

# Three-Terminal Linear Regulator Evolution Continues Unabated

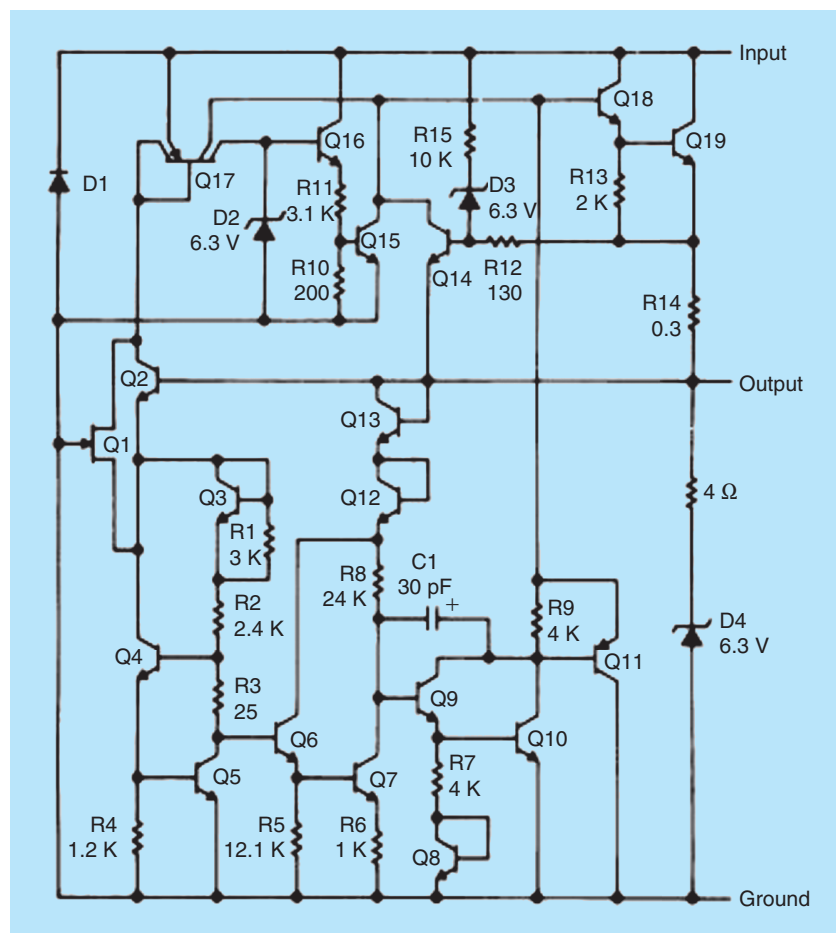
Despite severe competition from switching regulators for decades, the three-terminal linear regulator has not been given up. It continues to hold its niche space because backers like Linear Technology, National Semiconductor/Texas Instruments, Fairchild Semi, and a few others continue to improve the device and serve the applications whose performance requirements are stringent and cannot be met by the switching alternatives.

First introduced in 1969 by National Semiconductor, the three-terminal linear regulator has survived for over 45 years and continues to make progress. The first three-terminal buck linear regulator, LM309, was designed by the late Bob Widlar at National Semiconductor in 1969 (Figure 1). A fixed +5-V output with 200-mA or 1-A output current, this bipolar device was housed in a TO-5 or TO-3 Can package (Figure 2). Despite efforts at that time to make them simple to use, there were several limitations. First, it required bypass filtering capacitors at the input and output and a silicon diode at the output to keep the positive output from being pulled too far negative by the high current supply. Second, the output voltage was not adjustable. Third, these regulators were not suitable for paralleling.

In early 1969, Bob Dobkin joined National Semiconductor to work

alongside Widlar in the development of linear regulators. As a young engineer, he had many ideas about improving the fixed-output linear device. Therefore, he suggested that the fixed-output regulator must be redesigned as an adjustable-output, three-terminal linear part. But National's linear guru Widlar

was not supportive because he was convinced that with the floating n-p-n pass transistor at the output, it was not possible to build an adjustable-output three-terminal linear regulator with good performance. However, young and dynamic Dobkin was undeterred and continued to pursue his vision.



**FIG 1** The LM309 was the first three-terminal linear regulator introduced by National Semiconductor in 1969. (Figure courtesy of Texas Instruments.)



