A New Simple Wide-Band Current-Measuring Device

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Abstract—The current conveyor—a new circuit building block recently introduced—is applied to the design of a simple current-measuring probe. The monopolar version of this probe features high stability and accuracy (0.5 percent of nominal reading). A dc to 100-MHz frequency band is obtained from the bipolar version. Both versions minimize the disturbance to the measured circuit by presenting a very low impedance at the current-measuring terminals. The output voltage of the probe is directly proportional to the measured current with the transimpedance being chosen almost at will. The design makes use of a dual transistor and a commercially available integrated circuit.

Introduction

THE CURRENT CONVEYOR[1]—a new circuit building block recently introduced [1]—has made possible the design of a simple current-measuring probe. Two versions of this current-measuring probe are described: a monopolar one for measuring dc currents with high accuracy and stability, and a bipolar one for operation over a wide-frequency band extending from dc to 100 MHz. Both versions minimize disturbance to the measured circuit by presenting a very low input impedance at their current input terminals.

The dc probe can form a suitable plug-in unit for existing digital voltmeters thus providing a simple solution for a common instrumentation probe. This problem, namely, accurate measurement of dc current without attendant disturbance of the measured circuit, reoccurs over a broad spectrum of applications ranging from a simple bench-test situation to complex data-acquisition systems [2].

The wide frequency band of the bipolar version suggests its use in connection with wide-band oscilloscopes currently available. Both designs make use of a commercially available integrated circuit. It should be noted, however, that although the probes described present a very low impedance at the input terminals and thus minimum disturbance, it is always necessary to break the circuit being measured in order to insert the measuring probe.

Basic Principle

Fig. 1 shows a block diagram of the monopolar current probe. As a result of the characteristics of the current conveyor, input terminals x and y track each other in current and voltage. Thus, if x and y are used as the probe input terminals, a negligible voltage drop will appear across them and no disturbance to the tested circuit will be provided by the probe insertion. Moreover, by the conveyor action, the input current through x will be supplied through output terminal z. Therefore, if z is returned through a resistance R_t to y (used here as an internal common point), an output voltage V directly proportional to the current I being measured will appear at z. Connection of z to a digital voltmeter provides a digital reading of the current I with the probe transimpedance R_t as a calibration factor. It should be noted that R_t can be chosen almost at will to provide the required sensitivity.

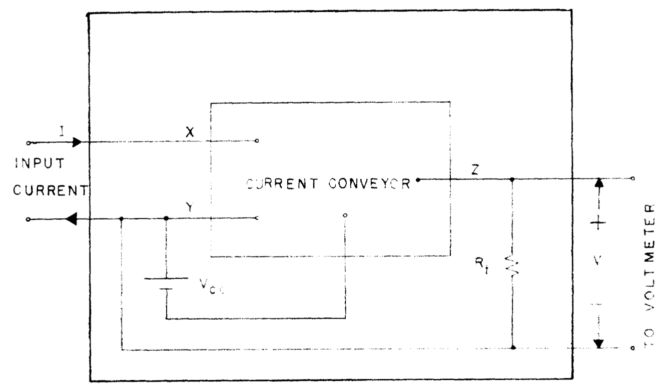

Fig. 1. Block diagram of the monopolar current probe; $V = -IR_t$.

Ac operation is made possible by applying the following two modifications to the block diagram in Fig. 1.

1) The conveyor should be biased at a reasonable operating point consistent with the required dynamic range. This can be provided simply by connecting x through a resistance R_B to a positive power supply V_{BB}, the negative terminal of which should be connected to y. In this case x is used as a summing point for the measured current I and a bias current V_{BB}/R_B with the sum being supplied through z. In order to eliminate the resulting level shift in the output voltage at z, the transimpedance R_t should be made equal to R_B and should also be returned to V_{BB} instead of the common point y. This technique [3] also eliminates the dependence of the output voltage on the exact value of the biasing supply V_{BB}.

