Chapter 7: Digital-to-Analog Conversion (DAC)

7.1 Introduction

Digital-to-Analog Converters (DACs) perform the inverse operation of ADCs: they convert digital (discrete) signals into continuous analog waveforms. DACs are critical in systems where digital computation must interface with the analog world, such as audio output, control systems, signal generation, and communications.

This chapter covers DAC principles, circuit architectures, and the essential performance parameters used to evaluate and choose appropriate DACs for different applications.

7.2 Principles of DAC Operation

A DAC takes a digital binary code as input and outputs a proportional analog voltage or current.

Key Concepts:

- **Resolution (N-bit)**: Determines the number of discrete output levels.
- **Reference Voltage (Vref)**: Defines the full-scale range of the output.
- **Output**: The analog value corresponding to digital input code.
  For an ideal N-bit DAC:
  Vout=D2N−1×VrefV_{out} = \frac{D}{2^N - 1} \times V_{ref}
  where DD is the digital input (0 to 2N−12^N - 1).

7.3 DAC Architectures

● Binary-Weighted Resistor DAC

- Simple design using resistors weighted by powers of two.
- Fast conversion but requires high precision resistors.
- Limited scalability for high-resolution designs.

- **R-2R Ladder DAC**
  - Uses repeating units of resistors with values R and 2R.
  - Easier to fabricate with matched resistors.
  - Scalable and widely used in integrated designs.
- **Current-Steering DAC**
  - Converts digital inputs into precise current outputs.
  - Excellent for high-speed applications (e.g., RF signal generation).
  - Common in high-speed communications and video systems.
- **Sigma-Delta DAC**
  - Converts a high-speed bitstream into analog output using oversampling and filtering.
  - High resolution with excellent linearity.
  - Ideal for audio and low-bandwidth applications.
- **Segmented DAC**
  - Combines thermometer-coded and binary-weighted architecture.
  - Reduces glitch energy and improves linearity.
  - Used in high-resolution and moderate-speed applications.

7.4 DAC Performance Metrics and Specifications

Metric	Description
Resolution (Bits)	Number of distinct analog output levels.
Settling Time	Time taken for output to reach final value after a code change.

Linearity (INL/DNL)	Measures how accurately output follows ideal linear response.
Monotonicity	Output must increase (or stay constant) as input code increases.
Glitch Impulse	Undesired transient output due to simultaneous bit switching.
Output Swing	Maximum range of analog output.
Noise Spectral Density	Quantifies the DAC's noise performance.
Spurious-Free Dynamic Range (SFDR)	Difference between fundamental and largest spurious tone.
Power Consumption	Total current and voltage demand during operation.

7.5 Output Types

- **Voltage Output DACs**: Provide output in volts; easy to use but sensitive to loading.
- **Current Output DACs**: Provide output in current; offer better speed and are easier to integrate in high-frequency applications.

7.6 Application-Based Architecture Selection

Application	Preferred DAC Type	Key Design Focus
Audio Playback	Sigma-Delta	Resolution, Noise, Linearity
Video/Graphics Generation	Current-Steering	High-Speed, Low Glitch
Data Acquisition Systems	R-2R Ladder or Segmented	Accuracy, Settling Time
Communication Systems	Current-Steering or Segmented	SFDR, Bandwidth
Microcontroller Systems	R-2R or PWM-based	Simplicity, Cost, Low Power

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7.7 Practical Considerations

- **Output Buffering**: DAC outputs are often buffered to drive external loads without affecting accuracy.
- **Power Supply Rejection**: Variations in supply should not affect output significantly.
- **Thermal Effects**: Can alter resistor matching and drift reference levels.
- **Layout Symmetry**: Critical for current-steering and R-2R DACs to ensure minimal mismatch and glitch.

7.8 Example: R-2R Ladder DAC

Working Principle:

- Binary input controls switches that either connect resistors to ground or reference voltage.
- The resistive network converts this binary value into a proportional analog voltage.
- Each bit contributes a weighted portion of the output voltage.

Advantages:

- Simple, regular layout.
- Easier resistor matching compared to binary-weighted DACs.

Limitations:

- Requires careful layout to avoid parasitic effects.
- Moderate speed and resolution.

7.9 Conclusion

DACs are essential components in systems that require digital control of analog processes. The choice of DAC architecture and its specification depends on the required resolution, speed, power, and noise performance. Understanding the underlying circuit principles and trade-offs in DAC design enables engineers to create optimized solutions for a wide range of real-world applications.