Chapter 1

Electrical transducers

1.1 Transducers

Transducers are generally components that transform an input signal which constitutes a certain physical variable, and which is the quantity to be measured, into an electrical signal.

1.1.1 Potentiometer or rheostat

It is the most common type of transducer consisting of a variable resistance; the mobile contact makes linear or angular movements possible.

A potentiometer can have different characteristics: sensitivities of the order of 5/100 *mm* for linear displacement or of 0.2 degrees for angular displacement can be obtained.

The error and noise in the measurement are highly dependent on the contact mode: potentiometers are very sensitive to the effects of temperature variation leading to changes in resistance. Potentiometers are mainly used for displacement measurements but this type of measures can also refer to those of other physical quantities such as angle, force and pressure.

In summary, a resistance potentiometer consists of a resistive element and a mobile contact. The movement of the contact element can be a linear displacement, a rotation or even a combination of the two movements; for displacement potentiometers, the strokes can range from a few *mm* to 50 *cm* while for rotation potentiometers, the strokes can range from a few degrees up to a few tens of revolutions. The resistive element can be fed in AD or DC: the output voltage is a linear function of the input displacement when referring to ideal condition. If the displacement-resistance relation is linear, the output voltage will linearly follow the input displacement as long as the terminals see an open circuit through which no current is flowing. Generally, the terminals are connected to a measuring device and a current flows in the output circuit. In Fig. 1.1 and in Fig. 1.2, the relative circuits are shown.

On the basis of the circuit characteristics of Fig. 1.2, we get:

$$\frac{e_0}{e_{ex}} = \frac{1}{1/(x_i/x_t) + \frac{R_p}{R_m}(1 - x_i/x_t)} \tag{1.1}$$

which, in the ideal case with $R_p/R_m = 0$ (open circuit condition), becomes:

