Digital Potentiometers

INTRODUCTION

Mechanical potentiometers have been used since the earliest days of electronics and provide a convenient method for the adjustment of the output of various sensors, power supplies, or virtually any device that requires some type of calibration. Timing, frequency, contrast, brightness, gain, and offset adjustments are just a few of the possibilities. However, mechanical pots have always suffered from numerous problems including physical size, mechanical wearout, wiper contamination, resistance drift, sensitivity to vibration, temperature, humidity, the need for screwdriver access, layout inflexibility, etc.

Digital potentiometers avoid all the inherent problems associated with mechanical potentiometers and are ideal replacements in new designs where there is either a microcontroller or another digital device to provide the necessary control signals. Manually controlled digital potentiometers are also available for those who do not have any on-board microcontrollers. Unlike mechanical pots, digital pots can be controlled dynamically in active control applications.

The digital potentiometer is based on the CMOS "String DAC" architecture previously described in Tutorial MT-014, and the basic diagram is shown in Figure 1. Note that in the normal string DAC configuration, the A and B terminals are connected between the reference voltage, and the W (wiper) terminal is the DAC output. There is also one more R resistor in the string DAC configuration which connects the A terminal to the reference.

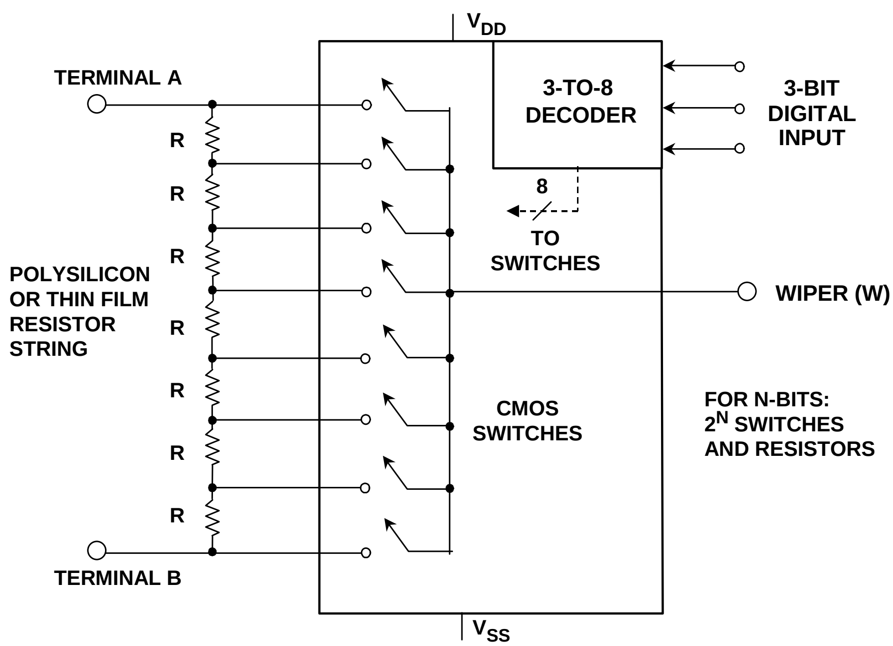


Figure 1: 3-Bit CMOS Digital Potentiometer Based on "String DAC" Architecture

The digital potentiometer configuration essentially makes use of the fact that the CMOS switches' common-mode voltages can be anywhere between the power supplies—the switch selected by the digital input simply connects the wiper to the corresponding tap on the resistor string. The relative polarity of A to B can be either positive or negative.

The resistor string represents the end-to-end potentiometer resistance, and the traditional "DAC output" becomes the wiper of the digital potentiometer. The resistors can be either polysilicon (TC ~ 500 ppm/°C) or thin film (TC ~ 35 ppm/°C), depending upon the desired accuracy.

The number of resistors in the string determines the resolution or "step size" of the potentiometer, and ranges from 32 (5 bits) to 1024 (10 bits) at present. The value of the programmable resistors are simply: $R_{WB}(D) = (D/2^N)\cdot R_{AB} + R_W$, and $R_{WA}(D) = [(2^N - D)/2^N]\cdot R_{AB} + R_W$, where R_{WB} is the resistance between W and B terminals, R_{WA} is the resistance between W and A terminals, D is the decimal equivalent of the step value, N is the number of bits, R_{AB} is the nominal resistance, and R_W is the wiper resistance.

