CHAPTER 34

Transducers and Sensors

The terms transducers, detector, and sensors are debatably interchanged depending on the country, company, and technological application area.

A transducer, by its very name, is an electronic device that measures a physical quantity, therein converting energy from one form to another. But in power electronics the overall transformation can be from an electrical current to electrical current as with a Hall effect based current transformer. That is, to classify a transducer as converting from one energy form to another is misleading, given the dc current transformer converts current to flux, then flux back to current. The transducers to be considered have in common that the output is an electrical quantity, suitable for control and monitoring purposes. While the energy source type to be transformed include electrical, mechanical, electromagnetic (including light), chemical, acoustic or thermal energy.

A terminology distinction is to use *sensor* for the actual sensing element and *transducer* for the sensing element plus any associated circuitry. All transducers would thus contain a sensor and most sensors would also be transducers.

Electromechanical output devices are generically called *actuators*.

It is important to know what the various applicable transducers do, what kind of signal they provide, and how to make them compatible.

The terms sensor, detector, and transducer are not differentiated in this chapter.

Broadly the transducers are classified into two main types: active transducers and passive transducers.

An *active transducer* is a device, which does not require external electrical power (a battery) to converter and generate an electrical circuit compatible output. It is a self generating transducer.

For example

- Solar cell:- when it is exposed to a light source, it converts light energy into a proportional dc voltage.
- Piezo-electric crystal:- when it is subjected to changing pressure it produces a proportional ac voltage.

A *passive transducer* is a device which requires external electrical power like battery to create an electrical circuit compatible output. It cannot generate its own voltage or current. It only changes its resistance or capacitance, etc. during conversion.

For example

- Light Dependent Resistor:- when exposed to light, its resistance decreases many orders (from less than 10Ω) proportionally and when it is dark its resistance is high (several MΩ).
- Thermistor:- when thermistor is exposed to heat its resistance decreases and when it is cooled its resistance increases.

34.1 General sensor/transducer properties

Transducers include image, current, magnetic, proximity, vibration, temperature, light, accelerometers, Hall Effect sensors, piezoelectric, level sensors, pressure sensors, barometers, thermistors, microphones, and speakers.

Table 34.1 Physical and chemical transduction principles

Input \ Output	*Mechanical*	*Thermal*	*Electrical*	*Magnetic*	*Radiant*	*Chemical*
Mechanical	Mechanical including acoustic effects. eg: diaphragm.	Friction effects, cooling effects. eg: thermal flowmeter.	Piezoelectricity, piezoresistivity, resistive, inductive, and capacitive changes.	Piezomagnetic effects.	Photoelasticity, interferometry, Doppler effect.	—
Thermal	Thermal expansion. eg: expansion thermometry.	—	Seebeck effect, pyroelectricity, thermoresistance. eg: Johnson noise.	—	Thermo-optical effects. eg: liquid crystals, thermo-radiant emission.	Thermal dissociation, thermally induced reaction.
Electrical	Electrokinetic effects. eg: inverse piezoelectricity.	Peltier effect, Joule heating.	Charge controlled devices, Langmuir probe.	Biot-Savart's electromagnetic law.	Electroluminescence, Kerr effect.	Electrolysis, electrically induced reaction. eg: electromigration.
Magnetic	Magnetostriction, magnetometers.	Magnetothermal effects (Righi-Leduc effect).	Ettinghaussen-Nernst effect, Galvanomagnetic effect. eg: Hall effect, magnetoresistance.	—	Magneto-optical effects. eg: Faraday effect, Cotton-Mouton effect.	—
Radiant	Radiation pressure.	Bolometer, thermopile.	Photoelectric effects. eg: photovoltaic cell, LDR's.	—	Photorefractivity, photon induced light emission.	Photodissociation, photosynthesis.
Chemical	Photoacoustic effect, hygrometry.	Thermal conductivity cell, calorimetry.	Conductimetry, potentiometry, voltametry, flame-ionization, chem FET.	Nuclear magnetic resonance.	Spectroscopy. eg: emission and absorption types, Chemiluminescence.	—

Transducers can be classified according to the operating principle and stimulus energy form namely

- Mechanical:- for example, strain gauge, LVDT, etc.
- Thermal:- for example, thermistor, thermocouple, etc.
- Magnetic:- for example, search coil, Rogowski Coil, etc.
- Radiation (electromagnetic) transducers:- for example, solar cell, photo diode, Hall effect.
- Photoelectric induction - frequency and pressure measurement,
- Electromechanical:- for example, strain gauge, load cell, etc.

- Electrochemical:- for example, fuel cell, etc.
- Electroacoustic:- for example, microphone, load speaker, piezoelectric crystal, etc.
- Thermoelectric:- for example, thermocouple, Peltier cooler, etc.
- Ultrasonic:- detector/sensor for vehicle parking

General sensor properties are

- Range:- predictable region of predictable performance and reliability
- Zero drift:- associated with changes in temperature, aging, and conditioning circuitry
- Sensitivity:- change in output for a per unit change in the parameter being measured.
- Resolution:- the smallest detectable change of input parameter
- Response:- time taken by a sensor to approach its true output
- Linearity:- output that is directly proportional to input over its entire range
- Hysteresis:- inability to faithfully reproduce data in both directions of operation
- Calibration:- accurate output measurement based on knowledge of the input
- Span:- dynamic range of measureable input parameter
- Full scale output:- algebraic difference between the electrical output signals measured with maximum input stimulus and the lowest input stimulus applied.
- Accuracy:- actually inaccuracy - ratio of the highest deviation of a value represented by the sensor to the ideal value.
- Threshold:- input variation limit that does not cause the sensor output to change
- Cross-Talk:- the gain of the sensor with respect to an unintended stimulus

Table 34.2: Transducers and sensors

Quantity being Measured	Input Device (Sensor)	Output Device (Actuator)
Light Level	Light Dependant Resistor (LDR) Photodiode Photo-transistor Solar Cell	Lights & Lamps LED's & Displays Fibre Optics
Temperature	Thermocouple Thermistor Thermostat Resistive temperature detectors (RTD)	Heater Fan
Force/Pressure	Strain Gauge Pressure Switch Load Cells	Lifts & Jacks Electromagnet Vibration
Position	Potentiometer Encoders Reflective/Slotted Opto-switch LVDT	Motor Solenoid Panel Meters
Speed	Tacho-generator Reflective/Slotted Opto-coupler Doppler Effect Sensors	AC and DC Motors Stepper Motor Brake
Sound	Carbon Microphone Piezo-electric Crystal	Bell Buzzer Loudspeaker

The generic stimulus are: acoustic, electrical, magnetic, optical, thermal, chemical, and mechanical. There are innumerable applications for transducers in power electronics and everyday life, in cars, machines, aerospace, medicine, manufacturing and robotics.

34.2 Current measurement

34.2.1 Current measurement: closed loop ferrite transformer

Figure 34.1 shows a ferrite current measurement transformer where a compensation winding maintains the air gap flux at zero, enabling dc (as well as ac) currents to be measured. (Transducers without the feedback compensation winding are termed open loop.) Measurement bandwidth is typically dc to 200kHz. The current to be measured, primary current I_p, produces an mmf in the ferrite toroidal core. A Hall effect transducer, with a Hall constant K, detects the flux in the core air gap and an op amp compensation circuit drives current through the high turns winding in an attempt to zero the core flux. The current in the compensation winding is therefore proportional to the current being measured, according to

$$N_p I_p = N_s I_s \qquad (34.1)$$

A Hall effect generator temperature dependence, offset voltage V_{OT}, can be compensated electronically. The same transducer can be used to measure voltage by adding an external series resistor in the primary, which produces a current that is measured, which is proportional to the voltage. The number of primary turns is usually large so as to minimize the resistor current. The resistance, in conjunction with the primary self inductance (and leakage), limit the measurement bandwidth, to the time constant L/R.

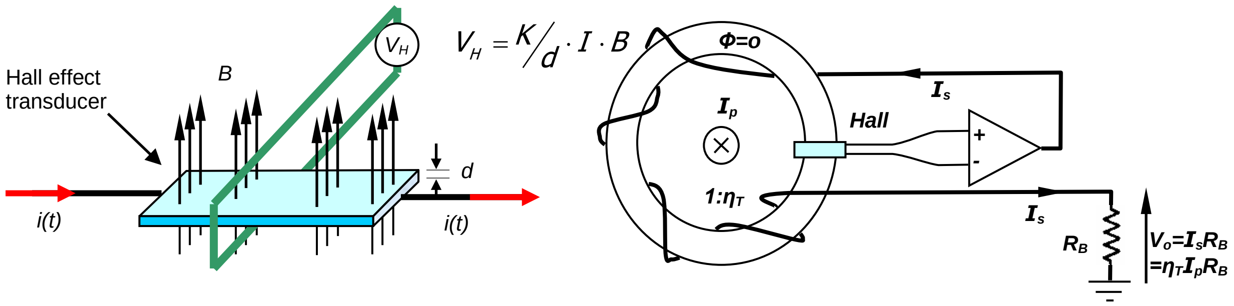


Figure 34.1.*Current measurement transducer using a flux compensated toroidal ferrite core.*

34.2.2 Current measurement: Rogowski Coil

Rogowski coils, shown in figure 34.2, are used for passive detection and versatile non-invasive measurement of alternating current (ac) or high speed current pulses (non-dc). It is typically wound on an air-core so in theory there are no hysteresis, saturation, or non-linearity effects.
The main part is the measuring head which is basically a coil uniformly wound around a flexible cylinder of insulating material. At one end, the winding is connected to a conductor located in the centre of the cylinder of insulated material. At the other end, the winding and centre conductor provide the signal output. This construction makes both electrical connections available at a single point.

The operating principle is that if a closely uniformly wound air-cored toroidal coil of N turns/m is placed axially around a straight conductor carrying current i in a closed path, the alternating magnetic field produced by the current in the conductor induces a coil output voltage E that is proportional to the rate of change of the cross section area A sq m which encircles any flux linked component produced by the current i, given by the expression:

$$E = -M\frac{di}{dt}$$

where M is the mutual inductance (or sensitivity, Vs/A) between the Rogowski coil and the conductor and di/dt is the rate of change of current in the conductor. If the coil outputs are connected to an integrator, the output signal reproduces the current waveform.
Rather than measuring the short circuit current through the coil directly, the measurement is the integral of the open circuit voltage.

There are two advantages to the Rogowski coil.

One advantage of a Rogowski coil over other types of current transformers is that it can be made open-ended and flexible, allowing it to be wrapped around a live conductor without disturbing the conductor.

A second advantage is that the Rogowski coil does not use a magnetically permeable core like a standard current transformer, making it of low inductance. The insertion impedance can be less than 1nH. Since it has no permeable core to saturate, it can respond linearly to extremely large currents. Being of low inductance it can also respond to very fast frequency pulses. A standard current transformer can have its core saturated at very high currents, and the inductance limits its frequency response. The closer in form to a perfectly symmetric toroidal uniform coil of wire, with equally spaced windings, the Rogowski coil is less susceptible to external electromagnetic interference.

