F11 (Mot 8)
Sensors-Practical examples

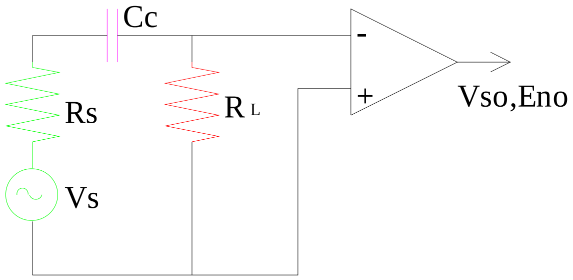
Six models are presented that "can be generalized to cover all types of sensors."

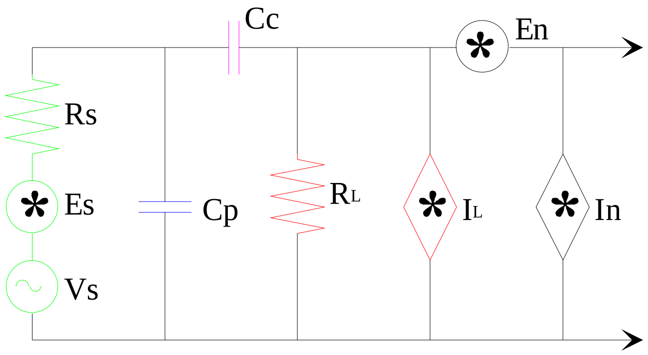
Naming:

- Sensor: All types
- Transducer: Energy from one form to another
  - Eg radiation => Power
  - Piezo electric element (bidireksjonal function): Motion ⇔ Voltage
  - Transducer = Sensor + Actuator
- Detector: Optics, Infrared, Particle

Simulators model the most common types of noise while special noise types such as. GR (Generation-Regeneration noise) must be represented by separate (typically user defined) noise models.

8-1 Voltaic Sensor





This type of sensor generates a voltage signal.
Sensors:

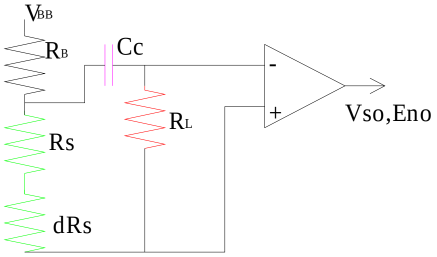
- Thermo coupler
- Thermopile
- Pyro electric infrared detector

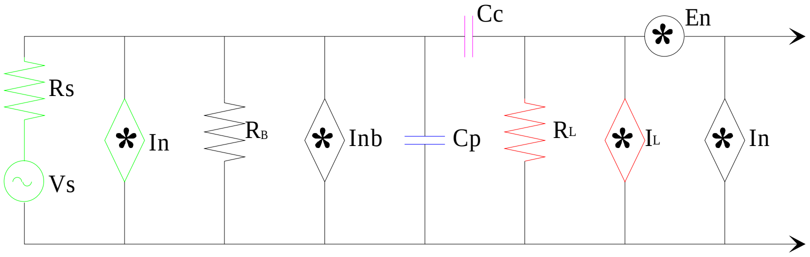
C_C: Because we are only interested in the AC portion of the sensor signal.
R_L: Provides bias to the amplifier and any impedance matching.
C_p: Parasitic capacitance of the sensor or between the connection lines.

Low noise => R_L should be large, C_p should be small and C_C large.

The amplifier should be chosen so that $R_0=R_S$ and E_nI_n is as small as possible.

8-2 biased resistive sensor





This type provides a variety in the sensor resistance ($dR_S <<< R_S$).

A bias network is required. Two new noise sources have to be considered: V_{BB} and R_B..
If the sensor resistance is placed a bridge there will also be contributions form the other bridge resistors.

Sensors:
- Stretch lapp (Strain gauge)
- Photo conductive infrared cell
- Bolometer radiation detector
- Resistive thermometer
- Piezoresistive sensors

R_B: Bias
C_C: Removing DC-signal
R_L: Bias: Provides pre-amplifier input.

$$V_S = I_B \Delta R_S \cong \frac{V_{BB} \Delta R_S}{R_S + R_B}$$

Alternatively, a power source in parallel with R_S: $I_S = V_S / R_S$.

