Analysis of a Transistor Monostable Multivibrator

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Unclassified

A demonstration of a simple and rapid process of numerical analysis, which furnishes practical values for specific transistor circuit designs. The measured characteristics of the transistor, rather than models chosen for analytical convenience, are used to get the final values.

The explosive growth of the electronic digital computer during the postwar years has aroused a profound interest in switching circuits. One of the switching circuits that is used extensively in the modern computer is the multivibrator. The multivibrator (MV) has three forms: a-stable MV (or free-running), monostable MV (or single-shot), and bi-stable MV (or flip-flop). The circuit to be analyzed is a monostable MV and was chosen because it is somewhat easier to analyze; but the same principles apply to the other two. The professional relevance of this paper does not lie in the circuit that is analyzed but in the *method* of analysis: that of making approximations and assumptions (later checked) as to the conditions in the circuit and then calculating specific values and waveforms. This method has wide application to digital and pulse circuits, and makes a relatively easy task out of an otherwise involved analysis. Moreover, when the analysis has been completed the designer is in an excellent position to note the effect of different component values and to make appropriate alterations. Our objective is to demonstrate this method by calculating the important waveform voltages of a specific MV circuit.

The monostable MV is an MV in which the circuit can stay indefinitely in one stable state, but only momentarily in the other. This usually means that one transistor (or tube) is permanently biased so as to be cut off (region I) while the other transistor is biased to be in the conducting region (either region II, the *linear* region; or region III, the *saturated* region). A pulse is applied which reverses the state of the circuit by turning the first transistor ON (conducting) and the second one OFF (non-conducting); but this condition exists for only a short time before the circuit reverts to its original state and awaits another pulse.

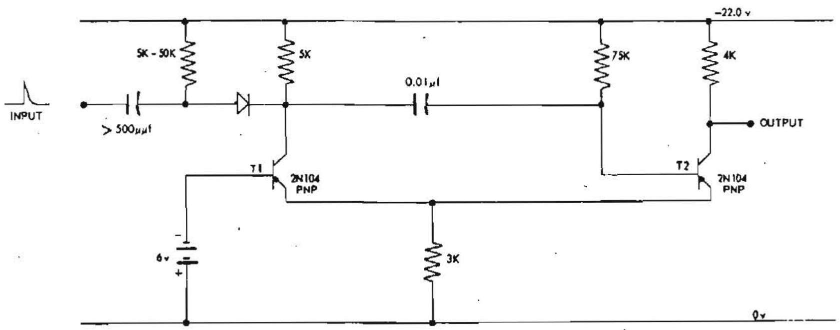

Fig. 1.

Such a circuit is shown in Fig. 1. It is called an emitter-coupled MV because part of the coupling between T1 and transistor T2 is through the common-emitter connection. The remainder of the coupling is from the collector of T1 through the 0.01 mfd capacitor to the base of T2. Observe that the first path is a DC coupling path whereas the second is an AC coupling path. This is quite common in monostable circuits but not necessary. The only necessary condition is that the circuit possess one stable state. By inspection of the above circuit, we notice that in the quiescent condition, ($t = T_o^-$) the base of T2 is biased through the 75K resistor to a negative voltage with respect to its emitter. Therefore T2 is ON (region II or region III?). As to whether T1 is ON or OFF we must begin with some quantitative calculation of the initial conditions. Let us assume for the moment that T1 is OFF, and also that T2 is saturated (region III). If any of the assumptions are incorrect, a contradiction will appear when the actual values are later calculated. We can find the initial conditions by substituting the standard equivalent circuit for T1 (OFF) and T2 (ON and saturated):

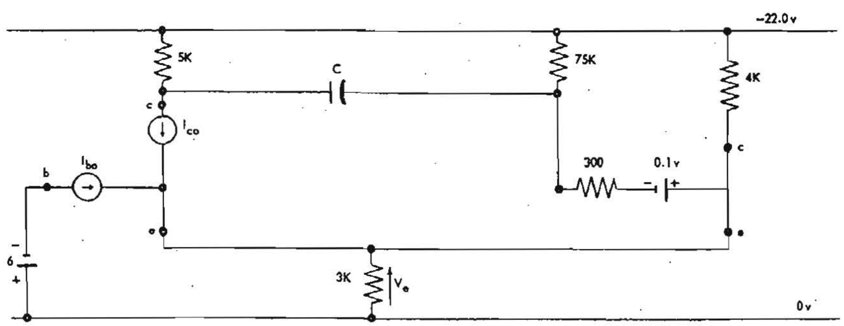

Fig. 2.

