DATA CONVERTER

About Digital to Analog Converters (DAC)

A Digital to Analog Converter (DAC) is a circuit that converts a digital input (binary code) into a proportional analog output voltage or current.

Key Points :

- DAC converts an n-bit digital input into an analog output.
- The output is an analog voltage or current proportional to the digital input value.
- Used in signal generation, instrumentation, audio systems, communication, process control, etc.
- Performance parameters: Resolution, Accuracy, Linearity, Settling time, and Stability.

Basic Notation :

$D_{n-1}\, D_{n-2} \ldots D_1\, D_0$ → n-bit Digital Input

V_o / I_o → Analog Output (Voltage / Current)

V_{REF} → Reference Voltage

2^n → Total Levels

(Output is proportional to decimal value of input)

Working Principle :

1. Each digital input bit (0 or 1) is weighted according to its binary significance.
2. These weighted signals are summed to produce an analog output.
3. The output is proportional to the decimal equivalent of the input code.
4. For an n-bit DAC, the output voltage is :

$$\boxed{V_o = V_{REF} \times \frac{D}{2^n}}$$

where,
D = Decimal equivalent of input
V_{REF} = Reference Voltage

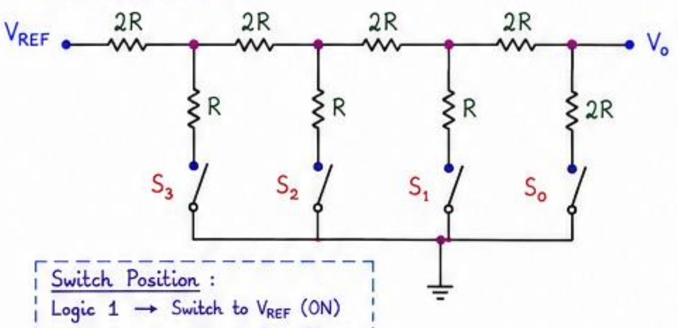
V_o ranges from 0 to $\left(1 - \frac{1}{2^n}\right) V_{REF}$

Types of DAC :

1. Binary Weighted Resistor DAC
   - Uses resistors in binary ratio (R, 2R, 4R, 8R...). Simple but requires precise resistors.
2. R-2R Ladder DAC
   - Uses only two resistor values (R and 2R).
   - Most popular due to accuracy and ease of IC implementation.
3. Current Steering DAC
   - Uses current sources to generate proportional current.
   - Faster and suitable for high speed.
4. Capacitor String DAC
   - Uses capacitors instead of resistors.
   - Low power and good for IC fabrication.

4-bit DAC using R-2R Ladder Network (Example) :

Circuit Diagram :



Switch Position :
Logic 1 → Switch to V_{REF} (ON)
Logic 0 → Switch to GND (OFF)

Digital Input vs Analog Output :

$D_3\ D_2\ D_1\ D_0$	Decimal (D)	$V_o = V_{REF} \times \frac{D}{16}$ (4-bit DAC)	Output (in terms of V_{REF})
0 0 0 0	0	0	0
0 0 0 1	1	$V_{REF}/16$	0.0625 V_{REF}
0 0 1 0	2	$2V_{REF}/16$	0.125 V_{REF}
⋮	⋮	⋮	⋮
1 1 1 0	14	$14V_{REF}/16$	0.875 V_{REF}
1 1 1 1	15	$15V_{REF}/16$	0.9375 V_{REF}

Features / Advantages :

- Provides a smooth analog output from digital codes.
- High resolution with more number of bits.
- R-2R ladder DAC gives better accuracy and stability.
- Widely used in audio systems, waveform generators, actuators, and process control.

Applications :

- Audio signal reconstruction in digital systems.
- Function generators and waveform synthesis.
- Process control and industrial instrumentation.
- Communication systems and data acquisition.
- Voltage controlled sources and motor control.

