Advanced Measurement Systems & Sensors
(0640732)

Lecture (5)

Interface Electronic Circuits

Part: 1

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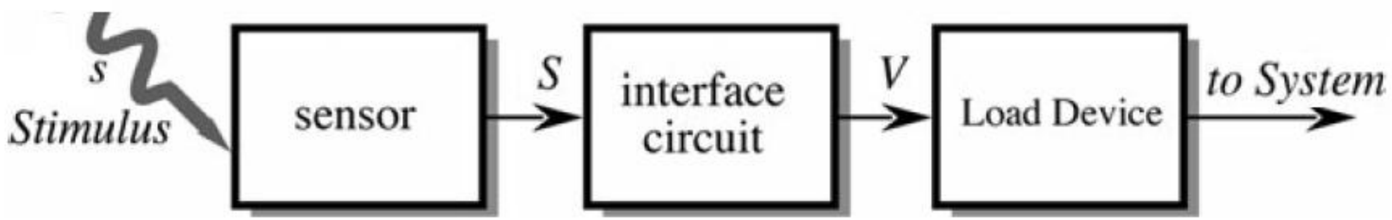
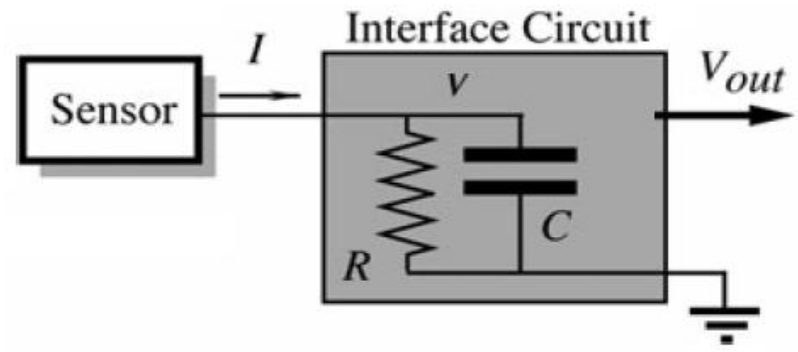
Interface Circuits:

An interface circuit is a signal conditioning circuit used to bring signal from the sensor up to the format that is compatible with the load device.



The input impedance: shows by how much the circuit loads the sensor, it is expressed by;

$$\mathbf{Z} = \frac{\mathbf{V}}{\mathbf{I}}$$



Example; if the input of a circuit is modeled as a parallel connection of input resistance (R) and input capacitance (C), the complex input impedance is;

$$\mathbf{Z} = \frac{R}{1 + j\omega RC}$$

- At very low frequencies, a circuit having a low input capacitance and resistance has an input impedance, which is almost equal to the input resistance: Z≈R.

The Output Impedance:

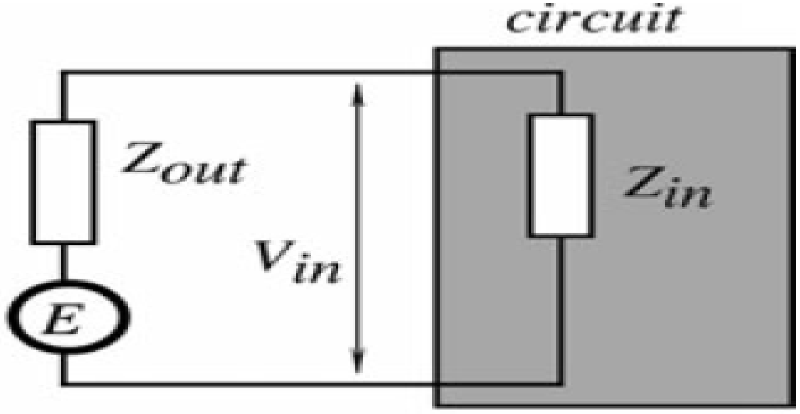
For voltage source sensor: the circuit is comprised of the sensor output impedance (Z_{out}), and the circuit input impedance (Z_{in}).

The output signal from the sensor is represented by a voltage source (e) connected in series with the output impedance.

For current source sensor: the current source is connected in parallel with the sensor output impedance.

The circuit input voltage (V_{in}) is represented as;

$$V_{in} = e\frac{Z_{in}}{Z_{in} + Z_{out}}$$



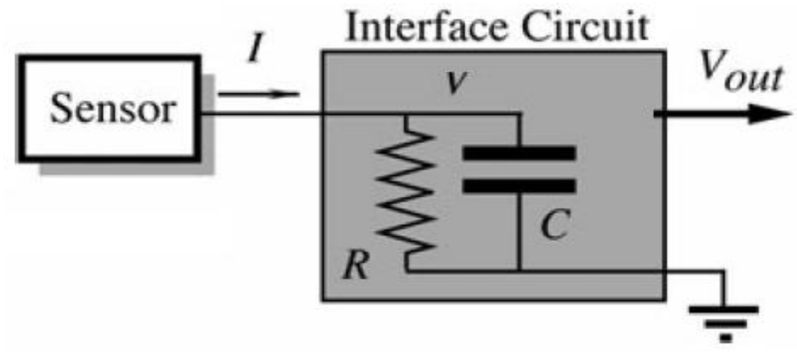
Importance of the input impedance:

Consider a purely resistive sensor connected to the input impedance.