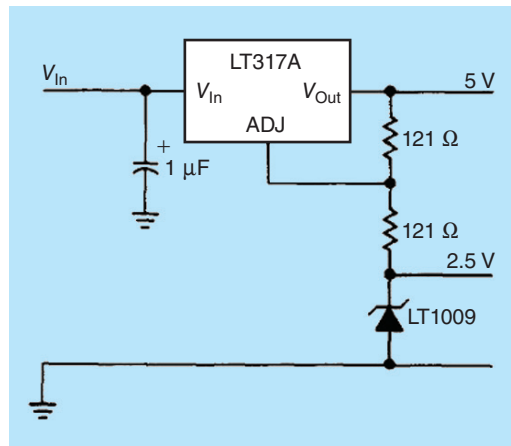
**FIG 2** LM309 in a TO-3 can package. (Figure courtesy of Texas Instruments.)

### Adjustable Output

Based on Dobkin's design and development work, National Semi released the first adjustable three-terminal positive-voltage linear regulator, the LM317, in 1976. Implemented in a 7- $\mu\text{m}$  bipolar process, LM317 offered a die size of 8,000–9,000 mil<sup>2</sup> and could handle about 1.5 A of output current. The output was adjustable from 1.25 V, which was the reference voltage, to 37 V using only two external resistors (Figure 3). It was housed in the metal TO-3 can, and the minimum low-output voltage was limited by the on-chip band-gap reference voltage. According to

LM317 Designer Dobkin, there were several barriers he had to overcome to realize the first adjustable three-terminal linear regulator. "Because the n-p-n pass transistor at the output was floating and there was no ground pin, I had to ensure that any feedback did not produce oscillations to make the regulator unstable," he said. In addition, he added, to make the device robust, the output transistors had to be protected using foldback current limiting.

Both the line and load regulation were better than standard fixed regulators, and it implemented on-chip current limiting, thermal overload protection, and safe operating-area protection. Soon after, legendary analog guru the late Bob Pease, who was working for National Semiconductor, designed the adjustable three-terminal linear regulator with negative output, the LM337. Its



**FIG 3** The adjustable three-terminal linear regulator LT317 uses only two external resistors to adjust positive output voltage. (Figure courtesy of Linear Technology.)

adjustable output voltage range was –1.2 to –37 V with an output current of –1.5 A. Another analog guru working for National Semiconductor, Carl Nelson, introduced the fixed output power negative regulator series LM320. It was widely adopted in the industry.

Dobkin left National Semiconductor in July 1981 to start his own linear IC company, Linear Technology

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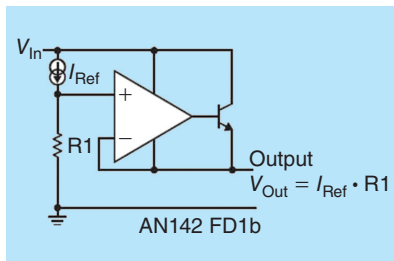
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<b>Current Range</b>	0-1.5 Adc to 0-250 Adc	0-0.2 Adc to 0-600 Adc	0-1.2 Adc to 0-2,700 Adc	0-72 Adc to 0-4,500 Adc	0-24 Adc to 0-24,000 Adc

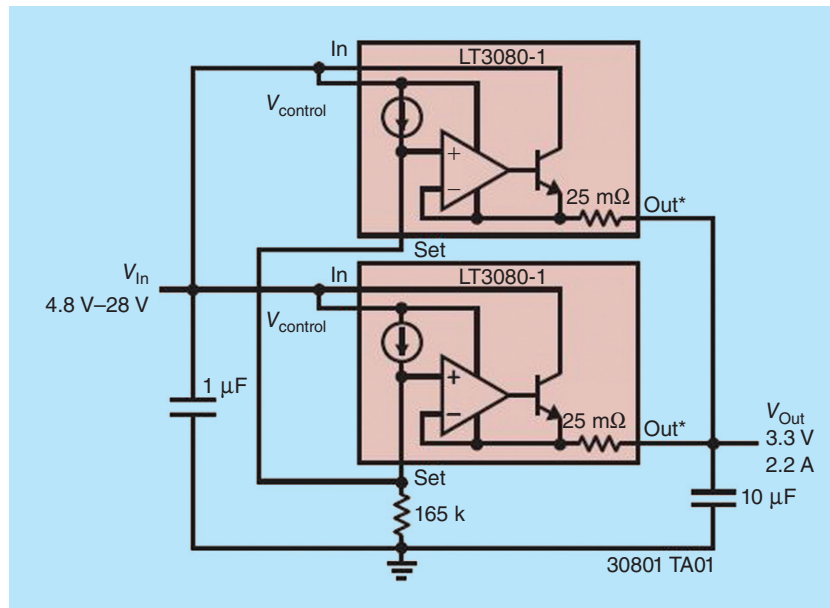


**FIG 4** The new architecture replaces bandgap reference with a current source and uses a voltage follower for the output amplifier. (Figure courtesy of Linear Technology.)