★ Note : The resolution of DAC increases with the number of bits (n). For n-bit DAC, number of levels = 2^n and maximum output = $\left(1 - \frac{1}{2^n}\right) V_{REF}$.

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Binary Weighted Resistor Type DAC

A Binary Weighted Resistor DAC is the simplest and most basic type of DAC. It uses resistors in binary ratio (R, 2R, 4R, 8R ...) to convert an n-bit digital input into a proportional analog output voltage.

Operation :

1. The digital input has n bits ($D_{n-1} \dots D_1 D_0$).
2. Each bit controls a switch ($S_{n-1} \dots S_1 S_0$).
3. If the bit = 1 (ON), the switch connects the corresponding resistor to V_{REF}.
   If the bit = 0 (OFF), the switch connects it to GND.
4. The currents from all resistors are summed at the inverting input of the op-amp.
5. The op-amp converts this summed current to an analog output voltage V_o.
6. The output voltage is proportional to the decimal equivalent (D) of the input code.

Key Points :

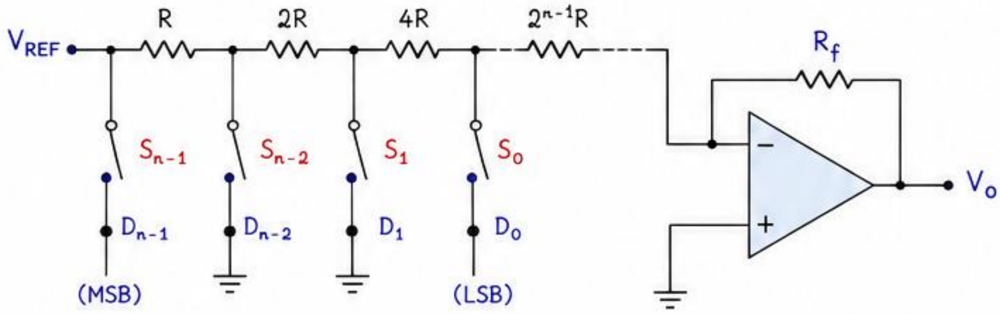
- Resistor values are in binary ratio : R, 2R, 4R, 8R ...
- More significant bit (MSB) uses smallest resistor (R).
- Less significant bit (LSB) uses largest resistor ($2^{n-1}R$).
- Requires only one operational amplifier.
- Simple but affected by resistor matching.
- Reference voltage (V_{REF}) sets the full scale output.

Output Voltage Equation :

$$V_o = -V_{REF}\left(\frac{b_{n-1}}{2} + \frac{b_{n-2}}{4} + \frac{b_{n-3}}{8} + \dots + \frac{b_0}{2^n}\right)$$

where, b_i = input bit (0 or 1)
V_{REF} = Reference voltage
n = number of bits

Circuit Diagram (n-bit Binary Weighted Resistor DAC)



Switch Position :

Bit = 1 (ON) → Switch to V_{REF}
Bit = 0 (OFF) → Switch to GND

Example : 4-bit Binary Weighted Resistor DAC

D_3 (MSB)	D_2	D_1	D_0 (LSB)	Decimal Equivalent (D)	Output Voltage (V_o) (in terms of V_{REF})
0	0	0	0	0	0
0	0	0	1	1	$-\frac{V_{REF}}{16}$
0	0	1	0	2	$-\frac{2V_{REF}}{16} = -\frac{V_{REF}}{8}$
0	1	0	0	4	$-\frac{4V_{REF}}{16} = -\frac{V_{REF}}{4}$
1	0	0	0	8	$-\frac{8V_{REF}}{16} = -\frac{V_{REF}}{2}$
:	:	:	:	:	:
1	1	1	1	15	$-\frac{15V_{REF}}{16}$

For n-bit DAC

Total levels = 2^n

Max Output (all 1's)

$$= -\left(1 - \frac{1}{2^n}\right)V_{REF}$$

Resolution (1 LSB)

$$= \frac{V_{REF}}{2^n}$$

Advantages :

- Simple circuit and easy to understand.
- Requires only one op-amp.
- Suitable for small resolution (4-8 bits).