The switches are CMOS transmission gates that minimize the on-resistance variations between any given step and the output. The voltages on the A and B terminals can be any value as long as they lie between the power supply voltages V_{DD} and V_{SS}.

MODERN DIGITAL POTENTIOMETERS IN TINY PACKAGES

Figure 2 shows three examples of digital potentiometers that are all offered in small packages. The I²C® serial interface is a very popular one, but digital potentiometers are also available with the SPI®, Up/Down Counter, and Manual Increment/Decrement interfaces.

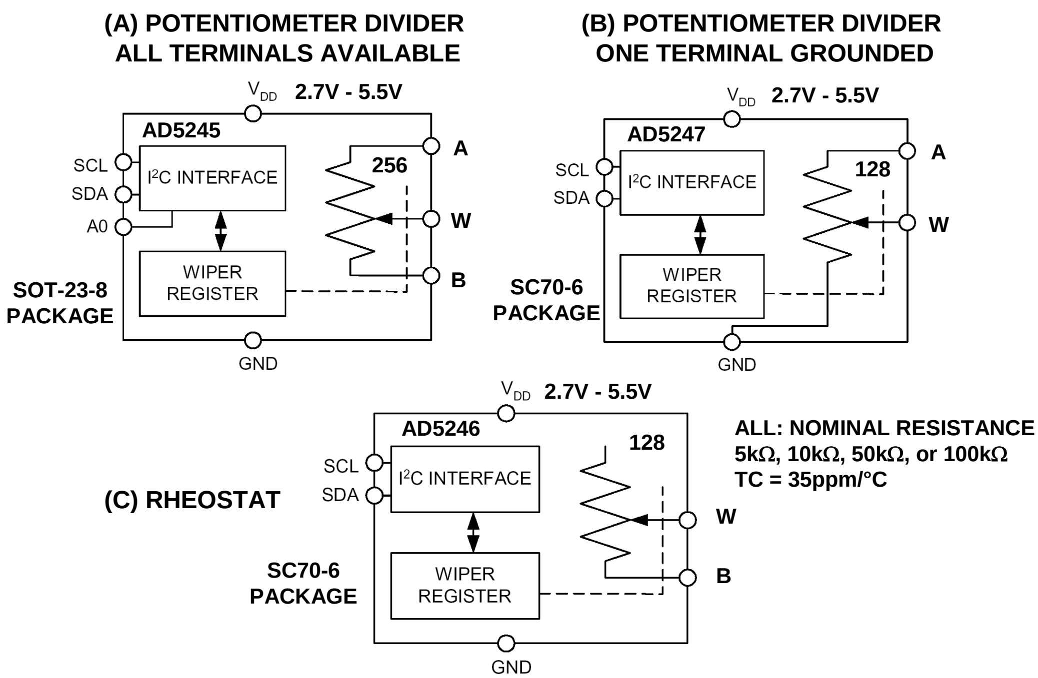


Figure 2: Typical Examples of Digital Potentiometers in Tiny Packages

The AD5245 shown in Figure 2A is available in an 8-lead SOT-23 package and has 256 positions (8-bits). The A0 pin allows the device to be uniquely identified so that two devices can be placed on the same bus. The thin film resistor string (R_{AB}) is available in 5 kΩ, 10 kΩ, 50 kΩ, or 100 kΩ, and the R_{AB} temperature coefficient is 35 ppm/°C. All three terminals of the potentiometer are available for use. The operating supply voltage can range from +2.7 V to +5.5 V. The power supply current is 8-µA maximum, and an internal command bit is available to shut down the device into a state of zero power consumption. The voltage noise is approximately the thermal noise of R_{AB}. (Recall that the thermal noise of a 1-kΩ resistor at room temperature is approximately 4 nV/√Hz).

The AD5247 shown in Figure 2B is similar to the AD5245, except it has 128 positions (7-bits), the B terminal is grounded, and the part comes in an SC70 6-lead package. The AD5247 does not have the A0 function. Finally, the AD5246 shown in Figure 2C is similar to the AD5245, but is connected as a rheostat with the W and B terminals available externally.

