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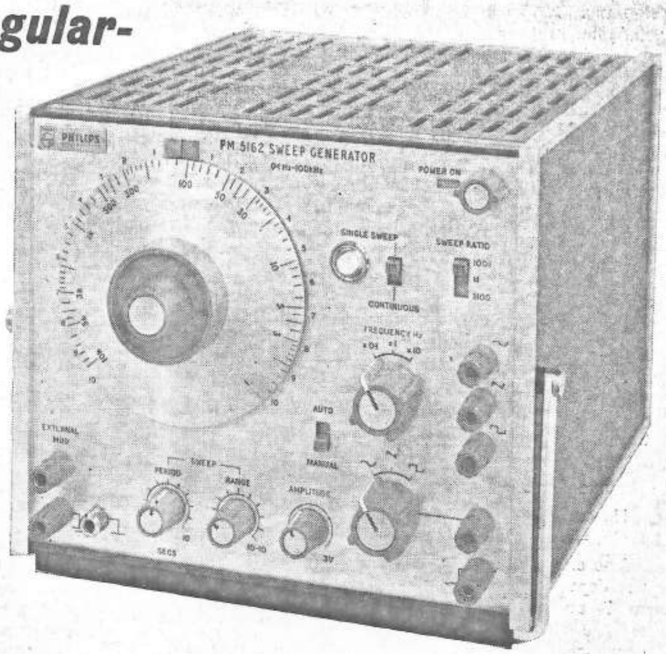
An Accurate Triangular-Wave Generator with Large Frequency Sweep



By G. Klein* and H. Hagenbeuk*

A triangular-wave generator is described which combines a wide frequency sweep ($\simeq 10^4$) with a very accurate symmetrical waveform. The amplitude response and the symmetry exhibit variations of less than 0·1 per cent, while the frequency stability is better than 1:10⁴. The circuit can serve as the basis for a single-sweep sine-wave oscillator or an f.m. modulator and voltage (current)-frequency convertor.

MANY applications require a generator of symmetrical triangular voltages, the frequency of which can be varied over a wide range by an external voltage or current. The stringency of the requirements made on the accuracy of the amplitude and the symmetry of the triangular waveform depend on the use. For most f.m. applications, these requirements are not particularly rigid. If, on the other hand, a single-sweep sine wave oscillator is to be designed by combining such a triangular-wave generator with an instantaneous triangle-sine convertor, the distortion in the sine-wave voltage will be determined by the symmetry and amplitude stability of the triangle. In order to be most universally applicable a generator was therefore designed to a very stringent specification.

Principle

The starting point for such a generator was a circuit that has been in use for a considerable time as an f.m.-modulator and already satisfies rigid requirements in many respects. Its principle is given in Fig. 1. The Schmitt-trigger is used to make the difference between the base-voltages of VT_1 and VT_2 alternately positive and negative by a few volts so that VT_2 carries either a current I_1 or no current. By this means the capacitor C is alternately charged with a current I_2 and discharged with a current $I_1 - I_2$, provided that $I_1 > I_2$. The amplitude constancy of the triangular waveform is determined by the difference between the changeover levels V_H and V_L of the Schmitt-trigger (about +2 and −6V in the example) which is, in turn, primarily determined by the resistance values and the supply voltages in the Schmitt-trigger, thus allowing considerable accuracy to be attained. The frequency can be varied over a wide range by changing I_1 but the triangular waveform is not symmetrical beeause I_2 is maintained constant. For the system to work properly, I_2 would have to vary simultaneously and satisfy the requirement $I_1 = 2I_2$, a condition which would be hard to be maintained for large variations of I_1. Fig. 2 gives a possible improvment which has been in use for some years†. Transistor VT_2 of the balanced pair carries the current I_1 in one position of the Schmitt-trigger. Since VT_1 then carries no current, the base voltage of VT_3 will be equal to the positive supply voltage, so that I_2 is then zero. Therefore, in this position, C is discharged by the current I_1. In the other position of the Schmitt-trigger, VT_1 carries the current I_1 and the base voltage of VT_3 will be

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about I_1R volts negative with respect to the positive supply voltage. If the emitter resistance of VT_3 is correctly chosen, I_2 can be made equal to I_1. The symmetry of the triangular wave which can be made perfect at a given value of I_1, is difficult to maintain if I_1 is varied over more than one decade because the base-emitter voltage of VT_3 will not remain equal.

In the proposal put forward here, care is taken to keep the current I_2 accurately equal to I_1, even when the latter varies greatly. Fig. 3 shows how this can be done by making use of a second capacitor C_2. Here, switching transistors VT_1 and VT_2 are symbolically represented by switches S_1 and S_2. These switches, together with S_3 and S_4, are controlled by the Schmitt-trigger as before in such a way that S_1 and S_4 are closed when S_2 and S_3 are open, and vice versa.

The basic principle of the circuit is the use of the voltage on capacitor C_2 to control the current I_2 in such a way that the average voltage across C_2 is kept constant.

