D/A Converters

CSE 211

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Introduction

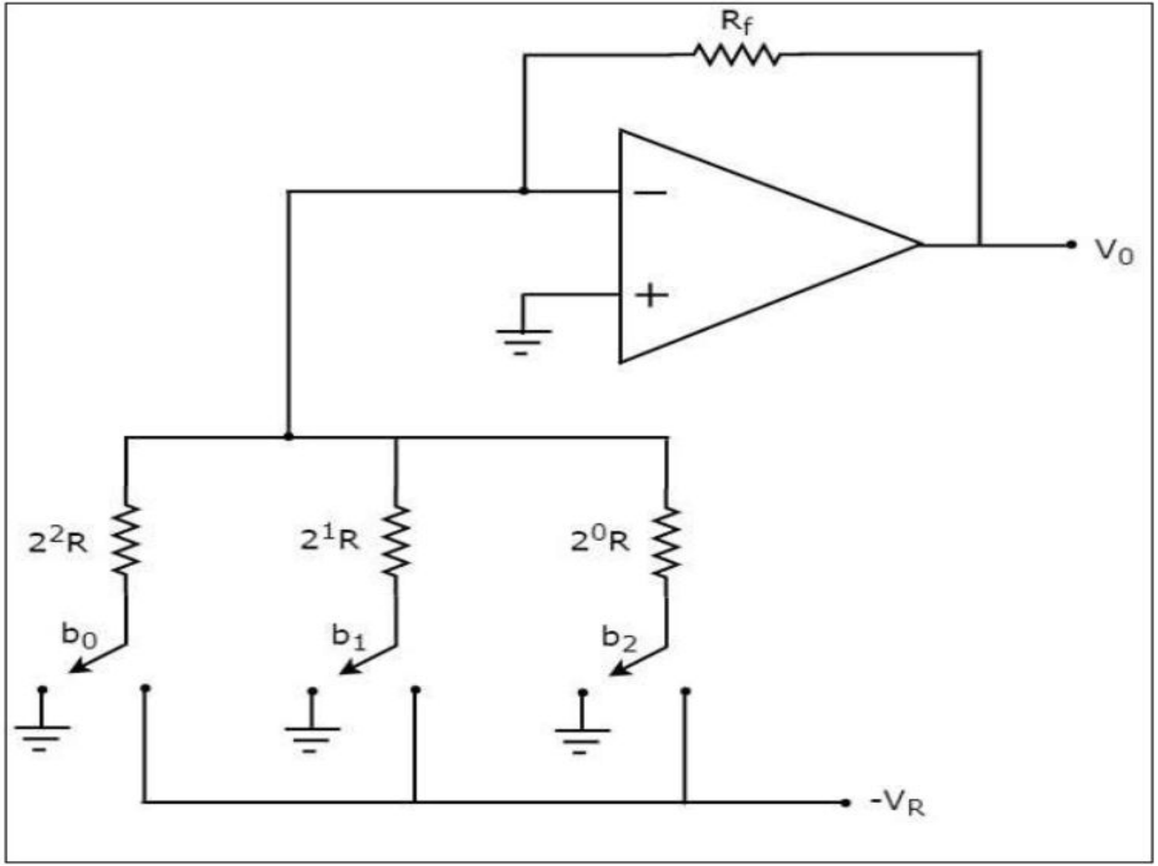
- All **Digital Electronics** like **Logic Gates, Flip-Flops, Microcontroller, Microprocessor** etc work with Digital Signals, while the **Analog Electronics** are like **Op-Amp, Power switches** etc.
- In a typical electronics design, these two signals **often have to be converted from one form to another**.
- A computer is a binary machine operating in an analog world, so to be able to produce an output that is understandable by other devices a **digital to analog converter** (DAC) is used.
- **For example**, **a computer stores audio in the form of binary values of the sound wave**. In order to play these back as sound on a speaker we need analog signals, because as we know the speaker's diaphragm vibrates based on the intensity of the analog signal to produce sound/music. **So here, we will need a DAC to convert the digital audio file to analog signal in order to play it on a speaker.**

Digital to Analog Converter

- This digital output from the computer is connected to a DAC, which converts it to a proportional analog voltage or current. For example, the computer might produce a digital output ranging from 0000000 to 11111111, which the DAC converts to a voltage ranging from 0 to 10V.
- A **Digital to Analog Converter (DAC)** converts **a digital input signal into an analog output signal**. That is, a **DAC**, **D/A** or **D2A** is a device **that converts binary values (0s and 1s) to a set of continuous analog voltages.** The digital signal is represented with a binary code, which is a combination of bits 0 and 1.
- A Digital to Analog Converter (DAC) consists of **a number of binary inputs and a single output**. In general, **the number of binary inputs of a DAC will be a power of two**.
- There are **two types** of commonly used D/A converters. These are: **Weighted-resistor D/A converter and R-2R ladder D/A converter**.

