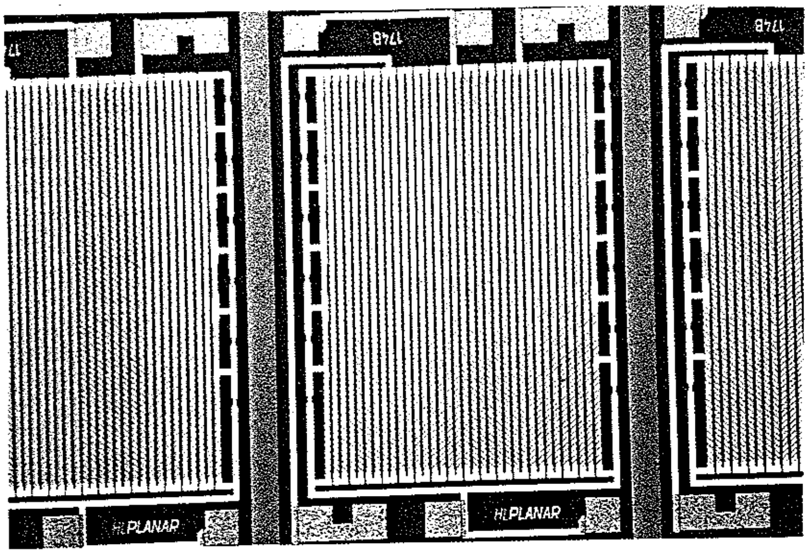


Fig. 1. Above, magnetoresistive magnetic field sensor chip photograph.

Applying magnetoresistance

With circuits examples including a sensor for the Earth's magnetic field and an overcurrent switch for protecting igbts, Neil Chadderton demonstrates the

Layout of a typical magnetoresistive chip is shown in **Fig. 1**, and is for example the chip used in the *ZMY20* sensor. Thin film stripes are a characteristic feature of a magnetoresistive chip. These stripes are made by photolithography and consist of permalloy, $Ni_{18}Fe_{19}$ – a magnetic material evaporated on an oxidised silicon wafer. The electrical resistivity of the stripes is changed by a magnetic field H_y due to the magnetoresistive effect. The field H_y causes a rotation of the magnetisation in the stripe, **Fig. 2**. Resistivity R of a permalloy stripe depends on the angle between the directions of electric current, I, and magnetisation M:

$$R = Ro_o + \Delta R_o \cos 2\alpha.$$

where ΔR_o describes the strength of the magnetoresistive effect.

The maximum relative change of resistivity $\Delta R_o/R$ is approximately 2 to 3% for permalloy. The relationship between an external field H_y and angle α is determined by the geometrical dimensions of the stripe and the magnetic anisotropy of permalloy. This is taken into account by introducing a field H_0 that represents the demagnetising and anisotropic field. One obtains,

$$\sin^2\alpha = \frac{H_y^2}{H_0^2} \quad \text{for } H \le H_0$$

$$\sin^2\alpha = 1 \qquad \text{for } H \ge H_0$$

The characteristic of a magnetoresistive stripe as a field sensor is:

$$R = R_0 + \Delta R_0\left(1 - \frac{H_y^2}{H_0^2}\right) \quad \text{for } H \le H_0$$

A linear characteristic of the magnetoresistive sensor is required to measure a small magnetic field. The linear behaviour of the magnetoresistive sensor is achieved by using a 'Barber-pole' geometry. The stripes in Fig. 1 are covered with aluminium bars having an inclination of 45° to the stripe axis. Aluminum has a low resistivity compared to permalloy. Therefore the Barber poles cause a change of the current direction. The angle between current and magnetisation is shifted by 45°, **Fig. 3**. The relationship between resistance and magnetic field is now,

$$R = R_0 + \frac{\Delta R_0}{2} \pm \Delta R_0\left(\frac{H_y}{H_0}\right)\sqrt{1 - \frac{H_y^2}{H_0^2}}$$

A linear characteristic of the sensor is given around $H_y^2/H_0^2=0$. The sign in this equation is determined by the inclination of the Barber poles, ±45°, to the stripe axis. The characteristic of a sensor with and without Barber poles is presented in **Fig. 4**.

