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Design and Analysis of Op-Amp based 3-Bit R – 2R,4-Bit R–2R & 8-Bit R–2R ladder Digital to Analog Converter using NI-Multisim 14.3

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Abstract - Using repetitive arrangements of precision resistor networks in a ladder-like shape, an R-2R Ladder is a quick and low-cost approach to do digital-to-analog conversion. Different resistor levels, an operational amplifier (LM741), and single pole double throw switches were the major building blocks for both circuits. MULTISIM software was used to build both circuits so that the circuit could be tested for its ideal use. The inclusion of both circuits in a real circuit helps with identifying and contrasting each's strengths and drawbacks. Using repetitive arrangements of precision resistor networks in a ladder-like shape, an R-2R Ladder is an easy and affordable approach to accomplish digital-to-analog conversion. The use of Multisim to implement R2R DAC fills the gap between theoretical and practical circuits. Using Multisim, this study presents an accurate, detailed representation of a 3 bit and a 4 bit R2R ladder. The binary's R-2R ladder circuit, which has a percentage inaccuracy of 4.16%, was discovered.

Keywords—R2R Ladder, DAC, Staircase, Multisim

1.INTRODUCTION

If the sensor devices are already digital in nature, connecting digital circuitry to them is easy. The on/off nature of switches', relays', and encoders' signals makes them simple to interface with gate circuits. However, interfacing becomes far more difficult when analog components are involved. An electrical method for converting analog signals into digital (binary) quantities and back is required [1]. Digital transmission in a communication system is quicker and more convenient, but at the receiving end, the digital signals must be transformed back to analog signals [2]. This paper focuses on the implementation of two distinct circuit designs for the digital to analog converter.

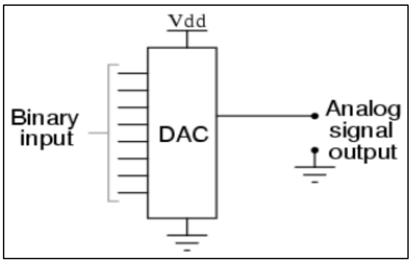


Fig 1: Block Diagram of a Digital-to-Analog Converter

DACs are employed in a variety of applications, including the conversion of computer data into audio-frequency tones for transmission over phone lines by a modem. Since it is used to create audio signals from digital data, DAC is frequently seen in music players. While digital video signals are transformed into analog to display colours and hues on TVs and mobile devices, respectively. In VoIP applications, the source is initially converted to digital form for transmission using an ADC, and at the receiving end, it is reconverted using a DAC [4].

1. 3-bit r-2r Digital analog converter

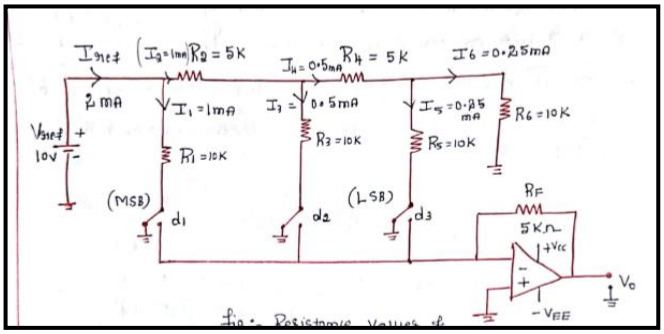


Figure. 2. Proposed System with resistance and current values.

A straightforward circuit that transforms a 3-bit binary input into an analog voltage is known as a 3-bit DAC (Digital-to-Analog Converter), and it is typically constructed using an R2R (Resistor-to-Resistor) ladder network. A frequent architecture for building DACs is the R2R ladder because of its simple construction and operation. Three digital input bits—Bit 2 (MSB), Bit 1 (middle bit), and Bit 0 (LSB)—are present in a three-bit R2R DAC. According to the digital value you want to convert to an analog voltage, each of these bits can be either 0 or 1, respectively. Each bit in the R2R ladder network corresponds to a particular resistor connection, and the resistors are organized in a ladder-like pattern.

Each "R" in this graphic stands for a resistor. The reference voltage, commonly denoted Vref, is linked to the top end of each resistor, and the output voltage of the DAC is formed by connecting the bottom ends of all resistors together.
Three control bits—Bit 2, Bit 1, and Bit 0—are available for the three-bit DAC. Connect the relevant resistor to the output line if a control bit is set to 1, otherwise leave it unconnected.
For instance, setting Bits 2 and 0 to 0 and Bits 1 and 0 to 1 will provide an analog output voltage equal to the binary value "010" (decimal 2). With the middle resistor disconnected and the bottom resistor connected, the top resistor would be connected. The outcome. The reference voltage and the resistor values would decide the voltage that would be produced at the output.
Please be aware that the precision of the resistors and the calibre of the connections determine the accuracy and resolution of such a DAC. To get accurate analog outputs in practical applications, the R2R ladder DAC may need careful resistor selection and layout.