Block diagram - 8 bit DAC

Weighted-Resistor D/A converter



- A **weighted resistor DAC** produces an analog output, which is almost equal to the digital (binary) input by using **binary weighted resistors in the inverting adder circuit**.
- The circuit diagram of a **3-bit binary weighted resistor DAC** is shown in the following figure

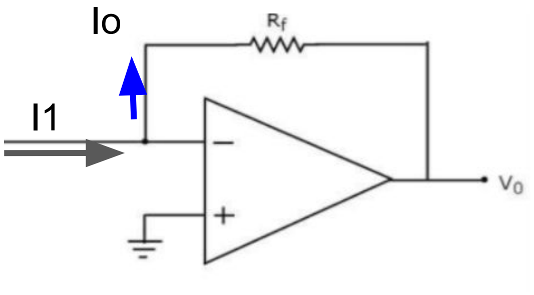
Weighted-Resistor D/A converter

- Let the 3-bit binary input is $b_2b_1b_0$. Here, the bits b_2 and b_0 denote the Most Significant Bit (MSB) and Least Significant Bit (LSB) respectively.
- The **digital switches** shown in the above figure **will be connected to ground, when the corresponding input bits are equal to '0'**. Similarly, the digital switches shown in the above figure **will be connected to the negative reference voltage**, **$-V_R$ when the corresponding input bits are equal to '1'.**
- In the above circuit, **the non-inverting input terminal** of an op-amp is connected to **ground**. That means **zero volts** is applied at the **non-inverting** input terminal of op-amp.
- According to the **virtual short concept**, the voltage at the inverting input terminal of opamp is same as that of the voltage present at its non-inverting input terminal. So, the **voltage at the inverting input terminal node will be also zero volts**.

Weighted-Resistor D/A converter

The **nodal equation** at the inverting input terminal node is:

I1 = Io, or -I1 + Io = 0



$$-\left[\frac{(-V_R-0)b_2}{R} + \frac{(-V_R-0)b_1}{2R} + \frac{(-V_R-0)b_0}{4R}\right] + \frac{0-V_0}{R_f} = 0$$

$$\frac{0+V_R b_2}{2^0 R} + \frac{0+V_R b_1}{2^1 R} + \frac{0+V_R b_0}{2^2 R} + \frac{0-V_0}{R_f} = 0$$

$$=> \frac{V_0}{R_f} = \frac{V_R b_2}{2^0 R} + \frac{V_R b_1}{2^1 R} + \frac{V_R b_0}{2^2 R}$$

$$=> V_0 = \frac{V_R R_f}{R}\left\{\frac{b_2}{2^0} + \frac{b_1}{2^1} + \frac{b_0}{2^2}\right\}$$

Weighted-Resistor D/A converter

Substituting, ***R = 2R$_f$*** in above equation, we get

$$=> V_0 = \frac{V_R R_f}{2R_f}\left\{\frac{b_2}{2^0} + \frac{b_1}{2^1} + \frac{b_0}{2^2}\right\}$$

$$=> V_0 = \frac{V_R}{2}\left\{\frac{b_2}{2^0} + \frac{b_1}{2^1} + \frac{b_0}{2^2}\right\}$$

The above equation represents the **output voltage equation** of a 3-bit binary weighted resistor DAC. Since the number of bits are three in the binary (digital) input, we will get eight possible values of output voltage by varying the binary input from 000 to 111 for a fixed reference voltage, V_R

Weighted-Resistor D/A converter

We can write the **generalized output voltage equation** of an N-bit binary weighted resistor DAC as shown below based on the output voltage equation of a 3-bit binary weighted resistor DAC.

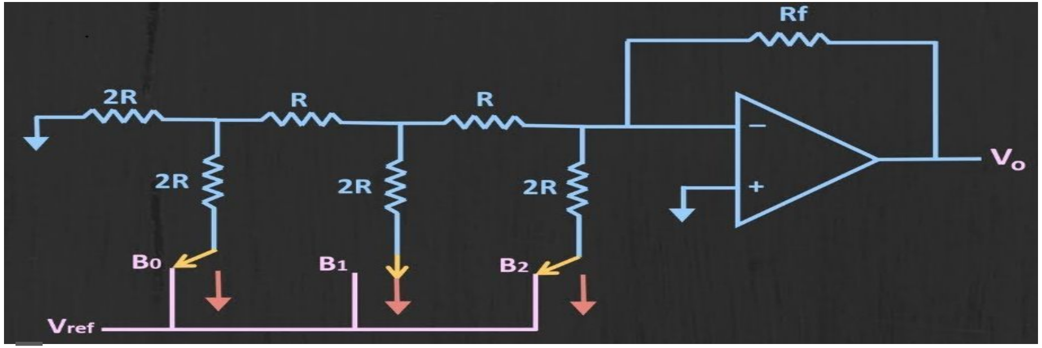
$$=> V_0 = \frac{V_R}{2}\left\{\frac{b_{N-1}}{2^0} + \frac{b_{N-2}}{2^1} + \dots + \frac{b_0}{2^{N-1}}\right\}$$

The **disadvantages** of a binary weighted resistor DAC are as follows −

- The difference between the resistance values corresponding to LSB & MSB will increase as the number of bits present in the digital input increases.
- It is difficult to design more accurate resistors as the number of bits present in the digital input increases.