Rogowski coil operating principle

A Rogowski coil works by sensing the magnetic field in the space around the conductor that carries the current. The relationship is given by the Ampere's Law. Accordingly, the line integral of the magnetic field around a closed loop is equal to the net current encircled by it, no matter what path the loop takes.

$$\oint H\cos\alpha \, d\ell = i(t) \qquad (34.2)$$

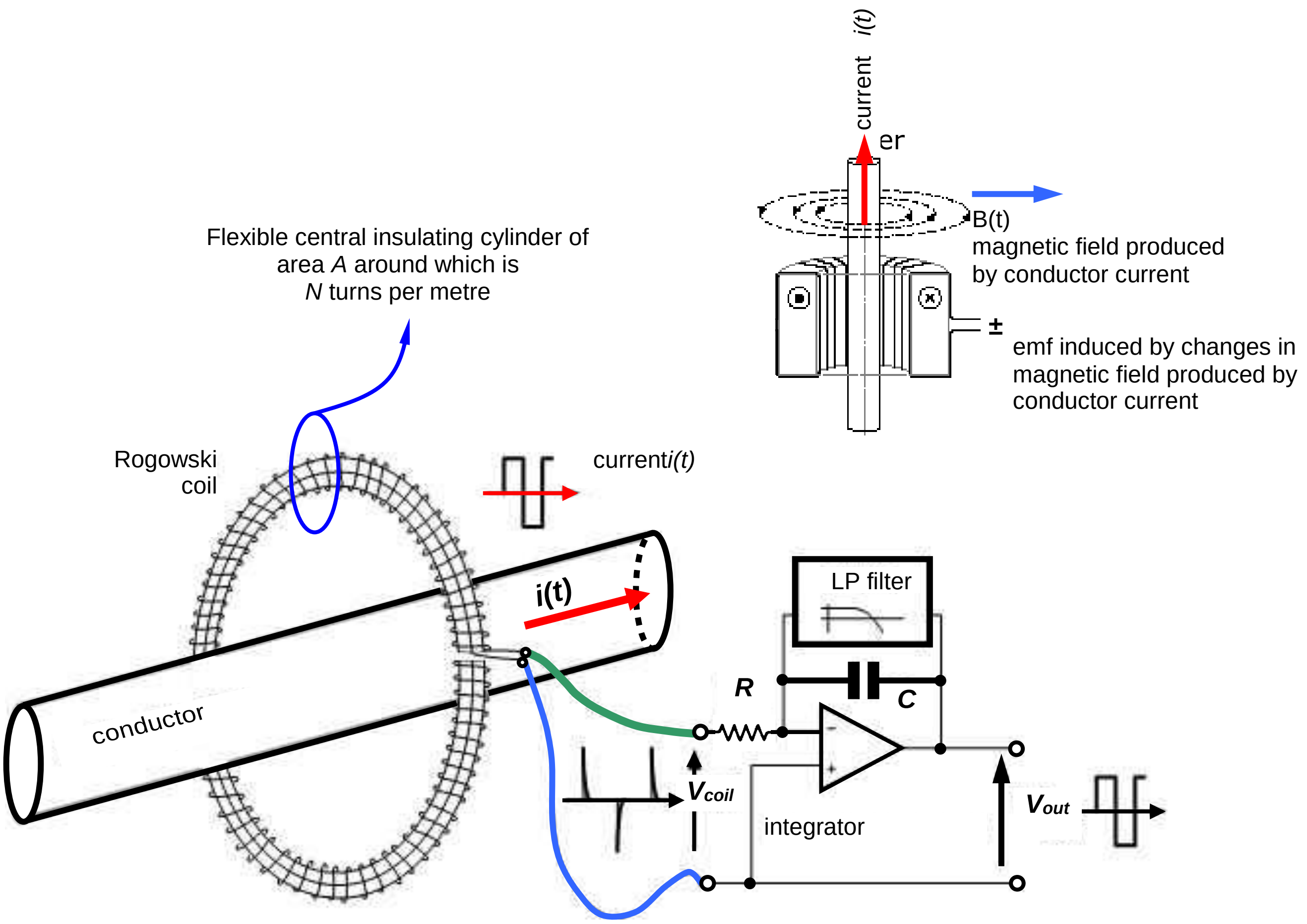


Figure 34.2. *Rogowski coil and active integrator basic operation*.

The mathematical expression that shows this effect where *dℓ* is a small element of length along the loop, *H* is the magnetic field in *dℓ* and is the angle between the direction of the field and the direction of the element.

The magnetic field due to a long straight conductor carrying current *i*, in air, is

$$B = \mu_o H = \frac{\mu_o i}{2\pi R}$$

where $\mu_o=4\pi\times10^{-7}$ and *R* is the perpendicular radial distance from the conductor to the point at which the magnetic field is calculated (the major radius of the toroid). The direction of the magnetic field being tangentially perpendicular to the current and to the radius *r*, and determined by use of the right hand rule.

Each turn of the Rogowski coil *N* turns produces a voltage proportional to the rate of change of the magnetic flux *B* through the turn. Assuming a uniform magnetic field density throughout the turn of area *A*, by Faraday's equation, the rate of change magnetic flux is equal to the rate of change of magnetic field density times the cross-sectional area of the turn $\pi\times r^2$ (toroid cross section radius, *r*).

$$V_{turn} = -\frac{d\Phi}{dt} = -A\frac{dB}{dt}$$

The output voltage from the coil with *N* turns, effectively series connected, is

$$V_{coil}(t) = -NA\frac{dB(t)}{dt}$$

Substitution of *B* gives

$$V_{coil} = -NA\frac{dB}{dt} = -\frac{\mu_o NA}{2\pi R}\frac{di}{dt} = -\frac{\mu_o NA}{S}\frac{di}{dt} = -M\frac{di}{dt} \qquad (34.3)$$

where *S* is the mean circumference of the toroid and *M* is the mutual inductance (sensitivity) between the coil and the conductor and is independent of the frequency.

The self-inductance *L* of a coil uniformly wound with a toroidal shape toroid, which affects the output voltage frequency response, is

$$L = \mu_o N^2 \left[R - \sqrt{R^2 - r^2} \right] \quad (34.4)$$

If a rectangular cross section ring is used then the emf produced is given by

$$V_{coil} = -\frac{\mu_o NH}{2\pi} \ell n \frac{c}{b} \frac{di}{dt}$$

where *H* is the rectangular core height and *b* and *c* are the inner and outer diameter of the coil.

In order to get a voltage proportional to current an integrator - either active or passive - must be used. An active integrator, as shown in figure 34.2, using an operational amplifier is a common solution. The op-amp needs to have sufficient frequency response (both upper and lower cut off half-power points) and current sourcing and sinking capability to drive the capacitor at the expected frequency.

The integrator needs a resistor placed across the capacitor in order to be made into a leaky integrator. The resistance placed across the capacitor should be just small enough to leak off the capacitor and keep it zeroed but not so small that it interferes with the integration performance in the frequencies of interest.

Ignoring any leaky resistance added to the integrator of figure 34.2 the output is

$$V_{out} = -\frac{1}{RC} \int V_{coil} dt$$

After integrating the signal of equation (34.3), the total output voltage is

$$V_{out} = \frac{1}{RC} \int M \frac{di}{dt} dt = \frac{M}{\tau} i$$

The transducer/amplifier sensitivity, or transfer function, is:

$$\frac{V_{out}}{i} = \frac{M}{\tau}$$

where V_{out} is the output voltage of the integrator, $\tau=RC$ is its time constant, and *i* is the conductor current. Changing τ, the operation range can be modified and it is possible to operate from mA to MA.

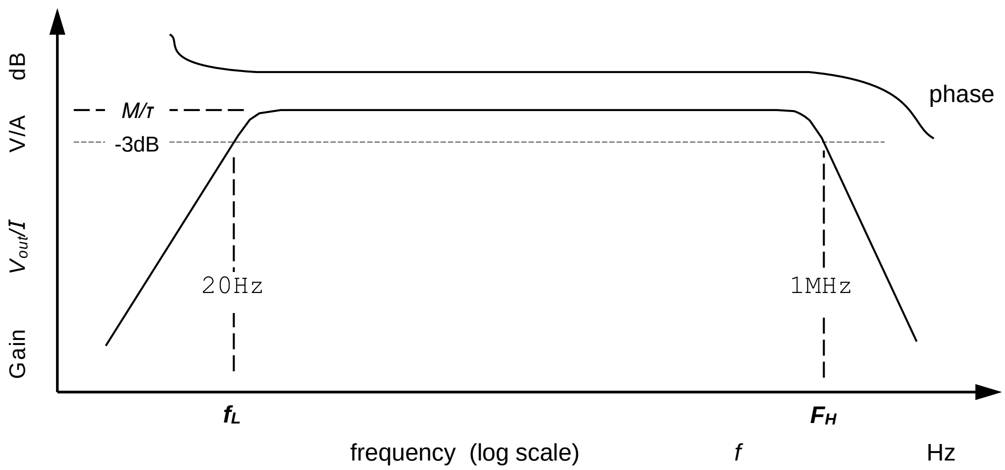


Figure 34.3. *Frequency response of a Rogowski coil and integrator*.

It is important to take into account linearity and bandwidth of the integrator, and design it according to the type of current to be measured. For high frequencies it is appropriate to use a passive integrator composed only of *R* and *C*, such that the mid-band gain is *M/CR* (V/A)

The relationship V_{out} proportional to *i* is constant across the transducer bandwidth. The bandwidth is defined as the range of frequencies from f_L to f_H for which sinusoidal currents can be measured to within 3dB of the specified sensitivity *M/CR*, as shown in figure 34.3.

At low frequencies, the integrator gain increases and theoretically becomes infinite as the frequency approaches zero. This would result in unacceptable dc drift and low frequency noise; hence the integrator gain is limited at low frequencies. This limitation is controlled by a low pass filter in parallel with the integrating capacitor *C*. The low pass filter sets the low frequency bandwidth f_L, typically less than 1Hz.

Furthermore, due to the distributed inductance, equation (34.4), and inter-turn capacitance of the Rogowski coil, there is a high frequency bandwidth f_H, (generally >1MHz) above which the measurement is attenuated and significant phase delay occurs.

Construction

There are a number of Rogowski coil current transformer types.

1 - Flexible Rogowski coil
The insulated winding is placed over a long and flexible plastic former typically between 3.5 and 15mm in diameter. The coil is fitted by wrapping it round the conductor to be measured and bringing the ends together. External insulation can be composed of one or several insulation layers (to increase the sensitivity), thermal shrinkable protection, electrostatic screen, which affects the flexibility of the coil. Electrostatic screen can be added to improve insulation of external influences.
Although less sensitive and less accurate than the rigid form, a flexible coil is better for high frequency measurements.
It is useful with large size or awkward shaped conductors or in places with limited access or where a lightweight transducer is needed which can be suspended on the conductor. As an open coil, it is not necessary to disconnect the conductor that carries the current to be measured and the user has only to connect the ends after the coil is placed around the conductor. Its form is compact and versatile.

Typical electrical features are:

Mutual inductance *M*:	between 30 and 300nH.
Maximum frequency:	between 100kHz and 1MHz depending on *M*.
Minimum frequency:	between 1 and 10Hz, depending on the integrator.
Current range:	from 1A to >1MA.
Accuracy:	1%.

2 - Rigid Rogowski coil
The rigid coils are wound on a solid plastic former, normally in a toroidal shape, and tend to be bulkier than flexible coils but have better stability. External insulation can be composed of one or several insulation layers, or varnished or encapsulated and potted. An electrostatic screen can be added to improve insulation to external influences.
The output voltage is stable and the accuracy is good. A rigid coil lower measurement frequency range is lower than with a flexible coil, hence is more applicable for low current and low frequency measurements. Disadvantageously, being a continuous ring, the current-carrying conductor must be disconnected and placed through the core centre hole before the measurement. It can be used for high precision measurements or for permanent installation.

Typical electrical features are:

Mutual inductance *M*:	between 3 and 5μH.
Maximum frequency:	between 10kHz and 30kHz depending on *M*.
Minimum frequency:	down to 0.1Hz, depending on the integrator
Current range:	from 100mA to >100A.
Accuracy:	0.1%

3 - Planar Rogowski coil
The sensor can be manufactured using a planar coil rather than a toroidal coil. In order to reject the influence of conductors outside the sensors measurement region, planar Rogowski current sensors use a concentric coil geometry instead of a toroidal geometry to limit the response to external fields. The main advantage of the planar Rogowski current sensor is that the coil winding precision that is a requirement for accuracy can be achieved using low cost printed circuit board manufacturing.

Features and applications

A Rogowski coil used as current sensor has numerous advantages:

- The air coil has no hysteresis or remanence, it does not saturate, and is linear. The mutual inductance is independent of the current, while its inductance is low, a few nH.
- Non-intrusive and flexible. Not closed loop during attachment. Can be retro-fitted.
- Good response to current transients, so they are appropriate for current pulse measurements or for protection systems. A simple RC output filter suffices for a basic protection scheme.
- High bandwidth. The high-frequency limit is determined by the self-resonance of the coil and depends on the coil design. Although not applicable to DC measurement, with an accurate integrator design, it is possible to measure frequencies lower than 1Hz.
- Can measure ac signals superimposed on large dc currents. Huge over current capability

- The same coil can measure a wide range of currents, from mA to MA, with a typical sensitivity of 1.0mV/A for ± 6000A peak, and a *di/dt* typically from 1 to 25kA/μs, over a coil temperature range from -20Cº to 100ºC.
- Easy calibration. Because of its linearity, coils may be calibrated at any current level.
- It is lightweight, compact and easy to install and to transport. Importantly, it is easy to use.
- Output variation with temperature is low.
- Low power consumption, and can be totally passive. Low cost.
- High frequency bandwidth (3dB) decreases with coil length, for example, 100mm 12MHz, 200mm 8MHz.
- Rogowski Coil cross sectional diameter specifies electrical isolation, for example, 3.5mm for 2kV isolation and 4.5mm for 5kV isolation. The open circuit output voltage is low, viz., safe.

Another useful feature of a Rogowski sensor is immunity to far-field interference. EMF components induced by the same far field source will cancel each other. Two components of EMF induced by the current passing through the wire inside the coil will be added to each other.

One disadvantage is that the Rogowski coil produces an EMF proportional to *di/dt*. Therefore, at connecting or disconnecting instants, the EMF goes 'infinite'. Transient voltage suppressors or other voltage protection is needed to prevent overloading the interfacing electronics. Also, accuracy is slightly dependant on the position of the current carrying conductor in loop.

