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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 7 : B61L 1/18, G01R 19/20, 15/18

A1

(11) International Publication Number: WO 00/63057

(43) International Publication Date: 26 October 2000 (26.10.00)

(21) International Application Number: PCT/GB00/01398

(22) International Filing Date: 12 April 2000 (12.04.00)

(30) Priority Data:
9908599.5 16 April 1999 (16.04.99) GB

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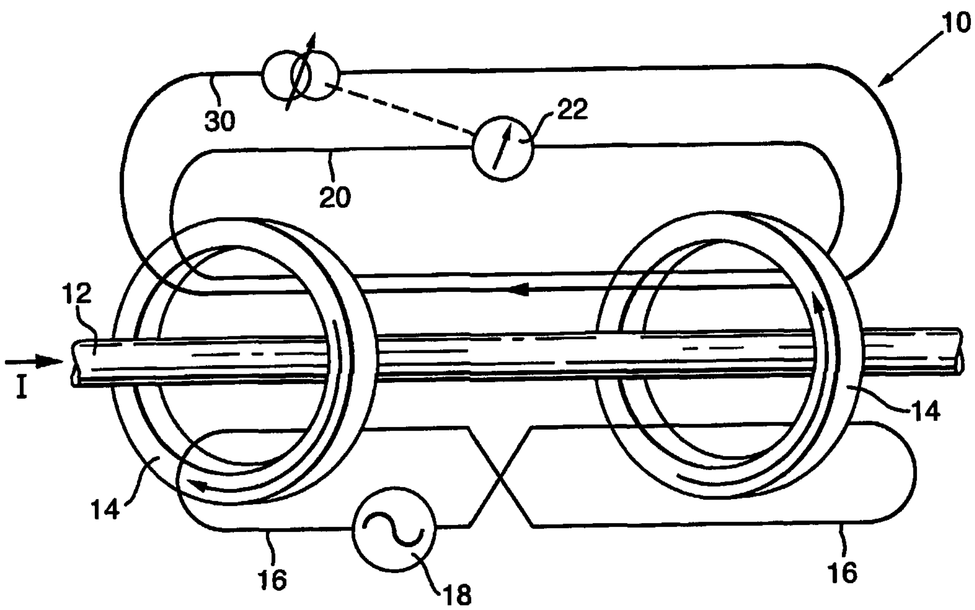
(81) Designated States: AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CR, CU, CZ, DE, DK, DM, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published
With international search report.

(54) Title: CURRENT SENSOR



(57) Abstract

An instrument (10) which can sense and measure a DC current in a conductor (12) consists of two adjacent rings (14) of magnetic material arranged to surround the conductor (12). Each ring (14) carries an energising winding connected to an AC source (18) and arranged so the rings (14) are magnetised is opposite directions. A sensing winding (20) is arranged to respond to the sum of the magnetic fluxes in the two rings. Any DC current in the conductor (12) causes a voltage to be induced in the winding (20). This instrument (10) is not affected by the earth's magnetic field, and can measure currents less than 10 mA, so it is suitable for monitoring the current flowing in a track circuit.

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Current Sensor

This invention relates to a non-contact method of, and instrument for, sensing and measuring a current, particularly but not exclusively a current which may be less than 1 A.

The instrument may be used, for example, to measure and monitor the current flowing in a track circuit. A track circuit detects the presence of a train in a section of track by applying a low DC voltage between the rails, and detecting the change in the resistance between the rails due to the presence of a train as the wheels and axles provide electrical connection between the rails. The DC electrical current which flows in the track circuit when a train is present is typically less than 1 A, and may be in the range 1 mA - 100 mA, and measuring such currents in a non-contact fashion (and so without modifying the track circuit) is difficult because the magnetic field of such a small DC current is significantly less than the earth's magnetic field.

According to the present invention there is provided an instrument for sensing and measuring a current in a conductor, the instrument comprising two rings of magnetic material arranged to surround the conductor, each ring carrying an energising winding, the energising windings being arranged to carry an alternating current and arranged to magnetise the rings with the same magnetising force (H) but in opposite directions, and a sensing winding connected to a current indicator, the sensing winding being arranged to respond to the sum of the magnetic fluxes in the two rings, wherein the magnitude of the alternating current supplied to the energising windings is sufficiently large to ensure that the magnetic flux density (B) in each of the rings varies in a non-linear manner with the instantaneous value of the alternating current, and that the frequency of the alternating current supplied to the energising windings is at least twice that of any alternating current to be measured in the conductor.