Applications :

- Audio signal generation and waveform synthesis.
- Instrumentation and process control.
- Industrial and communication systems.

★ Note : Binary weighted resistor DAC is easy to design but not suitable for very high resolution due to tolerance and matching of resistors.

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R-2R LADDER TYPE DAC

An R-2R Ladder DAC is a widely used DAC that uses only two resistor values (R and 2R). It converts an n-bit digital input into a proportional analog output voltage.

OPERATION :

1. The digital input has n bits ($D_{n-1} \dots D_1\ D_0$).
2. Each bit controls a switch connected to the R-2R ladder network.
3. If the bit = 1 (ON), the switch connects the ladder node to V_{REF}.
   If the bit = 0 (OFF), the switch connects the node to GND.
4. The R-2R ladder network divides the current in binary weighted proportions.
5. The op-amp (inverting summing amplifier) converts the summed current into output voltage V_o.
6. The output voltage is proportional to the decimal equivalent (D) of the input code.

KEY FEATURES :

- Uses only two resistor values : R and 2R.
- Resistor ratio is accurate and easy to implement using ICs.
- Good accuracy and monotonic output.
- No need for precise resistor matching.
- Suitable for medium to high resolution.
- Widely used in IC DAC chips.

APPLICATIONS :

- Audio signal generation
- Instrumentation
- Industrial process control
- Communication systems
- Waveform synthesis, etc.

OUTPUT VOLTAGE EQUATION :

$$V_o = -V_{REF}\left(\frac{b_{n-1}}{2} + \frac{b_{n-2}}{4} + \frac{b_{n-3}}{8} + \dots + \frac{b_0}{2^n}\right)$$

where,

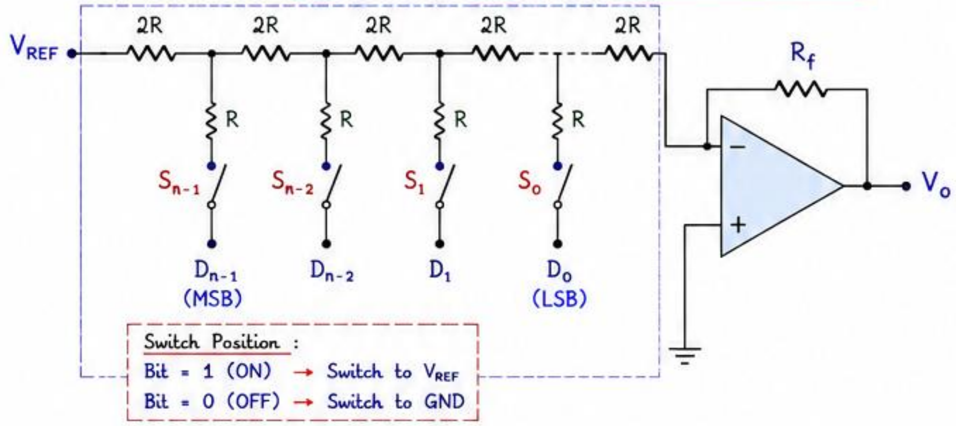
b_i = input bit (0 or 1)

V_{REF} = Reference voltage

n = number of bits

Negative sign indicates output inversion due to inverting op-amp.

R-2R LADDER DAC CIRCUIT DIAGRAM (n-bit)



HOW IT WORKS :

1. The ladder network splits current in binary weighted form.
2. The MSB current is $\frac{1}{2}$ of total, next is $\frac{1}{4}$, next $\frac{1}{8}$ and so on.
3. The op-amp sums these currents and produces output voltage.
4. Output is proportional to the decimal value of the input code.

