-wave frequency, with a peak-to-peak amplitude of $+V_o - (-V_o)$.

Designing and building square-wave generators using operational amplifiers is a simple task that can be accomplished by nearly everyone with a basic knowledge of electronics. Using the formulas provided here and a little common sense, you should be able to "roll your own" with ease. **ME**