2) The current conveyor used should be suitable for high-frequency operation by choosing transistors of high cutoff frequency and low junction capacitances. It is important to note that the conveyor demonstrates an inherent high-frequency capability as compared to the operational amplifier that can be used alternatively in some applications. Furthermore, as will be shown, extension of its bandwidth can be easily provided by an external compensating capacitor.

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[1] Patent applied for.

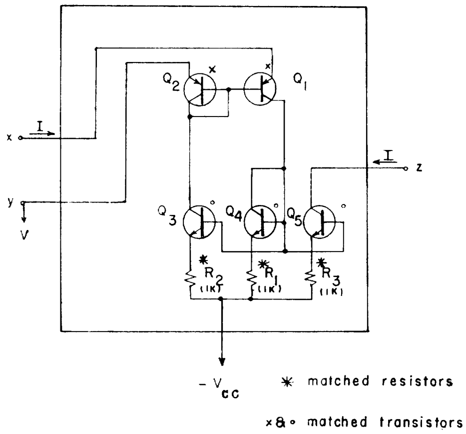

Fig. 2. A first-order circuit realization of the current conveyor.

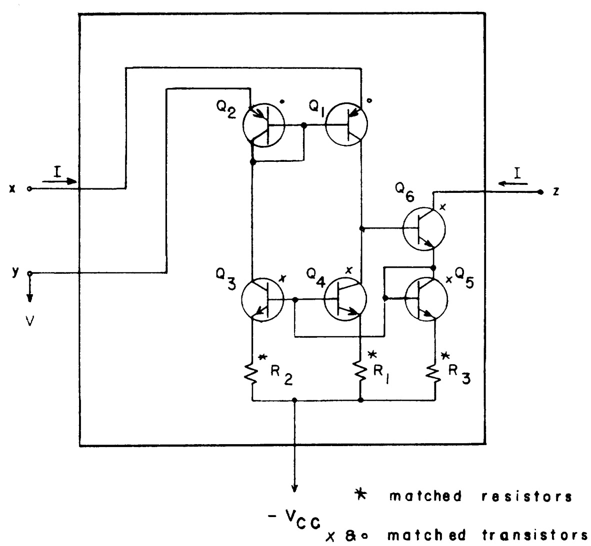

Fig. 3. A more accurate realization of the current conveyor.

Circuit Realization

It is apparent that the central part of the probe is the current conveyor. A first-order circuit realization of the conveyor has been described in a recent publication [1] and is shown for reference in Fig. 2. Fig. 3 introduces a more accurate realization in the form of a modification to the output stage of the conveyor in Fig. 2. The addition of transistor Q_6 in a positive feedback connection [4] compensates for the loss of the conveyor current gain resulting from the nonunity common-base current gains of each of the transistors. This connection also results in a better temperature stability and a higher output impedance. The Appendix provides a more detailed description of the circuit function and an approximate analysis of its operation.

Design Considerations

The design of the current conveyor is based upon the use of matched transistors and resistors. Transistors Q_1 and Q_2 should be a matched pair, while transistor Q_3, Q_4, Q_5, and Q_6 should be a matched quad. As accurate and stable performance is largely enhanced by maintaining all the transistors in the same environment, production

