Troubleshooting With dc Voltmeters

Helpful hints for getting the most out of your multimeter's dc voltmeter mode

By Robert G. Middleton

A dc voltmeter can be a very powerful tool in troubleshooting electronic circuits. To use it effectively, however, you must know how to interpret the readings you obtain during tests. Because this is a largely unexplored new world for many readers, here are a bevy of practical application hints on use of the dc voltmeter and the dc voltage function of multimeters. Armed with the information in this article, you will soon be optimizing your time at the testbench.

Types of Circuit Action

To effectively use any type of electronic test instrument, one must know something about how a circuit is supposed to work under proper conditions. Refer to the simple single-stage circuit shown in Fig. 1. This basic transistor circuit may operate under steady-state or transient conditions; in the linear or nonlinear mode; with voltage-divider bias, signal-developed bias, or a combination of both. When it is operating properly, this circuit outputs at its collector an amplified version of the signal applied to its base input. However, any of a number of things can go wrong in this circuit, resulting in a reduced-level output or no output at all. Locating the fault of a problem is the task of the dc voltmeter.

In Fig. 1, visible resistors are the voltage-divider biasing network made up of R_{b1} and R_{b2}, emitter resistor R_e and collector load resistor R_L. Invisible resistors are represented by the emitter-collector and collector-base junction resistances. Under fault conditions, invisible leakage resistance may shunt the collector-base junction resistance and may also shunt coupling capacitor C_c.

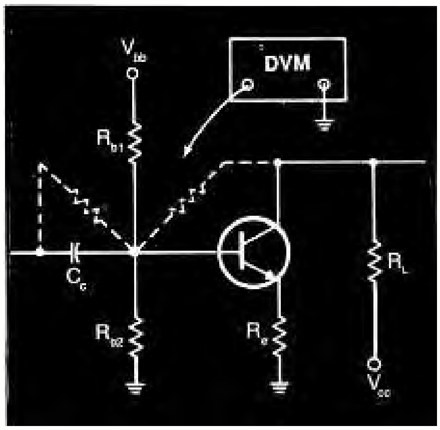

Fig. 1. A basic transistor circuit in which resistors shown phantomed represent possible leakage paths.

When a circuit malfunction occurs, the first thing you should do is measure dc supply voltages V_{cc} and V_{bb}. If you obtain the proper voltage readings in both cases, check the dc-voltage distribution in the circuit. In Fig. 1, for example, the collector, base and emitter voltages provide the pattern of dc-voltage distribution. Typical rated voltage and resistance values might be as follows:

R_{b1} = 10,000 ohms
R_{b2} = 1,000 ohms
R_e = 100 ohms
R_L = 15,000 ohms
V_{cc} = 30 volts
V_{bb} = 8.3 volts
dc beta (β) = 200
V_C = 15 volts
V_B = 0.75 volt
V_E = 0.1 volt

The potentials listed represent the dc-voltage distribution pattern for class-A operation of the circuit, wherein V_C is midway between V_{cc} and V_{dd}. Observe that the base-emitter bias voltage in this pattern is the difference between V_B and V_E, or 0.65 volt.

Fault Conditions

Under fault conditions, you should initially assume that only one defect exists. For example, the value of R_{b1}, R_{b2}, R_e or R_L might be too high or too low. Alternatively, the dc beta (β) value might be too low (don't worry if it's too high), collector junction leakage may be present or capacitor leakage may be present. Any one of these defects will cause a change in the dc-voltage distribution pattern. Among the tricks of the trade is recognition of the basic circuit action that is at work.

It is a general principle that defects in the collector circuit do not noticeably change the voltage in the base circuit. If R_L increases in value from 15,000 ohms to 20,000 ohms, for example, V_C falls from its normal value of 15 volts to 10 volts. However, V_B

and V_E will still measure 0.75 and 0.1 volt, respectively.

In another example, if R_L decreases in value from 15,000 ohms to 10,000 ohms, V_C will rise from its normal value of 15 volts to 20 volts. However, V_B and V_E will still measure 0.75 and 0.1 volt. From a theoretical point of view, voltage changes in the collector circuit do have a slight interaction with voltages in the base circuit; however, this interaction is so small that it can be ignored for all practical purposes.