34.2.3 Flux-gate Transformer

The term *fluxgate* refers to the operational principle of specific isolated current measurement transducers. The magnetic field generated by the current to be measured is detected by sensor. Current transducers based on the Hall-effect, usually called standard fluxgate transducers use a gapped toroidal magnetic circuit with the field measuring element in the gap, plus the toroid has a secondary winding as considered in section 34.2.1. Other fluxgate transducers avoid gapping the core and use magnetic saturation and magnetic balance as part of the measurement mechanism.

The ***flux-gate*** current measurement transducer detects the saturation state of a magnetic circuit. The magnetic core is a high permeability material, which surrounds the magnetic field source to be measured. Usually, magnetic core fluxgate sensors have a high magnetic permeability, very low coercitivity and many turns in a coil on the core to increase sensitivity. Ferrite is the standard core material, because of its good frequency response.

The magnetic material is excited by a square wave signal (typically 200Hz to 600Hz) that bidirectionally and symmetrically saturates the core, in the absence of an external magnetic field. This saturation symmetry is lost in the presence of an external magnetic field produced by the current to be measured.
Current injected in an auxiliary winding creates a compensating magnetic field that restores the symmetry of the hysteresis cycle. The injected compensating current is proportional to the current being measured. Thus inductance changes are use to detect the external field generated by primary current, and therefore the current flowing through the enclosed conductor.
This system is suitable for the measurement of dc and ac currents, with high accuracy, high frequency (in excess of 100kHz), and a high current range.

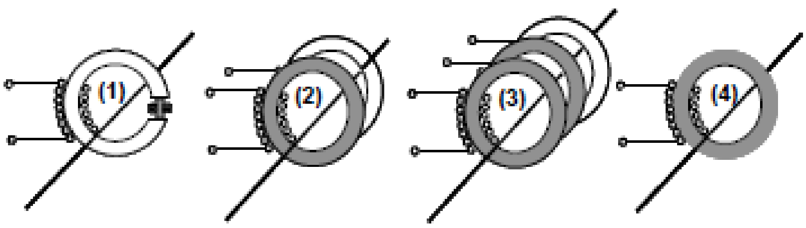


Figure 34.4. *Main types of fluxgate transducers*.

Main types of fluxgate transducers

The main types of fluxgate transducers are shown in Figure 34.4, namely:
i. *Standard* fluxgate, as with the Hall effect current measurement transducer in section 34.2.1.
ii. *Two magnetic cores* fluxgate, where performance is improved by: (a) making the field sensing head one (shaded) of the two magnetic cores, and (b) ensuring high frequency performance by using a separate core for the transformer effect, both without an airgap.
iii. *Three magnetic cores* fluxgate, where the performance is further improved by (a) duplicating the field sensing head, using two magnetic cores (dark color) with an excitation coil wound around each of

them; and (b) improving the way the high frequency current transformer is made and processed electronically.

iv. *Low frequency* fluxgate, using only the low frequency part of the *two magnetic cores* fluxgate transducer, not including the current transformer.

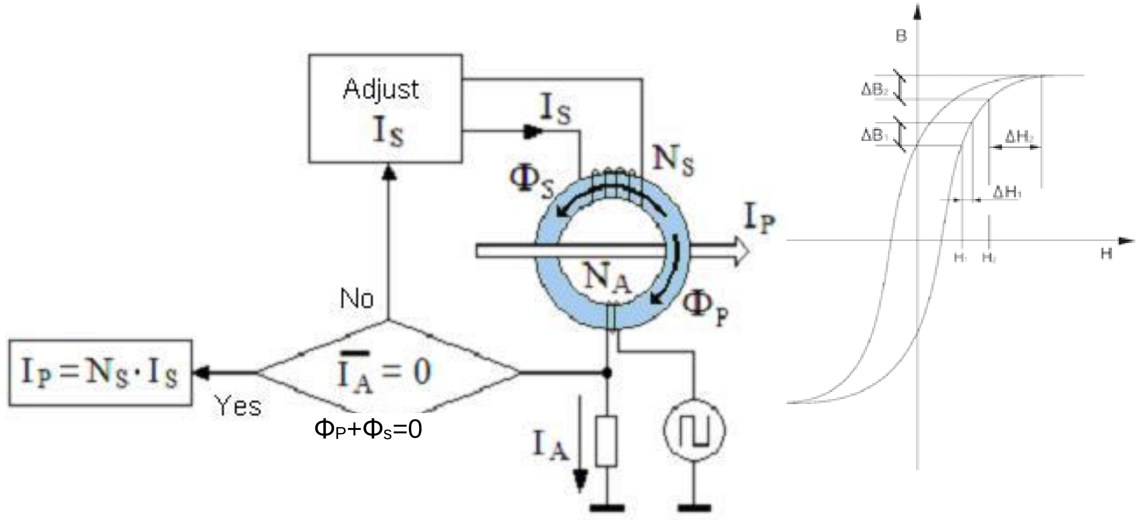


Figure 34.5. *Structure and principal of a Flux-gate transducer without an air gap in the magnetic path.*

Operating Principle

The gapless transducer uses its toroidal core as field detector, without an gap in the magnetic path. An auxiliary winding is added to the core forming a core-wounded set, which is used as a saturable inductor detector.

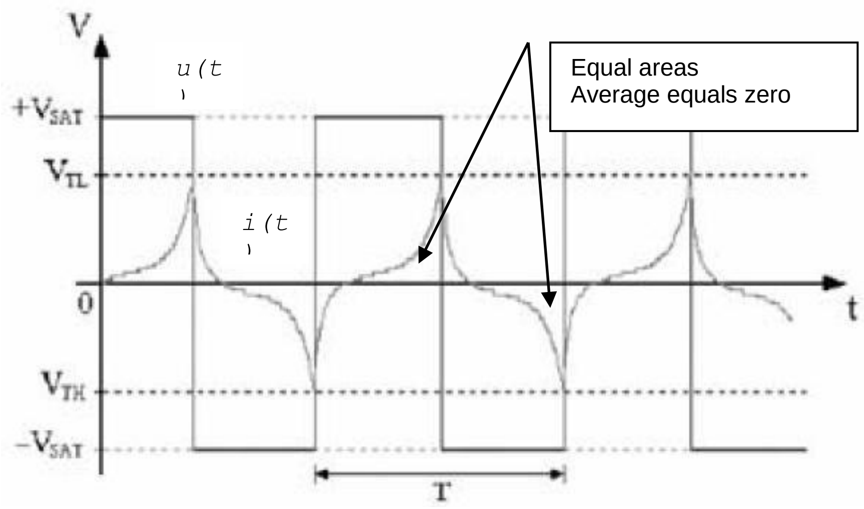


Figure 34.6. *Voltage waveforms of excitation and current by the auxiliary winding under zero flux (current) conditions.*

In order to detect a null field in the magnetic circuit, the secondary winding is excited with a compensating current. Hence the transducer operates with a zero field condition, as shown in Fig. 34.5. This null condition means the current I_S in the secondary winding is directly proportional to the primary current to be measured, I_P. The relationship between the primary and secondary current is equation (34.1), where N_S the number of the secondary winding turns.

$$I_p = N_s I_s \qquad (34.1)$$

The detection of the zero flux condition in the magnetic path of the transducer is based on the change of the inductance of the saturable inductor formed by the ferromagnetic core and the auxiliary winding. In absence of current to be measured I_P, the net flux through the saturable inductor core is zero. Under these conditions, with a squared voltage waveform *u(t)* applied to the auxiliary winding N_A, the magnetising current *i(t)* waveform in auxiliary winding, bidirectionally saturating the core in a zero average flux condition, is as shown Fig. 34.6.

The effect of the current to be measured I_P on the auxiliary winding current I_A, when a low frequency square voltage waveform is applied, leads to a non-zero average current, as shows Fig. 34.7. The average value and its sign depend on the value and direction of the current I_P.

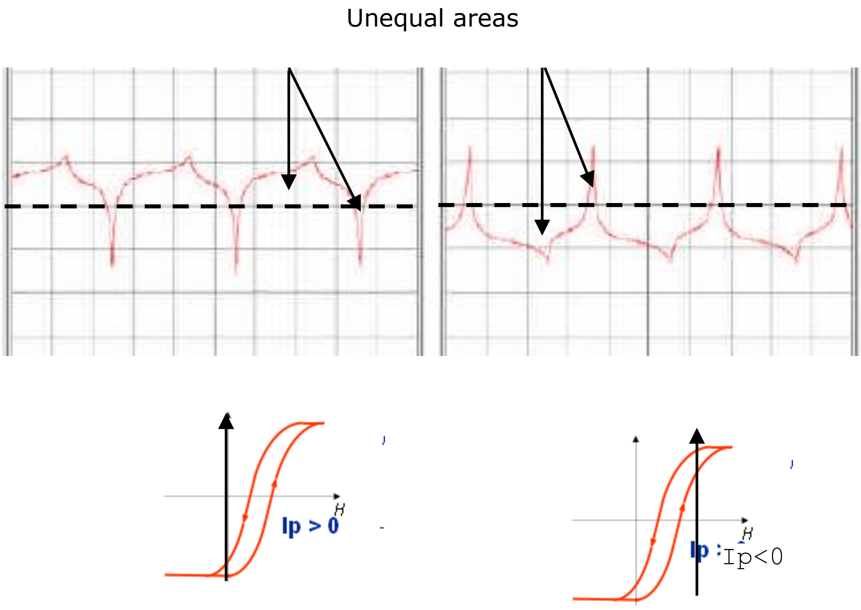


Figure 34.7. *Effect of square wave voltage source excitation current with external field produced by a primary current.*

The difference between the waveforms shown corresponds to the current direction applied. Then a magnetic field is generated to cancel this effect, to produce a zero flux condition. Knowing the current applied to cancel this effect by returning the system to the zero flux condition, allows accurate calculation of the current passing through the primary conductor.

A disadvantage of this structure is noise injection on the primary current I_P measure. This noise is induced from the auxiliary current I_A, because of coupling through the magnetic core of the transducer. The solution is to use of second core with its own auxiliary winding, for compensation. These two cores with their auxiliary windings must be identical. Now the secondary winding N_S in which the compensation current of flux in the transducer is applied is common to both auxiliary cores. If the second auxiliary core N_{A2} is excited with an equal current but in reverse direction to the current used for exciting the first auxiliary core N_{A1}, the currents induced on the primary current conductor (I_P) will be equal and opposite, cancelling the coupled effects.

Better performance, at increased cost, is obtained with a common compensation winding placed around both cores. Identical ampere-turns cancellation is ensured to cancel the external field.

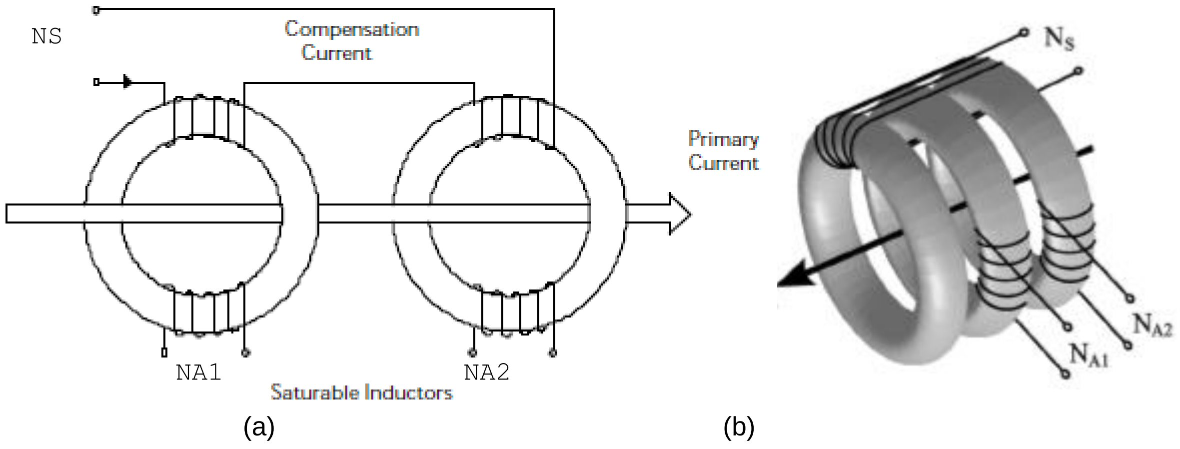


Figure 34.8. *Two saturable inductors and compensating windings: (a) two separate windings and (b) a common winding.*

As the winding N_{A1} of the flux detector is coupled with the compensation winding N_S, the applied square wave voltage is re-injected into the compensation winding and creates a parasitic current in the measurement resistor. However, the square wave voltage induced in the N_S winding by this flux is practically cancelled when a second N_{A2} winding is mounted on a second detector core (identical to N_{A1}) within the compensation winding N_S. The residual flux (the sum of the opposed fluxes in N_{A1} and N_{A2}) create small voltage peaks that cause the remaining signal to correlate with the fluxgate excitation.
In each N_S winding arrangement case, the system is completed with an electronic circuit to impose the zero flux condition monitoring the compensation current.