1.1. Circuit, Multisim, Results and Design

R_{eq}=5Kohm

R_f=5Kohm

V_{ref}=10V

$I_{ref}=\frac{Vref}{Req}=\frac{10}{5K}$=2mA

$V_0=\frac{Vref}{Req}*R_f$

$V_0=\frac{Vref}{Req}*R_f(\frac{d1}{2^1}+\frac{d2}{2^2}+\frac{d3}{2^3})$

Sample calculation for digital inputs D- 000

$V_0=\frac{10}{5K}*5K(\frac{0}{2^1}+\frac{0}{2^2}+\frac{0}{2^3})$

V_0=0V

D- 001

$V_0=\frac{10}{5K}*5K(\frac{0}{2^1}+\frac{0}{2^2}+\frac{1}{2^3})$

V_0=1.25V

D- 111

$V_0=\frac{10}{5K}*5K(\frac{1}{2^1}+\frac{1}{2^2}+\frac{1}{2^3})$

V_0=8.75V

1.2 Circuit diagram in NI Multisim 14.3

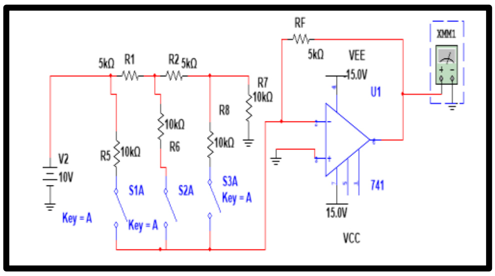
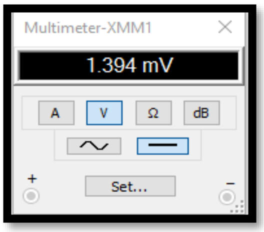
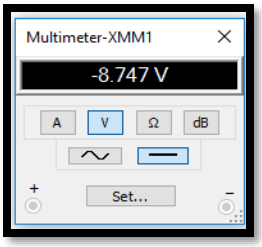


Fig.3.3Bit R2R DAC in Multisim 14.3

Output view in Multi-meter:





Digital input = 000 Digital input =111

Table 1: R2R DAC (3 Bit) circuit Theoretical and Experimental reading

3 bit R2R LADDER DIGITAL TO ANALOG CONVERTER				
DIGITAL INPUT			THEORETICAL OUTPUT	PRACTICAL OUTPUT
0	0	0	0	0.0013
0	0	1	1.25	1.66
0	1	0	2.5	2.72
0	1	1	3.75	3.74
1	0	0	5	4.99
1	0	1	6.25	6.66
1	1	0	7.5	7.72
1	1	1	8.75	8.74

2. 4-Bit R-2R Digital analog converter

A 4-bit R-2R DAC (Digital-to-Analog Converter) is a circuit that converts a 4-bit digital input into an analog voltage output. The "R-2R" refers to the ladder network of resistor values used in the circuit.

Here's a basic explanation of how it works:

1. Binary Input: The 4-bit digital input consists of four binary digits, ranging from 0000 to 1111, representing decimal values from 0 to 15.

2. R-2R Ladder Network: The core of the R-2R DAC is a ladder network of resistors. In a 4-bit DAC, you will have 4 "rungs" in the ladder, each representing a bit position from the input. The most significant bit (MSB) is connected to the highest value resistor, while the least significant bit (LSB) is connected to the lowest value resistor.

3. Weighted Output: The resistor values in the ladder network are chosen in a way that they follow a binary-weighted pattern. The resistor values for each bit position are typically in a 1:2 ratios. For instance, the resistor connected to the MSB might be 2R, the next one 4R, then 8R, and finally 16R.

4. Voltage Output: The ladder network is connected to a reference voltage. Depending on the binary input, switches are either closed or open at each rung. The closed switches connect the corresponding resistors to the reference voltage, while the open switches disconnect them. The voltage across the entire ladder is then the sum of the voltages across the connected resistors.

5. Analog Output: The sum of the voltages across the connected resistors gives you the analog voltage output. This output voltage is a fraction of the reference voltage and is proportional to the digital input value.

One of the advantages of the R-2R DAC architecture is that it can be relatively simple to implement, especially for lower bit resolutions. However, for higher resolutions, the number of precise resistor values required can become impractical, and other DAC architectures like sigma-delta or segmented DACs might be more suitable. Remember that practical implementations might involve additional considerations like resistor tolerances, switching accuracy, and op-amp buffering for improved performance.