$$e_0 = \frac{x_i}{x_t} e_{ex} \tag{1.2}$$

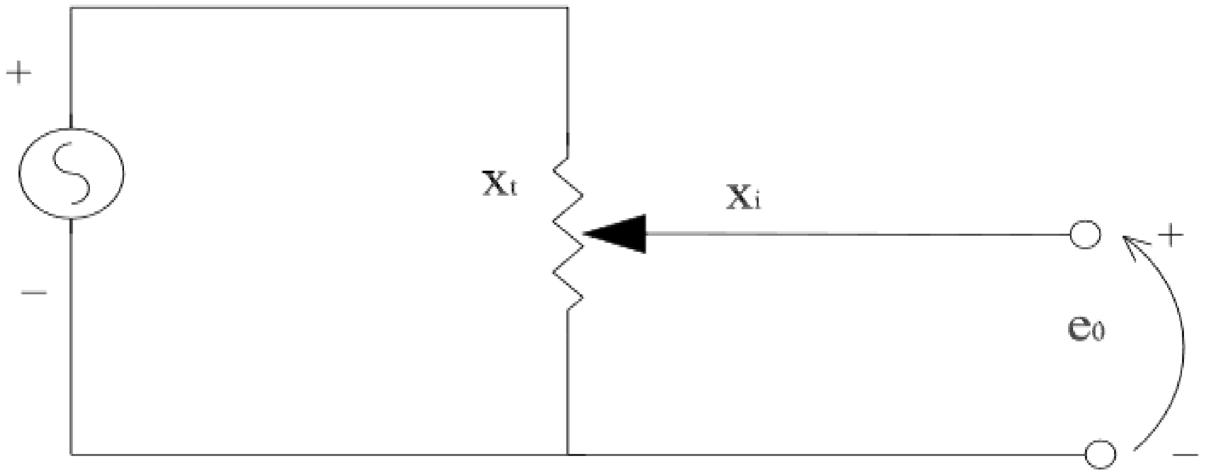

Figure 1.1: Potentiometer ideal circuit

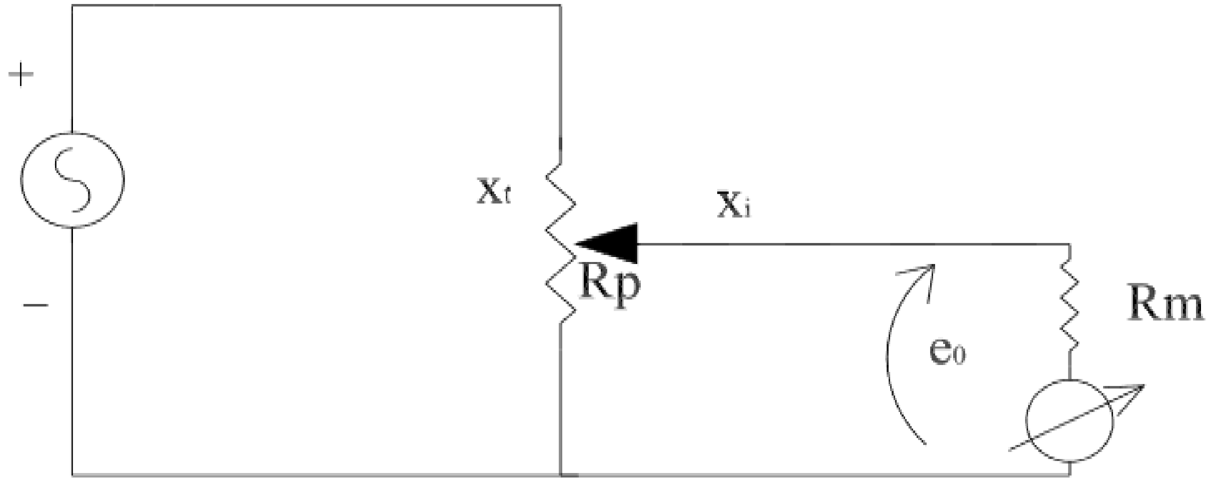

Figure 1.2: Potentiometer real circuit.

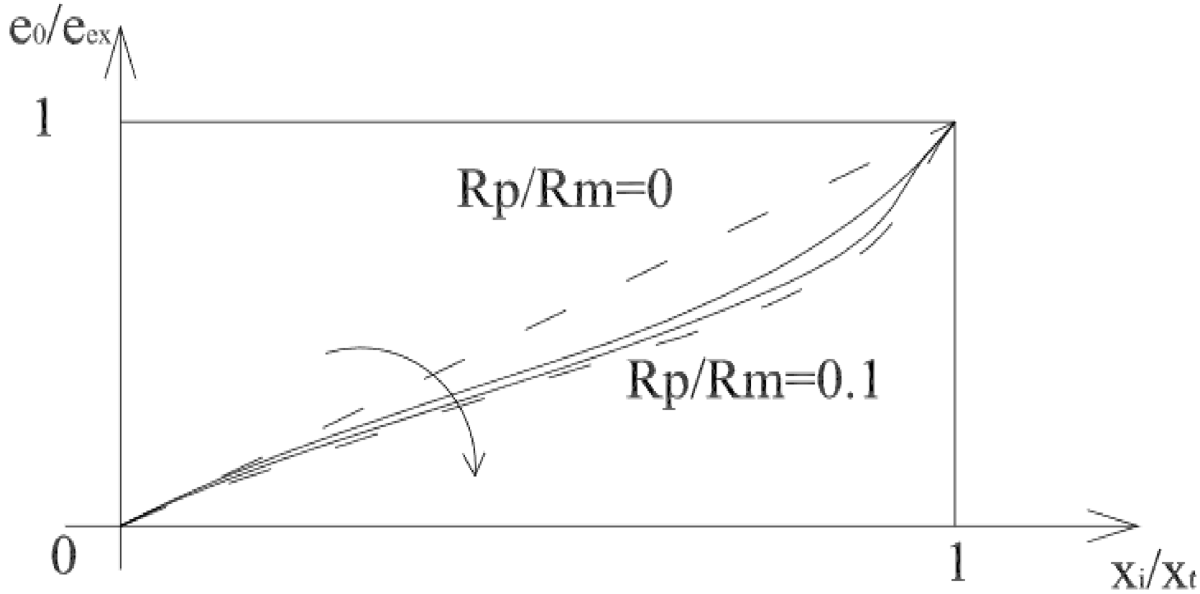

Figure 1.3: Error trend in a potentiometer.

