4.1.2 Requirements of the Reference Voltage Source*

The prime requirement of the reference voltage source is that it must maintain a stable output voltage with time and temperature. A voltage regulator can only be as good as its reference source; therefore, it is desirable to make the temperature coefficient of the reference as close to zero as possible. Reference sources are commonly made up of a series string of reverse- and forward-biased diode junctions having equal and opposite temperature coefficients of voltage drift. In combination, the opposing effects cancel and the net zero temperature coefficient is usually found only at a specific value of current in the diodes. For a reference diode to maintain the temperature coefficient within its specified limits, a well-maintained current drive is required.

Reference diodes are specified to various degrees of accuracy and, depending on the number of series junctions used, are available in various terminal voltages. One example is the 1N821 series, a 6.2-V, 7.5-mA diode available with temperature coefficients from 0.01%/°C down to 0.0005%/°C. Another example is the 1N935 series, a 9.0-V, 7.5-mA diode available with a range of temperature coefficients comparable to the 1N821. The 1N4611 series is a 6.6-V, 2.0-mA diode available with temperature coefficients from 0.005%/°C down to 0.0005%/°C. The 2.0-mA operating current of this diode is compatible with the output current of a standard IC op amp.

Since the terminal voltage of a reference diode is sensitive to the current flowing in it, one usual function of the circuitry associated with the diode is to regulate this current against variations in temperature and input voltage. The latter is the more difficult consideration, since in a simple resistor-fed reference diode as shown in Fig. 4-1, the current in R_1 will vary as $+V_{in}$ varies. This will result in variations in the reference voltage, since reference diodes do have a finite impedance. The dynamic impedance of the 1N4611, for example, is 75 ohms. It is also undesirable to load a reference diode to any extent because a varying load will result in a change in the reference voltage due to the nonzero source impedance of the diode. For this reason, reference diodes are usually buffered to minimize loading or, if they are loaded directly, the load is carefully maintained constant.

Monolithic IC diodes have been developed that have extremely low dynamic impedances, low temperature coefficients, and close tolerances. A type representative of this class of diode is the LM329, which will be used in these discussions. Others available (but not discussed here) are the LM336, the AD584, the AD589, and the ICL8069.

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* For a detailed discussion of references, see the author's *IC Converter Cookbook,* Howard W. Sams & Co., Inc., 1978.

4.1.3 A Basic Reference Voltage Source

The preceding considerations are illustrated in a simple but effective fashion in the +6.9-V reference voltage source of Fig. 4-2. This circuit uses a combination of negative and positive feedback to maintain the 1.0-mA current in D_1 constant, and it does this independent of variations in both the ambient temperature and the unregulated input. The circuit works as follows:

At the moment of turn-on, the circuit has heavy positive feedback due to the low resistance (R_1) from the output to the noninverting input of A_1, and the fact that D_1 is effectively an open circuit at voltages less than its breakdown voltage. This positive feedback forces the voltage across D_1 to rise in a positive-going direction until the breakdown voltage is reached. D_1 then clamps the noninverting input of A_1 at 6.9 volts, which, in turn, reduces the positive feedback due to the low dynamic impedance of D_1. At this point, the negative feedback through R_3 and R_2 predominates, and a stable condition is

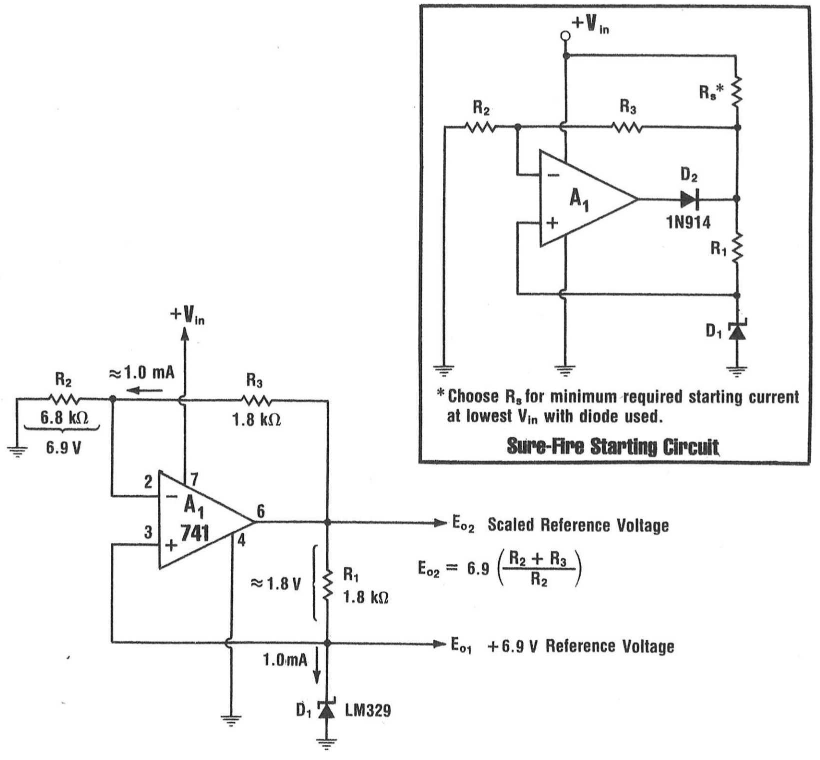

Fig. 4-2. Basic reference voltage source—positive output.