EXAMPLE : 4-BIT R-2R LADDER DAC

D_3 (MSB)	D_2	D_1	D_0 (LSB)	Decimal Equivalent (D)	Output Voltage (V_o) (in terms of V_{REF})
0	0	0	0	0	0
0	0	0	1	1	$-\frac{V_{REF}}{16}$
0	0	1	0	2	$-\frac{2V_{REF}}{16} = -\frac{V_{REF}}{8}$
0	0	1	1	3	$-\frac{3V_{REF}}{16}$
0	1	0	0	4	$-\frac{4V_{REF}}{16} = -\frac{V_{REF}}{4}$
:	:	:	:	:	:
1	1	1	1	15	$-\frac{15V_{REF}}{16}$

For n-bit R-2R DAC :

Total levels = 2^n

Max output (all 1's) = $-\left(1 - \frac{1}{2^n}\right)V_{REF}$

Resolution (1 LSB) = $\frac{V_{REF}}{2^n}$

ADVANTAGES :

- Uses only two resistor values (R and 2R).
- Easy to design and fabricate.
- No need for precision resistor matching.
- Less sensitive to resistor tolerances.
- Well suited for IC implementation.

IMPORTANT NOTES :

- The op-amp used is an inverting summing amplifier.
- R_f is usually chosen equal to R for simplicity.
- Output is negative; can be made positive using non-inverting configuration or by using $+V_{REF}$ and $-V_{REF}$ references.
- Monotonic and good linearity.

★ **NOTE** : R-2R ladder DAC is the most practical and popular DAC used in microcontrollers, audio systems, and data acquisition systems.

DATA CONVERTERS

About Analog to Digital Converters

1. Introduction

An Analog to Digital Converter (ADC) is a device that converts a continuous analog signal (voltage or current) into an equivalent digital number. The digital output is proportional to the magnitude of the analog input. ADCs are widely used in data acquisition systems, digital voltmeters, microprocessors, instrumentation and communication systems.

Key Points :

- ADC converts analog (continuous) signal into digital (discrete) form.
- The output is a binary number representing the input magnitude.
- It is the interface between real world analog signals and digital systems.
- ADC performance depends on resolution, accuracy and speed.
- Common parameters : Resolution, Accuracy, Conversion time, Range, Quantization error.

Example :

Example : If analog input = 2.5 V and ADC is 3-bit, output may be = 101 (binary) depending on the converter.

2. Types of Analog to Digital Converters (ADC)

S. No.	Type of ADC	Brief Description	Advantages	Disadvantages	Applications
1.	Flash ADC (Parallel ADC)	All possible levels are compared simultaneously using comparators.	Very fast (Highest speed)	Complex, Expensive, High power	High speed systems, Oscilloscopes
2.	Successive Approximation ADC (SAR ADC)	Uses binary search method to approximate the input.	Fast, Moderate cost, Good accuracy	Speed less than Flash ADC	Microcontrollers, Data acquisition systems
3.	Dual Slope (Integrating) ADC	Measures input by integrating and de-integrating.	High accuracy, Good noise rejection	Slow conversion speed	Digital voltmeters, Industrial instruments
4.	Ramp (Counter Type) ADC	A ramp signal is compared with input until it reaches it.	Simple, Low cost	Slow, Non-linear errors	Low cost instruments, Process control
5.	Sigma-Delta (Δ-Σ) ADC	Uses oversampling and noise shaping techniques.	High resolution, Excellent accuracy	Complex, Low speed	Audio systems, Digital weighing scales

3. Working of ADC (General Principle)

The basic steps involved in ADC operation are :

① Sampling : The analog signal is sampled at regular intervals.

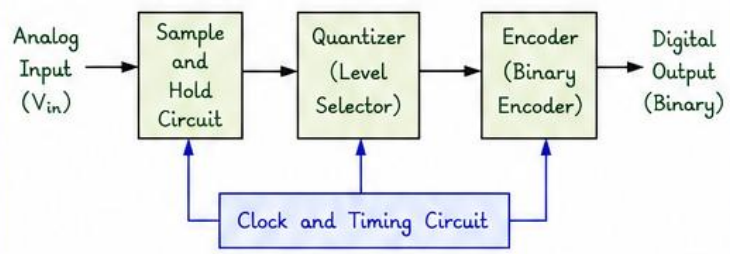
② Quantization : Each sample is approximated to the nearest level from a set of discrete levels.