When referring to ideal condition, the input/output curve is a straight line. Otherwise, the relationship is a non-linear, with a trend depending on R_p and R_m values (Fig. 1.3). The maximum error is around 12% if $R_p = R_m$, but it decreases to about 1.5% if R_p is one tenth of R_m. If R_p is even smaller, the maximum linearity error occurs at about two thirds of the full scale and the error is 15 R_p/R_m.

Therefore, to obtain a small linearity error, once the measuring instrument resistance R_m is set, a small resistance potentiometer must be chosen so that the ratio R_p/R_m is as small as possible. The output voltage e_0 depends linearly on the potentiometer supply voltage e_{ex}. In fact, it is not possible to increase the potentiometer sensitivity by an infinite increase in the supply voltage as there are constraints related to heat dissipation (a typical value of dissipated power can be 5 W at a room temperature of 20 ^oC).

So, once the dissipated power value P and the potentiometer resistance R_p (which can vary greatly depending on the characteristics, $100 < R_p < 100000$ ohm) have been set, the maximum potentiometer supply voltage is obtained:

$$e_{ex_{max}} = \sqrt{PR_p} \tag{1.3}$$

the smaller the R_p value, the smaller the e_{ex} value, and thus the sensitivity values are also limited.

Sensitivity limit values can be of the order of 15 $V/degree$ for rotary potentiometers and of 12 V/mm for displacement potentiometers (with limited stroke of 5 mm); normal sensitivity values are at least one order of magnitude lower.

The dynamic behavior is that of a zero-order instrument, i.e. ideal, in which the output, the voltage e_o, instantaneously follows the input, the displacement (whether linear, x_i, or angular, ϑ_i). Indeed, the impedance of the potentiometric circuit, at least for the frequencies of interest, can be considered as purely resistive. However, there are several issues related to friction phenomena that introduces noise to the measurement thus drifting away from the potentiometer

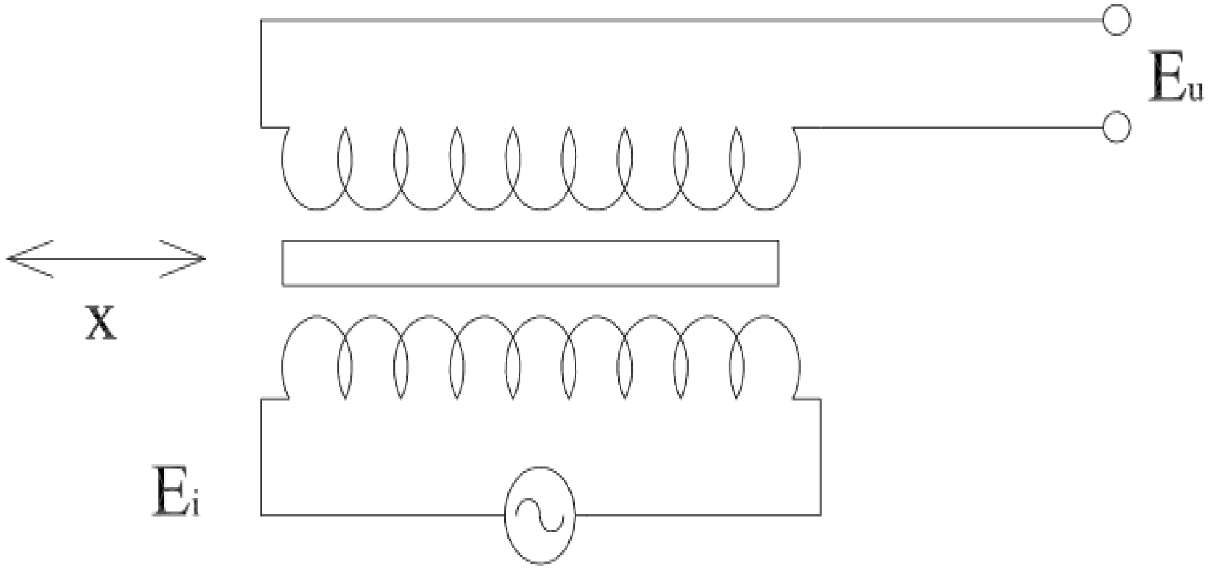

Figure 1.4: Differential transformer scheme.

ideal behaviour.
Several environmental factors must be taken into account. Indeed, very high or very low temperatures, vibrations, shocks and humidity variations can contribute to limiting the instrument nominal characteristics.