Though voltage changes in the collector circuit may not have much of an effect on the voltages in the base and emitter circuits, it is a different story altogether with changes that occur in the base circuit. Whatever changes occur in the base circuit greatly influence the voltage in the collector circuit. For example, if R_{b1} increases in value from 10,000 ohms to 11,000 ohms, V_B falls from its normal value of 0.75 volt to 0.69 volt. This causes V_C to rise from its normal value of 15 volts to 24 volts and V_E to fall from its normal value of 0.1 volt to 0.04 volt! This is a typical base fault condition dc-voltage distribution pattern. An easy way to visualize this effect is to view the base circuit as a valve and the collector circuit as a tank.

Now observe the dc-voltage distribution pattern that results from a weak (low-beta) transistor. If the dc-beta value of the transistor deteriorates from its normal rating of 200 to 10, V_B remains unchanged at 0.75 volt, but V_C rises from its normal value of 15 volts to 21.8 volts and V_E falls from its normal value of 0.1 volt to 0.05 volt. The pattern distinction between a high R_{b1} and a low beta is chiefly in the base voltage: if R_{b1} is high, V_B goes low and if beta is low, V_B remains unchanged.

It is helpful to observe why V_B remains unchanged when beta is low. Base current is normally quite small; so when a bias voltage divider such as 10,000/1,000 ohms is used, V_B is determined solely by voltage-divider proportions (from a practical viewpoint, the very small base current does not load R_{b2}). Beta is the current-amplification factor that simply "opens the valve" for V_{cc} to permit a comparatively large collector current to flow.

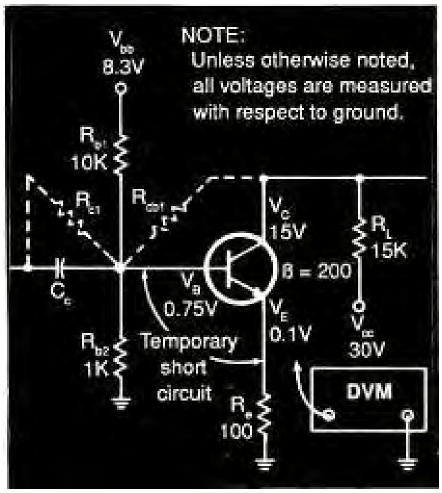

Fig. 2. Base-emitter short-circuit test shows whether off-value V_C is being caused by collector-junction leakage or by some other circuit fault.

Although a low dc-beta value results in a considerable change in the dc-voltage distribution pattern, a high dc-beta value causes comparatively little change in the pattern. If beta decreases from 200 to 10, a significant pattern change occurs, but if beta increases from 200 to 300, V_C edges down from its normal value of 15 volts to 14.8 volts—hardly a significant change. In practice, such a small change in the pattern is usually disregarded.

It is of technical interest at this point to note why low beta causes a large change in dc-voltage distribution, whereas high beta causes very little change in distribution. This distinction is evident in the dc-voltage equations for the configuration:

$$R_{TH} = R_{BT} \times R_{BT}/(R_{BO} + R_{BT})$$
$$V_{TH} = V_{bb} \times R_{BT}/(R_{BO} + R_{BT})$$
$$I_E = (V_{TH} - A(1))/(R_E + R_{TH}/\beta)$$
$$V_E = I_E \times R_E$$
$$V_C = V_{cc} - (I_E \times R_C)$$
$$V_{BE} = V_{TH} - V_E$$
$$V_{CE} = V_C - V_E$$

These equations state that the base of the transistor "sees" a Thevenin resistance R_{TH} and Thevenin voltage V_{TH} and that the emitter sees a current I_E in accordance with Ohm's law. Current I_E, in turn, produces a voltage drop I_E across the emitter resistor. Furthermore, the collector circuit is the servo circuit that sees I_E and produces the voltage drop V_C across the collector load resistor; the base-emitter voltage is the difference between the Thevenin and emitter voltages; and the collector-emitter voltage is the difference between the collector and emitter voltages. Dc-beta value β is the denominator in the second term of the denominator of the I_E equation. The mathematical significance of these formulas is that small values of β produce rapid changes in the second-term values, whereas large values of β produce slow changes in the second-term value.

Barrier Potential

Dc-voltage distribution patterns are responsive to the barrier-potential value, which is just another way of saying that a bipolar transistor does not conduct until the base-emitter voltage exceeds a threshold commonly referred to as the "barrier potential."