If T_c and T_d are the times during which S_1 and S_4 (S_2, S_3) are closed (open) and open (closed) respectively, the following equalities should apply:

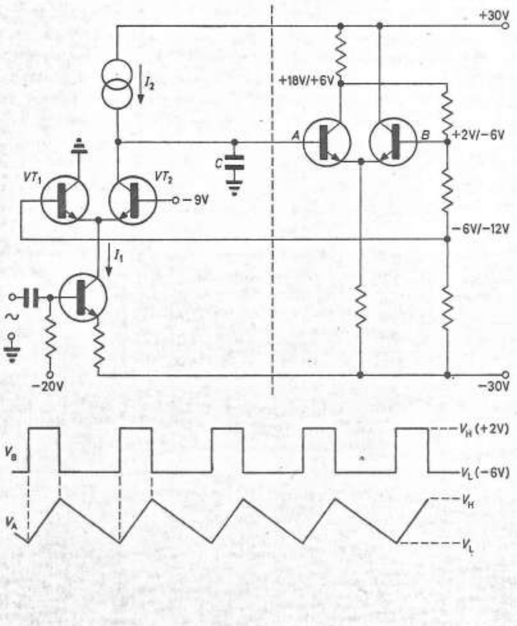
for C_1: $I_1T_d = I_2T_c$
and for C_2: $I_1T_c = I_2T_d$.

Hence:

$I_1 = I_2$ and $T_c = T_d$ as required.

The extent to which these equalities will apply in practice depends on the accuracy with which the currents fed to C_1 and C_2 are equal and this is determined by the leakage currents of the switching transistors and the base currents of the input stages of the Schmitt-trigger and the control amplifier. The inequality between the currents can be kept down to about 10^{-9}A in a transistorized circuit. This means that, if the currents I_1 and I_2 are no smaller than a few microamperes, the currents satisfy the above equations to within about 0·1 per cent. On the other hand, the currents should not be made greater than about 10mA. This means that where suitable current sources are used, a frequency sweep of 10^4 can be obtained. Furthermore,

Fig. 1. Basic circuit for triangular-wave generator



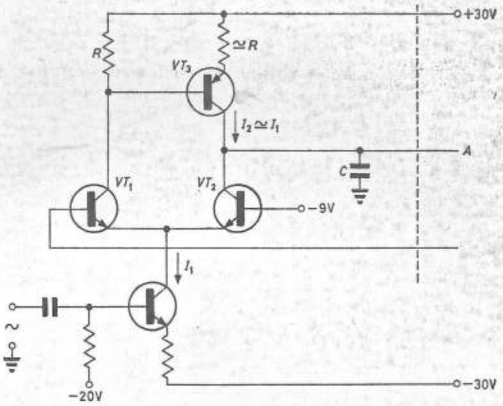


Fig. 2. Possible regulation of symmetry

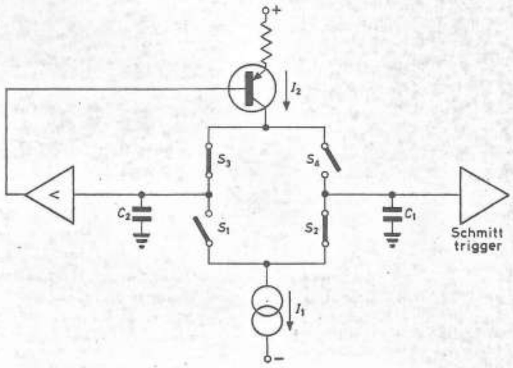


Fig. 3. Proposed regulation of symmetry

less than 0·1 per cent asymmetry can be guaranteed. With a reduced frequency sweep, higher minimum values of I_1 and I_2 may be used and the symmetry will be even better.

The principle as given in Fig. 3 has only one disadvantage: Since I_2 is controlled by the ripple voltage on C_2 as it charges C_1, the rising ramp of the triangular voltage on C_1 will exhibit a slight deviation from linearity. This effect is reduced by increasing C_2 and/or decreasing the loop gain. This means, however, that the speed with which I_2 follows a change in I_1 is reduced. A simple calculation shows that for this the following relation applies:

$$\tau = T/8\delta \quad \text{.................. (1)}$$

where T = period of the triangular voltage,

τ = time-constant of the control system of I_2,

δ = maximum relative deviation from linearity in the rising flank of the triangular voltage.

Thus, to limit δ to 0·1 per cent, the control would require more than 100 periods.

In the case of an external variation of I_1, the other current may be varied simultaneously by approximately the same amount. The control system would then only have to correct a possible deviation, and this could normally be allowed to take some time.