1.1.2 Differential transformer

It consists, Fig. 1.4, of inductors with a magnetic core moving in the magnetic field. The input voltage, E_i, is in alternate and the output voltage, E_u, is a function of the position of the magnetic core inside the transducer. This function has a trend of the type shown in Fig. 1.5: a linear relationship can be identified within a certain displacement range, indicated with the segment AB, while a non-linearity is certainly found around zero, which represents the reference position of the core. The operating frequency is limited by the transducer inertia characteristics and is generally about one tenth of the frequency of the input E_i.

1.1.3 Capacitive transducer

It consists of a condenser made up of a dielectric and two armatures, Fig. 1.6, whose capacity is given by:

$$C = K\epsilon\frac{A}{d} \tag{1.4}$$

where ϵ is the dielectric constant of the material between the armatures, d and A are the distance and the overlapping surface of the plates, and K is a constant. This transducer can be used to evaluate the variation in distance between the plates from the measurement of the capacity variation, which can be detected with a bridge circuit. If the distance between the plates is fixed,

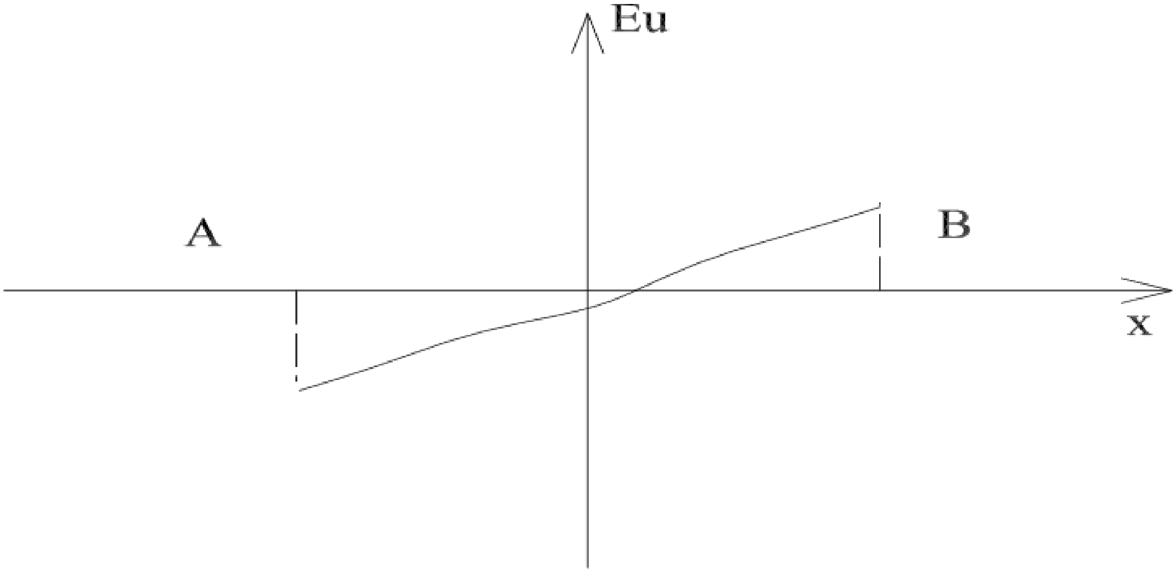

Figure 1.5: Typical calibration characteristic curve of a differential transformer