A fourth winding parallel to N_S is wound under the compensation winding N_S on the main core to extend the frequency range of the transformer effect to lower frequencies. It is connected to a circuit that adds voltage via the power amplifier to compensate the small induced voltage in the frequency range too high for the fluxgate detector.

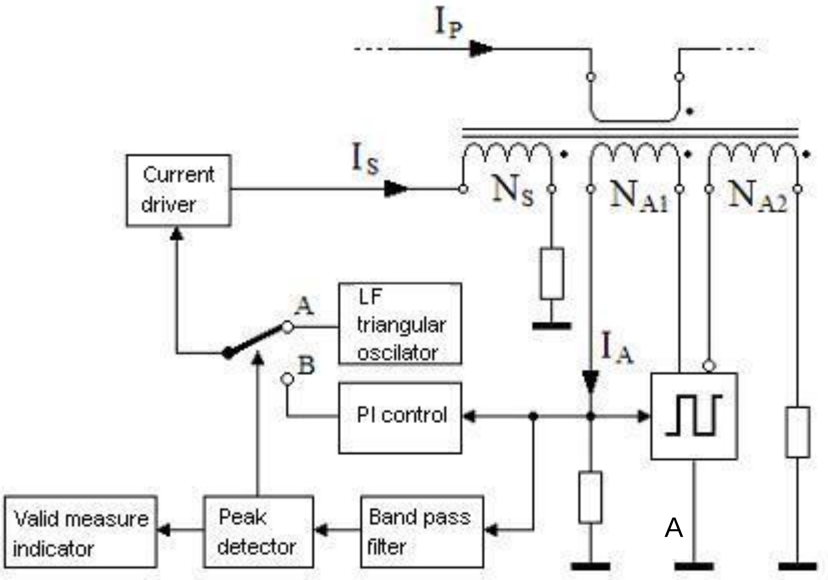


Figure 34.9. *Block diagram of the flux-gate transducer circuit.*

The block diagram of the flux-gate transducer measurement system is shown in Fig. 34.9.

PWM is used for zero flux condition control, where feedback forces the currents associated with the saturable cores to a net average value of zero.

i. Signal generator for excitation of the auxiliary windings, N_A
The generator is based on a comparator circuit with hysteresis (or Schmitt trigger). The circuit changes the output voltage when the circulating excitation current I_A in the main winding exceeds a threshold. The magnetic components form part of the oscillator circuit, and their electrical characteristics influence the frequency of the squared signal generator circuit, which is around 300Hz.

ii. Symmetry detector of the auxiliary current I_A
In the absence of primary current I_P the average value of the current of excitation I_A is zero. The effect produced by primary current is the appearance of an average value different from zero and sign dependent of the sense of this current. A PI controller is to automatic adjustment the value of the secondary current winding I_S, to ensure that the primary current excitation winding has zero mean value. This controller cannot guarantee the proper measurement system functionality at start-up if primary current I_P pre-exists, because under these conditions the two inductors will be saturated. A primary current through the measurement system in non zero flux conditions, produce a high frequency current (tens of kHz) in the main excitation winding I_A and a non zero average value, with independent sign of the primary current circulating sense I_P. To alleviate this drawback, an additional controller ensures that the zero flux condition is reached regardless the initial pre-existing primary current I_P. The operation of this controller is based on the property where the frequency of the current in the main excitation winding I_A is high frequency when the system is not balanced and low frequency when the system is operating in the vicinity of the point of zero flux. As shown in figure 34.9, this controller includes a triangular low-frequency oscillator, a frequency detector for the excitation current I_A and an analogue switch controlled by the frequency detector.

In a non-zero flux initial condition, the input of the current compensation driver I_S is connected to the triangular low-frequency signal generator. This winding compensation current I_S ensures the necessary zero flux condition occurs. When detected, the frequency of the current of the main excitation winding I_A decreases; then the PI controller is connected to the input of the current compensation driver.

iii. Valid measure indicator

The output of the low-frequency detector circuit is connected to a valid measurement indicator. This indicator is activated having detected a low frequency primary winding excitation current, that is when the system operates in zero flux conditions. A LED and relay are the output elements to indicate the zero flux valid measurement condition.

iv. Driver to generate the compensation current

This D class amplifier circuit is used to generate the current that flows through the secondary winding compensation N_S. Although the amplifier is highly efficiency compared to a linear amplifier, it adds harmonics at the same switching frequency and higher. It is based on a pulse width modulator (PWM), which generates a squared voltage waveform with a duty cycle proportional to the PI controller output signal.

The modulator output PWM square waveform is applied to the compensation winding N_S through a current driver implemented with a half or full bridge inverter.

The self inductance of N_S filters the current. The system output voltage is measured across a shunt resistance connected in series with this winding, and is proportional to the primary current being measured.

v. Measure of high frequency currents

The basic flux-gate principle is only suitable for the measurement of dc or low frequencies ac currents. The maximum frequency for the ac measurement is fixed by the operating frequency of the zero flux detection system. For the measure of high frequency ac currents and to obtain a suitable dynamic behaviour in case of fast transient currents, a third core is included. This third core is coupled only by the compensation winding N_S and it operates as a conventional current transformer, as shown in figure 34.8(b).

vi. Power supply

Two stable output voltages, ±12V, are derived from a flyback converter with a dc input voltage between 10V and 30V.

Typical main characteristics of the system are:

- maximum peak current: 1000A
- primary rated current, I_N: 700A
- small signal bandwidth, 5% of I_N: dc to 100kHz
- conversion ratio: 1:1000
- supply voltage: 10 to 30Vdc
- *di/dt*: > 100A/μs
- offset current: < 5μA
- linear error: < 5 ppm
- burden resistor > 20Ω, ½W

Main advantages are:

- High Accuracy over high bandwidth
- Very low output noise and offset drift (high frequency PWM ripple in output and references)
- Negligible insertion losses
- High immunity to interference
- Overload capability
- Excellent linearity

Applications include:

- Precise and high stability inverters
- Energy measurements
- High precision power supplies
- Feed back element in high performance gradient amplifiers for MRI
- Medical equipment

http://www.grupopremo.com/in/new/93/

34.2.4 Resistive Sensor

The resistive shunt, although a simple concept, *v=iR*, can be a complicated device due to three features, at any current, viz.,

i. shunt power losses, necessitating possible transducer cooling,
ii. internal shunt inductance which distorts voltage with increasing frequency transients, and
iii. galvanic isolation between the high voltage circuit and the control circuit, especially at high nominal and pulse voltages.

In the low current range film technology SMD-resistor shunts (2 and 4 terminal - Kelvin) are used, which provide good heat sinking and low inductivity. Typical characteristics are 0.3mΩ to 1Ω, ±1% tolerance, 0.1to 5W dissipation. The next higher power class uses thick film technology in a TO-220 housing for through-hole mounting; these resistors have good thermal characteristics because of the external heatsink and offer low inductivity.

For high accuracy measurement of high frequencies coaxial shunts are used, where influence of the internal inductivity is compensated what allows to measure current in the range up to several MHz. Coaxial shunts can register peak current in excess of 100kA in the 200MHz frequency range. Resistance ranges from 1mΩ to 0.1Ω, typically, and has a positive temperature coefficient, typically 10-12ppm/°C. The concentric manganin and copper cylinder structure, is ideal for forced air cooling and water cooling. As resistance decreases, bandwidth decreases and rise time increases, viz., 25µΩ [250kHz, 2µs, 840kJ, 50W] to 50mΩ, [1.2GHz, 0.3ns 75J, 20W].

Shunt manganin is a copper (87%) – manganese (9.5%) plus nickel, resistance alloy used for precision shunts in various high current applications. The alloy is long term stable (provided used below about 60°C) and has a low temperature coefficient of resistivity with peak (parabolic shaped) resistance at about 50°C, ±15 ppm/°C. The thermal emf against copper is low, less than -1µV/°C, down to -0.2µV/°C with a similar Cu/Mn based shunt alloy, zeranin.

It is possible to include a compensating element with the transfer function for approximate compensation of reactance into the measurement scheme:

$$H(s) = \frac{R_\omega^{-1}}{\frac{L_\omega}{R_\omega} s + 1}$$

L_ω and R_ω - shunt characteristics

However, frequency bandwidth of the overall device is limited by the bandwidth of the first order filter, and accuracy of measured values.

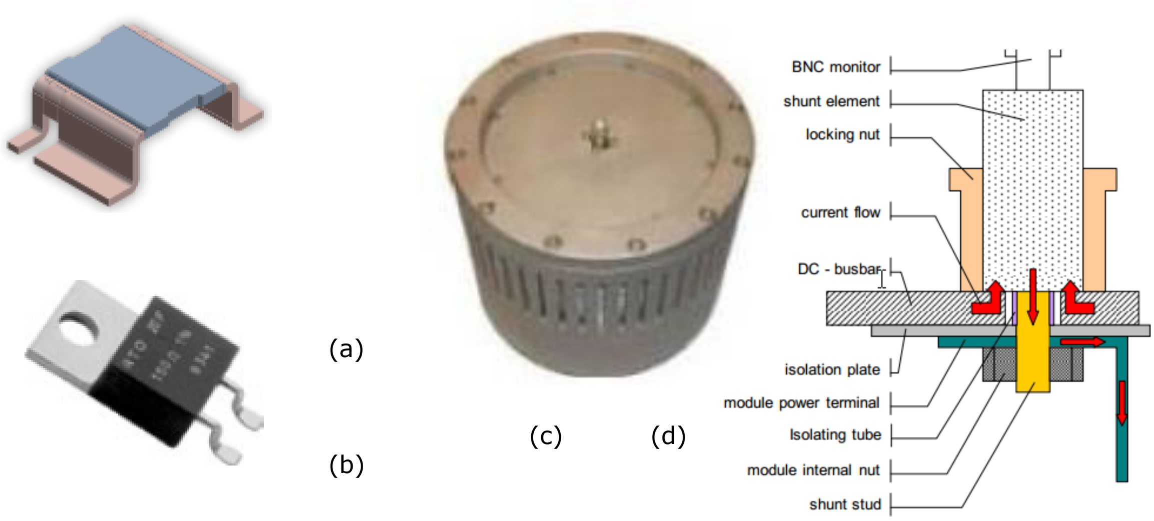


Figure 34.10. *Current measurement resistors:*
(a) thin film, four- terminal, (b) thick film, two terminal, (c) coaxial shunt and (d) its cross section.

There are the following major features of the resistive shunts.
Advantages:

- Simple design and mechanically robust;
- Wide frequency range, from dc to over 2GHz, with coaxial shunts;
- High overload capability and possibility to measure current peak values;
- Need no auxiliary power supply for operation.
- High EMC rejection and not susceptible to noise with double coaxial type designs
- Circular symmetry minimizes skin effects that limit bandwidth

Disadvantages:

- Need to be directly connected to power bus, power losses during heating-up of the shunt;
- External galvanic isolation is required.

