Vol. 24 SEPTEMBER - OCTOBER, 1959 No. 5

CORNELL-DUBILIER ELECTRIC CORP.
Hamilton Boulevard, South Plainfield, N. J.

POSTMASTER: If undeliverable for any reason, notify stating reason, on Form 3547 postage for which is guaranteed.

Sec. 34.66 P.L.&R.
U. S. POSTAGE
PAID
So. Plainfield, N. J.
Permit No. 1

FRANK EAMES
5 RICHARDSON AVE.
ATTLEBORO, MASS.

STABILIZING TRANSISTOR CIRCUITS

Semiconductors inherently are temperature-sensitive materials. Diodes, transistors, and other components made from these materials therefore operate differently at one temperature than at another. Such variations proved frustrating to early workers with transistor circuits, since this pronounced temperature dependence had not been encountered with vacuum tubes. Some transistors stop amplifying altogether when they are heated to a certain point. In addition to variations due to the temperature sensitivity of germanium or silicon, shifts of operating point can be caused by parameters of replacement transistors, which differ somewhat from those of original units.

Obviously, predictable and reliable performance of transistor circuits may be obtained only if the transistor operating point is stabilized against shifts. The development of methods of effectively compensating transistor circuits followed several lines of attack and has resulted in practical schemes which greatly improve circuit stability. This article presents a simple discussion of practical stabilization of the transistor circuit. A bibliography is given for more intensive readings.

Current vs. Temperature

Transistors and diodes are essentially current-operated devices, hence their current-temperature coefficients are of chief interest in stability studies. Their resistance-temperature coefficients are important but of secondary significance, since these have as their basis the underlying current variations. The transistor currents are i_b (base current), i_e (emitter current), and i_c (collector current). Especially important is the static leakage, or cutoff, current which flows in the collector circuit under zero-signal conditions. Each of these currents increases with temperature, since the semiconductor has a negative temperature coefficient of resistance. Internal, as well as ambient heating increases the transistor currents.

The cutoff current is lower in silicon than in comparable germanium transistors. Thus, at 25°C, this current might be as low as 0.005 microampere in a small-signal silicon transistor operated at a collector voltage of 20v, while it would be 6 μa or more in a germanium transistor of the same beta rating and operated at the same collector voltage. The cutoff current is higher in power transistors than in small-signal units; for example, being of the order of 10 ma in a power transistor designed for a maximum power dissipation of 10 watts and operated at a collector potential of 80v. Cutoff current doubles approximately for each 10°C rise in temperature.

Effect of Cutoff Current Shift

Figure 1 shows the simplest type of common-emitter amplifier circuit. This arrangement has no compensation whatever. From its configuration, with respect to Resistor R_b, this circuit is commonly referred to as the "series resistor-biased" type.

In this arrangement, the transistor receives its base-emitter bias current, i_b, from the collector battery, V_{cc}, through the series resistor, R_b. After a suitable value of i_b (i. e., the d-c operating point of the transistor) has been selected by reference to the family of v_c versus i_c i_b curves for the chosen transistor, the correct value of R_b may be determined by means of Ohm's Law: $R_b = V_{cc}/i_b$. The internal base-emitter resistance, r_{be}, does not enter into this calculation because this resistance is so small, with respect to R_b, that it can be neglected.

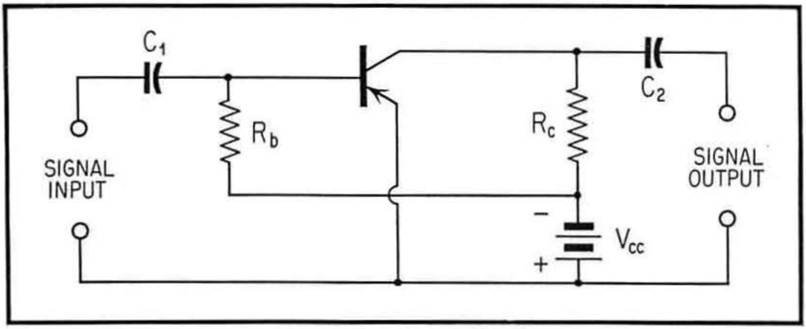

Fig. 1. Unstabilized Circuit.