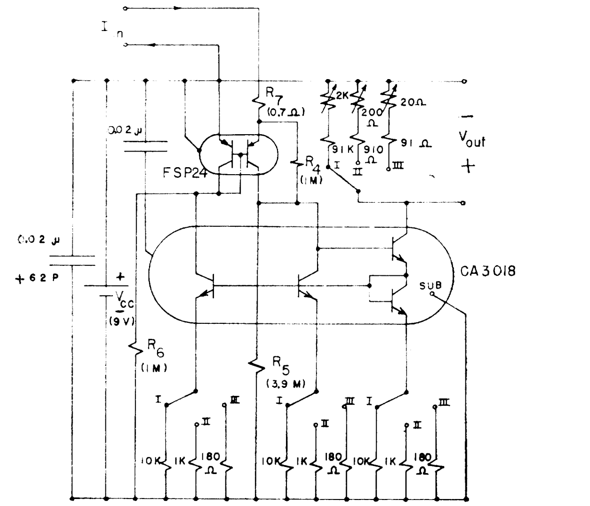

Fig. 4. Complete circuit diagram of the monopolar current probe. Accuracy is specified over Range I: 20 μA → 400 μA; Range II: 300 μA → 3.5 mA; and Range III: 3.5 mA → 20 mA. Where appropriate, ferrite beads are used to prevent any parasitic oscillation.

with integrated (or possibly hybrid) circuit techniques would be most suitable. In the prototype tested, a commercially available integrated circuit has been used for the quad Q_3–Q_6, while a matched dual has been used for Q_1 and Q_2.

The values of resistances R_1–R_3 should be chosen in connection with the power-supply voltage V_{cc} to ensure linear operation of all transistors and, at the same time, provide sufficient voltage drop to swamp any second-order differences in transistor-junction forward-voltage drop. It is also important to note that it is the matching rather than the exact value of resistances R_1–R_3 that is of prime interest.

As mentioned previously, to provide wide-band operation all the transistors should have a high f_t and low collector-base junction capacitances. Enhancement of the high-frequency response is also possible by connecting a capacitor C from the common bases of Q_3, Q_4, and Q_5 to the negative power supply $-V_{cc}$ (or the signal ground). Capacitor C will draw a signal current in quadrature (+90°) to that through the emitters of Q_3, Q_4, and Q_5.[2] This excess current being supplied by Q_6 boosts the output current at frequencies where the time constant CR_e (where $R_e = R_1 = R_2 = R_3$) becomes effective.

Performance

The complete circuit diagram of the monopolar current probe tested is shown in Fig. 4. This specific design is intended to cover a three-decade current range (20 μA → 20 mA) in three steps with an accuracy of 0.5 percent of nominal reading.

In addition to the current conveyor components described above, a resistor R_4 is connected across transistor

[2] This paper is true assuming the signal drop across the emitter-base junction of each of Q_3, Q_4, or Q_5 is much smaller than that across each of the emitter resistors. It should be noted however that this qualitative discussion is only for the sake of visualizing the compensating action of C.

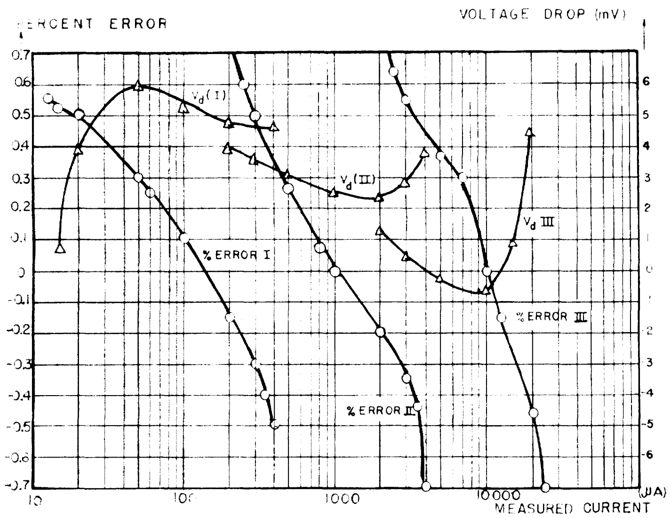

Fig. 5. Percent error in reading relative to each nominal value and the voltage drop across input terminals versus the measured current.