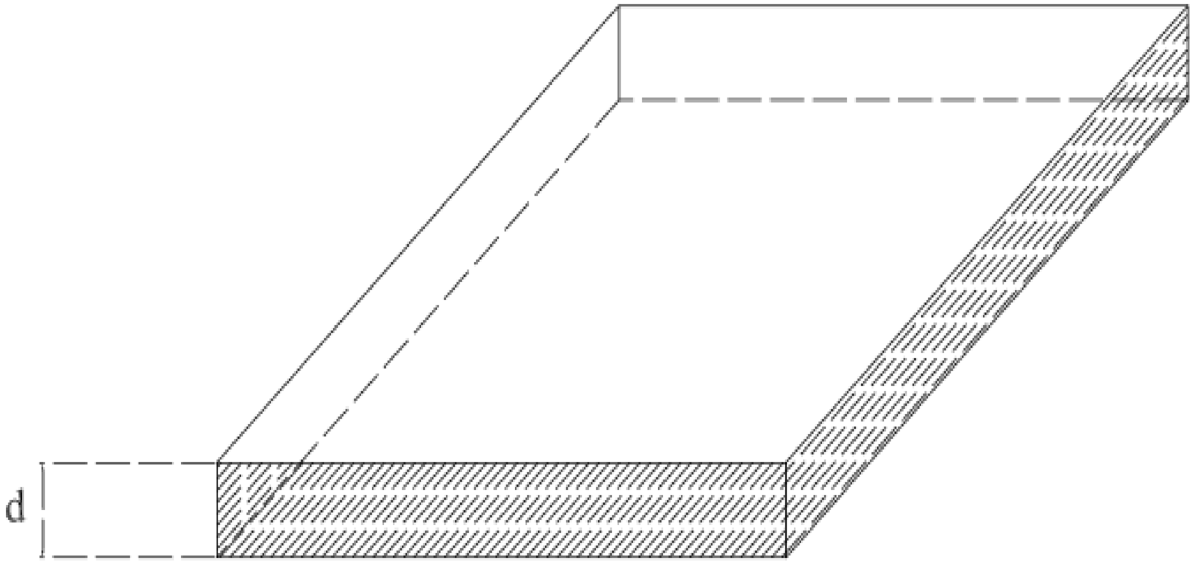

Figure 1.6: Capacitive transducer.

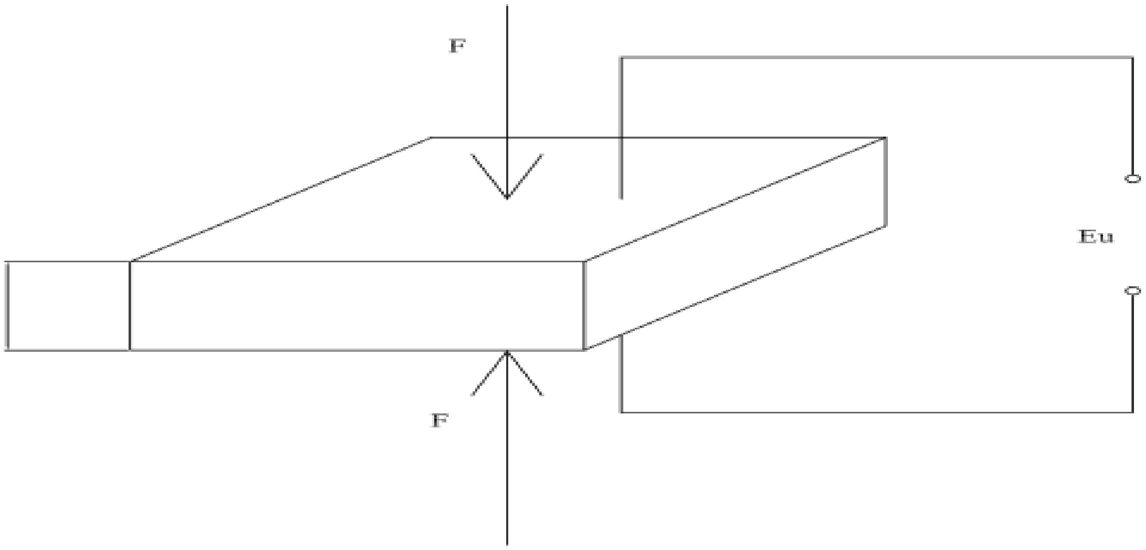

Figure 1.7: Scheme of a piezoelectric transducer.

the overlapping surface variation, i.e. the relative displacement of the capacitor armatures, can be evaluated. The trasducer impedance is very high:

$$Z = \frac{1}{2\pi f C} \tag{1.5}$$

and this characteristic can be useful in the measurement process.