③ Encoding : The quantized level is converted into an equivalent digital (binary) number.

④ Output : The digital word is available at the output.

Thus, ADC = Sampling + Quantization + Encoding

4. Block Diagram of Analog to Digital Converter



5. Important Terms

Term	Meaning
Resolution	Minimum change in input that can be detected. For an n-bit ADC, Resolution = $\frac{V_{FS}}{2^n}$
Accuracy	Closeness of the digital output to the actual input value.
Conversion Time	Time required by ADC to convert the analog input into digital output.
Quantization Error	Error due to approximation of analog value to the nearest discrete level.
Full Scale Range (V_{FS})	Maximum analog input value that ADC can handle.
LSB (Least Significant Bit)	Smallest value represented by the least significant bit of the digital output.

★ **Note :** ADC is an essential device in modern digital systems where real world analog signals like temperature, pressure, light, sound, etc, are to be processed by digital circuits.

DATA CONVERTERS

Comparator Type ADC

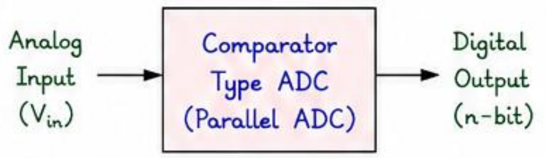
1. Introduction

Comparator type ADC (also called Parallel ADC) converts an analog input voltage into digital output by comparing it with a set of reference voltages using comparators working in parallel. It is a very fast ADC and is used in high speed applications.

Key Points :

- A set of $(2^n - 1)$ comparators are used for an n-bit ADC.
- The analog input is applied to all comparators simultaneously.
- Each comparator compares V_{in} with a reference voltage.
- The outputs are encoded to get the final n-bit digital output.
- Fastest ADC but requires more hardware.

Example :

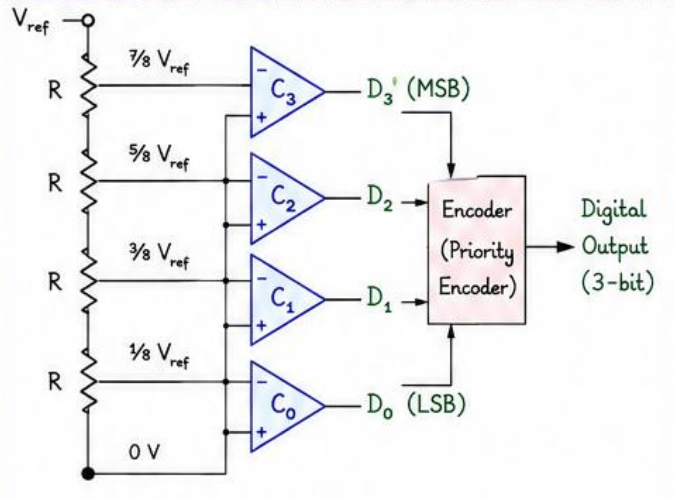


Example : If V_{in} = 3.2 V and ADC is 3-bit with V_{ref} = 5 V, then digital output may be 110 (6) depending on the reference levels.

2. Construction

It consists of a resistor ladder network that generates equally spaced reference voltages. These reference voltages are applied to the inverting inputs of comparators. The analog input V_{in} is applied to all non-inverting inputs. The comparator outputs are encoded to produce the digital output.