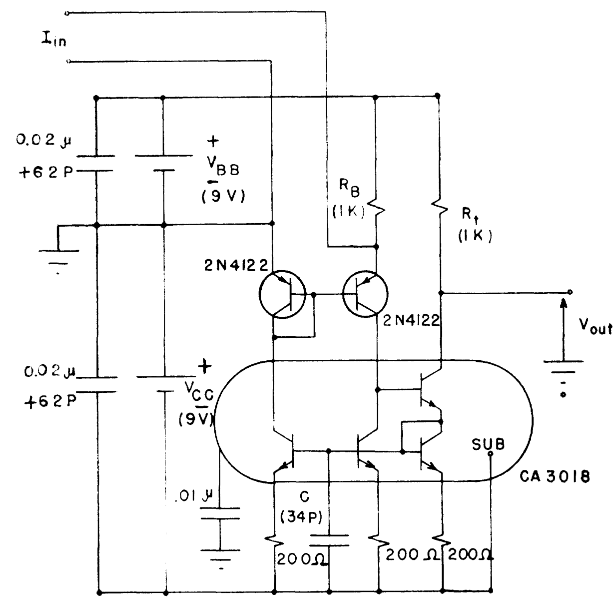

Fig. 6. Circuit diagram of the wide-band (dc to 100-MHz) current probe. Ferrite beads are used to prevent any parasitic oscillation.

Q_1 in order to provide some loop gain at low current levels thus eliminating the possibility of a second stable state in which all the transistors are cut off. To reduce the effect of the addition of R_4 on the accuracy of the probe at the low current levels two other resistors R_5 and R_6 are included.

Resistor R_7 (0.7 ohm) in the emitter of Q_1 has been added to compensate for a variation in the offset of the pair Q_1–Q_2, especially at high currents. Each of the output resistances (transimpedances) consists of a fixed part in series with a small variable part for initial adjustment. In this way errors can be distributed uniformly within each current range. However, it should be noted that no external adjustment is needed for drift.

Fig. 5 shows the percentage error in reading relative to each nominal value together with the voltage drop across the probe input terminals, both versus the measured current throughout the operating range. Errors less than 0.5 percent are obtained throughout the required three decades of current range. It may also be noted that if improved accuracy is desired, additional range switching can be provided with each range (an octave, for instance) being trimmed at its middle point. Less than a 6-mV drop across input terminals is obtained throughout the operating range. Better performance is expected to be obtained by using a more closely matched p-n-p pair.

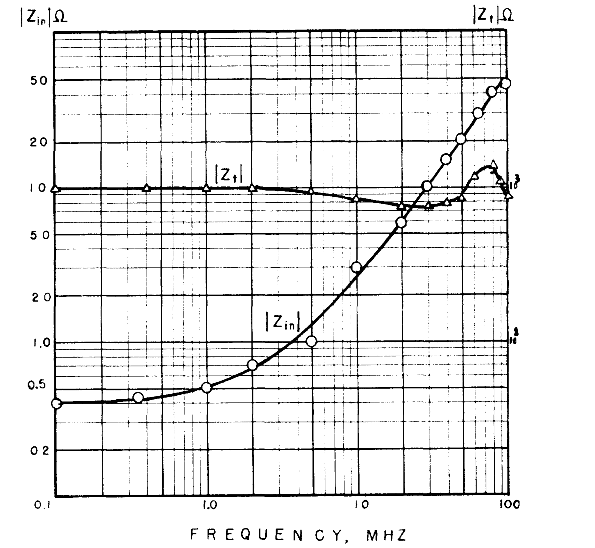

Fig. 7. The transimpedance and the input impedance of the current probe versus frequency, measured with an input sine wave current of 2 mA peak-to-peak.

Fig. 6 shows the circuit diagram of the wide-band current probe whose design follows the procedure described above. Two individual high-speed transistors were used for Q_1 and Q_2 in the unit tested. However, high-speed matched p-n-p pairs are currently available and could be advantageously used.