Both I_{co} and I_{bo} are quite small and can be ignored; moreover they tend to cancel each other in the emitter circuit because I_{co} is negative and I_{bo} positive. We can therefore consider T1 as an open circuit. In the base of T2 we shall substitute an equivalent resistor and battery, which are both typically small. However the small resistor and low voltage battery in series with the 75K resistor will make no practical difference in the value of v_e which we calculate. The equivalent circuit therefore reduces to:

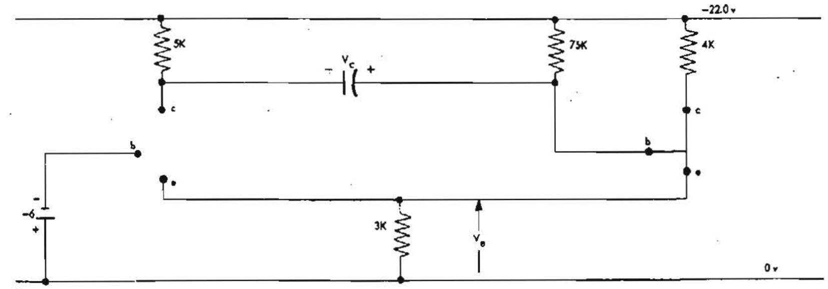

Fig. 3.

It is important to note why these simplifications were possible. We now solve for the initial conditions in the circuit:

$$v_e = \frac{(-22)(3K)}{3K + \dfrac{(4K)(75K)}{4K + 75K}} = -9.71 \text{ v.}$$

$$i_{b2} = \frac{-22 - (-9.71)}{75K} = -164 \ \mu\text{amps}$$

$$i_{c2} = \frac{-22 - (-9.71)}{4K} = -3.07 \text{ ma}$$

$$-i_{e2} = \frac{-9.71}{3K} = -3.24 \text{ ma}$$

We can now check our two assumptions. Since the emitter of T1 is at -9.71 v and the base is at -6 v, T1 is OFF. To check the saturation of T2 we look on the 2N104 transistor curves. Following the saturation line on the collector curves, which is the almost vertical line, we find that for $i_c = -3.07$ ma and $v_c \cong 0$ a base current of 75 μ amps is required to saturate T2. Since our calculated value for i_b was -164 μ amps, T2 is well-saturated (in region III); and so our assumptions were fortunately correct. Using the i_b vs v_b 2N104 curve, the equivalent base resistor and battery in the base circuit of T2 may be found respectively by measuring the slope of the curve at $i_b = -164$ μ amps and the intercept with the horizontal axis.

These turn out to be approximately 300 ohms and 0.1 volt respectively, which are small, as we assumed. We may now proceed to calculate the remaining initial conditions. (Subscript n denotes the voltage with respect to ground. V_c is merely the voltage across the 0.01 mfd capacitor.)

$v_{en1} = -9.71$ v. $\quad v_{en2} = -9.71$ v.

$v_{bn1} = -6$ v. $\quad v_{bn2} = -9.70 - 0.1 - (164\ \mu\text{amps})(300) = -9.9$ v.

$v_{cn1} = -22.0$ v. $\quad v_{cn2} = -9.71$ v.

$V_c = -(v_{cn1} - v_{bn2} = -[-22.0 - (-9.9)] = +12.1$ v.

A trigger pulse must now be applied to change the circuit to its temporary "quasi-stable" state. The positive pulse is applied through the differentiating capacitor and diode to the collector of T1, and also through the 0.01 mfd capacitor to the base of T2. This has no direct effect on T1 since T1 is already cut off; it tends however to turn T2 OFF, which in turn decreases the current through the 3K resistor, thereby reducing v_e. This tends to turn T1 ON, and the collector voltage of T1 thus receives an increase which is transmitted through the 0.01 mfd capacitor to the base of T2 and turns T2 completely OFF, thereby completing the normal multivibrator regenerative action. It is necessary to have a trigger-pulse amplitude large enough to start T1 conducting. Thus T1 is now ON (region II or region III?) and T2 is OFF. The circuit will stay in this quasi-stable state until the 0.01 mfd capacitor loses enough charge for the base of T2 to go negative. This will turn T2 ON and T1 OFF and we are back to our original condition.

We now need the equivalent circuit for the quasi-stable state of T2 OFF and T1 ON. First we must determine whether T1 is in region II or region III. Assume for the moment that T1 is saturated (region III):

$$v_e = \frac{3K(-22)}{3K + 5K} = -8.5 \text{ v}$$

The base-to-emitter voltage of T1 is: $v_{be} = -6 - (-8.5) = +2.5$ V and so is cut off. However, we assume that it was saturated. The contradiction forces us to consider that T1 is in the linear region (region II).