For silicon transistors, the barrier potential is ordinarily assumed to be 0.65 volt. In other words, the term A(1) in the foregoing I_E equation is routinely assigned the value 0.65, which "linearizes" the nonlinear system insofar as class-A operation is concerned.

Barrier potential is a function of temperature. At room temperature, a 0.65-volt value is assigned. However, at higher operating temperatures, an assignment of 0.6 volt is more realistic.

Barrier potential may range up to 0.7 volt at low temperatures. Therefore, it is helpful to observe the dc-voltage distribution patterns for the Fig. 1 circuit configuration at barrier potentials of 0.6 and 0.7 volt. If the barrier potential decreases from its median value of 0.65 volt to 0.6 volt, V_B remains unchanged at 0.75 volt, but V_C falls from its normal value of 15 volts to 7.8 volts and V_E rises from its normal value of 0.1 volt to 0.15 volt.

If the barrier potential increases from its median value of 0.65 volt to 0.7 volt, on the other hand, V_B again remains unchanged, but V_C rises to 22.2 volts and V_E falls to 0.05 volt. If you have a temperature probe for your DVM, you can easily measure the operating temperature of the transistor to determine whether the measured dc-voltage distribution reflects a barrier potential in the vicinity of 0.65 volt or of 0.6 volt, for example. This is one more helpful trick of the trade.

Now let us examine circuit action and dc-voltage distribution patterns in the presence of collector junction and coupling-capacitor leakages.

Patterns of dc-Voltage Distribution Under Test Conditions

	R_L		R_e		R_{b1}		R_{b2}		Beta	
	High	Low	High	Low	High	Low	High	Low	High	Low
V_C	Low	High	High	Low	High	Low	Low	High	—	High
V_B	—	—	—	—	Low	High	High	Low	—	—
V_E	—	—	—	—	Low	High	High	Low	—	Low

If R_L is high, V_C approaches its normal class-A value when R_L is shunted by a test resistor.
If R_L is low, V_C departs more from its normal class-A value when R_L is shunted by a test resistor.
If R_e is high, V_C approaches its normal class-A value when R_e is shunted by a test resistor.
If R_e is low, V_C departs more from its normal class-A value when R_e is shunted by a test resistor.
If R_{b1} is high, V_C approaches its normal class-A value when R_{b1} is shunted by a testresistor.
If R_{b1} is low, V_C departs more from its normal class-A value when R_{b1} is shunted by a test resistor.
If R_{b2} is high, V_C approaches its normal class-A value when R_{b2} is shunted by a test resistor.
If R_{b2} is low, V_C departs more from its normal class-A value when R_{b2} is shunted by a test resistor.

Fig. 3. Patterns of dc-voltage distribution under test conditions indicate the component or parameter that is off-value and whether it is too high or too low.

Test-Circuit Action

As shown in Fig. 2, an informative test circuit can be provided by temporarily short-circuiting the base and emitter terminals of the transistor when the collector voltage measures below normal and collector-junction leakage is suspected. This is called a "turn-off" test. If collector-junction leakage is present, V_C will not jump to the V_{cc} value when the short circuit is applied. On the other hand, if there is no collector-junction leakage, V_C *will* jump up to the V_{cc} value when the short circuit is applied.

For the time being, we will disregard the possibility of leakage R_{c1} in the coupling capacitor and focus on off-value components and parameters, as tabulated in Fig. 3, which lists the dc-voltage distribution patterns that encompass five measurements. Two of these measurements are checks of V_{bb} and V_{cc} values to ensure that a malfunction is not being caused by a fault in the power supply. After the V_{cc} and V_{bb} values have been verified (or corrected as required), you proceed to look at dc-voltage patterns that comprise three measurements: V_C, V_B and V_E.

Blank spaces in the Fig. 3 tabulation denote a dc-voltage change that is so small that it is ignored in tests. Note that there are various combinations of high and low dc-voltage measurements at the collector, base and emitter terminals. A measured value is "high" if it exceeds the normal value, and vice-versa. In this example, normal transistor terminal values are: $V_C = 15$ volts, $V_B = 0.75$ volt and $V_E = 0.1$ volt. (In any case, normal transistor terminal voltages will be specified in the service data.)