34.2.5 Magneto-optic Sensor

Current sensors based on magneto-optical (Faraday) effect are used for galvanically isolated measurement of uni- or bidirectional DC currents high currents (up to ±500kA, ±600kA peak), with ±0.1% accuracy and linearity, in high voltage buses. Current sampling rate is 4kHz.
Because it does not need a magnetic yoke, an FOCS is smaller and lighter than Hall effect current sensors, and suffers no reduction in accuracy due to saturation effects. Because magnetic field sensing is distributed around circumference, it is unaffected by stray magnetic fields, and there is no need for magnetic centring. It also does not need recalibration after installation or during its service life. Because the optical fibre is inherently insulating, electrical isolation is easier to maintain.
A fibre loop is wound around a busbar, where the Faraday effect (a phase shift) occurs when polarized light is experiences the magnetic field produced by the busbar current.
Right and left circularly polarized light waves through the coiled sensing fibre are reflected back at the end of the fibre, (and their polarization direction is swapped) to the sensor electronics. A dc current, accumulatively creates a phase difference which is proportional to the line integral of the magnetic field along the sensing fibre. This difference is thus a direct and highly precise measure of the current. The phase shift is

$$\Delta\phi_F = 4VI$$

$$I = \oint \vec{H}\,d\vec{s}$$

where V is material strength constant, Verdot constant, wavelength and temperature dependent
H is magnetic field
s is length of sensing fibre

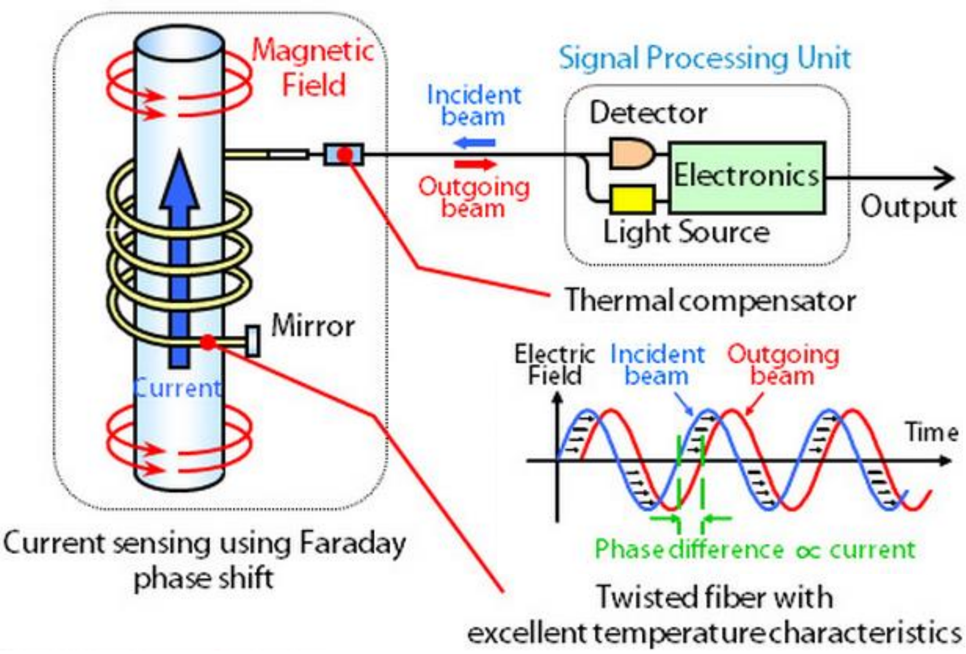


Figure 34.11. *Magneto-optic current transducer.*

Advantages:

- Possibility to measure high current values;
- Stability against the influence of the cross-magnetic field;
- Complete galvanic isolation;
- No power losses in the sensor.

Disadvantages:

- High cost and large dimensions.
- Requires light source, etc.

34.2.6 Integrated ac/dc current sensors

Integrated Hall-effect current sensor and Hall-effect linear integrated circuits can provide highly accurate (<1%, dc to 120kHz up to 1MHz, at up to 150°C), low noise output voltage signals that are proportional to a conducted AC or DC current. Current sensing from 0 A to ±2.5A to ±50 A to ±200 A (uni and bidirectional), with galvanic isolation up to 4.8 kV (for line-side or high-voltage applications) and low resistance primary conductor (≤200μΩ down to 0.8 μΩ for low Joule losses), is in surface mount and through-hole packages.

The block diagram in Figure 34.12 shows the internal block circuit diagram and construction of the device.

The IC consists of a low-offset linear Hall-effect analogue output circuit with a copper conduction primary path located near the Hall die. Applied current flowing through the copper conduction path generates a magnetic field that is concentrated by a low magnetic hysteresis ferromagnetic core, which is converted by the Hall IC into a proportional voltage. Device accuracy is optimized due the close proximity of the magnetic signal to the Hall transducer. A precise, proportional output voltage is provided by the low-offset, chopper-stabilized BiCMOS Hall IC, which is factory programmed (and EEPROM stored) for zero amperage output voltage and sensitivity accuracy. Digital temperature compensation improves the IC accuracy and temperature stability without influencing the high bandwidth operation of the analogue output.

A thick isolated copper conductor allows high overcurrent conditions. The conductor electrical isolation avoids the use of opto-isolators or other isolation techniques and along with an electric field integrated shield, provides dV/dt and stray electric immunity for low output voltage ripple and low offset drift, in high-side, high voltage applications.

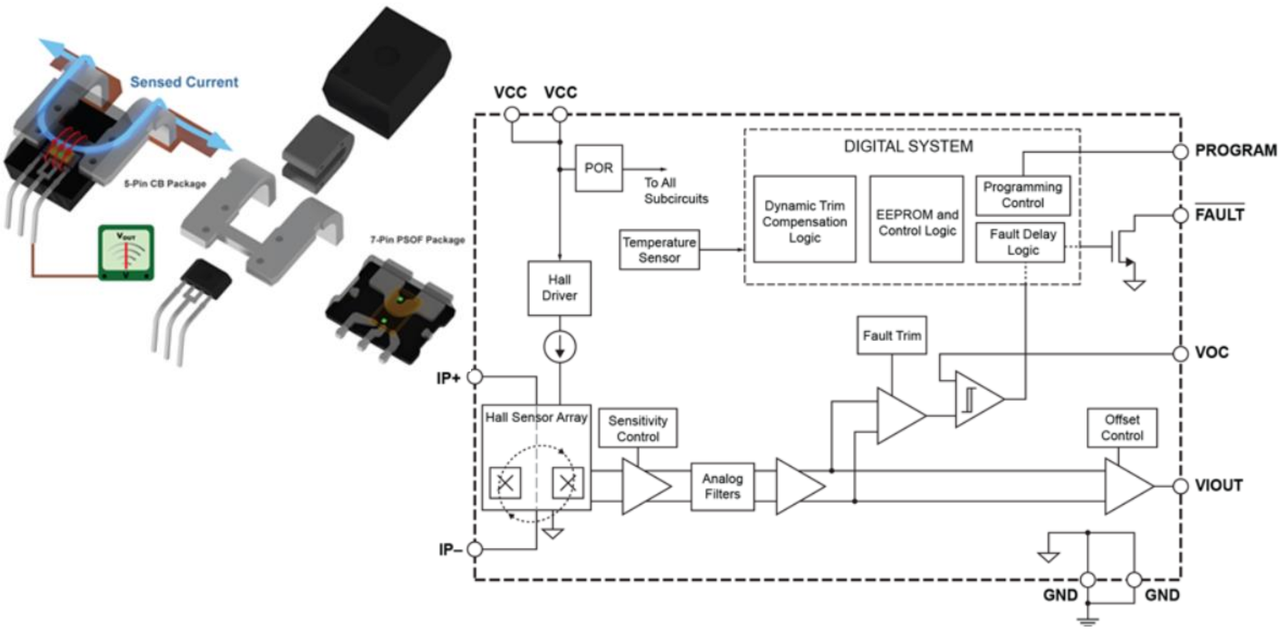


Fig 34.12 *Functional block diagram and IC construction.*

A high bandwidth (up to 1MHz) is accomplished by a high-speed analogue signal path that employs differential sensing to provide immunity to interfering common mode magnetic fields. By using two Hall plates measuring opposite polarities of the field created by the input current, the IC with differential sensing is able to reject common-mode (and external) fields. Thus with 40 dB of common-mode field rejection for a uniform and constant field, the IC can be used near other current paths.

http://www.allegromicro.com/en/Products/Current-Sensor-ICs.aspx

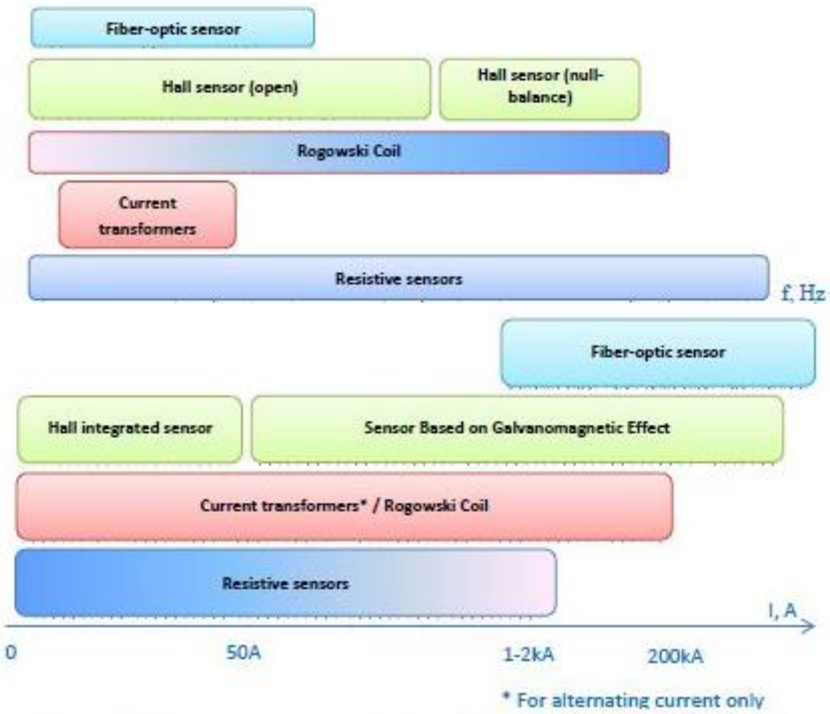


Figure 34.13. *Current transducer ratings.*

Table 34.3 highlights the parameter differences between and main characteristics of five current measurement techniques, namely the conventional current transformer, Hall effect sensor, current transformer based on a Rogowski coil, flux gate (which is a Rogowski coil with a magnetic core), and a co-axial shunt resistor.

Table 34.3: Features of six current measurement techniques

Feature	Current transformer	Hall effect	Rogowski coil	Flux gate	Co axial shunt resistor	IC Hall effect
	31.6.2	*34.2.1*	*34.2.2*	*34.2.3*	*34.2.4*	*34.2.6*
operating principle	$N_1 I_1 = N_2 I_2$	$V_H = IxB$	$V\alpha\mu_o dI/dt$	$V\alpha\mu_o\mu_r dI/dt$	$V_S = IxR_S$	$V_H = IxB$
output	current	voltage	voltage	voltage	voltage	voltage
bandwidth	low	medium	high	medium	low	very high
AC/DC measurement	AC	AC&DC	AC	AC&DC	AC&DC	AC&DC
isolation	high	high	high	high	low	high
linearity	good	medium	excellent	good	low	medium
precision	medium	medium	medium	very high	medium	medium
hi current measurement	good	good	very good	very good	low	good
saturation & hysteresis problems	yes	yes	no	no	no	yes
power dissipation	low	medium	low	medium	low	medium
temperature effects on output	low	medium	very low	low	medium	medium
transient response	medium	medium	very good	medium	medium	medium
low frequency response	medium	very good	good	medium	medium	very good
dc offset	no	yes	no	yes	no	yes
easy of installation	medium	medium	simple	medium	low	low
weight	medium	medium	low	medium	medium	low
dimensions/size	medium	medium	low	medium	low	low
cost	medium	high	low	high	medium	low

34.3 Voltage measurement

Hall effect closed loop voltage transducers

Construction and principle of operation
Hall effect voltage transducers are based on the same principle as their current transducer counterpart. They are a current transducer assembly where the primary circuit is a winding of a high number of turns. This realisation the ampere-turns for primary induction, with a low primary current, thus minimising power consumption from the circuit to be measured.
To measure a voltage it is therefore sufficient to shunt from the voltage the equivalent primary current which will supply the transducer. This is affected with a resistor connected in series with the primary winding (and its resistance).
Because of the multiple primary turns, high voltage isolation is challenging. At higher voltages, a few kV, a measurement bandwidth from dc to 500kHz, with a sub 1µs response time, is possible.

Resistor dividers
Up to 25kV, thick film on aluminium, 1M to 50GM at 0.5%, 1000:1, 9W. At 25kV, 0.5pF.

34.3.1 Differential Isolation (galvanic) Amplifier

A voltage sensing optical differential isolation amplifier, shown in figure 34.15, **is** designed for isolated single-ended low-voltage sensing. With a 2V input range and high 1GΩ input impedance, a shunt resistor divider makes it suitable for isolated voltage sensing in power electronic applications including motor drives and renewable energy systems. A resistive voltage divider is used to scale the DC-link voltage to suit the 2V input range of the voltage sensor. A differential output voltage (single supply) that is proportional to the input voltage is created on the other side of the optical isolation barrier.

With a gain 1V/V, operation on a single low-side 3.3V to 5V supply yields 0.1% linearity and a bandwidth from dc to 100kHz. The active-high shutdown reduces the high-side 15mA operating current to 15uA, thus is suitable for battery-powered and other power-sensitive applications.

The high common-mode transient immunity of 15kV/µs provides the precision and stability needed to accurately monitor DC-link voltage in high noise environments. Optical barrier coupling (giving 5kV peak galvanic isolation), sigma-delta (Σ-Δ) modulation, chopper stabilized amplifiers, and differential outputs provide (in conjunction with a 3-5.5V isolated power supply) high magnetic interference resistance, isolation-mode (common mode >108dB) noise rejection, low offset, high gain accuracy (±0.5% to ±3%), and stability (–40°C to +105°C).