In addition to single potentiometers, such as the AD5245, AD5246, and AD5247, digital potentiometers are available as duals, triples, quads, and hex versions. Multiple devices per package offer 1% matching in ganged potentiometer applications as well as reducing PC board real estate requirements. Figure 3 summarizes some of the characteristics and features of modern digital potentiometers.

- **Resolution (wiper steps): 32 (5-Bits) to 1024 (10-Bits)**
- **Nominal End-to-End Resistance: 1kΩ to 1MΩ**
- **End-to-End Resistance Temperature Coefficient: 35ppm/°C (Thin Film Resistor String), 500ppm/°C (Polysilicon Resistor String)**
- **Number of Channels: 1, 2, 3, 4, 6**
- **Interface Data Control: SPI, I^2C, Up/Down Counter Input, Increment/Decrement Input**
- **Terminal Voltage Range: +15V, ±15V, +30V, +3V, ±3V, +5V, ±5V**
- **Memory Options:**
  - **Volatile (No Memory)**
  - **Nonvolatile E^2MEM**
  - **One-Time Programmable (OTP) - One Fuse Array**
  - **Two-Time Programmable - Two Fuse Arrays**

Figure 3: Characteristics of CMOS Digital Potentiometers

DIGITAL POTENTIOMETERS WITH NONVOLATILE MEMORY

Digital potentiometers, such as the AD5245, AD5246, and AD5247, are used mainly in active control applications, since they do not have non-volatile memory. Therefore, the setting is lost if power is removed. However, most volatile digital potentiometers have a power-on preset feature that forces the devices to the midscale code when power is applied.

Obviously, there is a demand for digital potentiometers with the ability to retain their setting after power is removed and reapplied. This requires the use of nonvolatile on-chip memory to store the desired setting. The AD5235 is an example of a dual 10-bit digital potentiometer which contains on-chip E^2MEM to store the desired settings (Reference 4). A functional block diagram is shown in Figure 4.

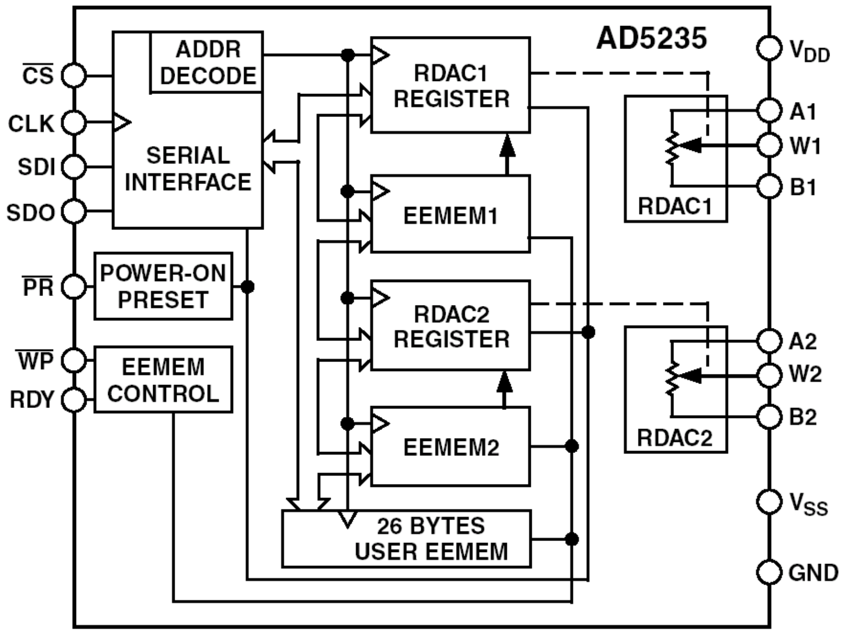


Figure 4: AD5235 Nonvolatile Memory, Dual 1024-Position Digital Potentiometers

These devices perform the same electronic adjustment function as a mechanical potentiometer with enhanced resolution, solid state reliability, and superior low temperature coefficient performance. The AD5235's versatile programming via a standard serial interface allows 16 modes of operation and adjustment, including scratch pad programming, memory storing and retrieving, increment/decrement, log taper adjustment, wiper setting readback, and extra user-defined E^2MEM. Another key feature of the AD5235 is that the actual resistance tolerance is stored in the E^2MEM at 0.1% accuracy. The actual end-to-end resistance can therefore be known, which is valuable for calibration and tolerance matching in precision applications. The new E^2MEM family of digital pots (AD5251/AD5252/AD5253/AD5254) also offer such a feature. In the scratch pad programming mode, a specific setting can be programmed directly to the RDAC register, which sets the resistance between terminals W-A and W-B. The RDAC register can also be loaded with a value previously stored in the E^2MEM register. The value in the E^2MEM can be changed or protected.