1.1.4 Piezoelectric transducer

Let us now consider a piezoelectric crystal placed between two conductive plates, Fig. 1.7. If a force F is applied to the crystal, a state of stress and therefore deformation of the crystal ensues. In the case of piezoelectric crystals, this deformation produces an output voltage, E_u. The charge q induced in the crystal is proportional to the force applied F according to the relation:

$$q = K_p F \tag{1.6}$$

where K_p is the piezoelectric constant. The output voltage is:

$$E_u = S_v p t \tag{1.7}$$

where S_v is the sensitivity in tension, p is the pressure applied to the crystal and t is the crystal thickness. The output depends not only on the chosen crystal, but also on the orientation with respect to the crystal axes. Piezoelectric crystals are also sensitive to shear forces, but the relationships linkng the output to the applied shear forces are more complex. Piezoelectric crystals are widely used in pressure transducers and dynamic measurements. For a quartz with a thickness $t = 1\ mm$ and a sensitivity in tension $S_v = 0.055\ V/m/Pa$, subjected to a pressure $p = 1\ MPa$, the output voltage is:

$$E_u = S_v p t = 0.055 \times 10^6 \times 10^{-3} = 55\ V \tag{1.8}$$

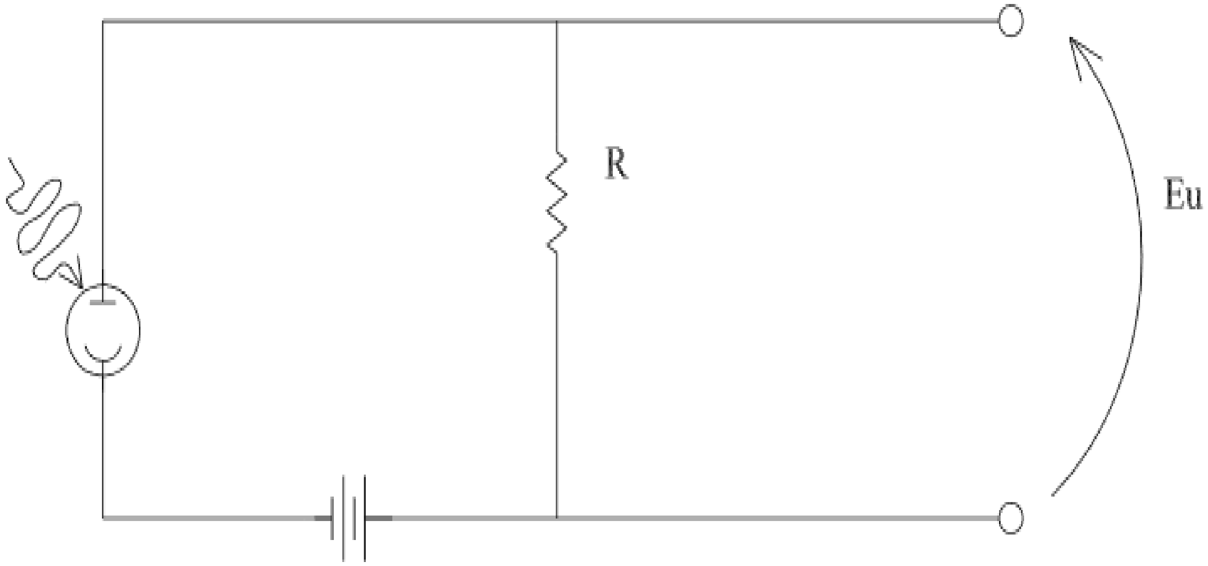

Figure 1.8: Scheme of a photoelectric transducer.

1.1.5 Photoelectric transducers

They translate a light beam into an electrical signal. As shown in Fig. 1.8, the light beam hits the cathode that emits electrons. The photoelectric sensitivity is defined by the relation:

$$I_f = S_f \phi \tag{1.9}$$

where I_f is the current obtained by photoelectric effect, S_f is the sensitivity and ϕ is the intensity of the light beam that reaches the cathode. The sensitivity characteristics depend on the sensor, in particular on the cathode material: different photoemissive characteristics are obtained in a wavelength range between 0.2 e 0.8 μ.

1.1.6 Hall effect transducer

A t-thick conductor or semiconductor element is connected so that a current i flows through it, Fig. 1.9. In the presence of a magnetic field B, which acts in the normal direction at the plate surface, there is an output voltage given by the relation:

$$E_u = K_H i \frac{B}{t} \tag{1.10}$$

where i is the current, in $Ampere(A)$, B is the magnetic field, in $Gauss(G)$, t is the thickness, in cm, and K_H is the Hall coefficient, in $V\ cm/A\ G$.