The circuit's input voltage as function of frequency (f) can be expressed by;

$$V = \frac{E}{\sqrt{1 + \left(\frac{f}{f_c}\right)^2}}$$

$$f_c = (2\pi RC)^{-1}$$



Assume that a 1% accuracy in the amplitude detection is required, then the maximum stimulus frequency is; $f_{max} \approx 0.14 f_c$, or $f_c \approx 7 f_{max}$

- Operational amplifiers usually have limited frequency bandwidths. There are programmable operational amplifiers, which allow the user to control the bias current and, therefore, the first stage frequency response. The higher the current, the faster would be the response.

Amplifiers:

Most passive sensors produce weak output signals with magnitudes on the order of microvolts (mV) or picoamperes (pA). Therefore, an amplification of the sensor output signals has to be made with a voltage gain up to 10,000 and a current gain up to 1 million.

The amplifiers are composed of standard building blocks, such as operational amplifiers and various discrete components.

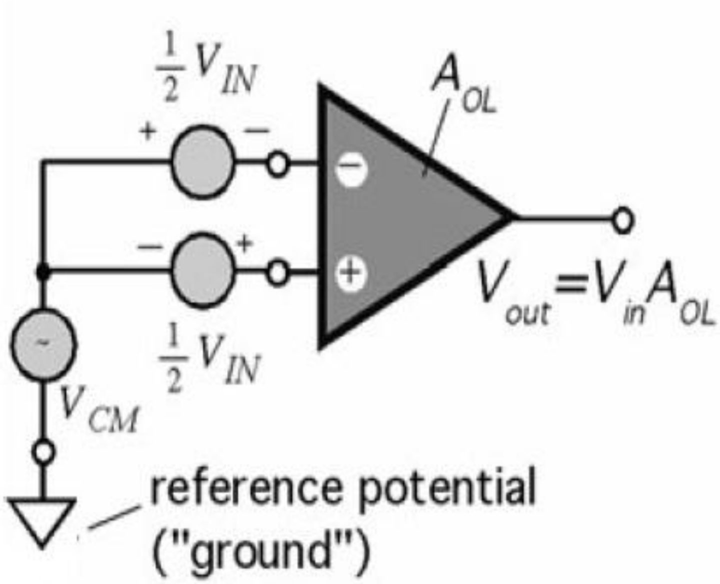
Operational Amplifiers:

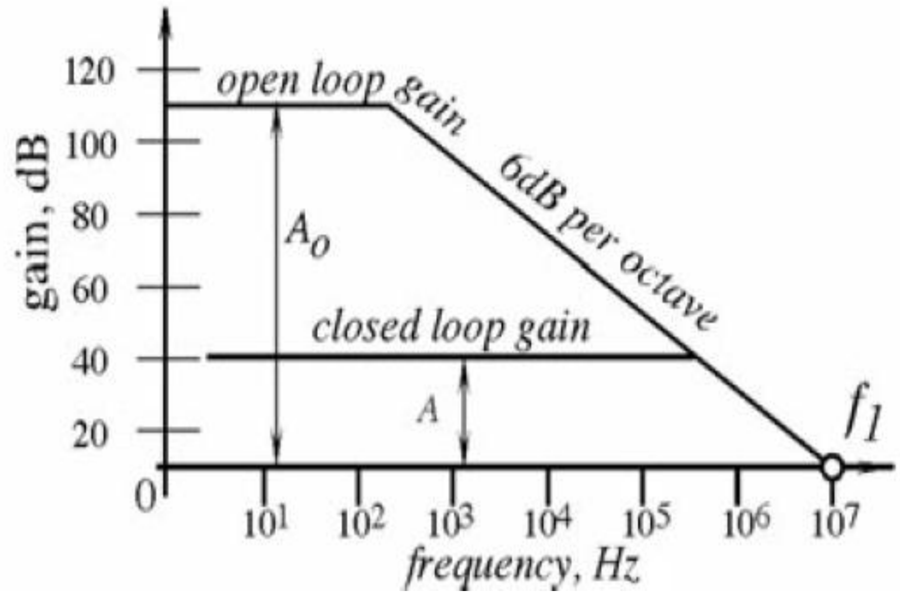
By using OpAmps and discrete components (resistors, capacitors, inductors, etc.), you may create an infinite number of useful circuits, such as; amplifiers, summers, integrators, differentiators.

