Digital to Analog Converter (DAC) and Analog to Digital Converter (ADC)

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In the experiment, we studied the working of an ADC and DAC amplifier and constructed them using ICs and resistors. We found that the AC output shows a small deviation from the expected values for the DAC circuit. In the second part, using a comparator, we converted analog output to 2-bit digital output. In the third part, we extended the circuit to obtain decimal output from the digital output, using IC 7447 (binary to BCD decoder) and BCD display.

I. THEORY

A device that translates a continuous physical quantity (typically voltage) to a digital number that indicates the quantity's amplitude is known as an analog-to-digital converter (ADC). A DAC, on the other hand, accepts a binary number and generates an analog voltage or current signal. They are frequently employed in digital systems in conjunction to offer a comprehensive interface with analog devices and output devices for control systems.

A. Digital to Analog converter (DAC)

A Digital to Analog Converter (DAC) has several binary inputs and one output. In general, a DAC's number of binary inputs will be a power of two. DACs are classified into two types: weighted resistor DACs and R/2R ladder DACs. The addition of digital inputs (0 or 1, where 1 equates to 5 volts) in a weighted resistor produces analogue output, which can be added with varied weights depending on their position in the binary number. However, because of the large number of bits, this form of circuit needs a large number of precise resistors. Using an R-2R ladder network in the inverting adder circuit, the R-2R Ladder DAC overcomes this disadvantage and delivers an analogue output that is almost identical to the digital (binary) input. The performance of DAC is characterized by the following:

- **Resolution:** The resolution of a DAC is determined by the number of bits (N). The resolution is the lowest output increment that the DAC can produce. The resolution of an 8-bit DAC is 8 bits, or one part in 2^8. This yields a percentage of 0.39%.

- **Linearity/ Linear Errors:** The maximum permitted variation from an ideal straight line drawn between the zero-scale and full-scale outputs is defined as linearity. It is frequently expressed as a percentage or as a fraction of an LSB. For an 8-bit DAC, $(\frac{1}{2})$ LSB linearity equates to 0.195%.

- **Monotonicity:** If each digital code increase generates an output equal to or greater than the preceding code, the DAC is monotonic. A DAC is often anticipated to be monotonic to increments as tiny as an LSB, but its monotonicity is determined by the smallest increment for which the DAC stays monotonic.

- **Settling time:** The settling time is calculated as the time it takes from the instant a digital input code changes to the time the analogue output achieves its matching new value within a given error band. Typically, the output is anticipated to settle within a $\frac{1}{2}$ LSB error range. Typically, the worst-case settling time is evaluated between the zero-scale and full-scale codes.

- **Accuracy:** The maximum divergence between the actual converter output and the ideal converter output is defined as absolute accuracy. The greatest variation after removing gain and offset errors is referred to as relative accuracy.

B. Analog to Digital Converter

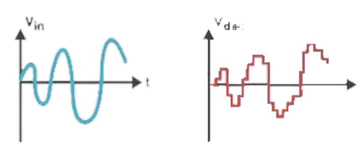

FIG. 1: Analog to Digital Converter

It can be done in many different ways to take an analog voltage signal and convert it into an equivalent digital signal. While many analog-to-digital converter chips are available, it is possible to build a simple ADC using discrete components.

One simple and easy way is by using parallel encoding, also known as flash, simultaneous, or multiple comparator converters, in which comparators are used to detect different voltage levels and output their switching state to an encoder.

II. OBJECTIVE

A. Design a 4-bit R/2R ladder DAC

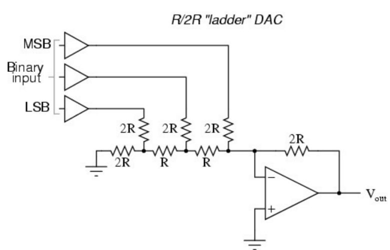

FIG. 2: Circuit diagram for digital to analog conversion

The DAC circuit consists of a 4-bit R/2R ladder DAC using 741 op amp by choosing components appropriately and testing the circuit. The figure is depicted above. The output voltage of the DAC circuit is given by:

$$V_{out} = \frac{-R_F}{R}\left(\frac{d_1}{2^1} + \frac{d_2}{2^2} + \frac{d_3}{2^3}\right)$$

where d_1 is M.S.B and d_3 is L.S.B. In the above circuit, feedback resistance $R_f = 2R$. The output impedance of the R-2R network is always R for any number of bits in the network. This Another advantage of the circuit is that it simplifies the design of circuits that use DAC, such as filtering, amplification, etc.

B. Construct an ADC circuit to convert 2-bit digital input to analog output

Figure 3 depicts the conversion's circuit diagram. This circuit employs an $LM339$ comparator and 74147 priority encoders. The $LM339$ comparator chip compares the analogue input from the DC power source with a reference voltage before passing it to the 74147 priority encoder circuit. The binary output from the 74147 chip may then be translated to BCD (Binary coded decimal) format and shown as a decimal digit on a common cathode 7-segment BCD display using the 7447 device. Use three of the four available comparators in $LM339$.