The stripes of the magnetoresistive chip are arranged as a meandering pattern. They form a Wheatstone bridge which is

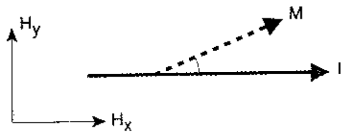


Fig. 2. Magnetoresistive effect depends on the angle between the direction of electric current I and magnetisation M. A rotation of the magnetisation in a permalloy stripe takes place when a magnetic field in the y direction is applied. Without an external field the magnetisation is along the x direction due the shape of the stripe.

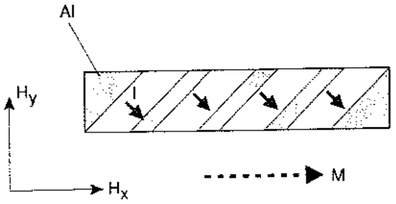


Fig. 3. Covering the stripe with 'barber poles' consisting of aluminium changes the direction of the current. This does not influence the direction of magnetisation.

shown schematically in **Fig. 5**. The applied voltage is V_b. Each half bridge consists of two resistors with different Barber-pole orientations. Voltage between the resistors of a half bridge changes upon application of a magnetic field.

The resistance of one resistor increases, while the other resistor has a lower resistance due to the differing field characteristic. Adding a second half bridge with an opposite arrangement of Barber poles provides a Wheatstone bridge.

Voltage difference V_0 is the output signal of the sensor. Each half bridge is trimmed to $V_b/2$ with an additional resistor in order to get an output voltage close to zero when no external field is applied. The trimming structures of the resistors in Fig. 1 mark off the meander stripes on the left and right side of the chips.

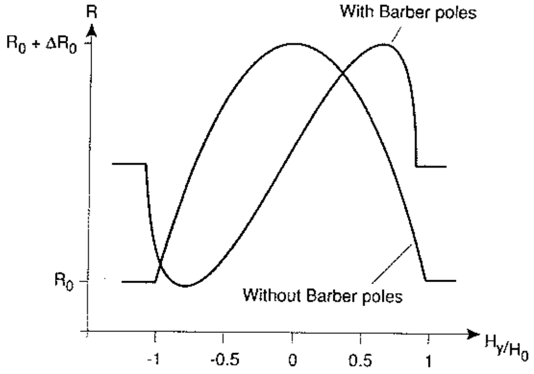


Fig. 4. Characteristics of magnetoresistive sensors. The barber-pole structure enables a linear behaviour of the sensor for a small magnetic field.

Operating conditions and parameters

The shape of the stripe and the anisotropy of permalloy only define an axis along the x-direction for the magnetisation without external field H_y. This means that in this state the stripe can have areas with a different direction of magnetisation (magnetic domains) and the sensor does not work in a stable way. A safe operation of the sensor is achieved by applying an auxiliary field H_x. This field defines the direction

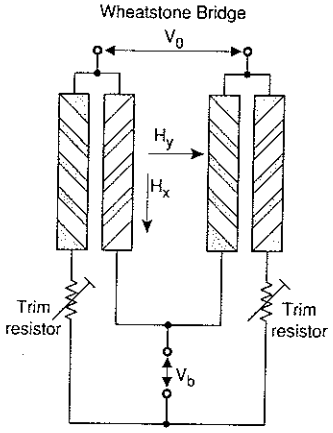


Fig. 5. Wheatstone bridge of a magnetoresistive sensor with barber-pole structure. The bridge is balanced by laser trimming.

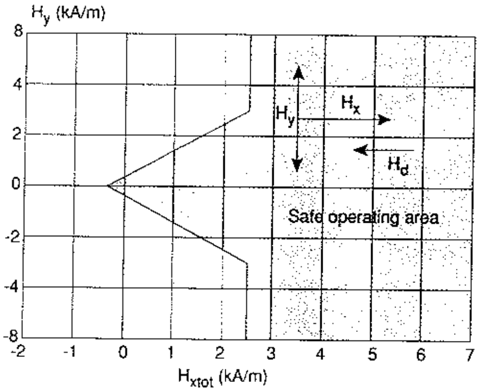


Fig. 6. Safe operating area of ZMY20/ZMZ20 magnetoresistive sensors. $H_{x(tot)}$ is H_x+H_d, ambient temperature is –25°C and H_d is the disturbing field.

Appendix B. Extract from the ZMY20/30, ZMZ20/30 magnetoresistive sensor data sheet. Most of these characteristics assume an ambient temperature of 25° and H_y of 3kA/m.