established, with A_1 amplifying the 6.9 volts applied from D_1. The 6.9-V reference voltage is scaled upward to a more positive level at the output of A_1. Because a regulated voltage now exists at either end of R_1, a well-defined and stable voltage drop is created across R_1. Thus, the value of R_1 very effectively establishes the current in D_1. The values of R_2 and R_3 are chosen to set the output level of A_1, then R_1 is chosen for the desired current in D_1.

The unique feature of this circuit is that the reference diode regulates its own current. This current depends primarily on the reference voltage itself and thus will be stable, which lends further overall stability to the circuit. The reference voltage output can be taken directly from D_1 for high-impedance loads, or from the output of A_1 where it is scaled upward by the $(R_2 + R_3)/R_2$ ratio. This output appears at a low impedance and can supply appreciable current without the basic or scaled reference voltages being affected.

The circuit is capable of temperature performance consistent with the selection grade of the diode and op amp used. The temperature coefficient of the LM329 diode can be as good as 20 ppm/°C (maximum) for the higher-quality versions, such as the LM329B. These monolithic IC diodes are also available in heated substrate versions with temperature coefficients down to 1.0 ppm/°C in the same nominal voltage. These types are the LM399A series. When these premium diodes are used, a premium op amp should also be used. Also, for a very low overall temperature coefficient, the current-determining resistors used should be stable 1.0% film or, preferably, wirewound types. This circuit configuration provides exceptional performance in all respects except stability, even with the basic components shown. With a standard 741 op amp and virtually any zener diode in the 5- to 7-volt region, the rejection of line input variations is over 100 dB at 100 Hz.

A word of caution is appropriate at this point with regard to the *starting* of this circuit. The circuit is definitely *not* guaranteed to start properly if bipolar power supplies are used for A_1—a single-ended supply *must* be used. Although extensive testing with various amplifiers has not as yet revealed a case where the circuit failed to come up to the proper operating state, "Murphy's" law states that somewhere in the world such an amplifier exists and that someone will try to use it without success. Should this happen, the "sure-fire" starting circuit shown in the inset of Fig. 4-2 will make the most stubborn amplifier behave properly.

4.1.4 Error Sources in Op-Amp Voltage Regulators

When a specific degree of output voltage precision must be met in a reference source (or regulator), the various error sources that influence the total performance must be separated and analyzed. Among

these error sources are the temperature coefficient of the reference diode, diode noise, wiring voltage drops, amplifier input offset voltage and current drift, amplifier noise, and rejection of power-supply and common-mode input changes. These error sources will be discussed briefly in this section, and the reader can apply the basic principles to any of the circuits covered in this chapter.

Input Offset Voltage Drift

Referring again to the basic regulator of Fig. 4-2, if we assume that a stable reference diode is used for D_1, another limitation on overall temperature performance is the input offset voltage drift of A_1. This parameter is not specified for the 741; therefore, it is not a good choice for applications where temperature drift is critical. The average temperature coefficient of input offset voltage ($\Delta V_{io}/°C$) for a 307 or a 301A is specified as 6.0 μV/°C (typical), and 30 μV/°C (maximum). We will now examine what this means to the overall circuit.

The input offset voltage will change by the average amount specified for each 1.0°C change in chip temperature. This chip temperature change can be due either to self-heating or to the effects of loading. For example, the thermal resistance (θ_{JA}) of a 307 or a 301A is 150°C/W for the TO-99 package, which means that for each watt of dissipation the chip temperature will rise 150°C above the ambient temperature. In the circuit of Fig. 4-2, if we assume a $+V_{in}$ of 30 volts and a V_{out} of 15 volts, then

$$V_{in} - V_{out} = 15\ \text{V}$$

Therefore, a 3.0-mA load represents a chip power dissipation (P_D) of 45 mW (15 V × 3.0 mA). We then divide the chip dissipation by the thermal resistance to determine the change in chip temperature (Δ°C) due to chip dissipation:

$$\Delta°\text{C} = \frac{P_D}{\theta_{JA}}$$

Knowing in this example that

$$\theta_{JA} = 150°\text{C/W} = 6.7\ \text{mW/°C}$$

and

$$P_D = 45\ \text{mW}$$

then

$$\Delta°\text{C} = \frac{45\ \text{mW}}{6.7\ \text{mW/°C}} = 6.7°\text{C}$$