It is evident in Fig. 2 that there is more than one possible fault for each three-group pattern of voltages. For example, V_C high with V_B and V_E low can be caused by a high value of R_{b1} or a low value of R_{b2}. To resolve this ambiguity, temporarily shunt R_{b1} with a resistor. In turn, if R_{b1} is high, V_C approaches its normal class-A value when R_{b1} is shunted by the test resistor. Otherwise, V_C will go even further from its normal class-A value when the test resistor is applied. (In this example, a 50,000-ohm shunt test resistor might be used. The resistor's value is not critical; just be sure to choose a "ballpark" value.)

In the event that all three transistor-terminal voltages are incorrect, the fault is in the base circuit. Thus, if beta is low, only two of the terminal voltages will be incorrect. If the fault is in the collector circuit, only one terminal voltage will be incorrect. Accordingly, the initial dc-voltage distribution patterns tell you which section of the circuit is malfunctioning so that you do not waste time making shunt tests in normally operating sections.

Because capacitor leakage resistance can cause confusion in base-circuit tests, it is important for you to know how to check for this possibility. To do so, apply a temporary short circuit between the left-hand terminal of C_c and ground in the Fig. 2 cir-

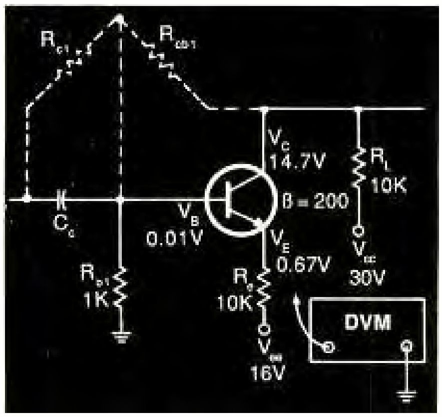

Fig. 4. Basic emitter-bias configuration is essentially the same as the basic base-bias configuration.

cuit and observe the change in base voltage (if any). If there is no change in V_B, there is negligible leakage in C_c. However, if there is noticeable change in V_B when this test is made, C_c is leaky and should be replaced.

Emitter-Bias Circuit

The basic emitter-bias circuit configuration shown in Fig. 4 is also in popular use. Closely related to the basic base-bias configuration, from a circuit-action viewpoint, it can be regarded as essentially the same. As noted, V_B is near ground potential at 0.01 volt, whereas V_E is 0.67 volt above ground. Thus, V_B and V_E are interchanged with respect to the base-bias circuit configuration. However, the base-emitter voltage (the difference between these two voltages) is the same in either circuit at 0.66 volt.

Conveniently, R_{b1} in Fig. 4 is regarded as the parallel combination of R_{b1} and R_{b2} in Fig. 2. Physically, the emitter-bias arrangement uses one less resistor. Functionally, the tradeoff is slightly less bias stability in the emitter-bias arrangement. In other words, R_{b1} in Fig. 2 has a comparatively high value, which makes the bias source appear more like a current source than a voltage source.

Localization of circuit defects in the Fig. 4 circuit follows the same principles discussed above for the Fig. 2 circuit. That is, the Fig. 2 tabulation applies to the emitter-bias circuitry, just as it does for the base-bias circuitry. A turn-off test is made in the same way, and ambiguous situations are resolved in the same way. The only difference is that there is only one base-bias resistor, so there is one less dc-voltage value in the distribution pattern. Capacitor leakage is checked as above, by monitoring V_B when a temporary short circuit to ground is applied to the left-hand end of capacitor C_c.

Differential Amplifier

Shown in Fig. 5 is a basic differential-amplifier circuit configuration. In this circuit, two transistors are operated in a balanced (push-pull or double-ended) mode. Emitter biasing is usually used in such an arrangement. The collectors of both transistors normally have the same dc voltage, and both bases normally have the same dc voltage on them.

The bases of the transistors are a bit above ground potential as a result of the base-emitter bias voltage developed chiefly in the emitter circuit. Note that both transistors are emitter-coupled. If emitter current in one transistor increases, emitter current in the other transistor is forced to decrease.

You are concerned primarily with whether the circuit is operating in class-A (collector voltages approximately half-way between V_{cc} and V_e) and whether the dc-voltage distribution pattern is balanced. That is, the two collector voltages are normally the same, within a slight tolerance range. Similarly, the two base voltages are normally the same, again within a very small tolerance range. Observe that if the collector load resistor (R_L) for the left transistor becomes too high, V_C for that stage will be subnormal. An off-value R_L has no noticeable effect on V_B and V_E, however.