Parameter	Symbol	Min.	Typ.	Max.	Unit	Test conditions
Bridge resistance	R_{br}					
ZMY20/ZMZ20		1.2	1.7	2.2	kΩ	
ZMY30/ZMZ30		2.0	3.0	4.0		
Output voltage range	V_o/V_B					
ZMY20/ZMZ20		16	18	22	mV/V	
ZMY30/ZMZ30		12	16	20		
Open-circuit sensitivity	S	3.2	4.0	4.8	(mV/V)/	No disturbing
ZMY20/ZMZ20		2.0	3.0	4.0	(kA/m)	field, H_d, allowed
ZMY30/ZMZ30						
Hysteresis of output	V_{OH}/V_B			50	µV/V	Hy≤2kA/m
Offset	V_{off}/V_B	–1.0		+1.0	mV/V	
Operating frequency	f_{max}	0		1	MHz	
Temp. coeff. of offset	TCV_{off}	–3		+3	(µV/V)/K	T_{amb} –25...+125°C
Temp. coeff. of bridge resistance	TCR_{br}		0.3		%/K	T_{amb} –25...+125°C
Temp. coeff.of open circuit sensitivity V_B=5V	TCS_V		–0.4		%/K	T_{amb} –25...+125°C
Temp. coeff. of open circuit sensitivity I_B=3mA	TCS_I		–0.1		%/K	T_{amb} –25...+125°C

of the magnetisation. The range of H_y for safe sensor operation is determined by the strength of the auxiliary field. The safe operating area of the sensor is demonstrated in **Fig. 6**.

Field $H_{x(tot)}=H_y+H_d$ determines the allowed field values for H_y, where H_d is an external disturbing field in the x-direction.

There is no limitation for H_y in the case of $H_{x(tot)} \geq 2.6$kA/m. A small permanent magnet is sufficient to create the auxiliary field. Where *ZMZ 20/30* or *ZMY 20/30* devices are used, the magnet can be glued on the sensor package. Another option is the *ZMY20M* which provides a very compact sensor including an integrated magnet, and is available in surface mount packaging.

The operating data sheet parameters of the Wheatstone bridge are referred to an input voltage V_b=1V, due to the linear relationship between input and output voltage in this region.

The sensitivity S [mV/V/kA/m] of the magnetoresistive sensor is defined as the slope of the output voltage versus external field for -1kA/m$\leq H_y \leq 1$kA/m. This parameter depends on the geometry of the permalloy meander and the auxiliary field. The latter is demonstrated in **Fig. 7** for H_x=3kA/m and H_x=6kA/m. Note the small operating area in the case of H_y=0kA/m. A high sensitivity of the sensor leads to a small operating area for H_y.

The Wheatstone bridge is balanced without the application of an external field of $H_y \leq 0.1$kA/m.

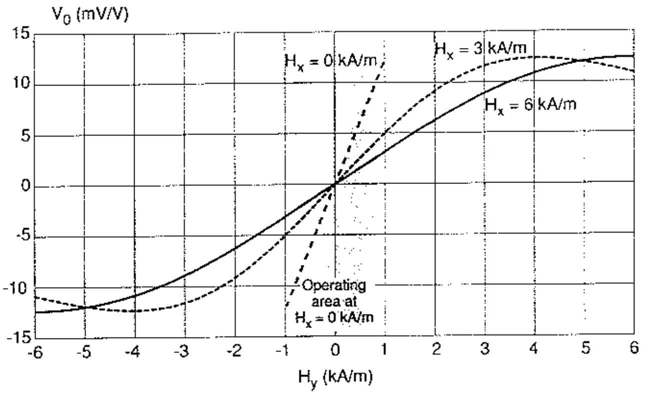


Fig. 7. Sensor output characteristic of ZMY20/ZMZ20. Sensitivity of the sensor can be controlled by applying auxiliary field H_x. This auxiliary field is necessary for sensor operation in a large field range, $V_o=f(H_y)$; H_x-parameter; V_b=const; T_{amb} –25°C.