The inadequacy of the series resistor bias method arises from the fact that the base-emitter current, and therefore the transistor operating point, is not determined solely by R_b; a large proportion of this current is due to current, i_c, flowing in the collector-emitter path. When i_c (which contains the i_{co} component) increases as the result of temperature rise, i_b therefore increases also. This causes a still further increase in i_c through action of the transistor base-collector current gain, beta — and a further increase in i_b. The net result of this action is to shift the operating point and also to cause the collector current to increase rapidly, producing further heating of the transistor and sometimes finally resulting in damage from collector current "runaway." The series resistor method of biasing therefore is not to be recommended in practical circuits.

Voltage Divider Stabilizing Circuit

It is evident that the circuit should be stabilized by rendering the base cur-

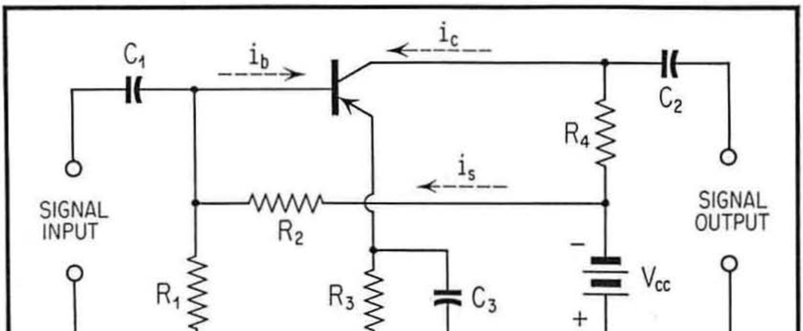

Fig. 2. Stabilized RC-Coupled Amplifier.

rent, and accordingly the operating point, less dependent upon variations in i_c and i_{co}. One such method developed by Richard F. Shea for stabilizing the base bias is illustrated by Figure 2.

In this circuit, the d-c base current is supplied by the tap on the voltage divider, R_1-R_2, operated from the collector battery V_{cc}. If the divider is properly proportioned, this voltage will not be subject to variations in transistor parameters, and the base current will not be significantly dependent or influenced by shifts in i_c and i_{co}. For this purpose, the total resistance of the R_1-R_2 combination is chosen such that the bleeder current, i_s, is much larger than the base current, i_b. The resulting stiffness of the voltage divider provides the required regulation. But since the base current available from the junction of R_1 and R_2 may be large enough to cause a higher collector current flow than the desired design value, a series resistor, R_3, will be required to reduce this current. Capacitor C_3 bypasses this resistor at signal frequencies but may be omitted if the degeneration introduced by R_3 is to be retained.

While the voltage divider must provide good regulation, the bleeder current must not be great enough to cause excessive drain on the battery. Another factor which must be taken into consideration is the position of the lower divider resistor, R_1, in parallel with the signal input. If this resistance is too low, the signal source will be heavily loaded, the net input impedance of the circuit will be lowered, and the power gain of the amplifier will suffer. Obviously, a compromise often must be reached in the selection of R_1 and R_2.

Practical Example

The following practical example illustrates the simple selection of resistance values for the circuit of Figure 2. Consider that a Type 2N77 transistor is to be operated at a d-c collector-to-emitter voltage (v_c) of —4v, a collector current of—0.7 ma, and that the supply potential (V_{cc}) is —6v. (The collector current and voltage are obtained from Typical Operating Conditions in the 2N77 characteristics table). Before stabilizing the circuit, the collector resistor, R_1, then would be equal to $(V_{cc}-v_c)/i_c = (6-4)/0.0007 = 2/0.0007 = 2857$ ohms. Now, it is noted from the characteristics sheet that $\beta = 55$. So the required base current will be $0.7/55 = 0.0127$ ma $= 12.7\mu$a. It is also noted from the tables that the emitter resistance (r_e) of this transistor is 23 ohms, and the base resistance (r_b) 1430 ohms. The total input resistance thus is $r_b + r_e = 1453$ ohms. This means that a base-emitter voltage (v_b) equal to $i_b\ (r_e + r_b)$ is required for the base current of 12.7 μa. In other words, $v_b = 1.27 \times 10^{-5}\ (1453) = 0.018$v.

Now, let us try a voltage divider ($R_1 - R_2$) through which the bleeder current will be approximately 10 times i_b, or 100μa. Since the divider will be operated from the 6-volt battery, its total resistance will be $6/10^{-4} = 60{,}000$ ohms. If the divider is proportioned to deliver 0.5v to the base of the transistor, the resistance ratio $(R_1 + R_2)/R_1$ must equal 12, in order to drop the 6v battery potential to 0.5v. Choosing $R_1 = 5$K, we find that R_2 must be 55K.