I_{ns}: Thermal noise
1/f-støy
G-R noise (Generation-Recombination)
I_{nb}: Thermal noise and any other noise due to R_B.

Low noise ⇒ R_B should be large. R_B may be replaced by L. C_C should be so large that $I_n X_c$ does not contribute even at the lowest frequencies.

If V_{BB} is constant R_B has to be selected as a compromise to get high enough V_S and low enough noise. The proper choice depends on the sensor characteristics. If V_{BB} can be increased it is possible to achieve both high gain and low noise. Further we should have $R_L >> R_S$ so that I_L does not contribute significantly.

8-3 Optoelectronic Detector

Applications:

- Infrared detection
- Heat metering
- Light and colour measurement
- Fibre optic sensors
- Sensors for CDs
- Laser detectors

Two types:

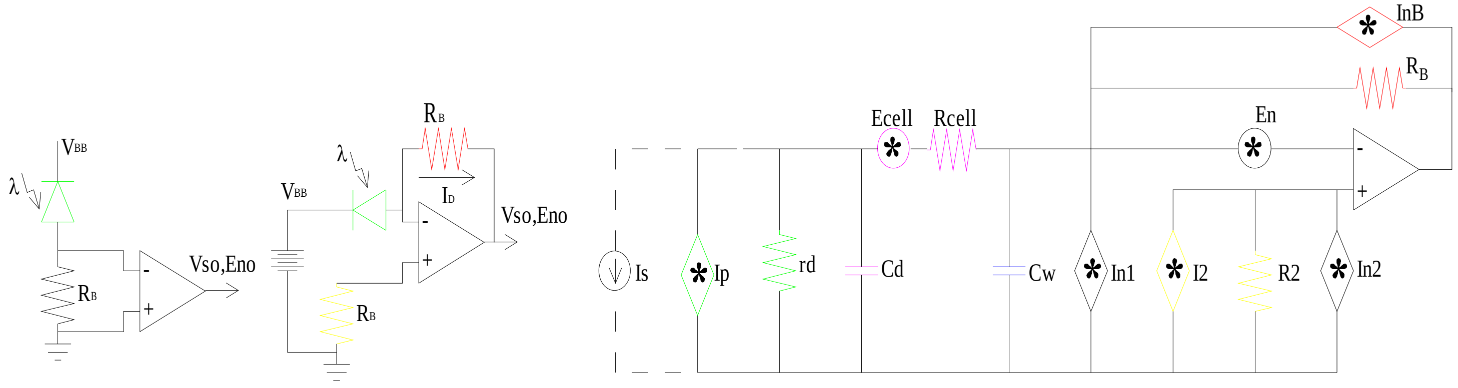
Photovoltaic: Light provides a voltage on output

Photoconductive: Light provides current (in addition to dark current). A bias is required to collect charges.

Photo conductive detectors have two subgroups:

1. One that is made of bulk semiconductor material and where the conductivity increases with exposure. Modelled as a variable resistance. Discussed earlier.
2. Perceive the detector as a diode. The diode is reverse biased..

In the following we will discuss a photo conductive diode of type 2 (i.e. with a diode model of the sensor)



The figure shows three elements: The simple connection, the common connection and the noise form of the common connection.

The voltage over R_B is a product of R_B and the current through the detector:

Current = leakage current + signal current.

R_B provides a virtual ground at the input that will reduce the input impedance and thus improve the frequency response $V_0=-I_DR_B$.

I_S: Signal current (not noise current)
I_P: Diode noise in the detector

$$\left(I_{sh}^2 + I_{G-R}^2 + I_{1/f}^2\right)^{1/2}$$

r_d: Dynamic noiseless resistance in the photo diode
C_d: Parasitic capacitance of the diode
R_{cell}: Series resistance of the diode
E_{cell}: Thermal noise in the diode
C_W: Parasitic capacitance of the wires
R_B: Feedback resistance

I_nB: Thermal noise in R_B
R_2: Resistance on the positive amplifier input
I_2: Thermal noise in the R_2
E_n,I_n1 and I_n2: Noise in the amplifier model.

FET input at the amplifier is probably the best choice here!