3. Circuit Diagram (3-bit Comparator Type ADC)

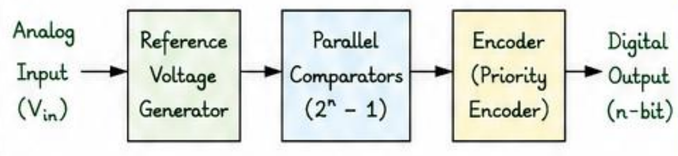


4. Operation

The comparators compare V_{in} with reference voltage levels. If V_{in} is greater than or equal to the reference voltage, the comparator output is HIGH (1). Otherwise, it is LOW (0). The encoder converts the thermometer code to binary code.

Range of V_{in} (0 to V_{ref})	Comparator Outputs ($C_3\ C_2\ C_1\ C_0$)	Digital Output ($D_3\ D_2\ D_1\ D_0$)
$0 \le V_{in} < \frac{1}{8} V_{ref}$	0 0 0 0	000
$\frac{1}{8} V_{ref} \le V_{in} < \frac{3}{8} V_{ref}$	1 0 0 0	001
$3/8\ V_{ref} \le V_{in} < 5/8\ V_{ref}$	1 1 0 0	010
$5/8\ V_{ref} \le V_{in} < 7/8\ V_{ref}$	1 1 1 0	011
$\frac{7}{8} V_{ref} \le V_{in} < V_{ref}$	1 1 1 1	100
$V_{in} = V_{ref}$	1 1 1 1	111

5. Block Diagram



6. Advantages, Disadvantages and Applications

Advantages	Disadvantages	Applications
• Very high speed (fastest ADC). • Simple concept. • No feedback required. • Accurate conversion.	• Requires a large number of comparators. • High power consumption. • Large chip area. • Not economical for high resolution.	• High speed data acquisition systems. • Video and image processing. • Oscilloscopes and instrumentation. • Communication systems.

★ **Note :** Comparator type ADC is suitable for low to medium resolution (upto 8 bits) due to hardware complexity. It provides the fastest conversion time among ADCs.

DATA CONVERTERS

Successive Approximation Type ADC

1. Introduction

Successive Approximation ADC (SAR ADC) is a high speed and medium resolution ADC. It uses a binary search technique to find the digital equivalent of an analog input. It requires fewer comparators and less hardware compared to Flash ADC.

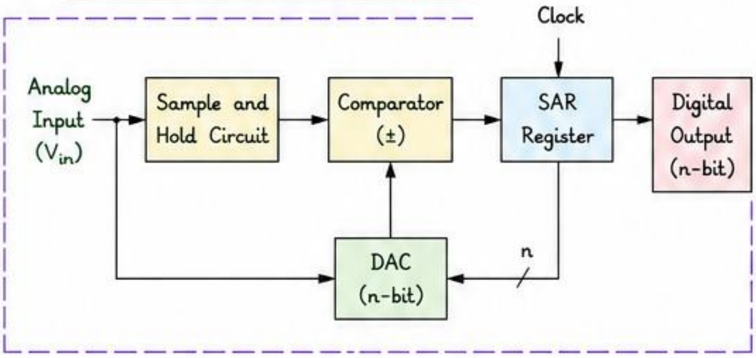
Key Points :

- Uses binary search (successive approximation) technique.
- Only one comparator and a DAC are used.
- Conversion is done in n clock cycles for n-bit ADC.
- Widely used in data acquisition systems, microcontrollers, instrumentation and portable devices.
- Provides good speed with moderate hardware.

Example :

Example : If V_{in} = 2.7 V and ADC is 4-bit with V_{ref} = 5 V, the digital output may be 1011 (11) depending on successive approximation.

2. Construction / Block Diagram



3. Working / Operation

The conversion is done in n clock cycles for an n-bit ADC.