It is clear, however, that a base potential of 0.5v will force a current, i_b, of approximately 0.34 ma through the 1453-ohm base-emitter resistance and this, in turn, will raise the collector current to $\beta i_b = 0.34(55) = 18$ ma. To reduce this current to the 0.7-ma design value, we now insert

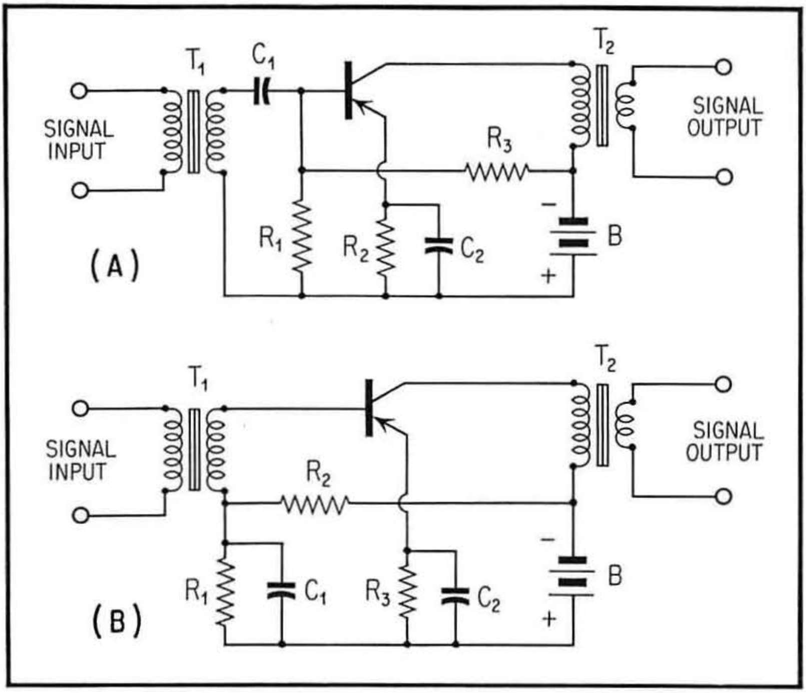

Fig. 3. Transformer-Coupled Circuits.

Resistor R_3 in the emitter circuit. The emitter voltage will be equal closely to the base voltage; that is, to 0.5v. So the required resistance of $R_3 = 0.5/i_c = 0.5/0.0007 = 714$ ohms.

It was determined in the beginning (in the calculation of R_4) that the maximum resistance in series with the collector, emitter, and battery would be 2857 ohms. This value therefore must be divided between R_3 and R_4: In order to maintain the desired d-c collector-emitter potential of −4v, R_4 may be decreased by 714 ohms to 2143 ohms.

Thus, the calculated values could be made up exactly with suitable resistors. However, the nearest commercial values may be employed, as shown below.

	Calculated	Nearest EIA Values
R_1	5K	4.7K
R_2	55K	47K
R_3	714 ohms	750 ohms
R_4	2143	2200

Additional Circuits

Figure 3 shows arrangements employed for the stabilization of transformer-coupled amplifier stages. In Figure 3(A), the base is connected directly to the tap on the voltage divider, $R_1 - R_3$. Blocking capacitor C_1 is required to prevent the secondary of the input transformer, T_1, from

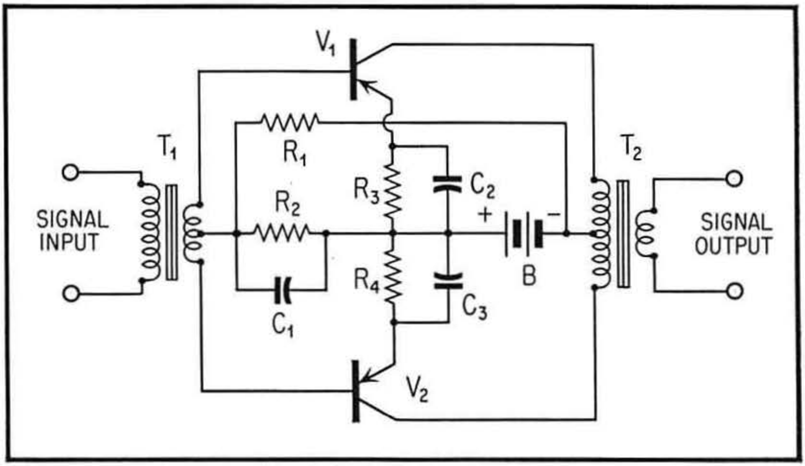

Fig. 4. Pushpull Arrangement.

short-circuiting the bottom resistor, R_1, of the divider. This arrangement is recommended when the d-c base current must be kept out of the input transformer.