8-3-1 Photo Diode Noise Mechanisms

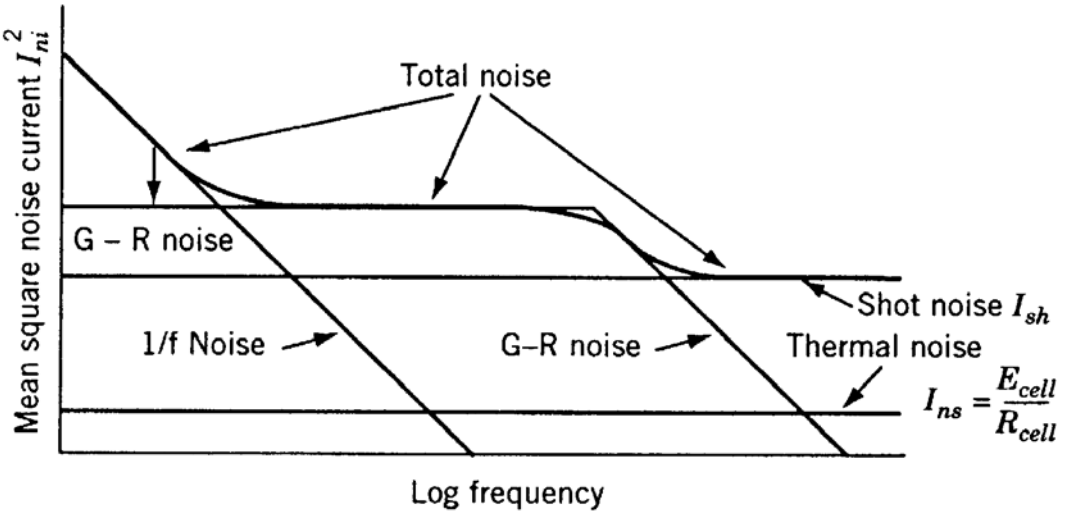


Figure 8-8 Noise sources in a photodiode.

$$I_p = \left(I_{sh}^2 + I_{G-R}^2 + I_{1/f}^2\right)^2$$

$$I_{ns} = E_{cell} / R_{cell}$$

$I_{sh}^2 = 2qI_D\Delta f$ (All current through the diode)

$$E_{cell}^2 = 4kTR_{cell}\Delta f$$

I_{G-R}: Generation-Recombination noise. The conductivity varies due to the variations in the free charge. The noise is "White" until 1/average life time of the e-h-pairs in the detector diode.

I_{sh}, I_{G-R} and $I_{1/f}$: Function of current and increases with current strength. Minimum noise when the current through the diode is only background photo noise.

NEP = Noise Equivalent Power
... ... is the value of an input signal (in this case the light power) that produces an electrical output signal that is as large as the output noise alone when there are no input signal.

8-3-2 PIN Photo Diode Sensor

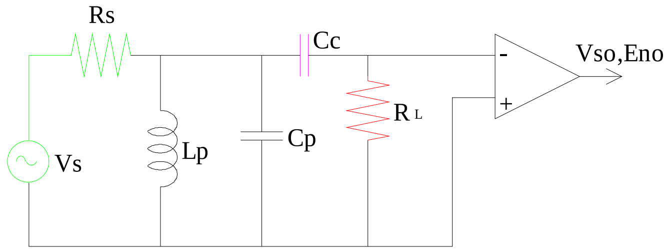
PIN diode is used for visible light and to the portion of the infrared spectrum that is closest to visible light.

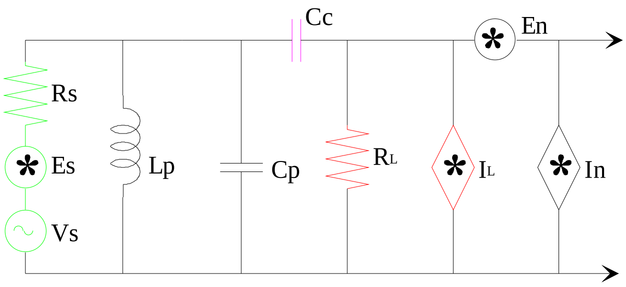
Need bias voltage <50V and typically in the range 5-20V.