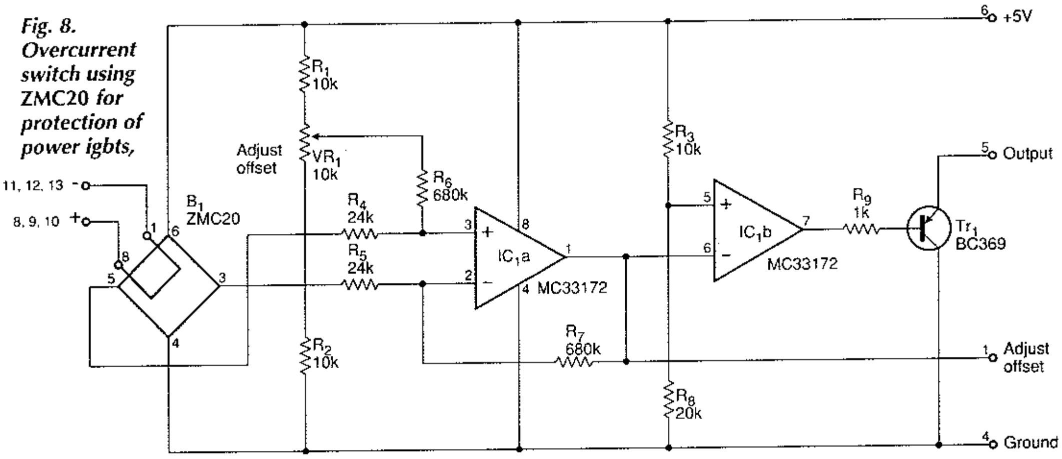


Fig. 8. Overcurrent switch using ZMC20 for protection of power igbts,

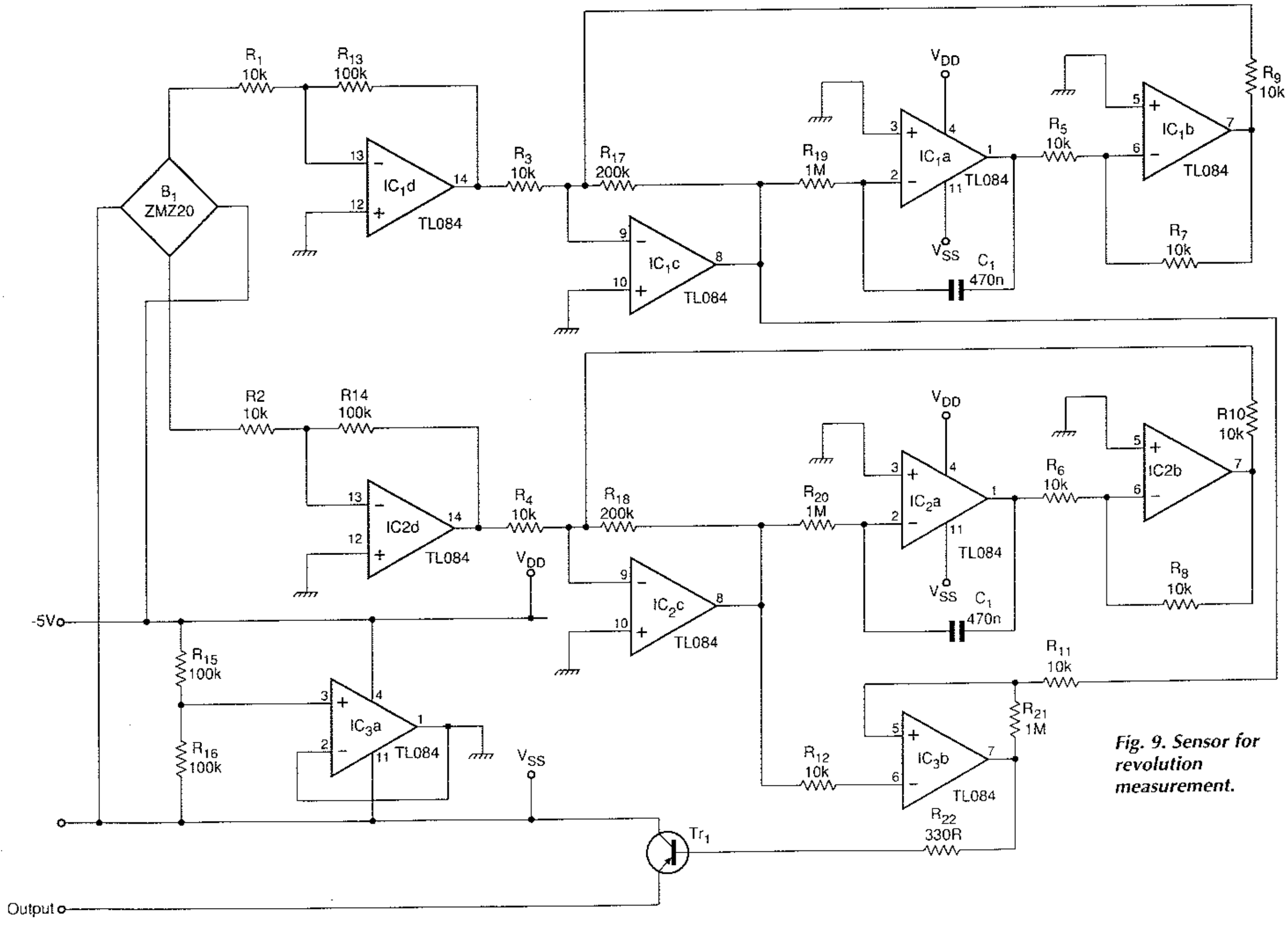


Fig. 9. Sensor for revolution measurement.