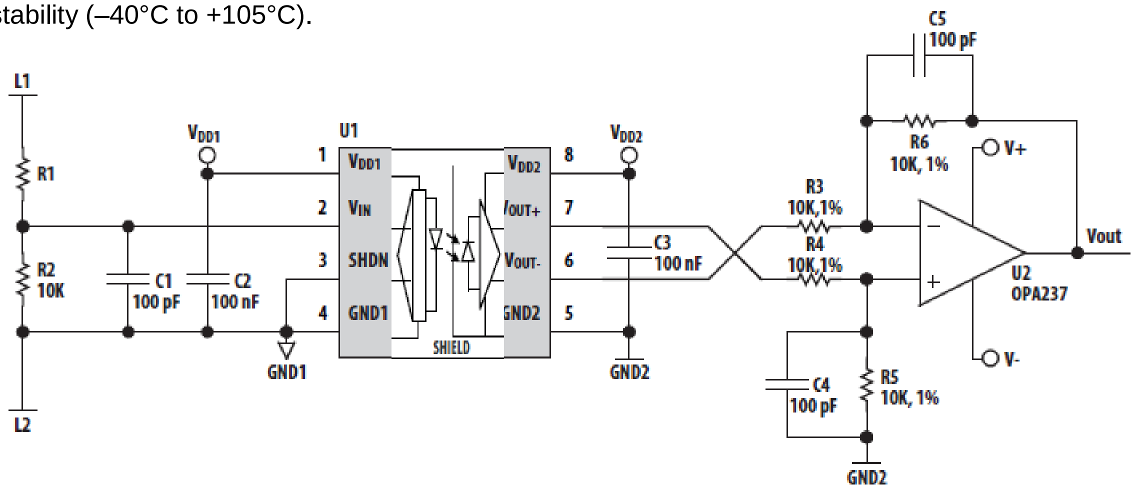


Fig 34.14 *Functional block diagram (optical isolation version)*

Figure 34.14 show the circuit for isolated measurement of a high dc voltage, where the resistor divider R1 and R2 ensures the isolating IC input voltage does not exceed 2V. The op amp U2 should have a bipolar input stage.

https://www.broadcom.com/products/optocouplers/industrial-plastic/isolation-amplifiers-modulators/isolation-amplifiers/

The differential isolator block diagram in figure 34.35 has capacitive (SiO2) ceramic isolation barriers (2pF) has dual (split) rail on the hv side, so is suitable for hv dc and ac measurement (although the manufacturer has not exploited zero dc offset ac input possibilities). Features (depending on the specific part) are 3500Vrms isolation (1500Vrms continuous), 0.01% linearity, 200k input resistance, -55°C to 125°C, 60kHz bandwidth, power supply range of ±4.5V to ±18V.

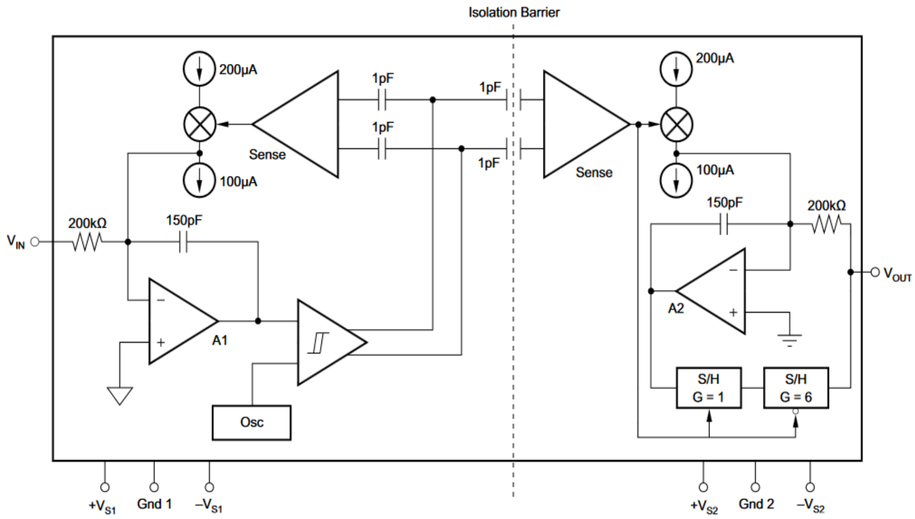


Fig 34.15. *Circuit diagram of capacitive isolator for measuring hv dc and ac voltages.*

The isolator is designed to have a 50kHz single-pole (Butterworth) signal output response. By cascading the isolator with a 50kHz, Q = 1, two-pole, low-pass filter, as in figure 34.16, the overall signal response becomes three-pole Butterworth. The result is a maximally flat 50kHz magnitude response with the output ripple reduced below the noise level.

http://www.ti.com/amplifier-circuit/special-function/isolated/products.html
http://www.ti.com/lit/ds/symlink/iso124.pdf

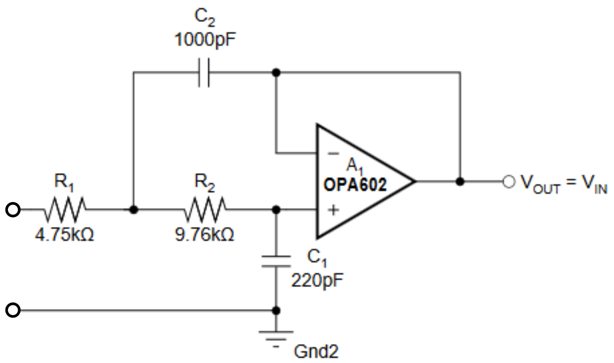


Fig 34.16. *Second order Butterworth output stage for the capacitive isolator in figure 34.15.*

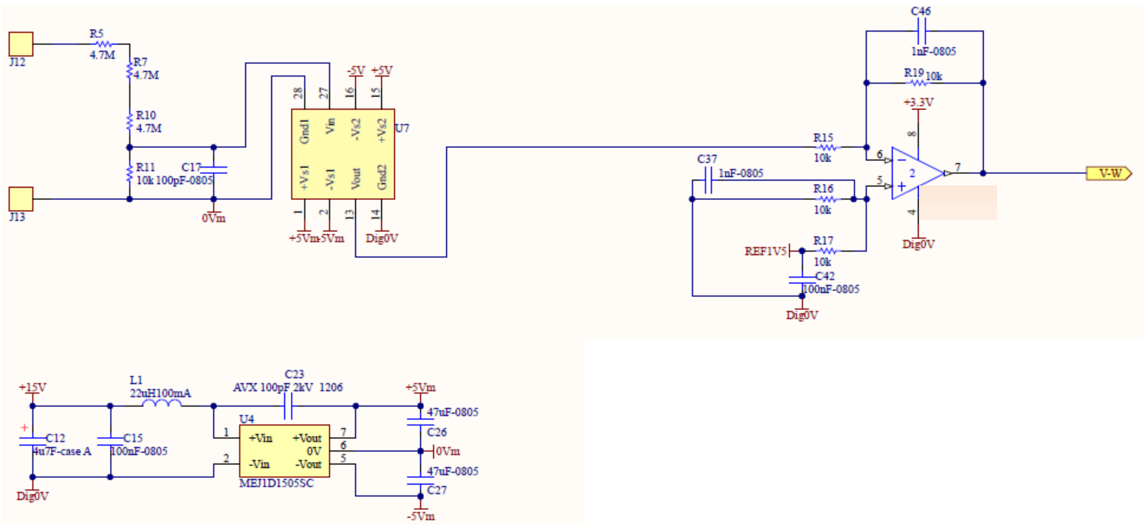


Fig 34.17. *AC voltage measurement suitable for the ac (single and three phase) mains.*

The split rail hv side supply means ac grid voltages can be measured, as shown in figure 34.17, where the resistor divider is reference to the high side Gnd1 (0V). Series connected resistors ensure the divider can withstand the main voltage level. The dc to dc converter to supply the HV side needs the appropriate hv voltage isolation rating. In a three phase system, lines *u*, *v*, *w*, without neutral, only one isolated dc to dc converter may be used (with two voltage isolator amplifiers), since two line to line voltages (for example V_{vw} and V_{uw}) can be measured in reference to a common line *w*, where either is inverted to recover the phase sequence, V_{vw} and $V_{wu}=-V_{uw}$. The third phase can be processed from the two known phases, $V_{uv}=-V_{vw}-V_{uw}$ or $V_{uv}=-V_{vw}+V_{wu}$.

An isolated dc to dc converter can be avoided by using the capacitive half-wave charging technique illustrated in figure 34.18a. Effectively the capacitor C_1 ac charges with the positive half cycle current diverted to charge the dc capacitor C_2, with a voltage clamped by Zener diode D_2. The half-wave near sinusoidal charging current to C_2 and the parallel load R_{load} is

$$\left|i(wt)\right| = V_1(wt) / \chi = V_1(wt) \times wC_1$$

where $V_{1peak} << V_{zener}$ and the average of *i(wt)* needs to larger than V_{zener}/R_{load}.

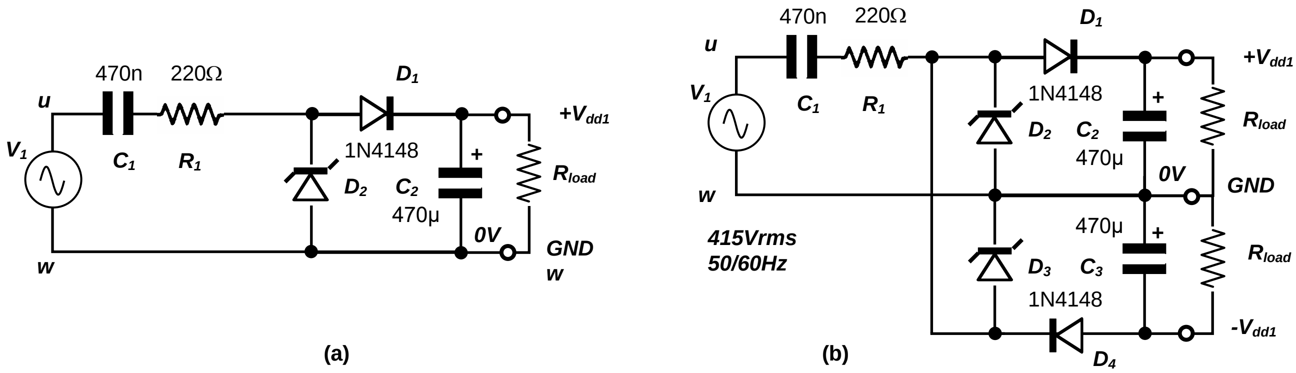


Fig 34.18. *Non isolated mains line voltage lv supply (a) single rail V_{dd1} and (b) split rail $\pm V_{dd1}$.*

Partial duplication of the circuit in figure 34.18a produces split rail dc supplies, as in the alternating half-wave rectifier in figure 34.18b.

34.4 Acceleration measurement

An accelerometer is an electromechanical device that measures acceleration forces and vibration of structures. It complies with:

$$a = \frac{\delta v}{\delta t} = \frac{\partial^2 x}{\partial t^2} \qquad \text{m/s}^2$$

In a piezoelectric based accelerometer, the force caused by vibration or a change in motion (acceleration) causes the mass to 'squeeze' the piezoelectric material which produces an electrical charge that is proportional to the force exerted upon it. Since the charge is proportional to the force, and the mass is constant, then the charge is also proportional to the acceleration.
The forces may be static, like the constant force of gravity, or dynamic - caused by moving or vibrating the accelerometer.

Table 34.4: Types of accelerometers

Sensor category	Key technologies
capacitive	metal beam or micromachined feature produces capacitance; change in capacitance related to acceleration
piezoelectric	piezoelectric crystal mounted to mass – voltage output converted to acceleration
piezoresistive	beam or micromachined feature whose resistance changes with acceleration
Hall effect	motion converted to electrical signal by sensing changing magnetic fields
magnetoresistive	material resistivity changes in the presence of a magnetic field
heat transfer	location of heated mass tracked during acceleration by sensing temperature

Table 34.4 show a range of accelerometer technologies, where three technologies widely used for acceleration measurements.