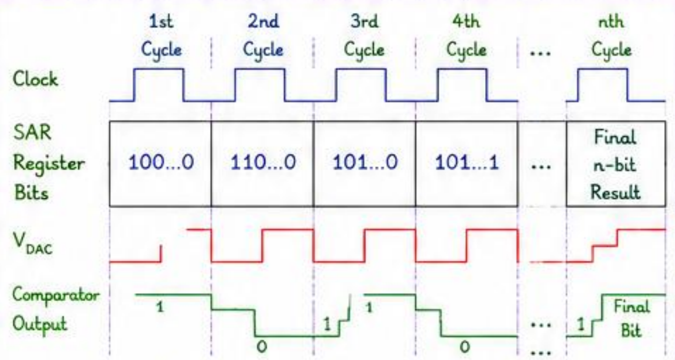
① Sample the analog input using Sample and Hold circuit.
② SAR sets MSB to 1 and all other bits to 0.
③ DAC converts this digital word to analog voltage.
④ Comparator compares V_{in} with V_{DAC}.
  ❖ If $V_{in} \geq V_{DAC}$, keep the bit as 1.
  ❖ If $V_{in} < V_{DAC}$, reset the bit to 0.
⑤ SAR proceeds to the next lower bit and repeats steps 3 and 4.
⑥ After n cycles, the SAR register contains the final digital output.

4. Example of 4-bit SAR ADC Operation

Step	SAR Register (D_3 D_2 D_1 D_0)	V_{DAC} (V)	V_{in} ? V_{DAC}	Decision	Final Bit
Initial	0 0 0 0	0	–	–	–
1	1 0 0 0	2.5	$V_{in} \geq V_{DAC}$	Keep	D_3 = 1
2	1 1 0 0	3.75	$V_{in} < V_{DAC}$	Reset	D_2 = 0
3	1 0 1 0	3.125	$V_{in} \geq V_{DAC}$	Keep	D_1 = 1
4	1 0 1 1	2.8125	$V_{in} < V_{DAC}$	Reset	D_0 = 0
Final Digital Output (D_3 D_2 D_1 D_0) = 1 0 1 0 (Decimal = 10)					

Example : If V_{ref} = 5 V and V_{in} = 2.7 V (approx.),
Digital Output = 1010 (10).

5. Timing Diagram (n-bit SAR ADC)



(1 = $V_{in} \geq V_{DAC}$, 0 = $V_{in} < V_{DAC}$)

6. Advantages, Disadvantages and Applications

Advantages	Disadvantages	Applications
• Medium to high speed. • Requires only one comparator. • Less hardware compared to Flash ADC. • Good accuracy. • Low power consumption.	• Conversion time depends on number of bits (n cycles). • Not as fast as Flash ADC. • Not suitable for ultra high speed applications.	• Microcontroller ADC interfaces. • Data acquisition systems. • Portable instruments. • Battery operated devices. • Industrial measurement systems.

7. Important Terms

Term	Meaning
Resolution	Smallest change in input that can be detected. For n-bit ADC, Resolution = $\frac{V_{ref}}{2^n}$
Conversion Time	Time taken to convert analog input to digital output (n clock cycles).
Accuracy	Closeness of digital output to the actual analog input value.
Quantization Error	Maximum error between input and quantized output (± 1/2 LSB).
LSB (Least Significant Bit)	Smallest value represented in the digital output.

★ **Note :** Successive Approximation ADC offers a good trade-off between speed, accuracy and hardware complexity. It is the most commonly used ADC in modern electronic systems.

DATA CONVERTERS

Dual Slope A/D Converter

1. Introduction

Dual Slope A/D Converter is an integrating type ADC. It converts an analog input voltage into a digital output (n-bit) based on the principle of measuring time. It is highly accurate and has excellent noise rejection, but the conversion speed is relatively slow.