OpAmp Properties:

- Two inputs: one is inverting (-) and the other is non-inverting (+);
- A high input resistance : on the order of hundreds of MΩ or even GΩ
- A low output resistance: a fraction of Ω
- An ability to drive capacitive loads
- A low input offset voltage (e_o): few mV or even μV
- A low input bias current (i_o): few pA or even less
- A very high open loop gain A_{OL} (at least 10^4 and preferably over 10^6). The OpAmp must be able to amplify a voltage difference (V_{in}) between its two inputs by a factor of A_{OL};
- A high common mode rejection ratio (CMRR): the amplifier suppresses the in-phase equal magnitude input signals (common-mode signals) V_{CM} applied to its both inputs;
- A low intrinsic noise;
- A broad operating frequency range;
- A low sensitivity to variations in the power supply voltage;
- A high environmental stability of its own characteristics.

Open Loop OpAmp:





An OPAM is very rarely used with an open loop due to;

- the high open-loop gain may result in circuit instability,
- a strong temperature drift,
- noise, etc.

Example: if the open-loop gain is 10^5, the input voltage drift of 10 mV would cause the output drifts by about 1 V.

Offset Voltages:

An interface circuit does not produce zero output when zero input signal is applied, due to offset voltages and bias currents.

If the input offset voltage is still too large for the desired accuracy, it can be trimmed out either directly at the amplifier , or in the independent offset compensation circuit.

The output offset voltage is given by;

$$V_o = A(e_o + i_o R_{eqv})$$

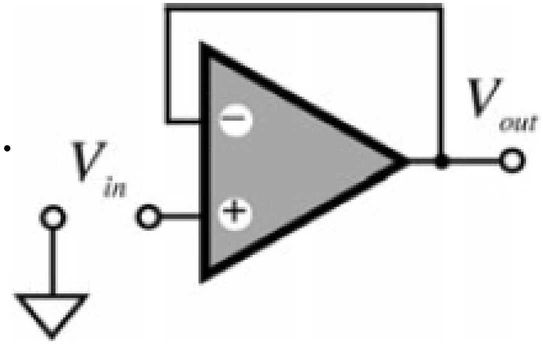
where;

- R_{eqv} : is the equivalent resistance at the input (a combination of the sensor's output resistance and the input resistance of the amplifier),
- e_o : is the input offset voltage, and
- i_o : is the input bias current.

To avoid offset voltages, select an amplifier with low bias current, high input resistance, and low offset voltage. Chopper-stabilized amplifiers are especially efficient for reduction of offset voltages.

Voltage Follower:

It is a an electronic circuit that provides impedance conversion from a high to low level.
It is a current amplifier and impedance converter used for sensor interfacing.



A typical follower has;

- high Zin; high input resistance and the low input capacitance.
- low output impedances ; low output resistance, the output capacitance makes no difference.
- voltage gain very close to unity (typically, 0.999 at lower frequencies) and a high current gain.

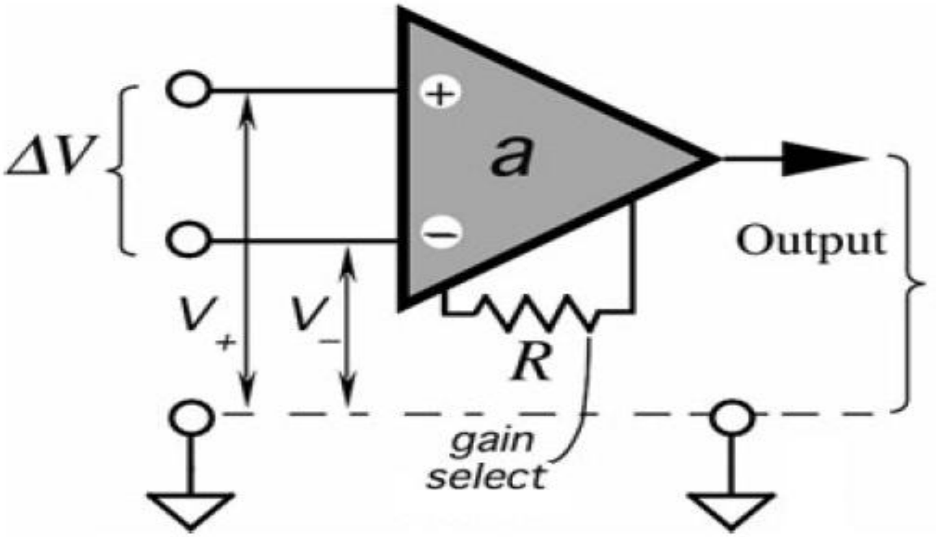
Voltage follower provides a buffering function between the sensor and the load. The following points should be considered;

1. For the current-generating sensors, the input bias current of the follower must be at least 100 times smaller than the sensor's current.
2. The input offset voltage must be smaller than the required LSB.
3. The temperature coefficient of the bias current and the offset voltage should not result in errors of more than 1 LSB over an entire temperature range.

Instrumentation Amplifier (IA):

An IA has two inputs and one output and is distinguished from an OpAmp by its finite gain (which is ≤100) and the availability of both inputs for connecting to the signal sources.