R-2R Ladder DAC

The **R-2R Ladder DAC** overcomes the disadvantages of a binary weighted resistor DAC. As the name suggests, R-2R Ladder DAC produces an analog output, which is almost equal to the digital (binary) input by using a R-2R ladder network in the inverting adder circuit.



The **advantages** of a R-2R Ladder DAC are as follows −

- R-2R Ladder DAC contains only two values of resistor: R and 2R. So, it is easy to select and design more accurate resistors.
- If more number of bits are present in the digital input, then we have to just include required number of R-2R sections additionally.

Due to the above advantages, R-2R Ladder DAC is preferable over binary weighted resistor DAC.

Specifications of D/A Converters

The **characteristics** of a D/A converter, which are generally specified by the manufacturers are:

1. Resolution

2. Linearity

3. Accuracy

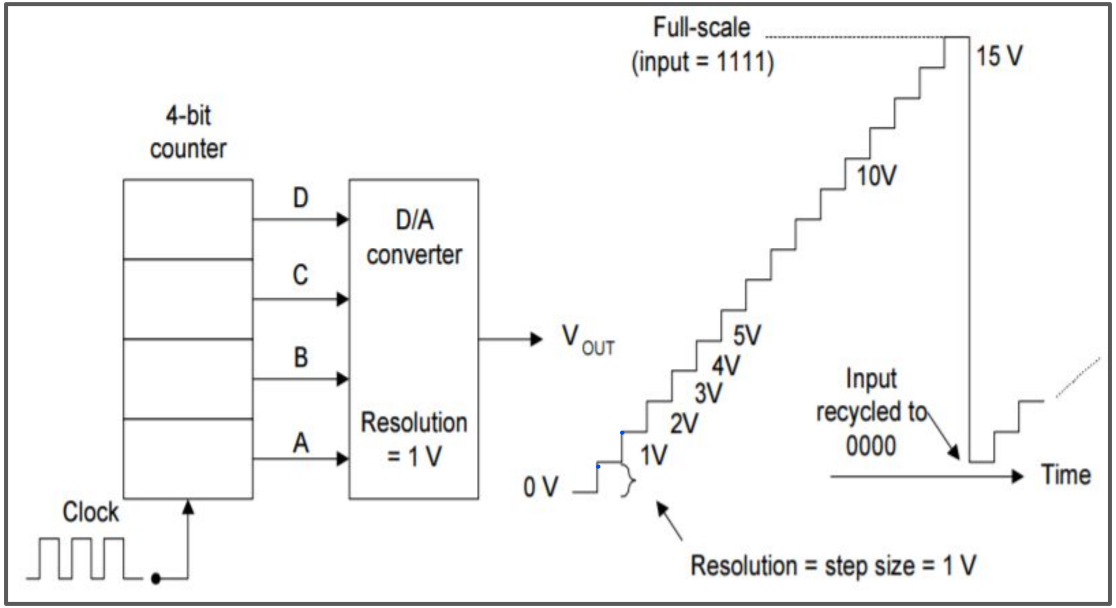
4. Settling time

5. Temperature sensitivity.

Specifications of D/A Converters - Resolution

Resolution of a D/A converter is defined as the smallest change that can occur in the analog output as a result of a change in the digital input.

In the fig. (Output waveforms of a 4 bit DAC) below, we can see that the resolution is 1 V, since Vout can change by no less than 1 V when the digital input value is changed.



Specifications of D/A Converters - Resolution

As the counter is being continually cycled through its 16 states by the clock signal, the DAC output is a staircase waveform that goes up 1 V per step. When the counter is at 1111, the DAC output is at its maximum value of 15 V; this is its full-scale output [With 4 bits, there will be $2^4 - 1 = 15$ steps of 1V each. So the F.S will be 1V x 15 = 15V]. When the counter recycles to 0000, the DAC output returns to 0V. In this case, **the resolution or step size** of the jumps in the staircase waveform is 1V (each step).