Example values:
V_B=20V
C_d= typically 1pF-5pF
R_{cell} = <50Ω
R_d=10GΩ
I_D: Dark current: 100pA typical + reverse current
1/f-noise: Noise corner: 20 - 30 Hz
10dB/dec increase below corner frequency
Max response: 0.5µA/µW in the visible frequency band 0.5-0.8µm, 0.75 electron/photon=75% quantum efficiency

NEP down towards -110dBm/√Hz

8-4 RLC Sensor Model





Sensors:

- Heads for magnetic tapes
- Inductive pick-ups
- Dynamic microphones
- Linear variable differential transformers
- "various other inductive sensors"

R_S: Sensor series resistance or the real part of the sensor impedance.
E_S: Thermal noise in R_S
L_P: Sensor inductance
C_P: Capacitance used to decide the resonance. It consists of internal and external parasitic and intended capacitances.

C_C: Isolate the DC-component from the amplifier so that it can be set up with the desired bias voltage.

I_L: Thermal noise in R_L

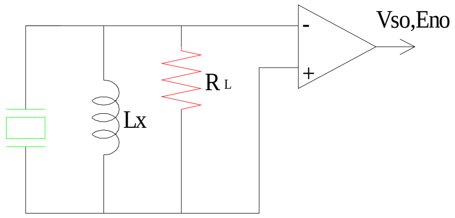
Low noise ⇒ At resonance *En* will be at its minimum, and *In* will only be dependent on the impedance of the serie inductance and resistance. (Eq. 7-13)

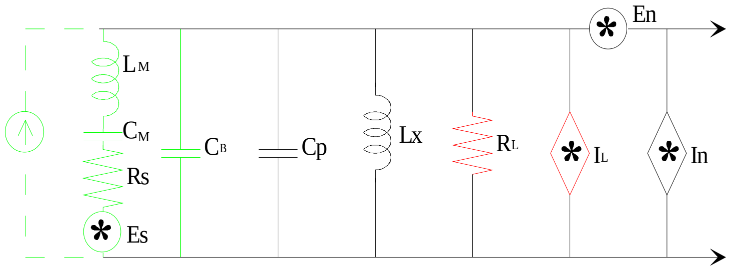
Coils with magnetic core have decreasing inductance and growing resistance at higher frequencies. It may therefore be necessary to model the coil at several frequencies.

Construction of the sensor coil and resonance capacitance can be done so that one gets a maximum S/N ratio.

V_S is proportional to the number of turns.
R(L) is proportional to the number of turns for small diameters. Noise is proportional to the square root of the number of turn. Thus, the signal level will increase more than the noise level with increasing number of turns until a certain limit. increased with the number turn up to a certain limit.

8-5 Piezoelectric Transducer





"Piezo" ⇔ "Electric"

Mechanical motion ⇔Electrical response

Applications:

Microphones

Hydrophones

Sonar

Seismic detectors

Vibration Sensors

Accelerometers

Two resonances

--- Series resonance L_M and C_M

--- Parallel resonance (C_M+C_B) and L_x.

Normally the parallel resonance is preferred

L_M: Mechanical inductance

C_M: Mechanical capacitance

R_S: Serial loss in the transducer

E_S: Thermal noise in RS

C_B: Transducer capacitance

I_S: Signal current (No noise)

C_p: Parasitic cable capacitance

Lx: External coil
R_L: Load resistance
I_L: Thermal noise in R_L

Equivalent input noise:

$$E_{ni}^2 = 4kTR_S + E_n^2\left(\frac{Z_S + Z_L}{Z_L}\right)^2 + \left(I_n^2 + I_L^2\right)Z_P^2$$

Z_S: The serial impedances of R_S, C_M and L_M.
Z_L: The parallel impedance of C_B, C_P, L_X and R_L.
Z_P: is $Z_S \,||Z_L$
R_S is typically small and the first term can usually be ignored. This is a high impedance system and E_n will be small compared to I_n. At low frequencies Z_P will be very large due to C_B and C_P.. To get the least amount of noise current should R_L be large and I_n small.

An FET amplifier should be chosen due to:

- Small I_n
- R_L can be made be very large

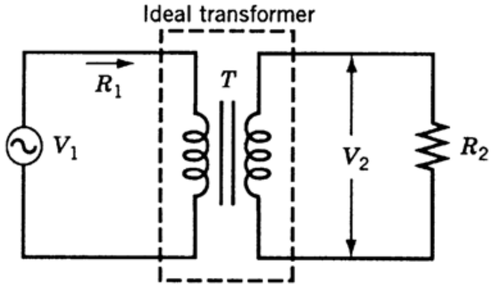
8-6 Transformer Model.