The equivalent circuit for the quasi-stable state—T1 in region II and T2 in region I—is shown below:

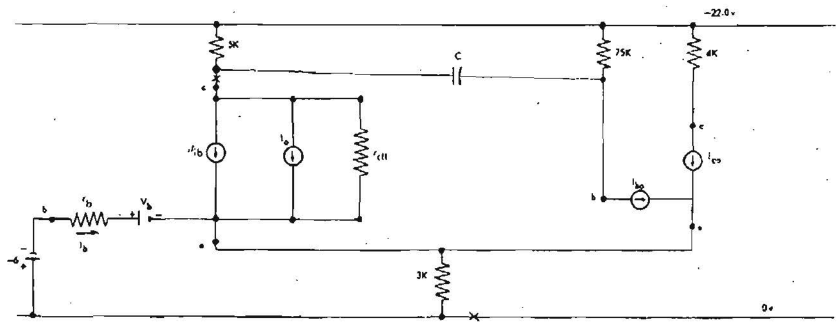

Fig. 4.

Observe that I_{bo} and I_{co} of T2 are negligible in calculating v_e; however, I_{bo} may be quite noticeable on the base waveform of T2 because of the large base resistor (75K) through which this current flows.

The above equivalent circuit can only be reduced with a great deal of effort, so we look for a short cut. By noting some particular properties of the 2N104 curves, we can find the operating point and greatly simplify the equivalent circuit of T1. Observe that in region II, $v_{be} \cong 0$; whence $v_e \cong v_{bn1} \cong -6$ v. Thus:

$$i_{e1} \cong \frac{6}{3K} = 2 \text{ ma} \cong -i_c \text{ (since the alpha of a transistor is nearly 1.)}$$

$$v_{cn1} \cong -22.0 + (2 \text{ ma})(5K) = -12 \text{ v.}$$

$$v_{ce1} \cong -12 + 6 = -6 \text{ v.}$$

Thus the operating point is approximately $v_{ce} = -6$ and $i_c = 2$ ma. On the transistor curves this gives a base current $i_b \cong 40\ \mu$ amps. Using the base characteristics we can correct our initial estimate of $v_{be} = 0$. For a base current of 40 amps, we find v_{bo} is actually 0.14 v. Since changes in v_{ce} do not perceptibly change v_{be}, the equivalent circuit simply replaces T1 by two current sources. By Kirchhoff's Law we can find the remaining current source:

$$i_e + i_b + i_c = 0, \quad i_c = -i_b - i_e = 0.040 - \frac{(6-0.14)}{3K}$$

$$= 0.040 - 1.95 = -1.91 \text{ ma.}$$

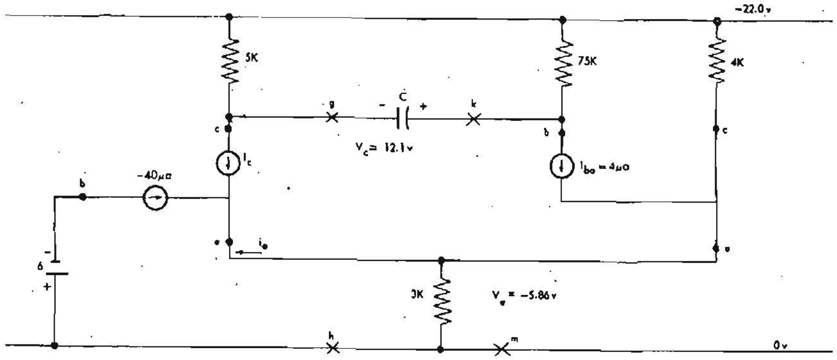

Fig. 5.

We can now reduce the circuit to the left of points *g–h* to a Thevenin equivalent circuit. Recall that a resistor in series with a current source does not change the current in that branch. So the circuit at the collector of T1 reduces as follows:

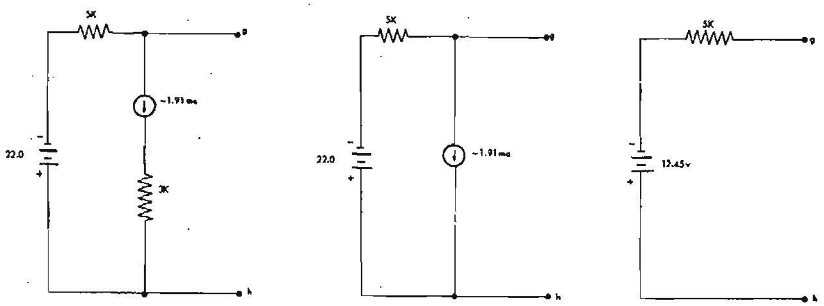

Fig. 6.