The earth's magnetic field, considered over a small region, is essentially a plane field inclined at the angle of dip below the horizontal (e.g. 67° in southern England), whereas the magnetic field due to the current in the conductor is a circular field around the conductor. Although the earth's magnetic field will be distorted by the presence of the railway track and any trains, this geometrical distinction can still be used to distinguish between the two sources of magnetic field. The two rings of magnetic material are therefore desirably close enough together that the earth's magnetic field is substantially the same for each ring. In the preferred arrangement the rings are coaxial and next to each other, separated only by the thickness of the electrical windings and insulation.

The magnetic material forming the rings ensures that the relationship between electric current and magnetic flux density (B) is non-linear. The material desirably has a high magnetic permeability, as this enhances the sensitivity of the instrument. The benefits of high permeability would be significantly reduced if there were any air gaps in the magnetic circuit, so preferably each ring is a continuous ring, and may be of laminated form wound from a continuous tape. Alternatively each ring may comprise part rings (e.g. two C-shaped half rings) which can be assembled around the conductor; in this case the mating faces of the part rings are desirably machined smooth so when assembled there is no significant air gap. Ideally the magnetic material would have an almost rectangular hysteresis (B/H) graph, which exhibits sudden magnetic saturation and has a high magnetic remanence, but practical materials can only approximate to this.

The instrument is capable of measuring DC currents, and AC currents of low frequency (ideally up to half the frequency of the alternating current source). It may be used to detect currents flowing in an electric cable, in which case the rings must be large enough for the cable to pass through them, and might for example be of 20 mm internal diameter. Alternatively it may be used to detect the track circuit current flowing through an axle of a train, in which case each ring must be large enough to surround the axle, and be of say 200 mm internal diameter.

The alternating emf connected to the energising windings might be sinusoidal, or more preferably square wave. The frequency is preferably sufficiently low that each ring is driven from saturation in one direction to saturation in the reverse direction in each cycle, and so is usually less than 10 kHz, more preferably less than 1000 Hz, but preferably at least 100 Hz. Reaching saturation has the advantage that the end points of the magnetic cycle are well-defined. If the rings were identical, and no current were flowing in the conductor, then there would be no signal supplied to the current indicator. Current flowing in the conductor will augment the magnetic flux in one ring while decreasing the flux in the other ring, and because of the non-linear characteristics of the rings there will then be a signal supplied to the current indicator. If the magnetic material in the rings had an ideal rectangular hysteresis curve one would expect a pulse output as one ring reaches saturation slightly before the other. In practice the output signals supplied to the current indicator are more complex, but nevertheless can be related to the current in the conductor.

In a second aspect, the invention provides a method of sensing and measuring a current in a conductor, using such an instrument.

The invention will now be further and more particularly described, by way of example only, and with reference to the accompanying drawings in which:

Figure 1 shows a diagrammatic view of an instrument for measuring the current in a conductor, partly showing the instrument in perspective;

Figure 2 shows an electrical circuit diagram for the instrument of figure 1;

Figures 3a and 3b show graphically the output voltage signals, plotted against time, obtained with the instrument of figure 1 at different values of current in the conductor;

Figure 4 shows graphically the variation in output signal with current for an instrument as in figure 1; and

Figure 5 shows graphically the variation in output signal with current for an instrument as in Figure 1, after integration of the voltage signal.

Referring to figures 1 and 2, an instrument 10 for sensing and monitoring DC currents in a cable 12 of external diameter 15 mm comprises two rings 14 each of internal diameter 20 mm, through which the cable 12 passes. The rings 14 are substantially identical, and each is wound from a 0.05 mm thick tape of mumetal, so it is of laminated form (mumetal is an alloy of approximate composition Fe 18%, Ni 75%, Cu 5%, and Cr 2%). Onto each ring 14 is wound a respective toroidal energising coil 16 (only one turn being shown in figure 1), of insulated wire, the coils 16 being connected in series with each other and connected to a source 18 of AC energising current. The coils 16 are arranged so the magnetising forces (H) in the rings 14 due to the energising current are equal, but are in opposite directions. Although shown spaced apart in the figures, the rings 14 are placed next to each other, separated only by the windings 16. A sensing winding 20 is then overwound around both rings 14 together (only one turn is shown in figure 1). The magnetic flux enclosed by the winding 20 is consequently the sum of the magnetic fluxes in the two rings 14, and any changes in that sum will generate a voltage in the winding 20. It will be appreciated that this is equivalent to winding separate sensing coils 20 around each ring 14 and then connecting these coils in series, as shown in the circuit diagram of figure 2. The sensing winding 20 is connected to a current indicator 22.