Why having a transformer between the sensor and the amplifier?

1) Impedance matching makes that both the sensor and the amplifier "sees" the impedance with the least noise.
2) Provide insulation between the source and amplifier. (Security, DC-currents, etc.)
3) To achieve maximum transfer of signal power.

However the transformer also contributes with some noise!

Impedance transformation



Assume ideal transformer:

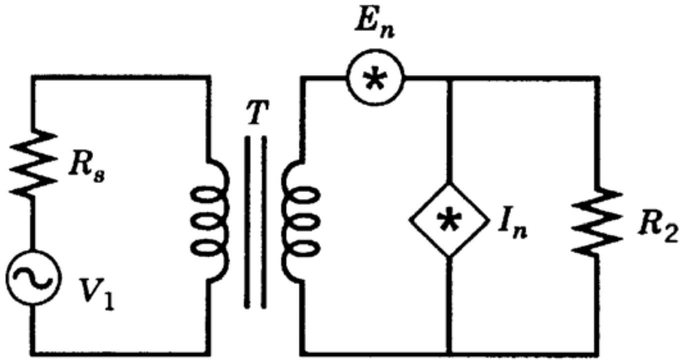
$$P_p = P_s \Rightarrow \frac{V_1^2}{R_1} = \frac{V_2^2}{R_2}$$

$$Def: T = \frac{N_S}{N_p} \quad V_2 = TV_1$$

We will then get

$$R_1 = \frac{R_2}{T^2}\left(= R_2 \frac{N_p^2}{N_s^2} \right)$$

In this way the sensor resistance is transformed so that the amplifier “sees” the optimal source resistance giving the least possible noise.



We have previously defined *R0=En/In*. When we let *En'* and *In'* represent their transferred value on the source side we get:

$$E'_n = \frac{E_n}{T} = E_n \frac{N_p}{N_s}$$

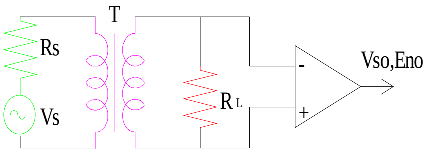
and

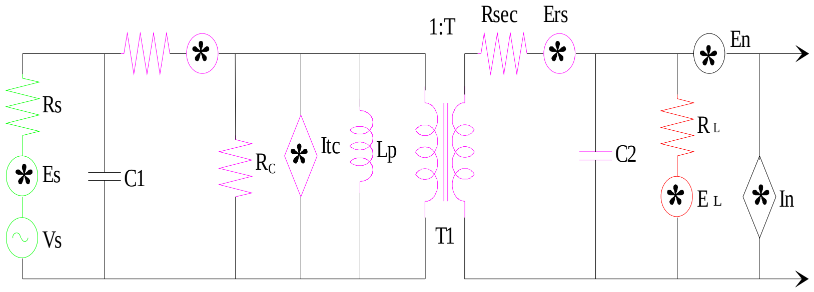
$$I'_n = TI_n = I_n \frac{N_S}{N_P}$$

We will then have on the source side:

$$R'_0 = \frac{E'_n}{I'_n} = \frac{E_n}{T^2 I_n} = \frac{R_0}{T^2} = R_0 \frac{N_S^2}{N_P^2}$$

We match so that $R'_0=R_S$ and have $R_S=R_0/T^2 => T^2=R_0/R_S$. We choose the turn ratio of the transformer so that $T^2=R_0/R_S$ to get the least possible noise.





V_S: Sensor signal voltage

R_S: Sensor resistance

E_S: Thermal noise in R_S

C_1: Primary shunts capacitance

R_P: Resistance primary side of transformer, series

E_P: Thermal noise in R_P

R_C: Resistance primary side of the transformer, parallel

I_{tc}: Thermal noise in R_C

L_p: Inductance at the primary side

T_1: Noiseless, ideal transformer

R_{sec}: Resistance secondary side of transformer

E_{rs}: Thermal noise in R_{sec}

C_2: Secondary shunts capacitance

R_L: Load resistance

E_L: Thermal noise in R_L