3.1. Circuit, Multisim, Results and Design

R_{eq}=5Kohm

R_f=5Kohm

V_{ref}=10V

$I_{ref}=\frac{Vref}{Req}=\frac{10}{5K}$=2mA

$V_0=\frac{Vref}{Req}*R_f$

$V_0=\frac{Vref}{Req}*R_f(\frac{d1}{2^1}+\frac{d2}{2^2}+\frac{d3}{2^3}+\frac{d4}{2^4})$

Sample calculation for digital inputs D- 0000

$V_0=\frac{10}{5K}*5K(\frac{0}{2^1}+\frac{0}{2^2}+\frac{0}{2^3}+\frac{0}{2^3})$

V_0=0V

D- 0001

$V_0=\frac{10}{5K}*5K(\frac{0}{2^1}+\frac{0}{2^2}+\frac{0}{2^3}+\frac{1}{2^4})$

V_0=0.625V

D- 1111

$V_0=\frac{10}{5K}*5K(\frac{1}{2^1}+\frac{1}{2^2}+\frac{1}{2^3}+\frac{1}{2^4})$

V_0=9.37V

2.1. Circuit diagram in Multisim 14.3

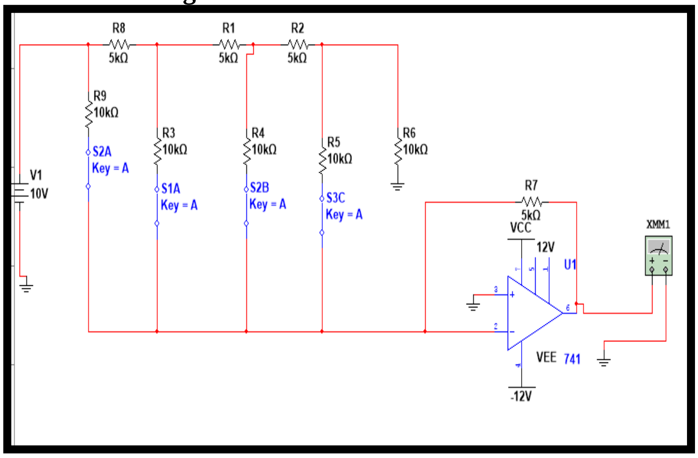
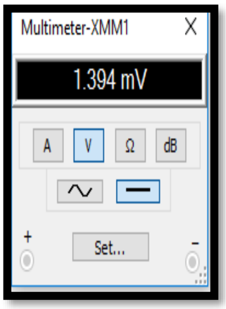
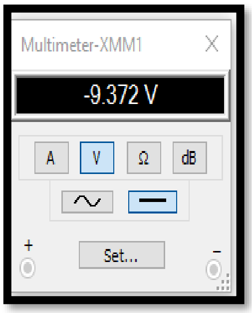


Fig.4.4Bit R2R DAC in Multisim 14.3





Digital input = 0000 Digital input = 1111

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Table 2: R2R DAC (4 Bit) circuit Theoretical and Experimental reading

4 bit R2R LADDER DIGITAL TO ANALOG CONVERTER					
DIGITAL INPUT				THEORETICAL OUTPUT	PRACTICAL OUTPUT
0	0	0	0	0	0.0039
0	0	0	1	0.625	1.24
0	0	1	0	1.25	1.87
0	0	1	1	1.87	2.49
0	1	0	0	2.5	2.85
0	1	0	1	3.127	3.63
0	1	1	0	3.75	3.95
0	1	1	1	4.37	4.37
1	0	0	0	5	4.99
1	0	0	1	5.62	6.24
1	0	1	0	6.25	6.87
1	0	1	1	6.87	7.49
1	1	0	0	7.5	7.85
1	1	0	1	8.12	8.63
1	1	1	0	8.75	8.95
1	1	1	1	9.37	9.37

3. 8-bit R-2R Digital Analog Converter

An 8-bit R2R DAC (Digital-to-Analog Converter) is a type of digital-to-analog converter that uses a resistor ladder network based on the R2R (resistor-to-resistor) architecture. In this architecture, the DAC converts a digital input value (usually an 8-bit binary number) into an analog voltage by using a series of precision resistors arranged in a ladder-like configuration.

Here's how an 8-bit R2R DAC works:

1. Binary Input: The DAC receives an 8-bit binary input, representing the digital value to be converted to an analog voltage. Each bit of the binary input corresponds to a resistor in the ladder network.

2. Resistor Ladder: The R2R ladder network consists of two types of resistors: R and 2R. The value of the 2R resistor is double that of the R resistor. The network's design ensures that each bit's contribution to the analog output voltage is proportional to its weight in the binary number.

3. Voltage Generation: The DAC generates an analog voltage by connecting the resistors based on the input bits. For each '1' bit in the input, the corresponding R resistor is connected to the output, and for each '0' bit, the corresponding R resistor is disconnected. The 2R resistors help set the reference voltage.