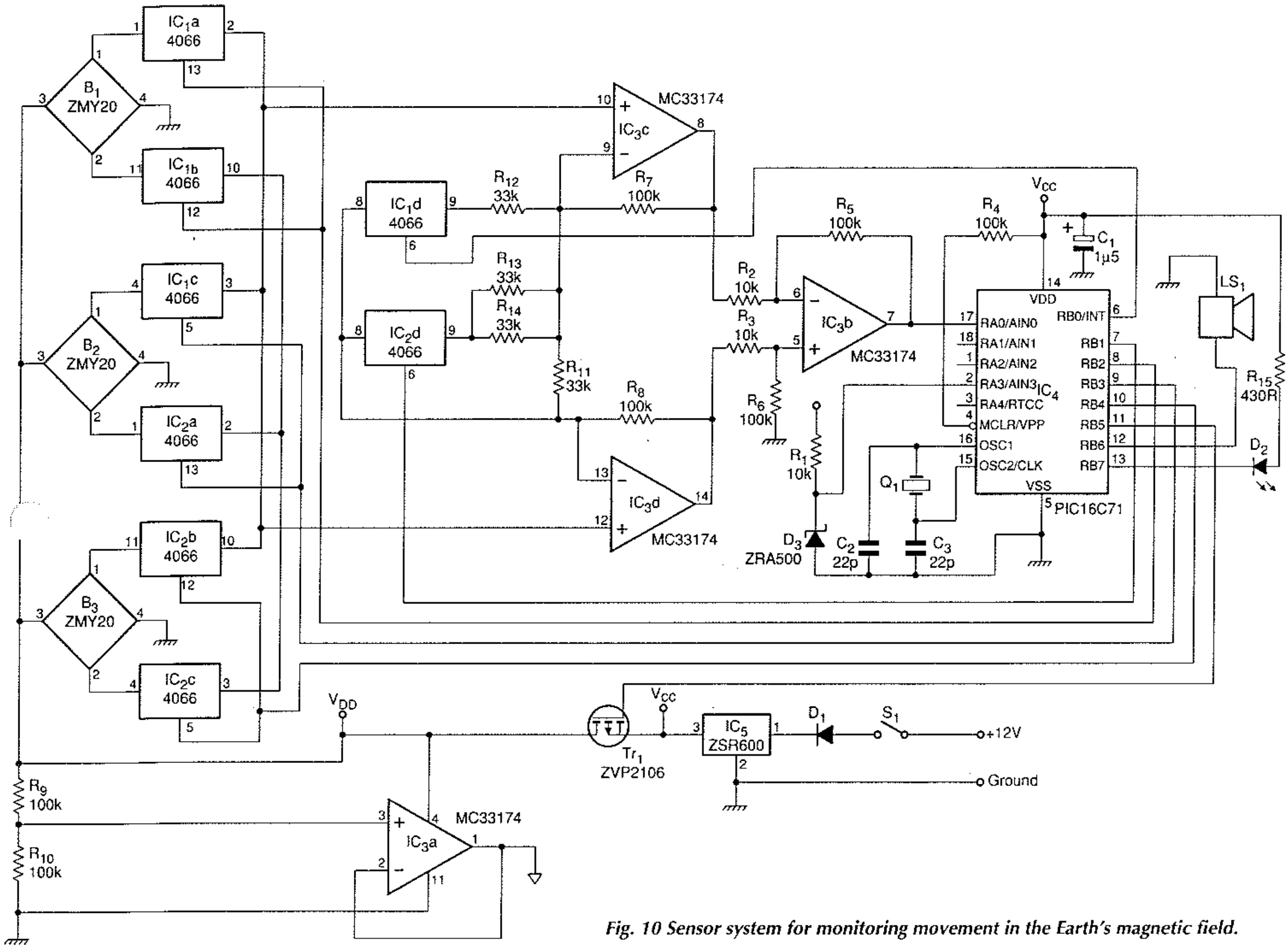


Fig. 10 Sensor system for monitoring movement in the Earth's magnetic field.

In this case, output voltage of the sensor is close to zero at room temperature.

Deviation of the output voltage from zero is called the offset voltage V_{off}/V_b [mV/V]. The offset is caused by small geometric variations of the bridge which occur during the photolithographic process. The offset of the bridge is adjusted by laser trimming. The voltage output of each half bridge is $V_b/2$.

Bridge resistance R_{br} [%/K] of the magnetoresistive sensor depends linearly on temperature. The temperature coefficient of bridge resistance TCR_{br} [%/K] is positive. This is typical for metals. The temperature coefficient of sensitivity, TCS [%/K] of the sensor is negative for V_b=const (TCS_V), because the strength of the magnetoresistive effect becomes smaller with increasing temperature.

In the case of I_B=const (TCS_I), when the sensor is powered by a constant current supply, the temperature dependence of the sensitivity is reduced due to the linear relationship between input and output voltage. A higher bridge resistance caused by a rise in temperature leads to an increased applied voltage, partly compensating the change of sensitivity.

The Wheatstone bridge cannot fully compensate the temperature dependence of the resistors. The temperature coefficient of offset voltage TCV_{off} [µV/V/K] is due to local changes of resistivity in the permalloy thin film and photolithographic variations. This characteristic of the magnetoresistive sensor limits the measurement of small magnetic fields in a wide temperature range, especially in the case of static fields. Two sensors can be selected having a comparable temperature coefficient.