It follows that although a high value of R_L for the left transistor results in a subnormal V_C there, this change in the dc-voltage distribution pattern is not reflected into the right transistor branch circuit. In turn, the circuit becomes unbalanced with unequal collector voltages.

Insofar as dc-beta values are concerned, it is helpful to consider the limiting case in which the beta value of the left transistor, for example, becomes zero. In this case, the two-section amplifier becomes a one-sec-

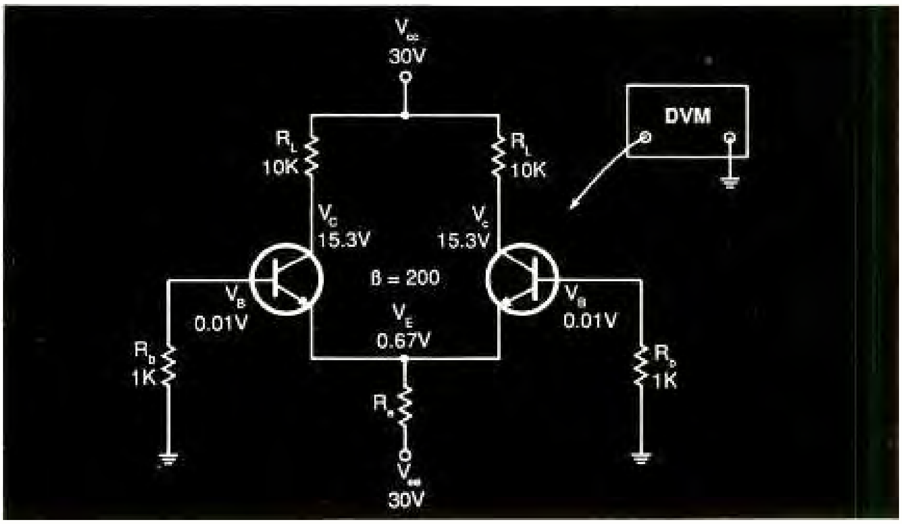

Fig. 5. Basic differential amplifier configuration is essentially a "twinning" of the emitter-bias configuration.

tion amplifier and its circuit action follows that discussed for the Fig. 4 circuit.

In this comparison, V_{ee} for the Fig. 4 circuit is now double its normal value, with the result that V_C falls to a very low value, saturating the transistor. Thus, if the beta value of one transistor in Fig. 5 becomes seriously subnormal, the other transistor will go into saturation. As would be anticipated, the value for R_b is not critical. If one base resistor in Fig. 5 goes considerably off-value, the circuit remains essentially in a balanced state. Of course, if one of the base resistors goes greatly off-value, the associated V_B will be significantly affected and the circuit will be in an unbalanced state.

It is helpful to note that R_E in the typical differential-amplifier arrangement ordinarily has a comparatively high value, resulting in signifi- is good and the value of R_E can go considerably up or down without causing serious shifts in the collector voltages.

Although you are primarily concerned with dc-voltage distribution patterns, you should also take note of the basic signal-voltage considerations in the Fig. 5 arrangement. For example, the bases of the transistors may be driven in push-pull such that when one base is driven positive, the other base is driven negative and when one collector goes positive, the other collector goes negative.

Suppose both bases of the transistors were driven positive (common-mode drive). Under this condition, both collector voltages would decrease equally. Consequently, there would be no collector-collector output, resulting in a condition known as "common-mode rejection."

In addition to push-pull drive, the shown in Fig. 5 is often driven by a single-ended source. Thus, the base of the left transistor may be driven positive while the base of the right transistor remains essentially at ground potential. Accordingly, V_C at the left transistor falls, due to increased emitter current. In turn, increased emitter current results in a higher V_E, with the result that the right transistor is driven toward cutoff and its V_C increases. Hence, the single-ended input has been changed into a double-ended output.

As the foregoing has demonstrated, a dc voltmeter can be an invaluable aid in troubleshooting circuits. However, it can be put to effective use only if you have a basic understanding of circuit-action conditions, both proper and otherwise. Once you understand and apply this, the first instrument you reach for to troubleshoot an ailing circuit is likely to be