Percentage Resolution: *In the previous fig, the DAC has a* ***full-scale output*** *of l5 V (when the digital input is 1111). The* ***step size*** *is l V, which gives a percentage resolution of :*

$$\% \; resolution = \frac{step\ size}{full\ scale\ (F.S.)} \times 100\%$$

$$= \frac{1\,V}{15\,V} \times 100\% = 6.67\%$$

Specifications of D/A Converters - Resolution

Problem: A 10-bit DAC has a step size of 10 mV. Determine the full-scale output voltage and the percentage resolution.

Solution

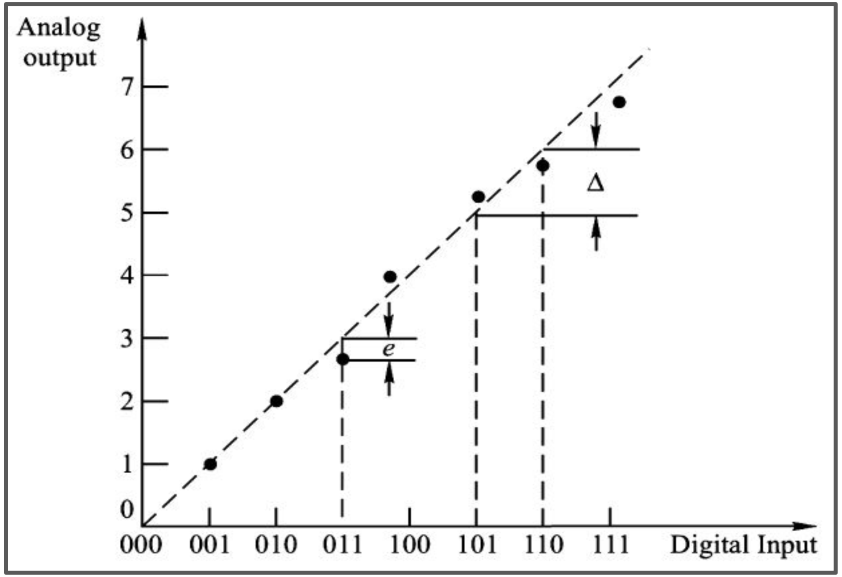
With 10 bits, there will be $2^{10} - 1 = 1023$ steps of 10mV each. The full-scale output will therefore be $10\text{mV} \times 1023 = 10.23$ V and

$$\%\ resolution = \frac{10\ mV}{10.23\ V} \times 100\% \approx 0.1\%$$

Specifications of D/A Converters - Linearity

In a D/A converter, equal increments in the numerical significance of the digital input should result in equal increments in the analog output voltage. But, **in an actual circuit, the input—output relationship is not linear**. This is due to the error in resistor values and voltage across the switches. The linearity of a D/A converter is usually specified with its *Linearity error* which is the maximum deviation in step size from the ideal step size.

That is, ***linearity error*** for a digital input is the difference between the voltage corresponding to the dot and the voltage obtained from the straight line (expected output). This is indicated by e [See fig]. The normal analog output voltage change corresponding to a digital input change is indicated by Δ. The linearity of a D/A converter is generally specified by comparing e with Δ.



Specifications of D/A Converters - Accuracy

The ***accuracy*** of a D/A converter is a measure of the difference between the actual output voltage and the expected output voltage. It is specified using full-scale error which is normally expressed as a percentage of full-scale or maximum output voltage. [Full-scale error is the maximum deviation of the DAC's output from its expected (ideal) value, expressed as a percentage of full scale voltage.]

For example, assume that a D/A converter has 9.375 V full-scale (maximum) output voltage and an accuracy of ± 0.01% F.S, then the maximum error possible for any output voltage will be

$\pm$ 0.01% x 9.375 V = $\pm$ 0.9375 mV.

This means that the output of this DAC can, at any time, be off by as much as 0.9375mV from its expected value.

Specifications of D/A Converters

Settling Time: When the digital input to a D/A converter changes, the analog output voltage does not change suddenly. The change in the o/p takes time to finally settle down. The operating speed of a DAC is usually specified by its settling time, which is the time required for the DAC output to go from zero to full scale as the binary input is changed from all 0's to all I's. Typical values for settling time range from 50 ns to 10 μs.

Temperature sensitivity: The analog output voltage for any fixed digital input varies with temperature. This is due to the temperature sensitivities of the reference voltage source, resistors, OP AMP, etc. It is specified as ± ppm/°C.

Digital to Analog Converter

Few common **applications** of DACs:

Video Encoder : The video encoder system will process a video signal and send digital signals to a variety of DACs to produce analog video signals of various formats, along with optimizing of output levels.

Display Electronics : The graphic controller will typically use a lookup table to generate data signals sent to a video DAC for analog outputs such as Red, Green, Blue (RGB) signals to drive a display.

Data Distribution System : Many industrial and factory lines require multiple programmable voltage sources, and this can be generated by a bank of DACs that are multiplexed. The use of a DAC allows the dynamic change of voltages during operation of a system.