1.1.7 Photovoltaic transducer

It consists of a semiconductor element connected as indicated in Fig. 1.10. When the light beam strikes the photovoltaic element there is an output voltage, E_u, whose value depends on the load

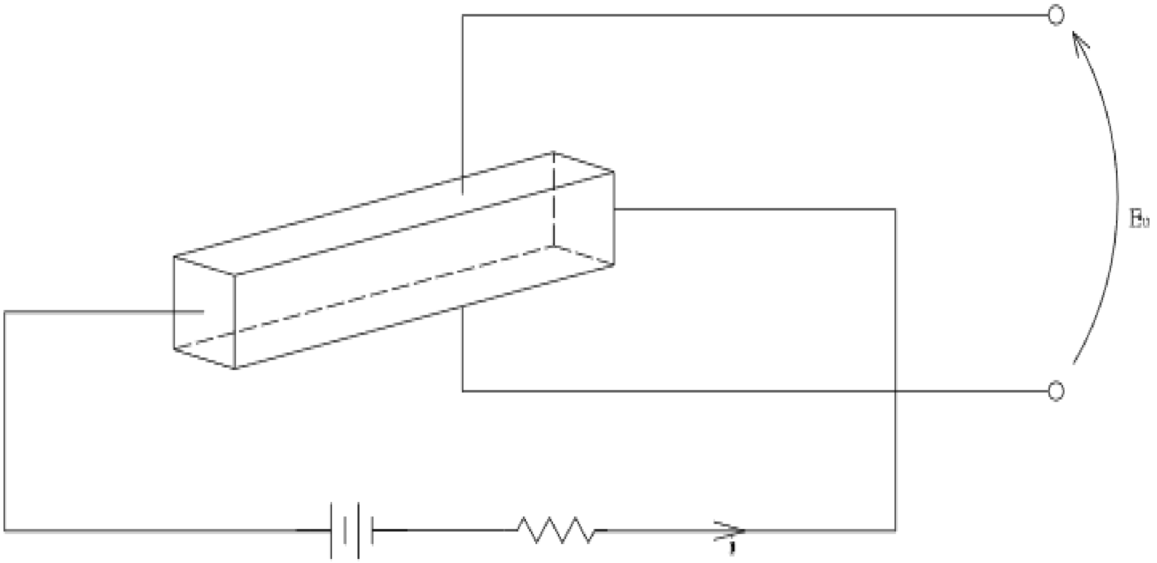

Figure 1.9: Hall effect transducer.

resistance, R. The open-circuit voltage is logarithmic with respect to the light intensity, which can be an advantage for some applications such as photography. However, different behaviors can be obtained by varying the resistance values R.

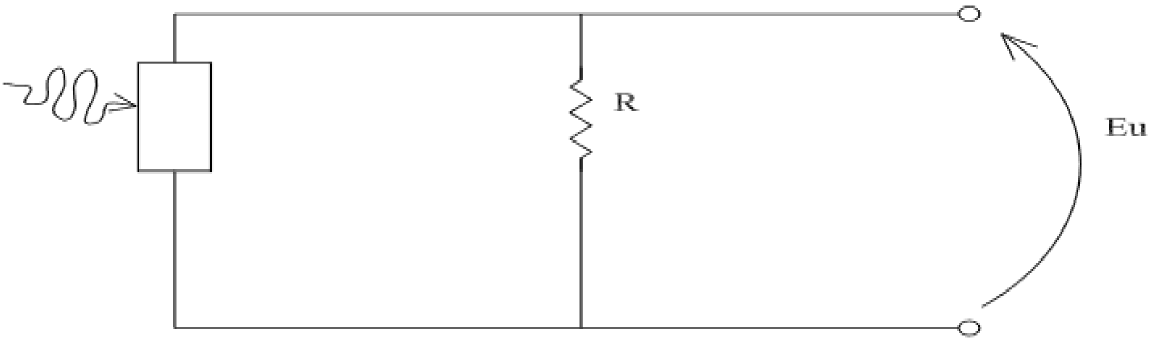

Figure 1.10: Photovoltaic transducer