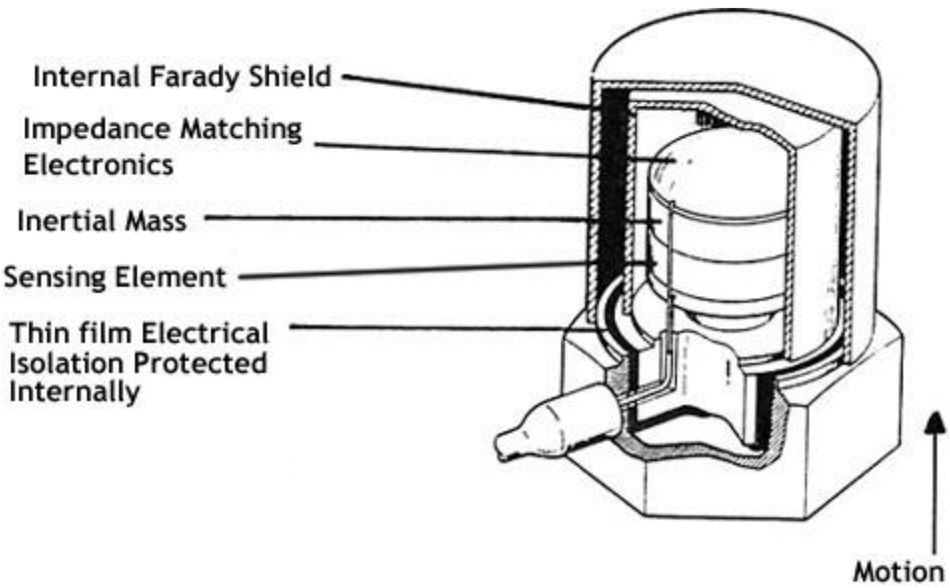
- Piezoelectric accelerometers are the most widely used accelerometers for test and measurement applications. They contain microscopic crystal structures that get stressed by accelerative forces, which causes a voltage to be generated. These devices offer a very wide measurement frequency range (a few Hz to 30 kHz) and are available in a wide range of sensitivities, weights, sizes, and shapes. These accelerometers are applicable to both shock and vibration measurements. Piezoelectric accelerometers can have either a charge or voltage output.
- Piezoresistive accelerometers generally have low sensitivity making them desirable for shock measurements. They are also used extensively in transportation crash tests. Because of the low sensitivity, they are not generally used for vibration measurements. Piezoresistive accelerometers generally have a wide bandwidth and the frequency response goes down to zero Hz (often called 'dc responding') or steady state, so they can measure long duration transients.
- Variable capacitance is among the newer accelerometer technologies. Two microstructures next to each other have a certain capacitance between them. If an accelerative force moves one of the structures, then the capacitance changes. By adding circuitry to convert from capacitance to voltage, gives an accelerometer. Like piezoresistive accelerometers, they are dc responding. Variable capacitance accelerometers have high sensitivities, a narrow bandwidth, and outstanding temperature stability. These devices are highly desirable for measuring low frequency vibration, motion and steady state acceleration.

In addition to the methods shown in Table 34.4, other methods include the use of hot air bubbles and light.

There are two main types of piezoelectric accelerometers (vibration sensors).

The first type is a 'high impedance' charge output accelerometer. In this type of accelerometer the piezoelectric crystal produces an electrical charge which can be connected directly to the measurement instruments. The charge output requires special accommodations and instrumentation. This type of accelerometer is used in high temperature applications (>120°C) where low impedance models can not be used.

The second type of accelerometer is a low impedance output accelerometer. It has a charge accelerometer as its front end but has a tiny built-in micro-circuit and FET transistor that converts that charge into a low impedance voltage that can readily interface with standard instrumentation. This type of accelerometer is commonly used in industry. An accelerometer power supply provides the proper power to the microcircuit 18V to 24V @ 2mA constant current and removes the dc bias level, they typically produce a zero based output signal up to +/- 5V depending upon the mV/g rating of the accelerometer.



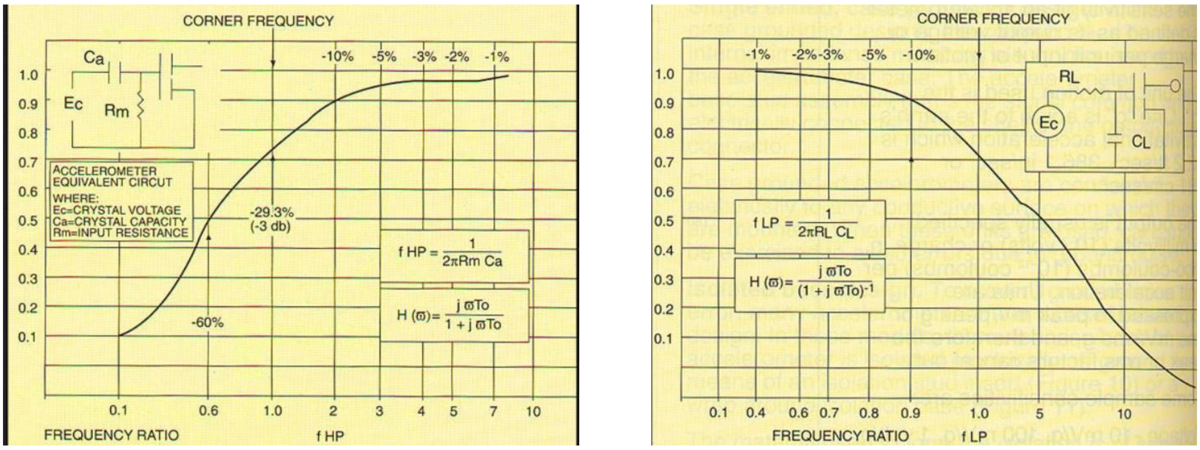


Figure 34.19. *Piezoelectric accelerometer:*
(a) cross sectional view and (b) upper and lower cut-off frequency characteristics.

High frequency limit is the frequency where the output exceeds the stated output deviation. It is typically governed by the mechanical resonance of the accelerometer. From the equivalent circuit in figure 34.19b, the -3db low-pass corner frequency f_{LP} is

$$f_{LP} = \frac{1}{2\pi R_L C_L}$$

$$H(\bar{\omega}) = \frac{j\bar{\omega}T_o}{\left(1 + j\bar{\omega}T_o\right)^{-1}}$$

where E_c is the crystal voltage
R_L is the series resistance
C_L is the shunt capacitance
$\omega = 2\pi f$

Low frequency cut-off is the frequency where the output starts to fall off below the stated accuracy. The output does not ‘cut-off’ but the sensitivity decreases rapidly with lower frequencies. From the equivalent circuit in figure 34.19b, the -3db high-pass corner frequency f_{HP} is

$$f_{HP} = \frac{1}{2\pi R_m C_a}$$

$$H(\bar{\omega}) = \frac{j\,\bar{\omega}T_o}{1 + j\,\bar{\omega}T_o}$$

where E_c is the crystal voltage
R_m is the input resistance
C_a is the crystal capacitance

Linearity is the maximum deviation of the calibration curve from a straight line and is given by

$$\text{linearity} = V_{out}^{0g} - ½\left(V_{out}^{+1g} + V_{out}^{-1g}\right)$$

Sensitivity is a measure of how much the output of a sensor changes as the input acceleration changes and is given by

$$\text{sensitivity} = \frac{\Delta V_{out}}{\Delta g} = ½\frac{V_{out}^{+1g} - V_{out}^{-1g}}{g}$$

Example 34.1: ***accelerometer sensitivity and linearity***

A capacitive accelerometer has an acceleration versus voltage output characteristic as shown in figure 34.20. Calculate transducer linearity and sensitivity.

Solution

$$\text{linearity} = V_{out}^{0g} - ½\left(V_{out}^{+1g} + V_{out}^{-1g}\right)$$

$$= 2.1\text{V} - ½\left(1.1\text{V} + 2.5\text{V}\right) = 0.3\text{V}$$

$$\text{sensitivity} = \frac{\Delta V_{out}}{\Delta g} = \frac{V_{out}^{+1g} - V_{out}^{-1g}}{2g}$$
$$= \frac{1.1\text{V}-2.5\text{V}}{2\text{g}} = -0.7\text{V/g}$$

♣

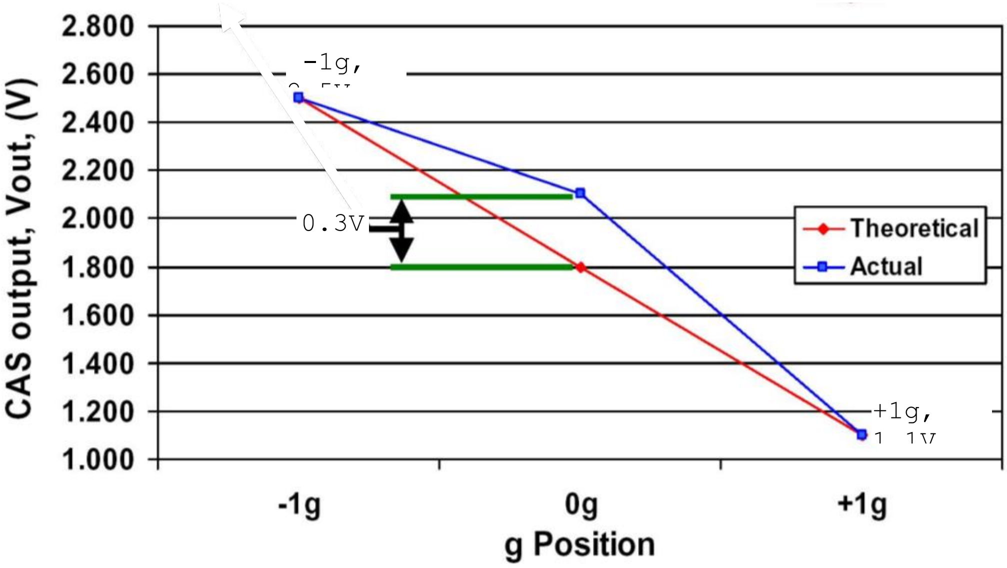


Figure 34.20. *Capacitive accelerometer characteristics.*

34.5 Resolver and synchro

Synchro and Resolver position sensors are similar to electric machines, being electromechanical rotary transformer transducers that convert shaft angle to an absolute analogue signal. They share the same rotor, stator, and shaft components as electrical rotating machines, as shown in fig 34.21.

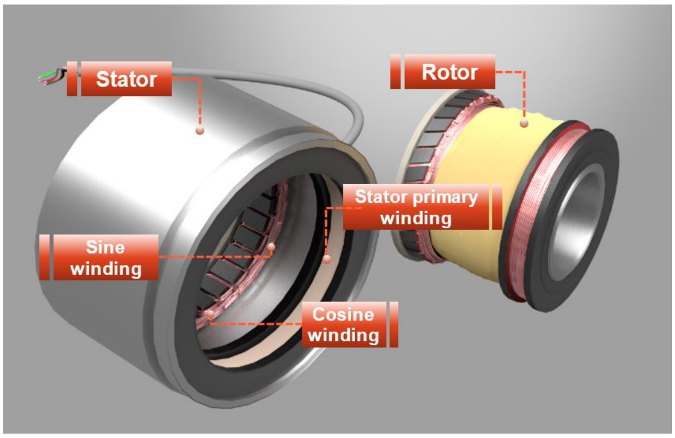


Figure 34.21. *Resolver stator and rotor.*

34.5.1 Resolver Design

The resolver is a rotary transformer that consists of a cylindrical rotor and stator, both having multi-slot laminations and two sets of windings. The windings are normally designed and distributed in the slotted lamination with either a constant pitch-variable turn or variable pitch-variable turn pattern. In either case, the winding distribution is in a sinusoidal pattern.

The windings create one complete sine curve and cosine curve in one mechanical revolution. The two sets of windings are positioned in the laminations at 90 degrees to each other. These are called the sine and cosine windings. One rotor winding may be shorted internally to improve the accuracy.
The primary difference between a synchro and a resolver is a synchro has three stator (secondary side) windings at 120º offsets, while the resolver has two stator (secondary side) windings at 90º angles. The number and angular mechanical orientation of the rotor windings varies. The resolver is considered hereafter.
A resolver is an angle sensor that outputs rotational angles as two-phase AC voltages (analogue signals). An AC output voltage is induced (like a voltage transformer) in the winding on the output side through excitation of the excitation (input) winding using an AC voltage. As this output voltage will vary depending on the angle of rotation, the angle of rotation can be calculated using the voltage reading, and transformed to a digital form with an R to D converter IC.

34.5.2 Resolver output functions

Three and four winding resolver electrical arrangements are shown in figure 34.20. The input winding(s) on the stator or rotor is sinusoidally excited, and because of orthogonal winding alignments and rotor rotation, various output functions are attained on the externally unexcited winding(s).
Resolvers used to describe angular measurement and for solving geometric functions are known as Data Transmission Resolvers, while those used for control data transmission are termed synchro resolvers.