When changes are made to the RDAC register, the value of the new setting can be saved into the E^2MEM. Thereafter, it will be transferred automatically to the RDAC register during system power on. E^2MEM can also be retrieved through direct programming and external preset pin control. The linear step increment and decrement commands cause the setting in the RDAC register to be moved UP or DOWN, one step at a time. For logarithmic changes in wiper setting, a left/right bit shift command adjusts the level in ±6-dB steps. The AD5235 is available in a thin TSSOP-16 package. All parts are guaranteed to operate over the extended industrial temperature range of –40°C to +85°C.

ONE-TIME-PROGRAMMABLE (OTP) DIGITAL POTENTIOMETERS

The AD5172/AD5173 are dual channel 256-position, one-time programmable (OTP) digital potentiometers, which employ fuse link technology to achieve the memory retention of resistance setting function (Reference 5). A functional block diagram is shown in Figure 5. Note that the AD5172 is configured as a three-terminal potentiometer, while the AD5173 is pinned out as a rheostat. The AD5172/AD5173 is available in 2.5-kΩ, 10-kΩ, 50-kΩ, and 100-kΩ versions. The temperature coefficient of the resistor string is 35 ppm/°C. The power supply voltage can range from 2.7 V to 5.5 V.

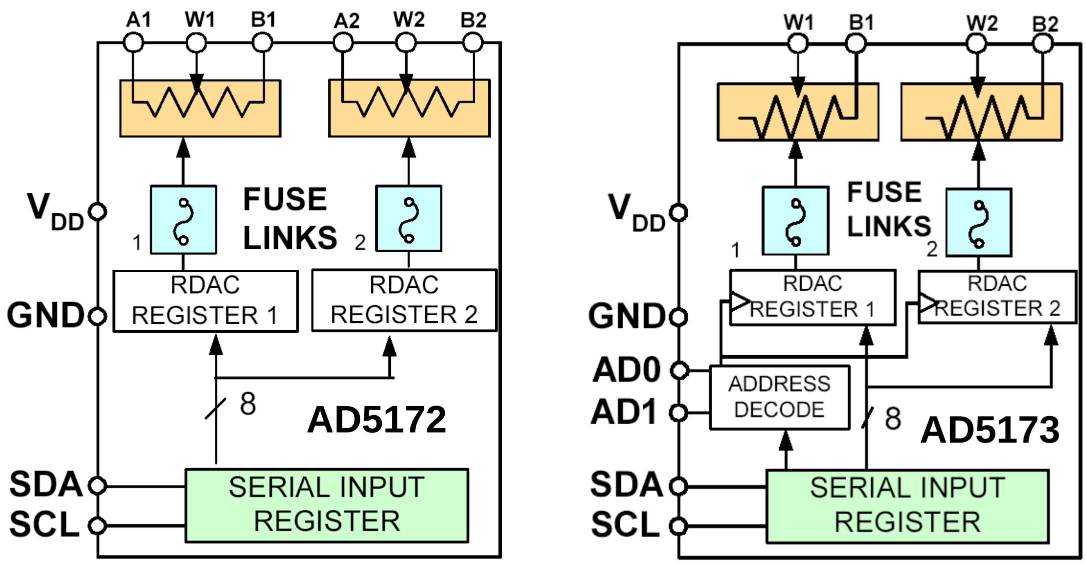


Figure 5: AD5172/AD5173 256-Position One-Time Programmable Dual-Channel I²C Digital Potentiometer

OTP is a cost-effective alternative over the E^2MEM approach for users who do not need to program the digital potentiometer setting in memory more than once, i.e., "set and forget." These devices perform the same electronic adjustment functions most mechanical trimmers and variable resistors do but offer enhanced resolution, solid-state reliability, and better temperature coefficient performance.