The main function of the IA is to produce an output signal which is proportional to ΔV;



$$V_{out} = a(V_+ - V_-) = a\Delta V$$

- It is important to assure high input resistances for both inputs, so that the amplifier can be used in a true differential form.
- The IA should have a high common-mode rejection ratio (CMRR); i.e. its output signal should be insensitive to the value of V_+ or V_- but responsive only to their difference.
- An example: IA type (INA118) from Burr-Brown/Texas Instruments, it offers low offset voltage of 50 mV, high CMRR (110 dB), and its gain is programmed by a single resistor.

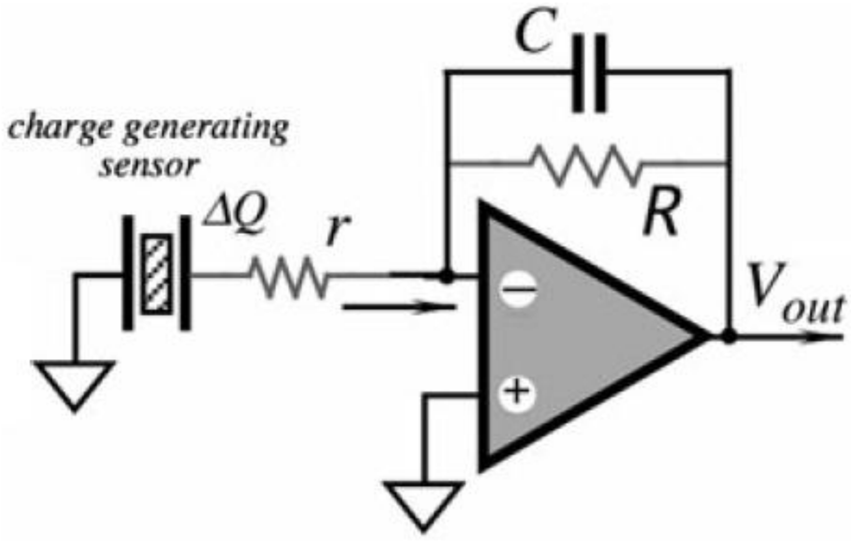
Charge Amplifier (CA):

It is a very special class of circuits, which must have extremely low bias currents. These amplifiers are employed to convert to voltage signals from devices generate very small charges, such as capacitive sensors.

Charge-to-voltage converter :

A capacitor (C) is connected into a feedback network of an OpAmp. Its leakage resistance (r) must be substantially larger than the impedance of the capacitor at the lowest operating frequency. A transfer function of the converter is;

$$V_{out} = -\frac{\Delta Q}{C}$$



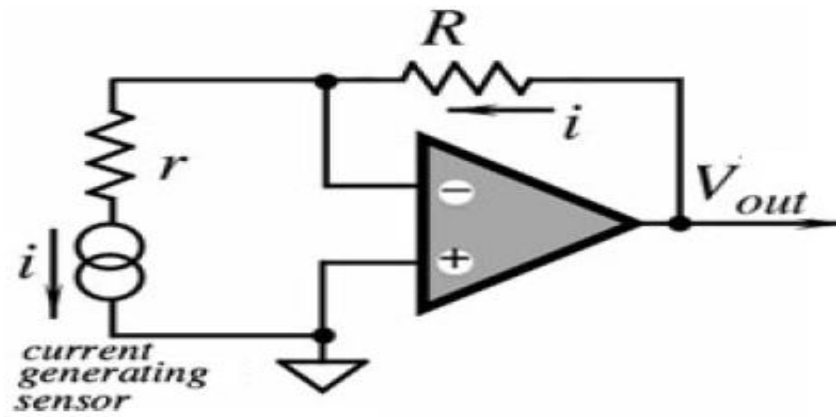
Capacitive sensors are either active or passive;

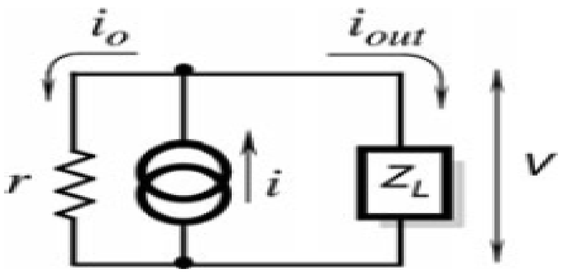
Active capacitive sensors require an excitation signal, such as microphones, capacitive force, and pressure transducers and humidity detectors.

Passive capacitive sensors directly convert a stimulus into an electric charge or current. Examples are the piezoelectric and pyroelectric detectors.

Current generating sensor:

It is modeled by a leakage resistance (r) connected in parallel with a current generator that has an infinitely high internal resistance.





Since r>> Z_L then the current (i_o) is useless and to minimize the error of the current-to-voltage conversion.