Corporation, which he cofounded with Bob Swanson. A few years later, Dobkin's linear team at Linear Technology created another milestone in this area. Around 1986 or 1987, the newly founded precision analog company unveiled high-output-current positive adjustable regulators with very low dropout and pin compatible with older three-terminal regulators [1]. The LT1083 series was designed to provide up to 7.5 A with higher efficiency and a maximum dropout of only 1.5 V at maximum output current, which was substantially lower than the previous generation and continued to use only two external resistors to set the output voltage.

During this period, the switching regulators were encroaching the linear turf. According to Dobkin, "Switching regulators began to grow significantly in the late 1980s and early 1990s, driven by the portable PCs and portable electronics markets, which required low voltage and high current." Switching regulators were initially used primarily in offline applications and later moved to point-of-load applications. Linear regulator applications were limited to 5–25 W. "In the 1980s and 1990s, linear regulators were focused on general-purpose applications. Now, linear regulators are used when designers want reduced complexity, low noise, low power, and lower solution cost," notes Dobkin. The market for linear regulators has grown as has the market for switching regulators. "A lot comes down to a designer's individual preference," he asserts.

By the early 1990s, the three-terminal linear regulators were going



**FIG 5** The internal ballast resistor eases paralleling of LT3080-1 for higher output current. (Figure courtesy of Linear Technology.)

through another major boost. The n-p-n pass transistor in the output stage of the design was replaced by its p-n-p counterpart. The result was very low dropout and high robustness with low quiescent current and a ground pin. The low power dissipation also enabled the company to offer these regulators in surface-mount packages. As a result, using bipolar technology, Linear introduced the first-generation p-n-p micropower low-dropout linear regulators with adjustable output voltages in 1992. The first member in this line was LT1121, with 150-mA output current, adjustable and fixed outputs, 0.4-V dropout, and 30-µA quiescent current. In addition, it did not require protection diodes and was available in multiple package choices. The company continued to add members with higher output current capabilities. In 1995, a 3-A version, the LT1529, was introduced.

The second-generation parts offered lower noise and faster transient response. Concurrently, the company also improved the input voltage capability. A good example is the LT3010, a part that was released in February 2003, and handles a wide input voltage range of 3–80 V. Though LT3010 supported only 50-mA output cur-

rent, a 250-mA version (LT3013) was added to this line in 2006.

### Transition to Current Source

Ever since the introduction of the first three-terminal adjustable linear regulator in 1976, the architecture has more or less remained the same. Therefore, the reference-voltage-dependent adjustable output could not go below the 1.25-V reference voltage, making it unsuitable for powering low-voltage integrated circuits that were emerging in the market based on low-geometry complementary metal-oxide-semiconductor processes. A new architecture was needed to end the low-voltage limitation of three-terminal linear regulators. Linear Technology answered the call by replacing the bandgap voltage reference with a current source and using a voltage follower for the output amplifier [2], [3] (Figure 4). It was implemented in LT3080, which was introduced in 2007. Per Dobkin's explanation in [3], the architecture delivers two key benefits: the ability to operate down to 0 V and to allow paralleling of regulators for more output current. Furthermore, because the output amplifier always operates at unity gain, both the bandwidth and the regulation are constant, explains Dobkin. Also, transient response is

independent of output voltage, thus allowing regulation to be specified in millivolts rather than the traditional percentage of output.

The LT3080 specifications from the data sheet show that this 1.1-A adjustable single-resistor, low-dropout linear regulator incorporates an internal ballast resistor that eases direct paralleling of these devices for higher output current, as shown in Figure 5. Since these devices can be paralleled directly on a surface mount board, a board layout is simple and easy. As can be seen, any output voltage can be obtained from zero up to the maximum defined by the input power supply.

Last June, the company started adding monitoring functions to the adjustable single-resistor, low-dropout linear regulator. The LT3081 was introduced with current and temperature monitoring functions and built-in protection circuitry for reverse input

protection, reverse-current protection, internal current limiting, and thermal shutdown. Other features include an extended safe operating area, 1.5-A maximum output current, stable with or without input/output capacitors, and a wide input voltage range of 1.2–36 V.

In summary, three-terminal linear regulators have come a long way since they were first introduced in 1969. They will continue to play an important role in applications where noise, cost, and simplicity are important. As a result, they continue to be used in general-purpose applications of a wide variety. Bipolar has enough juice left to keep pushing the performance of these devices at lower cost and adding new bells and whistles as needed by the market. The evolution continues.

#### About the Author

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