The AD5172/AD5173 are programmed using a 2-wire I^2C compatible digital control. They allow unlimited adjustments before permanently setting the resistance value. During the OTP activation, a permanent fuse blown command is sent after the final value is determined; therefore freezing the wiper position at a given setting (analogous to placing epoxy on a mechanical trimmer). Unlike other OTP digital potentiometers in the same family, AD5172/AD5173 have a unique temporary OTP overwriting feature that allows new adjustments if desired, the OTP setting is restored during subsequent power up conditions. This feature allows users to apply the AD5172/AD5173 in active control applications with user-defined presets.

To verify the success of permanent programming, Analog Devices patterned the OTP validation such that the fuse status can be discerned from two validation bits in read mode. For applications that program AD5172/AD5173 in the factories, Analog Devices offers device programming software, which operates across Windows® 95 to XP® platforms including Windows NT®. This software application effectively replaces the need for external I^2C controllers or host processors and therefore significantly reduces users' development time. An AD5172/AD5173 evaluation kit is available, which include the software, connector, and cable that can be converted for factory programming applications. The AD5172/AD5173 are available in a MSOP-10 package. All parts are guaranteed to operate over the automotive temperature range of −40°C to +125°C. Besides their unique OTP features, the AD5172/AD5173 lend themselves well to other general-purpose digital potentiometer applications due to their programmable preset, superior temperature stability, and small form factor.

The AD5170 (Reference 6) is a two-time programmable 8-bit digital potentiometer, and a functional diagram is shown in Figure 6. Note that a second fuse array is provided to allow "second chance" programmability. Like the AD5172/AD5173, there is unlimited programmability before making the permanent setting. The electrical characteristics of the AD5170 are similar to the AD5172/AD5173.

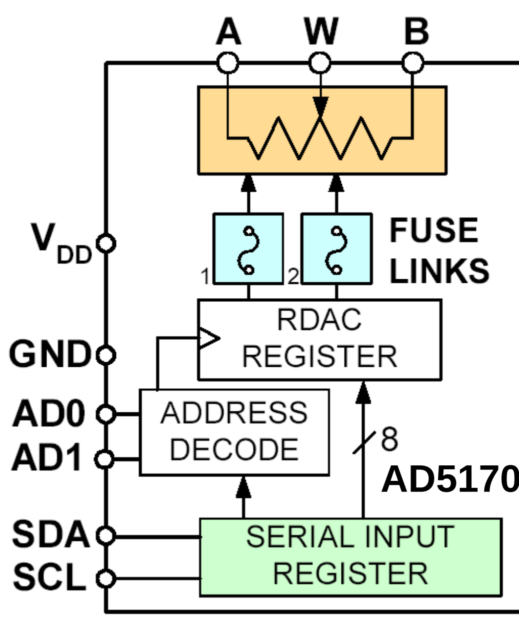


Figure 6: AD5170 256-Position Two-Time Programmable I^2C Digital Potentiometer

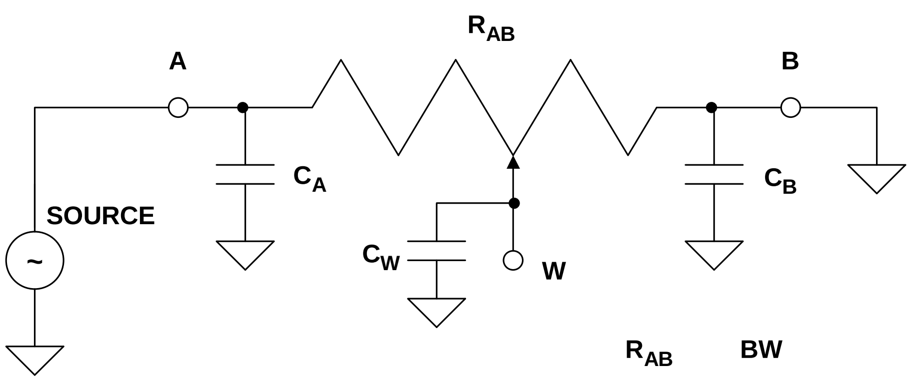
DIGITAL POTENTIOMETERS WITH 1% ACCURACY

The AD5291/AD5292 are single-channel, 256/1024-position digital potentiometers1 with less than 1% end-to-end Resistor Tolerance error, nominal temperature coefficient of 35 ppm/ºC, and 20-Time Programmable Memory. These devices are capable of operating at high voltages; supporting both dual supply ±10.5 V to ±15 V and single supply operation +21 V to +30 V.

