9.2 Basic DAC techniques

The DAC converts digital or binary data into its equivalent analog value. The DAC accepts n bit input words b_1, b_2, b_3,........b_n in binary and produces equivalent analog signal proportional to it. The bit b_1 is called most significant bit (**MSB**) and b_n is called as least significant bit (**LSB**).

The symbolic representation of an n–bit DAC is as shown in Figure 9-2.

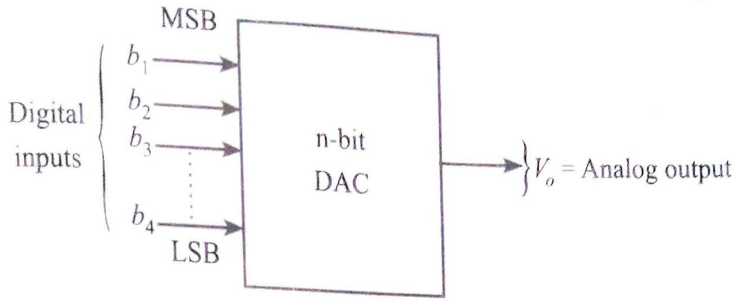

FIGURE 9-2: n-bit DAC

If $n = 4$, indicates it is 4 bit DAC. Each digital input requires an electrical signal representing either a logic 1 or a logic 0.

The DAC output can either be a voltage or current signal.

For a voltage output DAC, the conversion characteristic can be expressed by

$$\boxed{V_o = kV_{FS}\left(b_1 2^{-1} + b_2 2^{-2} + b_3 2^{-3} + \cdots b_n 2^{-n}\right)} \qquad (9\text{-}1)$$

Where, V_o = output voltage

V_{FS} = Full scale output voltage

k = Scaling factor usually adjusted to unity.

$b_1 \ldots, b_n$ = n-bit binary fractional word with decimal point located at the left.

b_1 = MSB with a weight = $\frac{V_{FS}}{2}$

b_n = LSB with weight = $\frac{V_{FS}}{2^n}$

Before discussing about different DAC techniques, let us discuss some of the important performance parameters of DAC.

1. **Resolution:**

Resolution is the number of various analog output values that is provided by a DAC. Therefore for n-bit DAC.

Resolution = 2^n

Resolution can also be defined as the ratio of change in output voltage resulting from a change of LSB at the digital inputs.

For n–bit DAC, resolution is = $\frac{V_{oFS}}{2^n - 1}$

Where V_{oFS} = full scale output voltage if $n = 8$, and V_{oFS} = 10.4 V

$$\text{Resolution} = \frac{V_{oFS}}{2^n - 1} = \frac{10.4}{2^8 - 1} \tag{9-2}$$

$$= \frac{10.4}{255} = 40.78 \text{ mV / LSB.}$$

∴ We can say that an input of 1LSB cause the output to change by 40.78 mV.

If we know the resolution, we can obtain input–output relation for DAC is

$$\boxed{V_o = \text{Resolution} \times b} \tag{9-3}$$

where, b is Decimal values of digital input

2. **Accuracy:**

Comparison of actual output with expected output is called as accuracy.

If the $V_{oFS} = 10.0$ for 8 bit DAC,

$$\text{Accuracy} = \frac{V_{oFS}}{\left(2^n - 1\right)2} \tag{9-4}$$

$$= \frac{10.0}{\left(2^8 - 1\right)2} = \frac{10}{255 \times 2} = 19.8 \text{ mV.}$$

3. **Setting time:**

It is time required for a DAC output to settle within $\pm\frac{1}{2}$LSB of final value for a given digital input.

4. **Stability:**

As performance of converter changes with parameters such as temperature, power supply variations and also due to ageing, it is important to note the relevant parameters such as offset, gain, linearity error variation.

Now, let us discus the basic DAC techniques

1. Binary weighted resistor DAC
2. R-$2R$ ladder DAC

1. Binary weighted Resistor DAC

This DAC is one of the simplest circuit of n-bit DAC shown in Figure 9-3. Here op-amp is used to sum n-binary weighted currents derived from a reference voltage V_R via current scaling resistors.

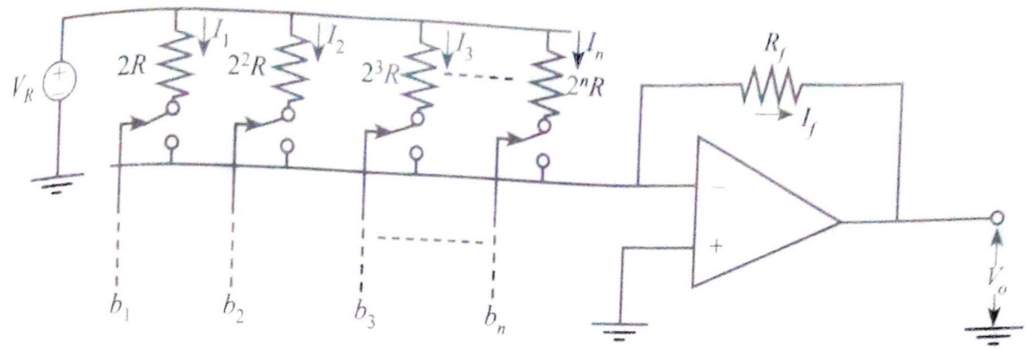

FIGURE 9-3: Binary weighted resistor DAC

Figure 9-3 shows Binary weighted resistor DAC circuit uses n-electronic switches controlled by the binary inputs b_1, b_2, ..., b_n. If the binary input is high (logic 1), then switch connects the resistance to reference voltage V_R.