Offset drift is partly eliminated by using the difference of the output voltages of both sensors. Another elegant way to avoid offset drift is to invert the direction of the auxiliary field, thus inverting the output voltage of the sensor. This can be done by small coils providing an auxiliary field that can change its direction.

Hysteresis of output voltage $V_{off(H)}/V_b$ [mV/V] describes the accuracy of the magnetoresistive sensor. The magnetisation of the permalloy stripe is not completely homogeneous. There are small areas of the meander, especially at the corners of the stripes, where the magnetisation is pinned and does not correctly follow the external field. The hysteresis is measured in a magnetic field loop, where H_y goes from –3kA/m to 3kA/m and back to 0kA/m (H_x=3kA/m). $V_{off(H)}/V_b$ denotes the shift of the offset voltage caused by this loop.

The maximum range of output voltage $\Delta V_0/V_b$ [mV/V] is defined as the difference of output voltage for α=0° and α=90°, where α denotes the angle between current and magnetisation of the magnetoresistive stripe. This means that $\Delta V_0/V_b$ represents the strength of the magnetoresistive effect. This parameter decreases with temperature and determines the sensitivity of the sensor.

Applications

Some examples of applications for magnetoresistive sensors are presented in the panel.

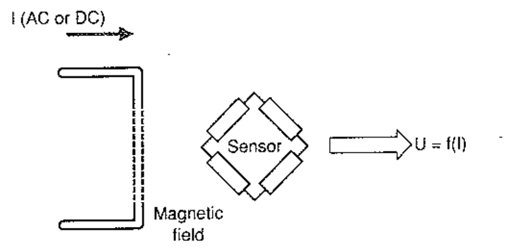
Figure 8 shows a *ZMC20* current sensor being used as a basis for an overcurrent trip switch used to protect power igbts within a motor driver system. The circuit reacts within 3μs to prevent latch-up related failure under transient/pulse conditions, and was built within a module measuring 35×20×25mm. An external 10kΩ preset potentiometer is required for offset adjustment. Supply voltage is +5V ±10% at 10mA; output is via an open-collector transistor rated at 1A, 20V; operating temperature range is 0 to80°C.