We can also reduce the circuit to the right of *l–m* to its Thevenin equivalent:

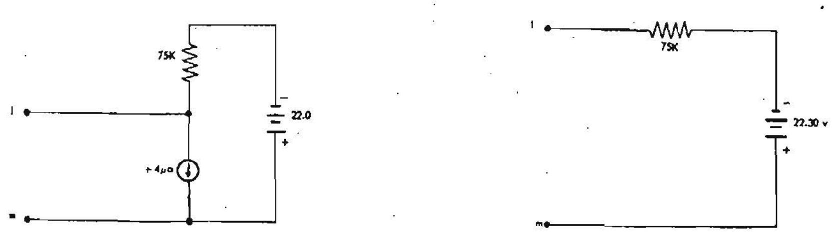

Fig. 7.

Observe that the effect of I_{bo} in the cut-off transistor T2 is to increase the equivalent battery voltage. This has the effect of shortening the quasi-stable period, and, while negligible in this case, it becomes significant as the temperature increases.

Placing the two equivalent circuits together again, we have the complete equivalent just after the circuit changes to the quasi-stable state ($t = T_0^+$). Note that the stored voltage v_c on the 0.01 mfd capacitor is the same as during the stable condition. This is because the voltage on a capacitor can not change instantaneously and so is the same immediately *after* the trigger pulse as it was *prior to* the trigger pulse:

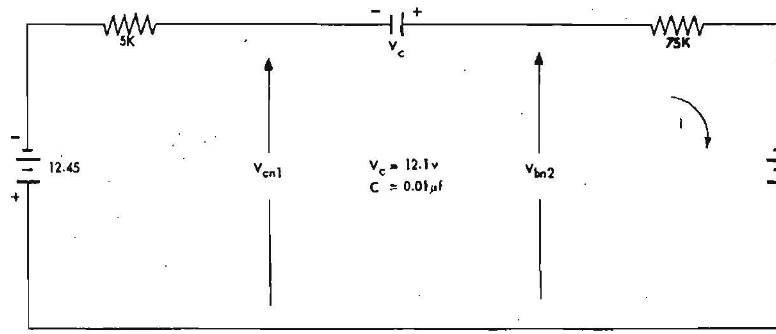

Fig. 8.

It will be easier to solve for the waveforms by finding the current in the circuit:

$$i = \frac{E}{R} e^{-t/\tau} = \frac{22.3 + 12.1 - 12.5}{80K} e^{-t/\tau} = 0.274\, e^{-t/\tau} \text{ ma},$$

where $\tau = RC = (0.01 \text{ mfd})\ (80K) = 800\ \mu$ sec.

Now solve for the waveforms at the collector of T1 and base of T2:

$$v_{bn2} = -22.3\ \ i(75K) = -22.3 + (0.274\, e^{-t/\tau}\ (75K)$$
$$= -22.3 + 20.6\ e^{-t/\tau}$$

$$v_{cn1} = -12.5\ \ -i(5K) = -12.5\ \ -1.37\ e^{-t/\tau}$$

$$v_e = -5.86 \text{ (previously calculated)}$$

$$v_{cn2} = -22.0\ -I_{co}\ (4K) = -22.0\ -(\ -4\ \mu a)\ (4K)$$
$$= -22.0 \text{ v.}$$

Thus we have all the important waveforms during the quasi-stable state. We must next determine the length of time *T* that the circuit remains in the quasi-stable state before switching. The circuit will switch ($t = T_1$) when T2 becomes conducting (region II), i.e., when the base of T2 goes negative with respect to its emitter. An excellent approximation is to assume that this regeneration takes place at $v_{be} = 0$. The circuit therefore switches at $v_{bn2} = v_e$ ($= -5.86$ v.). The period T is found by solving the equation:

$$v_{bn2}(T) = -5.86 = -22.3 + 20.6\, e^{-T/\tau}$$

$$T/\tau = 0.226, \quad T = (0.226)\ (800\ \mu s) = 180.8\ (180\ \mu s)$$

The value of v_{cn1} at $t = T_1$ will also be useful in our next calculations:

$$v_{cn1} = -12.5 \ -1.37\, e^{-T/\tau} = -12.5 \ -1.37\ (0.798) = -13.6 \text{ v.}$$