The sensor generates current (i) which has two ways to outflow:

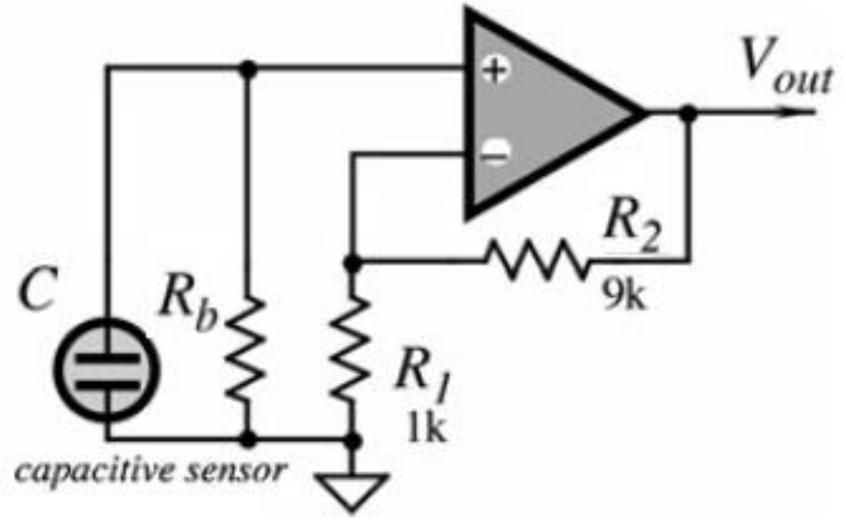
- i_o : to the sensors leakage resistance (r),
- i_{out}:, to the interface circuit i/p impedance (Z_L).

Since voltage at the inverting input is almost equal to that at the non-inverting input (which is grounded), then the sensor operates at nearly zero voltage and its current defines the output voltage of the OpAmp;

$$V_{out} = -iR$$

- The advantage of the virtual ground is that the output signal does not depend on the sensor's capacitance.

Non-inverting current to voltage converter:
It can convert and amplify the signal, however, its speed response depends on both the sensor's capacitance (C) and the converting resistor (R1). Thus, the response to a step function in a time domain can be described by;



$$V_{out} = iR_b\left(1 + \frac{R_2}{R_1}\right)\left(1 - e^{-\frac{t}{rC}}\right)$$

Note: When converting currents from such sensors, the resistor R_b may be required on the order of tens or even hundreds of gigohms. (!!!)

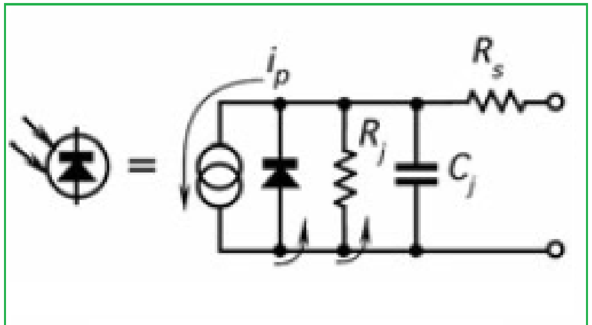
Light-to-Voltage Converters:

They are based on combination of photosensors and current-to-voltage converter circuits.

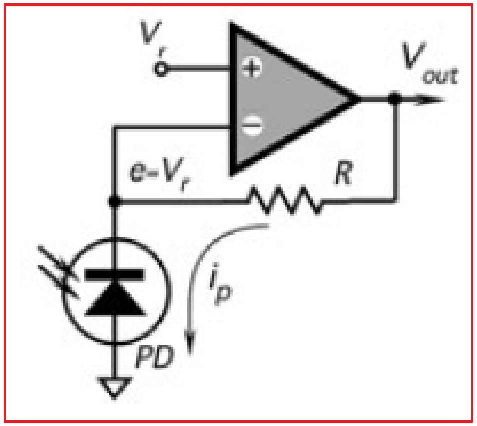
Three types of a photosensor are available:

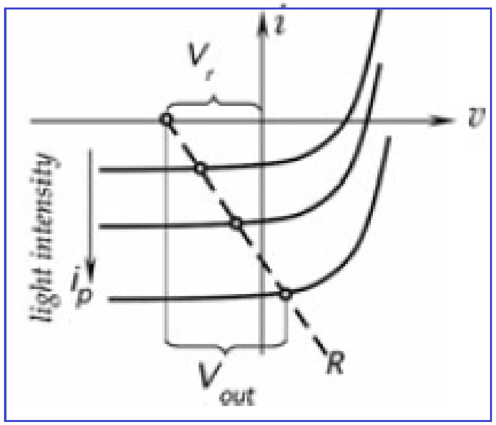
1. Photodiode,
2. Phototransistor, and
3. Photoresistor.

The difference between a photodiode and a phototransistor is in construction of the semiconductor chip. A photodiode has one p-n junction, while a phototransistor has two junctions. The base current is a photo-induced current that is multiplied by the transistor's β to produce the collector current. Thus, a phototransistor is equivalent to a photodiode with a built-in current amplifier.