The AD5291/AD5292 device wiper settings are controllable through the SPI digital interface. Unlimited adjustments are allowed before programming the resistance value into the 20-Time Programmable memory. These parts do not require any external voltage supply to facilitate fuse blow, and there are 20 opportunities for permanent programming. During 20-TP activation, a permanent blow fuse command freezes the wiper position (analogous to placing epoxy on a mechanical trimmer).

DIGITAL POTENTIOMETER AC CONSIDERATIONS

Digital potentiometers can be used in ac applications, provided the bandwidth limitations created by the internal capacitance are considered. Figure 7 shows an ac model of a digital potentiometer, where the capacitances are modeled as C_A, C_B, and C_W.



FOR AD5245:

$C_{A,B}$ = 90pF
C_W = 95pF

R_{AB}	BW
5kΩ	1.0MHz
10kΩ	500kHz
50kΩ	100kHz
100kΩ	50kHz

BW MEASURED FROM A TO W WITH B GROUNDED, MIDSCALE CODE, DRIVEN FROM A LOW IMPEDANCE SOURCE

Figure 7: Digital Potentiometer Bandwidth Model

The bandwidth of the digital pot is configuration dependent. It is also dynamic because of the variable resistance. For example, if A terminal is the input, B terminal is grounded, and W terminal is the output; then the bandwidth can be approximated by $BW = 1/[2\pi(R_{WB}||R_{WA})\cdot C_W]$. The lowest bandwidth occurs at midscale, where the equivalent resistance is at its maximum in this configuration. The typical values for the AD5245 are shown as well as the corresponding bandwidths for the various resistance options measured at midscale. This simple model can be used in SPICE simulations to predict circuit performance, such as when the digital potentiometer is used as a part of the feedback network of an op amp. The other issue to consider when placing digital potentiometers directly in the signal path is their slightly nonlinear resistance as a function of applied voltage. This effect leads to a small amount of distortion. For example, the AD5245 has a THD of 0.05% when a 1-V rms, 1-kHz signal is applied to the configuration described above at midscale. Examples of the application of digital potentiometers in ac applications can be found at the end of this tutorial.

APPLICATION EXAMPLES

Like op amps, digital pots are the building blocks of many electronic circuits. Because they are digitally controlled, digital pots can be used in active control applications, in addition to basic trimming or calibration applications. For example, digital pots can be used in programmable power supplies as shown in Figure 8A. Typical adjustable low dropout voltage regulators (such as the anyCAP series) have a FB pin, where applying a resistor divider yields a variable output voltage. As shown, R1 and R2 are the feedback and input resistors, respectively. The FB circuit has an internal non-inverting amplifier which gains up a 1.2-V bandgap reference to the desired output voltage.