Digital binary output can be produced through $D0$, $D1$, $D2$ and $D3$. It should be noted that the $LM339$ is a quad comparator integrated circuit. Because it has an open collector, it requires pull-up resistors at the comparator's output, as illustrated in Figure 3. Pull-up resistors of $3k\Omega$ are recommended. When utilising the $LM339$ chip, always connect a $1k\Omega$ resistor in series with the LEDs. The supply voltage to the $LM339$ can be as high as $15V$. Adjust the reference voltage as needed. Before connecting the ADC circuit, learn how the $LM339$ works by connecting one of the comparators and testing the output. 74147 is a priority encoder with a range of 10 to 4. This IC's input and output are both low. The unused pins should be pulled up to $5V$.

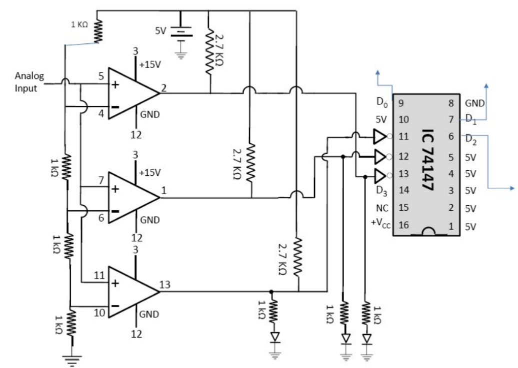

FIG. 3: Circuit diagram for 2-bit binary Analog to Digital conversion

C. Conversion of the binary display to decimal display

After converting analog voltage to binary number, it can be converted to binary coded decimal and displayed on a BCD display. 7447 is an input active high IC and output active low IC. The output of the 7447 must be connected to BCD display via a 330Ω resistor.

III. OBSERVATIONS AND CALCULATIONS

A. 4 bit R/2R ladder DAC using 741 op-amp

We constructed 4 bit R/2R ladder DAC circuit using IC741 op-amps, with a constant power supply of 5.16V corresponding to 1 bit and 0V corresponding to 0 bit. In the Table 1, we can see that observed values are very close to the theoretical value.

bit-0 (MSB)	bit-1	bit-2 (LSB)	$V_{out}(V)$	$V_{out} theoretical(V)$
0	0	0	-0.0002	0
0	0	1	-1.297	-1.29
0	1	0	-2.582	-2.58
0	1	1	-3.883	-3.87
1	0	0	-5.00	-5.16
1	0	1	-6.45	-6.45
1	1	0	-7.72	-7.74
1	1	1	-8.75	-9.03

TABLE I: Output of 4 bit DAC using $1K\Omega$ resistor and $5.16V$ constant power supply.

B. Analog to Digital Converter

1. *working of comparator*

We used three out of four comparators available in LM339 and verified it's working for a 5.2V constant power supply.

voltage(V)	D_3	D_2	D_1
0 to 1.3V	0	0	0
1.3 to 2.6V	0	0	1
2.6 to 3.9V	0	1	1
3.9 to 2.5V	1	1	1

TABLE II: Comparator output

2. *Construction of an ADC circuit to convert 2-bit digital input to analog output*

Using LM339 comparator and 74147 priority encoder, we constructed the 2-bit digital to the analog circuit as shown in figure 2. From Table 2 and the figures below, we can verify it's working.

Analogue	comparator outputs				Digital outputs	
Voltage(V)	D_3	D_2	D_1	D_0	q_1	q_2
0 to 1.3V	0	0	0	0	0	0
1.3 to 2.6V	0	0	1	x	0	1
2.6 to 3.9V	0	1	1	x	1	0
3.9 to 2.5V	1	1	1	x	1	1