Equivalent circuit of a photo-diode





Photodiode operation:

The current generator generates a photocurrent proportional to the photon flux.

This current flows in the direction from the cathode (-) to the anode (+) of the photodiode.

A photodiode can be used in voltaic or current modes;

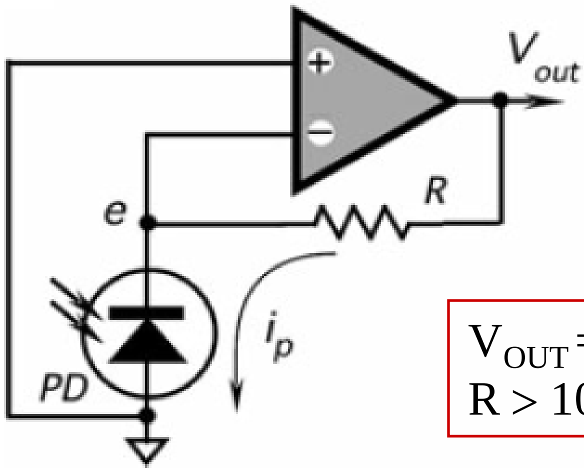
Voltaic mode;

- The photodiode is connected to a very high resistor (10^7–10^9 Ω) and a good voltage amplifier.
- The diode will work like a battery with voltage proportional to the light intensity. This voltage is the result of a photocurrent ip passing through the internal junction resistance (R_j).

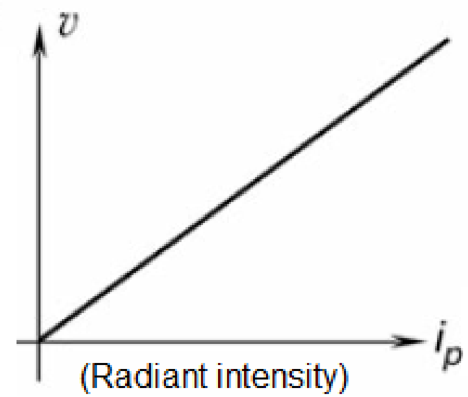
Current mode;

- The photodiode is virtually shorted (a voltage across the diode is zero) and current (i_p) is drawn to the current-to-voltage converter as described below.
- This node is more popular, especially for applications where a high-speed response is required.

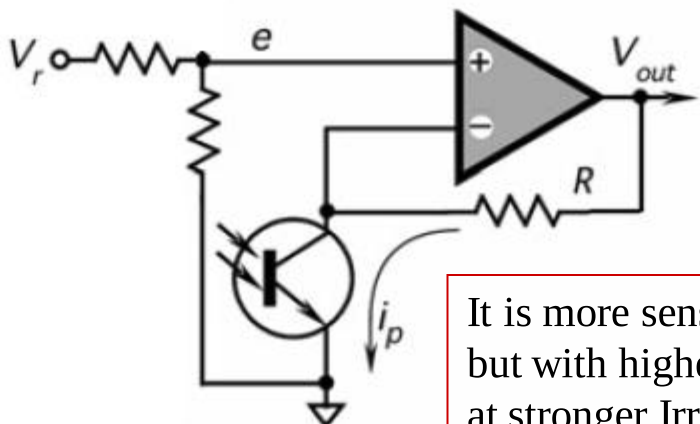
A zero-biased photodiode with a current-to-voltage converter:



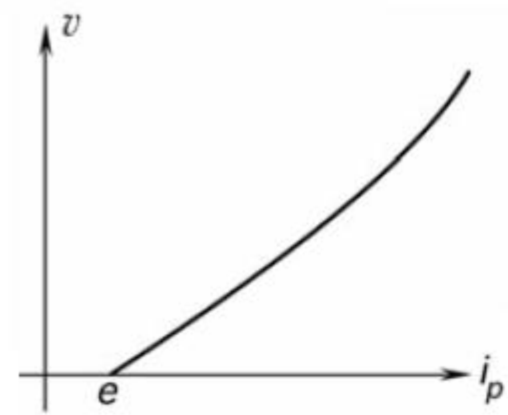
$V_{OUT} = i_p R$
R > 100 MΩ



Light-to-voltage converted with a photo-transistor:



It is more sensitive to light but with higher nonlinearity at stronger Irradiances.



Excitation Circuits:

External power is required for operation of the active sensors, such as; temperature sensors (thermistors and RTDs), pressure sensors (piezoresistive and capacitive).

The power may be delivered to a sensor in different forms;

- a constant voltage, a constant current, and sinusoidal or pulsing currents,
- it may be delivered in the form of light or ionizing radiation.

It is imperative to generate the signal with such accuracy that the overall performance of the sensing system is not degraded.

Voltage-to-Frequency Converter (VFC):

The output frequency of the VFC is proportional to the average value of the input voltage.

When acting as an A/D converter, the V/F converter is coupled to n-bit counter, which is clocked with the required sampling rate. For example, if a full-scale frequency of the converter is 32 kHz, and the counter is clocked 8 times per second, the highest number of pulses, which can be accumulated every counting cycle is 4,000, which means 12-bit resolution.