A better solution is given in Fig. 4. The ripple in the control voltage can be made zero by making C_2 equal to

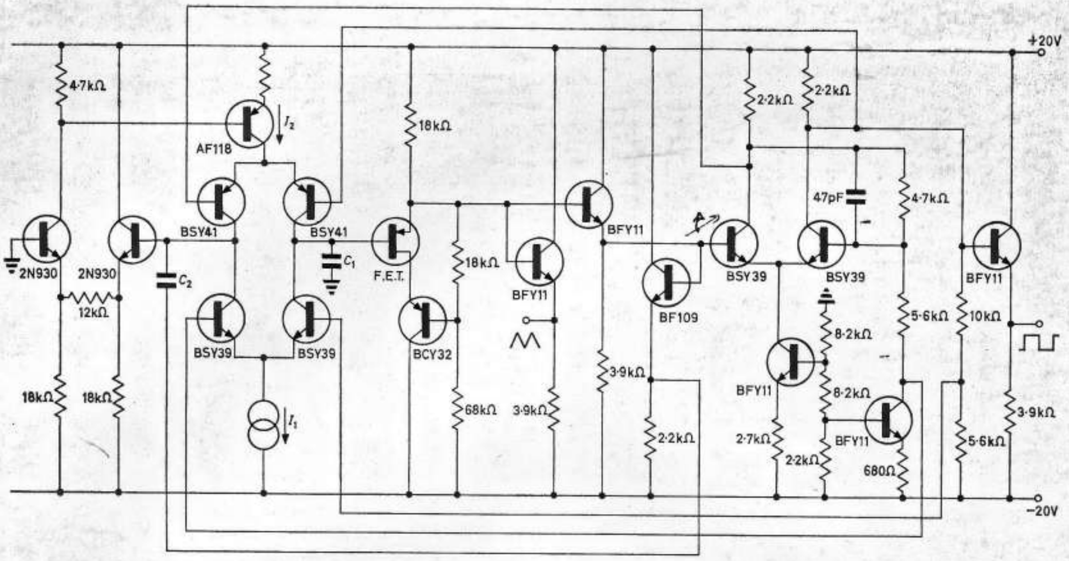


Fig. 5. Practical circuit

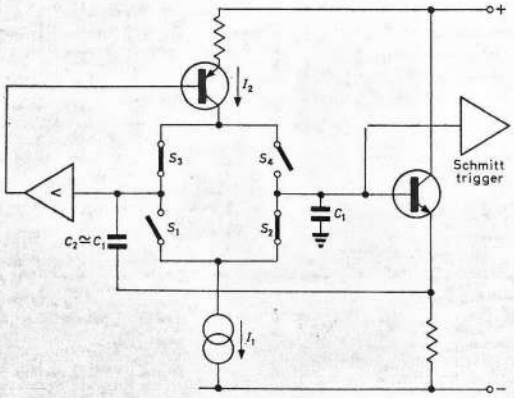
C_1 and by connecting one side of C_2 to a point that follows the voltage on C_1. In theory, the non-linearity and the control speed are now no longer related. If the adjustment is perfect, the ripple is zero and no distortion occurs. In practice, however, this perfect adjustment cannot be relied upon as deviations in the values of the capacitors will occur. The ripple voltage can, however, easily be compensated to within 1 per cent. Hence, the denominator in equation (1) is multiplied by 100 and this is adequate for all practical purposes.

Practical Circuit

Fig. 5 gives a simplified diagram of a triangular wave-generator incorporating the principles given above. Where necessary, the transistors were arranged as Darlington pairs. Since only currents are switched, the transistors may be replaced, with advantage, by field-effect transistors.

Various current sources may be used for I_1, thus providing, for instance, linear or exponential relationships between the frequency and a voltage which may be controlled externally. I_1 may also be supplied by two or more current sources connected in parallel. Where the switching circuit is designed with Darlington pairs the asymmetry proved to be much smaller than 0·1% for frequencies below some tens of kilohertz. At higher frequencies an inaccuracy will be introduced by the finite switching time and by parasitic effects of the switching circuit. With the available h.f.-transistors very good symmetry is still possible for frequencies up to some hundreds of kilohertz.

Fig. 4. Improved regulating circuit



The frequency stability is determined by the constancy of the current source I_1 and the switching level of the Schmitt-trigger. At normal ambient temperatures a frequency stability better than 10^{-4} was easily obtained for linearly variable current sources. Using sources with exponentially varying currents, the stability is generally less by one order of magnitude. The influence of temperature changes can be kept below 0·01 per cent/°C without difficulty. The amplitude is also determined by the constancy of the switching levels of the Schmitt-trigger.

The amplitude constancy with changing frequency is perfect as long as the transit times of the switching circuit are negligible. Due to this effect some increase in amplitude will occur at higher frequencies. It is obvious that the application of high-frequency field effect devices for the switches will give still better results.

The instrument shown in the photograph on page 388 is the first commercially available generator in which the described circuits have been applied. The main characteristics of this function generator—the Philips type PM 5162—are :

Frequency range: 0·1Hz to 100kHz, divided in three;
Ranges: 0·1 to 10^3, 1 to 10^4 and 10 to 10^5Hz;
Waveforms: sine, triangular, square;
Output voltage: 3V peak-to-peak into 600Ω.
Sweep mode: internal and external with a maximum sweep ratio of 1 : 10 000.

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