4. Summing the Voltages: The analog output voltage is obtained by summing the voltages developed across the connected R resistors. Since each R resistor contributes less to the output voltage than a 2R resistor, the overall voltage output is weighted according to the binary input.

5. Voltage Range and Precision: An 8-bit R2R DAC can produce 256 distinct output levels (2^8), each corresponding to a different digital input value. However, due to the precision of the resistors and the potential for errors in their values, the accuracy and linearity of the generated analog signal might not be as high as with other DAC architectures.

6. Applications: 8-bit R2R DACs are commonly used in applications where moderate precision and resolution are acceptable. They can be found in audio equipment, simple waveform generators, and other scenarios where cost-effectiveness and simplicity are prioritized over extreme precision.

It's worth noting that while R2R DACs were common in earlier digital systems, modern DACs often use more advanced architectures, such as sigma-delta modulation or segmented architectures, to achieve higher precision and performance.

4.1 Circuit, Multisim, Results and Design

R_{eq}=5Kohm

R_f=5Kohm

V_{ref}=10V

$$I_{ref}=\frac{Vref}{Req}=\frac{10}{5K}=2mA$$

$$V_0=\frac{Vref}{Req}*R_f$$

$$V_0=\frac{Vref}{Req}*R_f*(\frac{d1}{2^1}+\frac{d2}{2^2}+\frac{d3}{2^3}+\frac{d5}{2^4}+\frac{d5}{2^5}+\frac{d6}{2^6}+\frac{d7}{2^7}+\frac{d8}{2^8})$$

Sample calculation for digital inputs

D- 00000000

$$V_0=\frac{10}{5K}*5K*(\frac{0}{2^1}+\frac{0}{2^2}+\frac{0}{2^3}+\frac{0}{2^4}+\frac{0}{2^5}+\frac{0}{2^6}+\frac{0}{2^7}+\frac{0}{2^8})$$

V_0=0V

D- 00000001

$$V_0=\frac{10}{5K}*5K*(\frac{0}{2^1}+\frac{0}{2^2}+\frac{0}{2^3}+\frac{0}{2^4}+\frac{0}{2^5}+\frac{0}{2^6}+\frac{0}{2^7}+\frac{1}{2^8})$$

V_0=0.039V

D- 11111111

$$V_0=\frac{10}{5K}*5K*(\frac{1}{2^1}+\frac{1}{2^2}+\frac{1}{2^3}+\frac{1}{2^4}+\frac{1}{2^5}+\frac{1}{2^6}+\frac{1}{2^7}+\frac{1}{2^8})$$

V_0=9.96V

4.2 Circuit diagram in Multisim

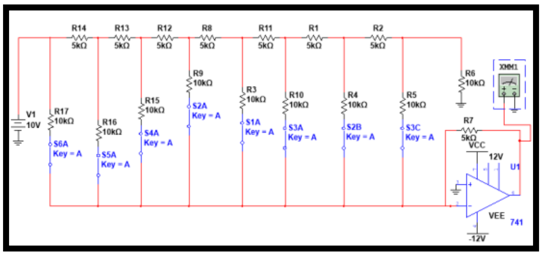
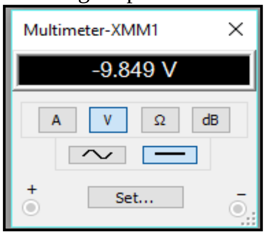
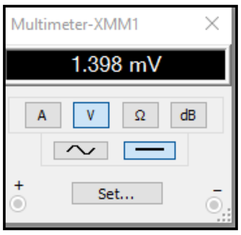


Fig.4.8Bit R-2R DAC in Multisim 14.3

4.3 Analog output in Multi-Meter.



Digital input 11111111



Digital input 00000000

Table 3: R2R DAC (8- Bit) circuit Theoretical and Experimental reading

Table of Readings										
Decimal Equivalent	Digital Inputs								Analog output	
	D0	D1	D3	D4	D5	D6	D7	D8	Therotical	practical
0	0	0	0	0	0	0	0	0	0	1.3mV
1	0	0	0	0	0	0	0	1	39mV	623mV
2	0	0	0	0	0	0	1	0	78mV	831mV
126	0	1	1	1	1	1	1	0	4.9V	4.9v
255	1	1	1	1	1	1	1	1	9.96v	9.849

4. Conclusion

Using two separate Circuits, the researchers were able to create a digital to analog converter. In contrast to the binary weighted resistors DAC, where different resistor values were used and making it difficult to achieve the desired output, a DAC using the R-2R Ladder was designed and implemented with only two different values of resistors. Both circuits were monotonic in addition. The binary weighted circuit is considered to be a much more efficient DAC circuit than the R-2R Ladder circuit, as shown in Figure 3.2, even though the latter has easier implementation. Both circuits were properly designed, fabricated, tested, and compared in this research.

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