At time $t = T_1$ the circuit switches back to its stable state of T1 OFF and T2 ON. However the circuit is not ready for another trigger pulse because we must wait for the circuit to "settle down." That is, we must wait for the 0.01 mfd capacitor to regain the charge lost during the quasi-stable state. Therefore we must find the voltage across the 0.01 mfd capacitor at time $t = T_1^+$. We need a new circuit at time $t = T_1^+$ to calculate our final "settling" waveforms. The voltage V_c at time $t = T_1$ is the same as at time $t = T_1^-$:

$$V_c = v_{bn2} - v_{cn1} \quad t = T_1^- = -5.86 - (-13.6 \text{ v.}) = +7.7 \text{ v.}$$

Now the recharge current must flow through the $75\,K$ resistor to the base of T2; hence T2 is even more saturated at $T = T_1^+$ than it was initially, and so is in region III. Our equivalent circuit at $t > T_1$ is T1 OFF (regarded as an open circuit) and T2 ON (and saturated):

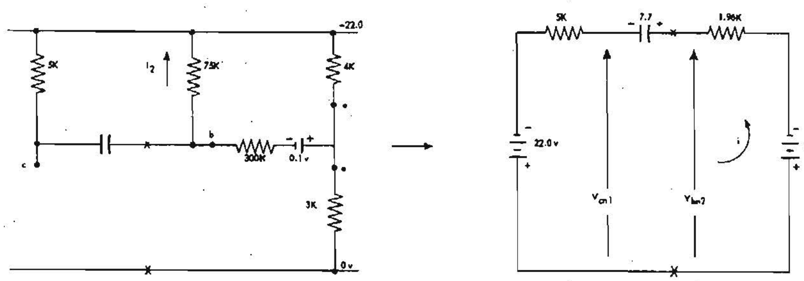

Fig. 9.

$$i = \frac{E}{R}\, e^{-t/\tau_2} = \frac{22.0 \ -9.9 \ -7.7}{6.96\,K}\, e^{-t/\tau_2} = 0.6\, e^{\,t/\tau_2} \text{ ma.}$$

$$\tau_2 = (0.01 \text{ mfd})\ (6.96\,K) = 69.6\ \mu \text{ sec.}$$

$$v_{bn2} = -9.9 \ -i(1.96\,K) = -9.9 \ -1.2\, e^{-t/\tau_2}$$

$$v_{cn1} = -22.0 + i(5\,K) = -22.0 + 3\ e^{-t/\tau_2}$$

$$v_e \cong v_{bn2} + (i + i_2)\ (300) + 0.14 \text{ v.}$$

Observe that if the circuit is eventually to return to the original condition, the 9.9 v. must be the original v_{bn2}—as indeed it is.

$$i_2 \cong \frac{22 - 9.9}{75\,K} = 160\ \mu\text{amps.}$$

$$v_e = -9.9 \ -1.2\, e^{-t/\tau_2} + 300\ (160\ \mu a + 0.6\, e^{-t/\tau_2} \text{ ma}) + 0.14$$

$$= -9.71 \ -1.2\, e^{-t/\tau_2}$$

$$v_{cn2} = v_e$$

We now have calculated all the important waveforms for a monostable MV and these are shown summarized on the last page. Time constants are shown, as are the initial and final voltage of the waveforms. Also the voltage toward which the waveform is heading is shown.

The only remaining inquiry is that concerning the trigger pulse itself. In order for the circuit to be in the regenerative condition we must cause both transistors to be in region II. As stated previously, a trigger pulse applied through the 0.01 mfd capacitor causes the base current to decrease in magnitude and if the pulse is large enough, will cause v_e to decrease. v_e must decrease enough to cause T1 to conduct slightly. Therefore v_e must change from -9.71 v. to -6 v. Since $v_{be} = 0$ in either region II or region III, the minimum amplitude of the trigger pulse applied to the base of T2 must be equal to the required change in v_e. The minimum amplitude is hence 3.7 volts. Observe that the diode will disconnect the trigger source from the MV as long as the amplitude is less than 8.1 v., so that the trigger will not affect the operation of the circuit.

In closing, an interesting sidelight is that this monostable MV circuit becomes an a-stable or free-running MV if the battery voltage applied to the base of T1 is increased. By increasing the battery voltage to approximately 10 volts we no longer have the stable initial condition, and so the circuit oscillates.

REFERENCE

Jacob Millman and Herbert Taub, *Pulse and Digital Circuits*, McGraw-Hill, New York, 1956.