The time required to convert an analog voltage into a digital number is related to the full-scale frequency of the VFC and the required resolution. The VFC output (f_{out}) is proportional to the input voltage (V_{in});

$$\frac{f_{out}}{f_{FS}} = \frac{V_{in}}{V_{FS}}$$

where; f_{FS} and V_{FS} are the full-scale frequency and input voltage, respectively.

For a given linear converter, ratio $f_{FS}/V_{FS}= G$ is constant and is called a conversion factor, then

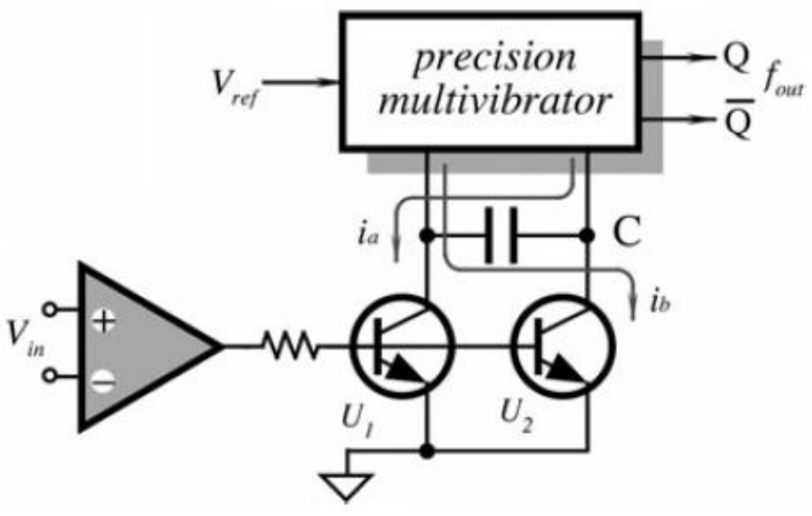
$$f_{out} = GV_{in}$$

VFC Types:

The most popular types of the VFC are the multi-vibrator and the charge-balance circuit.

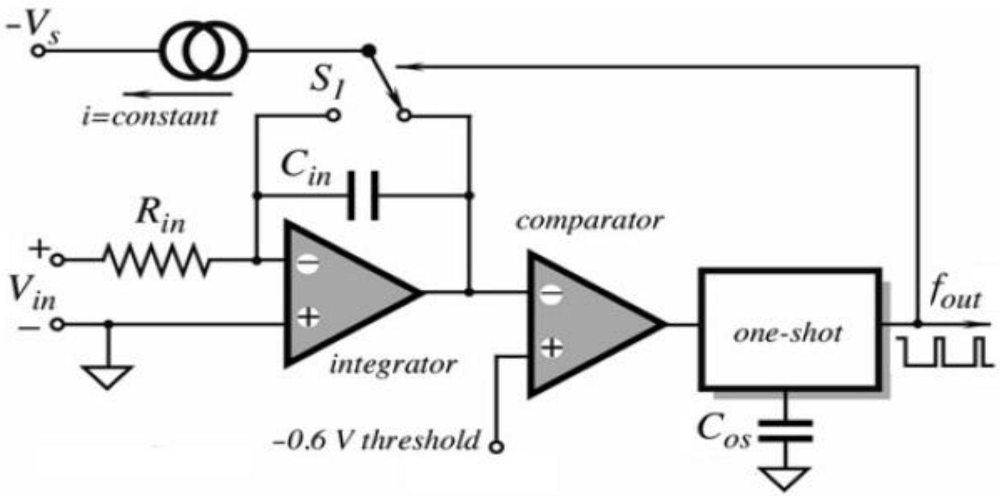
A multi-vibrator VFC: employs a free-running square-wave oscillator where charge-discharge currents of a timing capacitor are controlled by the input signal.

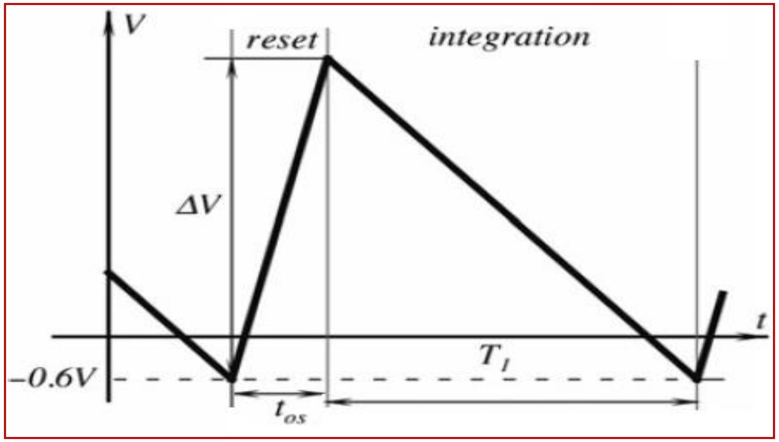
The capacitor (C) is charged for a half of period through transistor U_1 by the current (i_a). During the second half of the timing period, it is discharged by the current (i_b) through transistor U_2. Since currents (i_a & i_b) are controlled by the input signal, the capacitor charging and discharging slopes vary accordingly, thus changing the output frequency.