Figure 9 provides a method for revolution measurement by reacting to a modulated magnetic field due to a rotating cog. The circuit gives a signal whose frequency is proportional to the rotational velocity of the cog, and a high level output for no rotation.

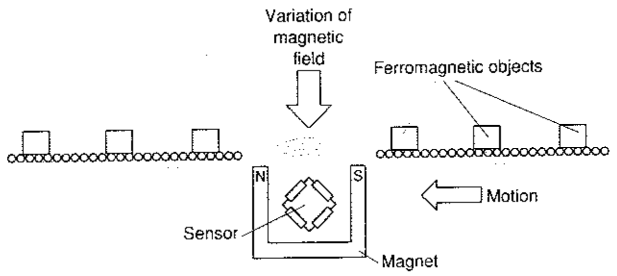
Figure 10 shows an application circuit for three-dimensional magnetic field observation. When the unit is enabled, it calibrates itself to the existing magnetic field of the earth, and then generates a warning signal if it is moved. The system employs three *ZMY20* sensors – one for each dimension – and a c-mos e-prom microcontroller with an a-to-d converter. Similar circuits have been designed for automotive immobiliser/alarm systems that monitor the position of the vehicle by sensing the magnetic field of a movable permanent magnet. This magnet is necessary to shield the sensor from disturbing fields (generated by supply lines, car alternators, etc.) Supporting software for these systems is available on request. ■

Magnetic sensors discussed in this article are available from 2001 Electronics Components Ltd, Stevenage Business Park, Pin Green, Stevenage ST1 4SU, tel. 01438 742001, fax 742002.

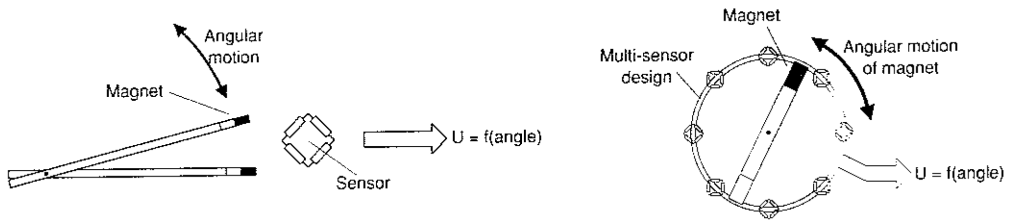
Application outlines for the magnetoresistive sensor.



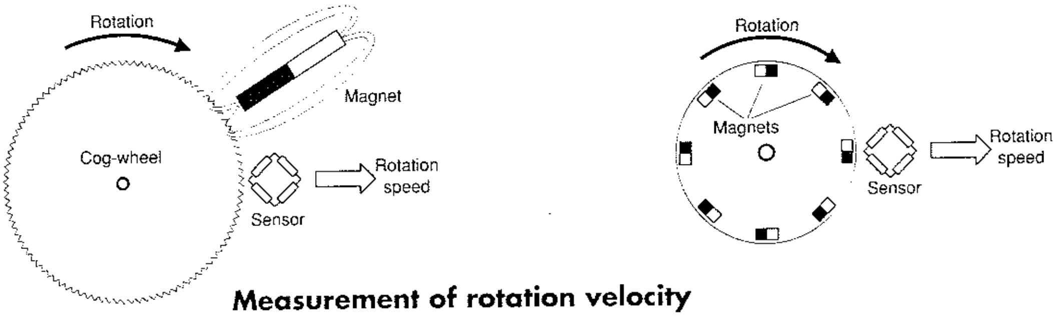
Measurement of Current – ac or dc



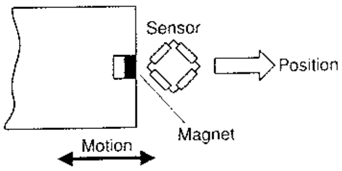
Detection of ferromagnetic objects



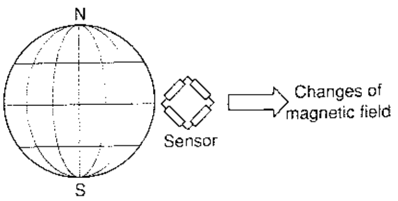
Measurement of angular position



Measurement of rotation velocity



Position sensing



Measurement of the Earth's Magnetic Field