When digital input bit is low (logic 0), it disconnects the resistor from V_R and no current flows through corresponding circuit.

i.e., mathematically

for ON switch current $I = \dfrac{V_R}{R}$

for OFF switch current $I = 0$.

Due to high input impedance of op-amp summing current will flow through R_f.

∴ The total current through R_f is written as

$$I_f = I_1 + I_2 + I_3 + \cdots + I_n \tag{9-5}$$

$$= \frac{V_R}{2^1 R} b_1 + \frac{V_R}{2^2 R} b_2 + \frac{V_R}{2^3 R} b_3 + \cdots + \frac{V_R}{2^n R} b_n$$

$$= \frac{V_R}{R}\left[b_1 2^{-1} + b_2 2^{-2} + b_3 2^{-3} + \cdots + b_n 2^{-n}\right]$$

The output voltage across R_f is

$$V_o = -I_f R_f$$

Substituting for I_f, $V_o = \dfrac{-V_R}{R} R_f \left[b_1 2^{-1} + b_2 2^{-2} + b_3 2^{-3} + \cdots + b_n 2^{-n}\right]$ (9-6)

If $\boxed{R_f = R}$,

$$V_o = -V_R\left[b_1 2^{-1} + b_2 2^{-2} + b_3 2^{-3} + \cdots + b_n 2^{-n}\right] \tag{9-7}$$

equation(9-7) indicates analog output which is proportional to the digital input words.

Drawbacks

i) Large range of resistor values are required. Example for 8 bit DAC, we require 2^1R, 2^2R, 2^3R, ..., 2^nR. Therefore, the largest resistor is 128 times the smallest one

ii) These larger range values of resistor has restriction on higher and lower end. It is impractical to fabricate large value of resistor on integrated circuit (IC).

These drawbacks can be overcome by R-$2R$ ladder type DAC and is a better choice for practical applications.

2. R-2R ladder type DAC

In R-$2R$ ladder network DAC, only two values R and $2R$ are used. Hence can be used in IC- based applications. The R-2R ladder DAC is as shown in Figure 9-4.

Here also, DAC uses shunt resistors for generating n–binary weighted currents, it uses voltage scaling and identical resistors.

Each binary bit connects switch either to ground or to the inverting terminal of the op-amp. Due to virtual ground concept, both the positions of switches are at ground potential and currents through resistances are constant and independent of switch position.

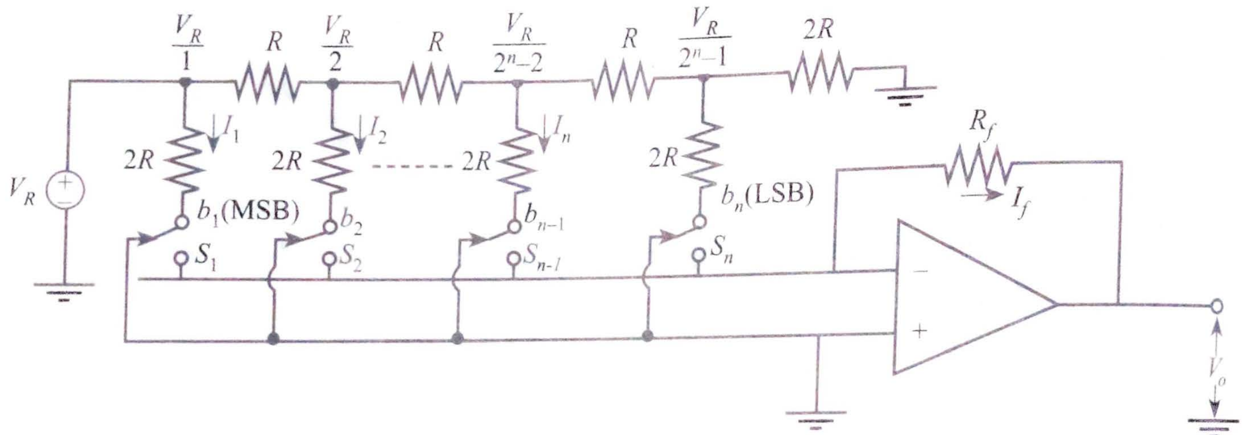

FIGURE 9-4: R-2R ladder type DAC

Now let us write currents flowing through each of these $2R$ resistances

$$I_1 = V_R / 2R$$

$$I_2 = \frac{V_R/2}{2R} = \frac{V_R}{4R}$$

$$\text{also } I_3 = \frac{V_R/4}{2R} = \frac{V_R}{8R}$$

$$\text{and } I_n = \frac{V_R/2^n-1}{2R}$$

But WKT

$$V_o = -I_f R_f$$

$$V_o = -R_f\left(I_1 + I_2 + \cdots + I_n\right)$$

$$= -R_f\left[\frac{V_R}{2R}.b_1 + \frac{V_R}{4R}.b_2 + \cdots + \frac{V_R}{2^n R}.b_n\right]$$

$$= \frac{-V_R}{R} R_f \left(b_1 2^{-1} + b_2 2^{-2} + \cdots + b_n 2^{-n}\right)$$

When $\boxed{R_f = R}$ V_o can be

$$\boxed{V_o = -V_R \left(b_1 2^{-1} + b_2 2^{-2} + \cdots + b_n 2^{-n}\right)} \tag{9-8}$$

This V_o expression indicates that the DAC works on the principle of summing i.e., output (V_o) of DAC is analog and is proportional to digital inputs.

Advantages of R-2R DAC

i) As it uses only two types of resistors helps in fabrication and accurate value of *R-2R* can be designed.

ii) Binary input length can be increased by adding more *R-2R* sections

iii) Node voltages remain constant with changing binary input in inverted *R-2R* DAC. This helps in avoiding slow down effect by stray capacitance.