The frequency response of the probe is shown in Fig. 7. Deviation of the transimpedance gain from nominal value is less than 3 dB from dc to 100 MHz. An input impedance of about 0.4 ohm is obtained at frequencies below 1 MHz. These results compare favorably with a recently reported design [5]. It may be also useful to note that trimming the compensating capacitor C can minimize the deviations from the nominal transimpedance over any narrow band of frequencies in the range of operation. The results shown are obtained with C trimmed to provide the best distribution of the deviations over the frequency range of dc to 100 MHz. Measurements have been made with a type 454 Tektronix oscilloscope.

Conclusions

A simple but accurate wide-band current-measuring device that makes possible the digital measurement of current while minimizing disturbance to the circuit being measured has been introduced. Its performance is suitable for use as a plug-in unit or probe for digital voltmeters or as a probe for attachment to a wide-band oscilloscope.

The design of the probe is a direct application of the current conveyor. The prototype tested makes use of a commercially available integrated circuit and a matched transistor pair.

Appendix

A Second-Order Realization for the Current Conveyor

Fig. 3 shows an improved realization for the current conveyor in which the output current is made exactly equal to the input current under the condition that all transistors have the same current gain. To see that this is approximately true assume that all transistors have a common base current gain α given by

$$\alpha = 1 - \epsilon$$

where ϵ is a small fraction. Assume also that a unit of current is being forced through x. As all the transistors carry almost the same current, assume that the base current of each is approximately ϵ. Also, since Q_3, Q_4, and Q_5 are matched, their bases are interconnected, and R_1, R_2, and R_3 are matched, the emitters of Q_3, Q_4, and Q_5 may be assumed to carry equal currents.

Following the above assumptions, the current in each branch will be as shown in Fig. 8. The output current can be seen to be exactly equal to the input current. However, there exists a difference between the currents in the emitters of Q_1 and Q_2.

To see the effect of this difference on the offset of this matched pair assume that the emitter junction characteristic of Q_1 and Q_2 is roughly directly exponential, i.e.,

$$I_E = I_S e^{bV} \tag{1}$$

where

I_E = the emitter current
I_S = a saturation current
V = the emitter-base junction drop
$b = q/\eta KT$

with q, η, K and T being well defined in the literature. For the usual parameter values, b is 38.9 volts^{-1} for germanium junctions at room temperatures and less by a factor of almost 2 for silicon junctions. Using (1), it can be shown that the difference V_{off} in junction drops of Q_1 and Q_2 is approximately

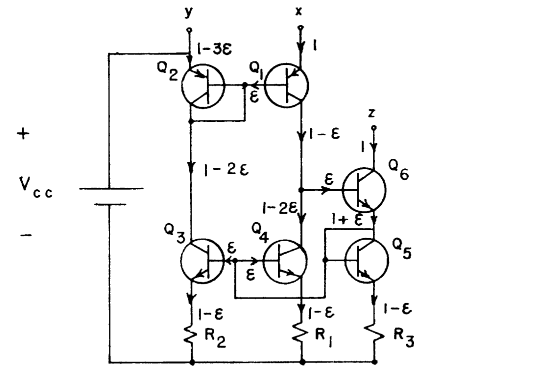

Fig. 8. The current values at different points in the conveyor circuit of Fig. 3.

$$V_{off} = 3\epsilon/b \text{ volts.} \tag{2}$$

For a current gain α of 0.99 ($\beta \simeq 100$), $\epsilon = 0.01$, and using b of 20 (2) shows that V_{off} is about 1.5 mV, which is considered negligible.

It should be noted, however, that some compensation for this offset can be provided by a slight mismatch in the emitter resistors R_1 and R_2. However, this modification is not very desirable as it necessitates an extra adjustment.

Using the positive feedback connection of Q_4, Q_5, and Q_6 also provides a higher output impedance for the current-source output than that of the normal connection shown in Fig. 2. A subsequent publication will consider a detailed comparative analysis of the various possible current-source connections using incremental hybrid-pi equivalent circuit models for the transistors.

References

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