Rotor-Excited Resolver. With the windings as defined in Fig. 34 22, the basic equations for voltage vectors in a sinusoidally rotor-excited resolver, $E_{r1\text{-}3}$, $E_{r2\text{-}4}$, are

$$\begin{aligned} E_{s1-3} &= k\left(E_{r1-3}\cos\theta - E_{r2-4}\sin\theta\right) \\ E_{s2-4} &= k\left(E_{r2-4}\cos\theta + E_{r1-3}\sin\theta\right) \end{aligned} \qquad (34.2)$$

where

k = transformation ratio (hereafter assumed unity)
θ = angle of counter-clockwise displacement from resolver zero.

Electrical zero EZ position for the resolver is so established that, when θ is zero, with rotor winding $R_{1\text{-}3}$ excited (at rated voltage) and rotor winding $R_{2\text{-}4}$ open, $E_{s1\text{-}3}$ (the cosine winding) will be at a maximum and $E_{s2\text{-}4}$ (the sine winding) will be zero. If winding $R_{2\text{-}4}$ is excited and $R_{1\text{-}3}$ is open, the outputs will be reversed.

Stator-Excited Resolvers. The basic equations for voltage vector θ in a stator-excited resolver are:

$$\begin{aligned} E_{r1-3} &= k\left(E_{s1-3}\cos\theta + E_{s2-4}\sin\theta\right) \\ E_{r2-4} &= k\left(E_{s2-4}\cos\theta - E_{s1-3}\sin\theta\right) \end{aligned} \qquad (34.3)$$

When θ is zero, with stator winding $S_{1\text{-}3}$ excited and stator winding $S_{2\text{-}4}$ open, $E_{r1\text{-}3}$ will be at a maximum and $E_{r2\text{-}4}$ will be zero. If winding $S_{2\text{-}4}$ is excited and $S_{1\text{-}3}$ is open the outputs will be reversed.

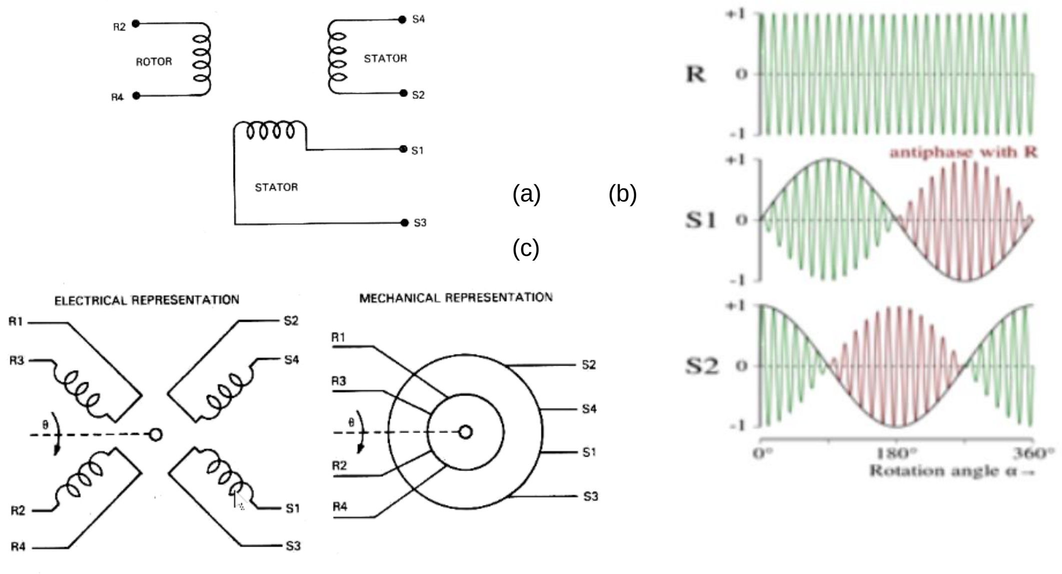


Figure 34.22. *Electrical representation of resolver:*
(a) single rotor winding, (b) two rotor windings, and (c) its associated waveforms.

A. Three winding resolver

Rotor excited, three winding
The simplest resolver would have a rotor with a single winding and a stator with two windings at 90º to each other, as shown in Fig. 34-21a.
If the rotor is excited by an AC reference voltage, across R2 to R4:

$$E_{r2-4}\ \sin\omega t$$

Then the resolver format voltages appearing on the stator terminals, shown in Fig. 34.22b, are:

$$E_{s1-3} = E_{r2-4}\ \sin\omega t \sin\theta$$

$$E_{s2-4} = E_{r2-4}\ \sin\omega t \cos\theta$$

where θ is the resolver shaft angle. These equations are based the 4 winding equations with E_{r1-4} =0, s/c, in equation 34.3.

Stator excited, three winding
The stator excitation is E_{s2-4} and stator S1-S3 is short circuited if a 4 winding resolver.
Since the rotor windings are in space quadrature the voltage induced in rotor winding R1-R3 is proportional to the cosine of the angle of rotation and the voltage applied to stator winding S1-S3. The voltage induced in rotor winding R2-R4 is proportional to the sine of the angle of rotation and the voltage applied to stator winding S1-S3. The relationship between input voltage E_{s1-3}, output voltages (E_{R1-3} and E_{R2-4}), end shaft angle θ is:

$$E_{r1-3} = E_{s1-3} \cos\theta$$

$$E_{r2-4} = E_{s1-3}\ \sin\theta$$

Such a resolver can be used as an angular position transducer.

B. Four winding resolver

A more complex resolver uses two orthogonal rotor windings and two orthogonal stator windings, as shown in Fig. 34-22c. The following computations can be performed.

i. ***Sine computation*** A voltage representing the hypotenuse of a right triangle is applied to one stator winding, and the rotor is positioned to the angle θ. The outputs of the rotor windings represent the coordinates of a right triangle. This method of operation is used to convert polar coordinates to rectangular coordinates.

ii. ***Conversion of Polar Coordinates***. Assume that voltage E_{s1-3} represents one polar coordinate, the radius vector, and is applied to the stator winding of the resolver; the rotor is positioned to angle θ, which represents the other polar coordinate. Output voltages E_{r2-4} and E_{r1-3} represent the legs of a right triangle, of which the radius vector is hypotenuse. Thus, the polar coordinates of a point, P, can be converted to the rectangular coordinates.

iii. ***Vector Addition***. A resolver is capable of adding values vectorially. If the two stator windings are excited with voltages corresponding to the coordinates of a right triangle, an output may be produced representing the radius vector and the vector angle. This method of operation is used to convert rectangular coordinates to polar coordinates.

iv. ***Conversion of Rectangular Coordinates***. Assume that E_{s1-3} and E_{s2-4} represent rectangular coordinates and are applied to the stator windings of the resolver 34.21b. The servo loop connected to one rotor winding positions the rotor to an angle θ,

$$\theta = tan^{-1} \frac{E_{s1-3}}{E_{s2-4}}$$

such that one output, E_{r2-4}, is zero. That is,

$$E_{r2-4} = E_{s2-4} \cos\theta - E_{s1-3} \sin\theta = 0$$

The other output, E_{r1-3}, being orthogonal, will be at a maximum. Expressed vectorially, the output

$$E_{r1-3} = E_{s1-3} \cos\theta + E_{s2-4}\ \sin\theta$$

becomes

$$E_{r1-3} = \sqrt{\ E_{s1-3}^2 + E_{s2-4}^2}$$

which is the radius vector, or equivalent polar coordinate. θ, is the radius angle, or vector angle.

v. ***Rotation of Rectangular Coordinates***. A four-winding resolver may be used for the rotation of rectangular coordinates. The orthogonal stator windings represent the input voltages corresponding to X and Y coordinates of a point, P, the output voltages from the rotor windings correspond to X' and Y' coordinates, where the coordinate axes have been rotated through an angle θ. This relationship is

$$X' = X \cos\theta + Y \sin\theta$$
$$Y' = X \cos\theta - Y \sin\theta$$

With angle θ representing the displacement of the rotor from resolver zero, the resulting equations of rotation are the same as those for a standard four winding resolver, stator excited. The input voltages on the stator windings form a resultant flux vector whose position, determined by the arctangent of Y/X, is independent of the rotor angular position. The rotor windings will at all times develop voltages which are proportional to the sine or cosine of the angle the rotor makes with the flux vector.

34.5.4 Resolver Applications

An electromagnetic resolver transducer can be used in a wide variety of position and velocity feedback applications which includes light duty/servo, light industrial or heavy duty applications. Resolvers, are commonly used in servo motor feedback applications due to their good performance in high temperature environments.

Because the resolver is an analogue device and the electrical outputs are continuous through one complete mechanical revolution, the theoretical resolution of a single speed resolver is infinite. Because of its simple transformer design and lack of any on internal electronics, the resolver is a much more rugged device than most feedback devices (like a shaft angle encoder), hence applicable where reliable performance is required in high temperature, high shock and vibration, radiation and contamination environments.

The rotor position or angle is simply the arc tan of the voltage output of the sine winding divided by the output of the Cosine winding. This ratio metric format provides an inherent noise reduction feature for any injected noise whose magnitude is approximately equivalent on both windings and also results in a large degree of temperature compensation.

The 7 functional operating parameters which define the resolver operation are:

1. Accuracy
2. Input Excitation Voltage
3. Input Excitation Frequency
4. Input Current Maximum
5. Transformation Ratio of Output Voltage to the Input Voltage
6. Phase shift of the Output Voltage from the Input Voltage
7. Null Voltage

34.5.5 Resolver-to-Digital Conversion

The resolver-to-digital converter performs two basic functions: demodulation of the resolver format signals to remove the carrier, and angle determination to provide a digital representation of the rotor angle. A common method of performing these functions is called ratiometric tracking conversion. Since the resolver secondary signals represent the sine and cosine of the rotor angle, the ratio of the signal amplitudes is the tangent of the rotor angle. Thus the rotor angle, θ, is the arc tangent of the sine signal V_{sin} divided by the cosine signal V_{cos}:

$$\theta = tan^{-1}\frac{V_{\sin}}{V_{\cos}}$$

The ratiometric tracking converter performs an implicit arctangent calculation on the ratio of the resolver signals by forcing a counter to track the position of the resolver. This implicit arc tangent calculation is based on the trigonometric identity

$$\sin(\theta-\delta) = \sin\theta\cos\delta - \cos\theta\sin\delta$$

The sine of the difference between two angles can be calculated by cross multiplying the sine and cosine of the two angles and subtracting the results. Provided the difference between the two angles is relatively small ($\delta = \theta \pm 30°$), the approximation $\sin(\theta-\delta) \cong \theta-\delta$ can be used, further simplifying the equation. Thus, if the two angles are within 30° of each other, the difference between the angles can be calculated using the shown cross multiplication.

In the R/D converter, this equation is implemented using multiplying D/A converters to multiply the resolver signals (proportional to $\sin\theta$ and $\cos\theta$) by the cosine and sine of the digital angle, δ, which is the output of the converter.

The results are subtracted, demodulated by multiplying by the reference signal, and filtered to give a DC signal proportional to the difference or error between the resolver angle, θ, and the digital angle, δ. The digital angle, δ, stored in the counter, is then incremented or decremented using a voltage controlled oscillator until this error is zero, at which point $\delta = \theta$ (the digital angle output of the converter is equal to the resolver angle). This incrementing and decrementing of the digital angle, δ, causes it to track the resolver angle, θ, hence the name of this type of converter.

34.5.6 Resolver versus Encoder

With no internal electronics, resolvers can survive extreme temperatures, radiation, tolerate shock and vibration, and withstand electrical noises, making resolvers suitable in applications where encoders would fail. As feedback devices, resolvers can be used as alternatives to both incremental encoders and absolute encoders. However, resolvers output an analogue signal and require a separate analogue-to-digital converter where encoders output digital signals.

Compared to absolute encoders, single-speed resolvers provide absolute position and can be used as absolute devices, making them alternatives when environment conditions do not allow for the use of absolute encoders.

Encoders are better suited applications which have high acceleration and deceleration rates.

Table 34.5. Comparison between the encoders and the resolver

		encoder	resolver
Standard resolution	counts/rev	32,640	16,384
Maximum speed	counts/sec	2,448,000	500,000
Typical/best accuracy	Arc-minutes	1.5/<1 (27 bits)	15/7
Typical tracking response time	ms	<1	15
Tolerable shock level	G	5	50
Operating temperature range	ºC	0 to 100	-55 to 175
Cost, relative		similar	Similar (with R/D converter)
Weight/inertia, relative		lower	higher

34.5 **Other sensors** elsewhere within this text.

12.2 Positive temperature coefficient PTC thermistors
12.2.2i Polymeric PTC devices
12.2.2ii Ceramic PTC devices
12.3.2iii Polymeric voltage variable material technologies

30.7.3 Temperature sensing resistors
30.7.4 Current sense resistors
30.7.5 Negative temperature coefficient NTC thermistors
30.7.6 Light dependent resistors