Charge-Balance VFC;

It employs an analog integrator and a voltage comparator. This circuit has advantages; high speed, high linearity, and good noise rejection.





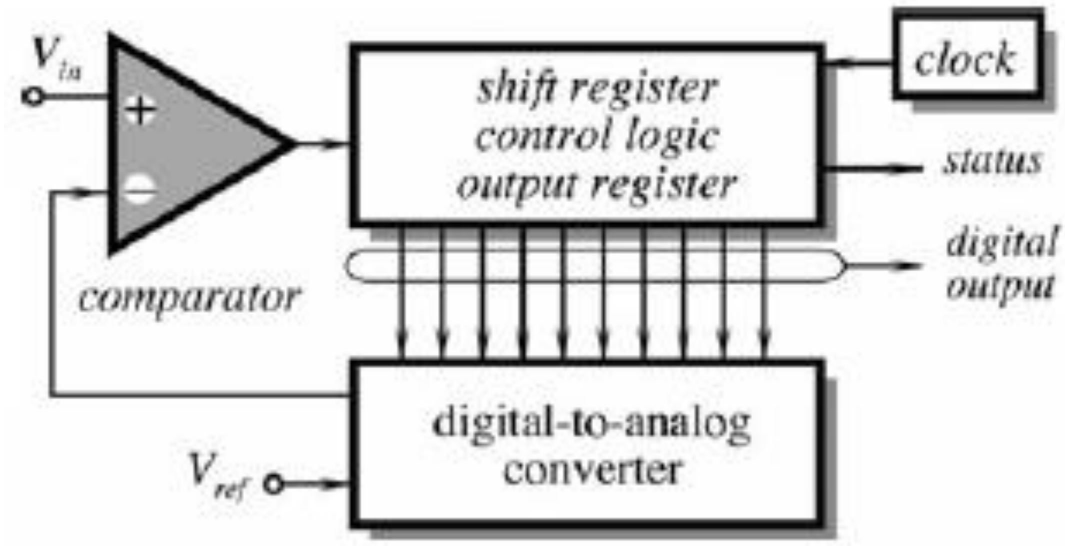
Operation: The integrator generates a saw-tooth voltage that results in a transient at the comparator's output. That transient enables a one-shot generator, which produces a square pulse of a fixed duration (t_{os}).

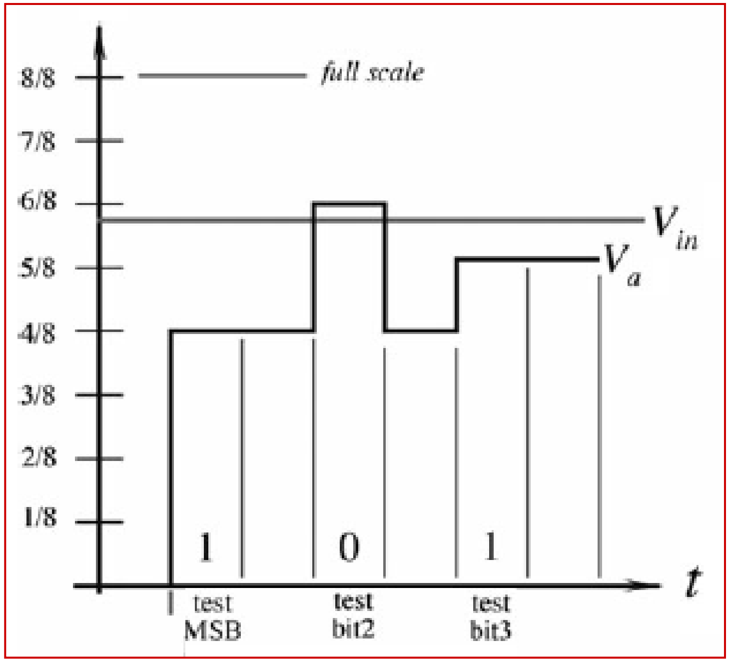
$$\Delta V = t_{os}\frac{\mathrm{d}V}{\mathrm{d}t} = t_{os}\frac{i - I_{in}}{C_{in}}$$

$$T_1 = \frac{\Delta V}{dV/dt} = t_{os}\frac{i - I_{in}}{C_{in}}\frac{1}{I_{in}/C_{in}} = t_{os}\frac{i - I_{in}}{I_{in}}$$

$$f_{out} = \frac{1}{t_{os} + T_1} = \frac{I_{in}}{t_{os} i} = \frac{V_{in}}{R_{in}}\frac{1}{t_{os} i}$$

Successive Approximation ADC:





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