In Figure 3(B), the d-c bias voltage developed at the tap of the voltage divider, R_1–R_2, is applied to the base of the transistor through the secondary of the input transformer, T_1. The bottom resistor, R_1, of the divider is bypassed by C_1 to prevent loss by input-signal voltage drop across this resistor.

In each of the transformer-coupled circuits, the emitter series resistor (R_2 in Figure 3A; R_3 in Figure 3B), is shown bypassed for maximum gain. This capacitor may be omitted if the degeneration provided by the emitter resistor is desired.

Figure 4 shows the stabilizing bias arrangement in a typical pushpull amplifier stage. Here, the d-c bias voltage for both bases is developed at the tap of the voltage divider, R_1-R_2, and is applied to the bases through the center-tapped secondary of the input transformer, T_1. The bottom resistor, R_2, of the divider is bypassed by C_1 to prevent loss due to input-signal voltage drop across this resistor. A separate series resistor (R_3, R_4) is provided for each emitter. For maximum gain, these resistors are bypassed by C_2 and C_3. However, these capacitors may be omitted if the current degeneration provided by the emitter resistors is desired.

Some designers recommend bias resistors having positive temperature coefficients to compensate for the negative temperature coefficient of transistor resistive parameters. Along this line, Figure 5 shows a positive-temperature-coefficient thermistor in use as the emitter series resistor. Semiconductor-type resistors having positive temperature coefficients also are available commercially. Whichever type of compensating resistor of this sort is employed, its positive coefficient must be exactly equal to the negative coefficient of the transistor resistance, in order to reduce to zero the current variation due to temperature. If the

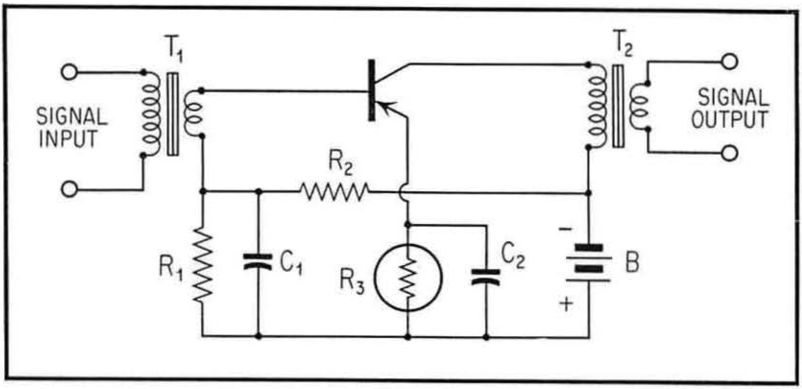

Fig. 5. Use of Thermistor.

positive resistor has a lower coefficient, undercompensation will result; and if it has a higher coefficient, overcompensation will result.

While, for purposes of illustration, simple amplifier circuits have been shown in this article, the voltage-divider method of transistor stabilization is not confined to amplifiers. Oscillator and converter circuits, for example, are stabilized in the same manner.

References

The subject of transistor stabilization has been treated in great detail in the literature. This article has been intended as an introduction to the practical application of circuit compensation, so topics such as stability factor, optimum loading, and battery economy have not been elaborated. The reader is referred to the following sources for more extensive treatment of the subject.

1. "Transistor Operation: Stabilization of Operating Points." Richard F. Shea. **Proceedings of the I. R. E.,** November 1952.
2. "Stabilizing Transistors." Sol Sherr and Theodore Kwap. **Tele-Tech and Electronic Industries,** March 1955.
3. "Designing Reliable Transistor Circuits." Norman B. Saunders. **Electronic Design,** April 1955.
4. "Predictable Design of Transistor Amplifiers." Richard B. Hurley. **Tele-Tech and Electronic Industries,** August 1955.
5. "Transistor Bias Stabilization." Paul Penfield, Jr. **Audio,** May 1956.
6. "Stabilizing Transistors." L. Fleming. **Radio and Television News,** August 1956.
7. "Transistors in Audio Circuits." Paul Penfield, Jr. **Audiocraft,** March 1957.
8. "Systematic Design of Transistor Bias Circuits." Ray P. Murray. **Electronic Industries and Tele-Tech,** November 1957.
9. TRANSISTORS, THEORY and PRACTICE (Book) 2nd Edition. Rufus P. Turner. pp. 69, 70.