TABLE III: Output of ADC circuit to convert 2-bit digital input to analog output

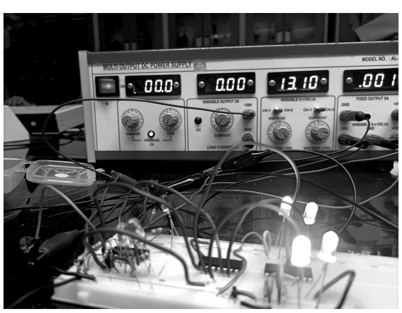

FIG. 4: circuit output for 0 to 1.3 V

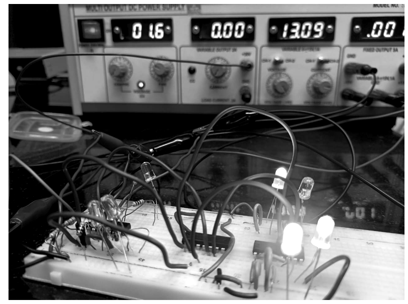

FIG. 5: circuit output for 1.3 to 2.6 V

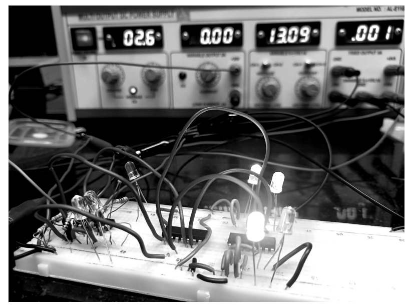

FIG. 6: circuit output for 2.6 to 3.9 V

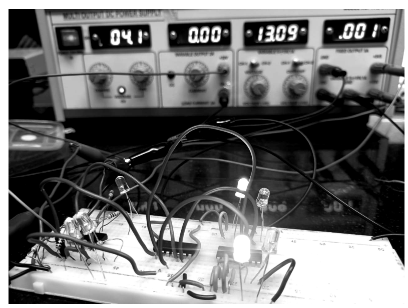

FIG. 7: circuit output for 3.9 to 5.2V

C. Conversion of binary display to decimal display

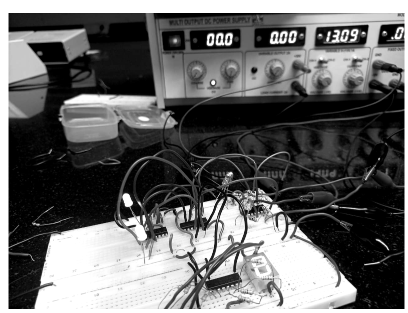

FIG. 8: decimal display output for 0 to 1.3V

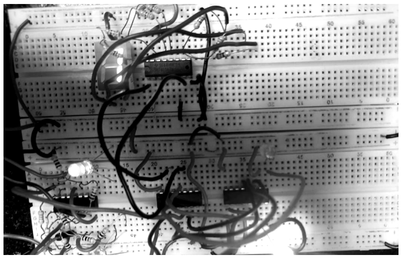

FIG. 9: decimal display output for 1.3 to 2.6 V

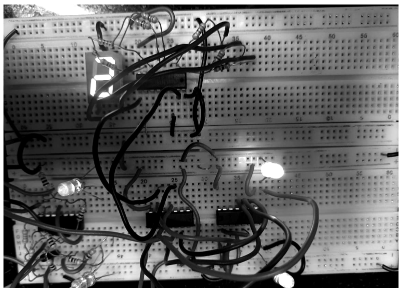

FIG. 10: decimal display output for 2.6 to 3.9 V

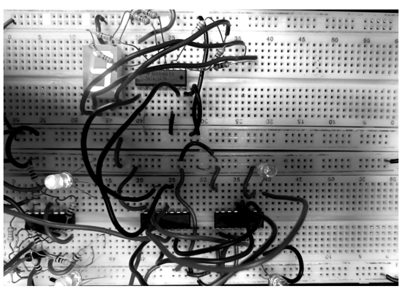

FIG. 11: decimal display output for 3.9 to 5.2V

IV. ERROR ANALYSIS

Error in observed value of analog voltage in DAC:

The theoretical value of slope m = 1, and experimental value from graph s = 0.759. Therefore Error Δs is given by:

$$\delta s = \left| \frac{m - s}{m} \right|$$

$$\delta s\% = 2.0.8\%$$

Thus experimental values show a deviation of 2.8%, which is small and negligible. This could be because the resistance values R were not exactly $1K\Omega$ and the same for the 2R resistor, which could lead to a lesser to more voltage drop.

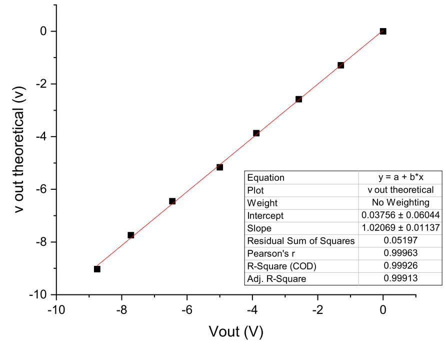

FIG. 12: V_{EXP} VS $V_{THEORETICAL}$ for DAC

A. Precautions:

- To avoid loose connections and short circuits, the connections should be correctly constructed.
- Resistors and integrated circuits must be tested for characteristics and functionality before being used in a circuit.
- To avoid fusing, connect the LEDs to the resistor.
- To avoid burning an op-amp, the biassing voltage should not exceed the specified value.

V. CONCLUSION

As a result, in the experiment, we investigated the operation of an ADC and DAC amplifier and built them with simple electronic components. We discovered the linearity error in the slope of the DAC plot between the theoretical and experimental values using our understanding of the numerous parameters governing the performance of a converter and discovered that it agreed more for smaller number of bits at the digital input. We noticed that while the DAC converter is operational, it displays a tiny deviation from the required voltage, which may be ignored. However, with larger bit converters, the variation may increase. We also learnt how to convert digital output to decimal using a BCD display.

[1] SPS. Lab manual. *Website*, 2022. `https://www.niser.ac.in/sps/sites/default/files/basic_page/p341_2023/Study_and_construction_of_ADC_and_DAC_circuit.pdf`.