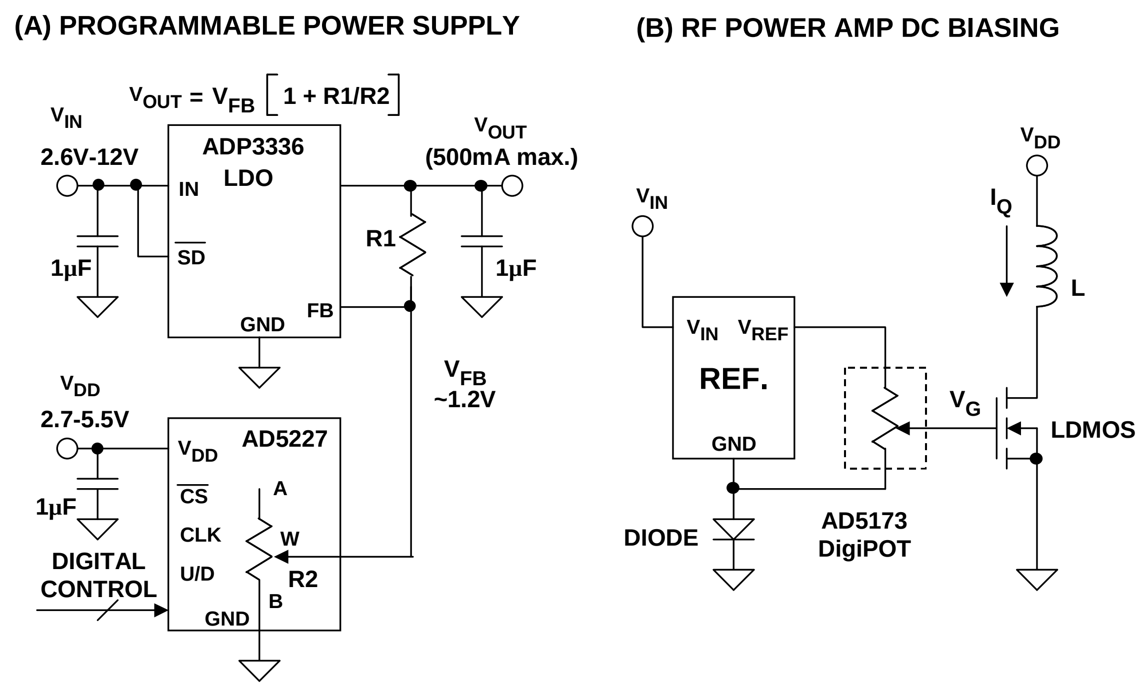


Figure 8: Two Circuit Applications for Digital Pots

Similarly, electronic equipment makers use digital potentiometers in power supplies by adjusting the supplies to the tolerances that cover all supply voltage conditions during reliability testing. This voltage-margining approach accelerates the burn-in process, and therefore reduces the system time-to-market.

Because of the optimized cost/performance benefits, digital pots have been gaining popularity in replacing traditional DACs in many applications. For example, in wireless basestations, the optimum threshold voltages of the RF power amplifiers vary widely in production. Such variation affects the transmitted signal linearity and power efficiency. Too much power delivered from a poorly regulated amplifier can also interfere with neighboring cells within the wireless network. Although DACs are widely used in biasing RF power amplifiers, many users find digital pots to be more suitable in such applications because of the availability of non-volatile memory, which simplifies the designs. As shown in Figure 8B, the one-time-programmable digital pot is used to calibrate the dc bias point of the RF power amplifier, and the calibration is programmed by factory software without the need for any external controllers. Note that the diode is added to the circuit to compensate for the amplifier's temperature coefficient.

SUMMARY

Digital potentiometers offer many obvious advantages over mechanical potentiometers and trimpots®, and therefore they have become widely accepted in modern systems. Their reliability, flexibility, and ease of use makes them popular replacements for the traditional potentiometer. Digital pots can also be used as programmable building blocks in many active control applications.

There are virtually endless applications for digital potentiometers in modern electronic systems—one only has to consider the many traditional applications for mechanical pots and trimpots as a starting point. References 1-13 should be consulted for more ideas on how these devices can enhance a design. A few applications are summarized below:

- *General Purpose Applications:* sensor calibration, system gain and offset adjustments, programmable gain amplifiers, programmable filters, programmable set-points, traditional digital-to-analog converters, voltage-to-current converters, line impedance matching.

- *Computer and Network Equipment:* programmable power supplies, power supply margining, battery charger set-points, temperature control set-points.

- *LCD Displays:* backlight, contrast, and brightness adjustments, LCD panel common voltage adjustment, programmable gamma correction, LCD projector reference voltage generator.

- *Consumer Applications:* PDA backlight adjustment, electronic volume controls.

- *RF Communications:* RF power amplifier biasing, DDS/PLL amplitude adjustment, VCXO frequency tuning, varactor diode biasing, log amp slope and intercept adjustment, quadrature demodulator gain and phase adjustment, RFID reader calibration.

- *Automotive:* set-points in the engine control unit, sensor calibrations, actuator controls, instrumentation control, navigation/entertainment display adjustments.

- *Industrial and Instrumentation:* system calibration, floating reference DACs, programmable 4-to-20-mA current transmitters.

- *Optical Communications:* laser bias current adjustments, laser modulation current adjustments, optical receiver signal conditioning, optical attenuators, wavelength controllers.

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