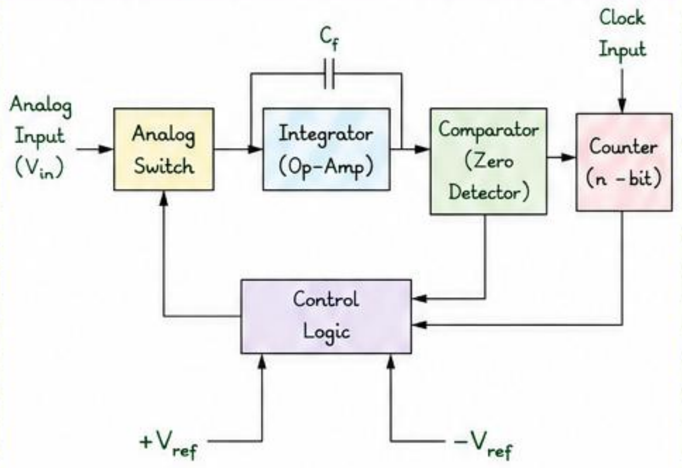
Key Points :

- It uses an op-amp integrator, comparator, control logic and a counter.
- Conversion is done in two slopes (two integrations).
- It is self-calibrating and gives high accuracy.
- Widely used in digital voltmeters, multimeters and process measurement systems.

Example :

Example : If V_{in} = 3 V and Full Scale = 10 V with n = 3 bits, the digital output may be = 011 (3) depending on conversion.

2. Block Diagram



3. Working / Operation

The conversion is completed in two phases (two slopes).

Phase 1 (Run-up / Integration):

① The analog input V_{in} is applied to the integrator for a fixed time T_1.

② The output of integrator is a linear ramp (slope) whose magnitude is proportional to V_{in} and T_1.

Phase 2 (Run-down / De-integration):

③ The input is switched to a reference voltage of opposite polarity ($-V_{ref}$).

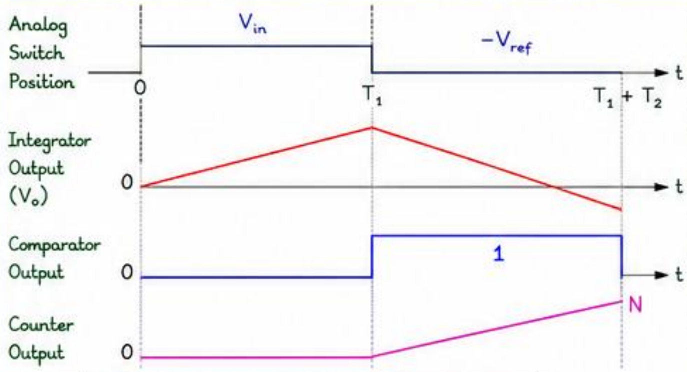
④ The integrator output now ramps back towards zero.

⑤ When the integrator output again reaches zero, the comparator output changes state and stops the counter.

⑥ The count obtained during T_2 is proportional to the input voltage V_{in}.

Thus, $V_{in} \propto T_2$ (For fixed V_{ref} and T_1)

4. Waveforms



T_1 = Fixed time (set by control logic)
T_2 = Variable time (measured by counter)
N = Count during T_2

5. Relationship

$$\frac{V_{in}}{V_{ref}} = \frac{T_2}{T_1} \quad \text{or} \quad V_{in} = \left(\frac{T_2}{T_1}\right) \times V_{ref}$$

Since T_1 and V_{ref} are fixed, the digital output (count N) is directly proportional to the input voltage V_{in}.

6. Advantages, Disadvantages and Applications

Advantages	Disadvantages	Applications
• High accuracy. • Excellent noise rejection. • Self-calibrating. • High resolution. • Good stability.	• Slow conversion speed. • Not suitable for high speed applications. • More complex control circuit.	• Digital voltmeters. • Multimeters. • Process control systems. • Laboratory instruments.

7. Important Terms

Term	Meaning
Run-up Time (T_1)	Fixed time during which input voltage is integrated.
Run-down Time (T_2)	Time required for de-integration (output returns to zero).
Full Scale Input (V_{FS})	Maximum input voltage that gives full scale output.
Resolution	Smallest change in input that can be detected. For n-bit ADC, Resolution = $V_{FS} / 2^n$
Conversion Time	Total time required = $T_1 + T_2$ (varies with input).

★ **Note :** Dual Slope ADC provides very high accuracy and is ideal for low frequency and precision measurement applications where speed is not critical.