In use of the instrument 10, the source 18 provides a square wave alternating voltage to the energising coils 16, which in this case is at a frequency of 750 Hz. The instrument is effectively an AC bridge network, and an output signal from the sensing winding 20 only occurs if there is a difference between the magnetic fluxes in the two rings 14. This happens if there is a current in the conductor 12, as this increases the flux in one ring 14 and decreases the flux in the other ring 14. Because of the non-linear characteristics of the magnetic material, the increase and the decrease will not be the same, and so there will be a voltage induced in the sensing winding 20. This frequency of AC current is such that each ring

14 is driven to saturation on each half cycle, using a peak current of 100 mA. (As excitation frequency is increased, the time available for saturating the magnetic material decreases, and therefore energy would have to be introduced at a greater rate. For a given number of turns in the energising windings 16, this may be achieved by adjusting the drive current, but there is no benefit in increasing the power consumption. Other considerations involved in selecting this frequency are that, in principle, one measurement of the current in the conductor 12 may be made per cycle; for accuracy it is preferable to average over a number of cycles. To enable measurements of currents in the conductor 12 up to say 10 Hz, the excitation frequency must therefore be at least 20 Hz and is preferably at least 40 Hz. To avoid potential interference from other electrical appliances it is desirable to select a frequency which is a multiple of mains frequency, i.e. 50 Hz in Europe.)

The voltage induced in the sensing winding 20 may be detected in a variety of ways, and be related to the current in the conductor 12. Referring now to figures 3a and 3b, these show graphically the variation of the induced voltage V with time t (through a cycle of the square wave energising voltage), for different values of electric current I in the conductor 12, as observed with the instrument 10 described above. Figure 3a shows the results obtained using positive values of current I, and figure 3b shows the results obtained with negative values of current I, being shown separately only for clarity. It will be observed that the induced voltage V varies in a complex fashion through each cycle, but that the graphs obtained with different values of current can be clearly distinguished; in figure 3a the differences are most marked on the right hand side of the graph, whereas in figure 3b the differences are most marked on the left hand side. The detailed shape of these graphs depends on the shape of the hysteresis curve for the material of the rings 14, and may also differ for rings of different dimensions.

A modified current sensing instrument has been made, differing from that described above in that the rings 14 of mumetal tape were wound onto plastic formers of internal diameter 200 mm, this being large enough that an axle can pass through the rings 14. The energising coils 16 and the sensor coils 20 were wound as described above. The energising coils 16 were supplied with a 750 Hz square wave, with a peak energising current of 100 mA. The current indicator 22 in this case comprised a time gate, a filter and an output amplifier connected to a voltmeter. The time gate in this case was synchronized with the energising signal, and arranged to select only the voltage signal at a well defined point in the cycle; the resulting signal was filtered to remove the 750 Hz switching frequency; and the resulting DC signal was amplified (by x10) to obtain convenient readings on a digital voltmeter. Referring now to figure 4, there are shown graphically the readings on the digital voltmeter for a range of different values of current flowing in a conductor 12 passing through the rings 14. It will be observed that in this particular case there is a generally linear relationship between the output voltage and the current over this range of currents.

An alternative and preferable way of determining the current I from the measurements of induced voltage V involves integrating the induced voltage V over parts of the cycle, as this provides an output which is less sensitive to any timing errors. The preferred approach is to carry out this integration through the first and third quarters of each cycle. This may be performed using analogue electronics in the current indicator 22 of Figure 1, with a solid state switch to control the times for which the voltage signal is supplied to the integrator, and a sample-and-hold circuit to output the result of the integration at the end of each cycle. This signal processing generates an output signal which, as shown in Figure 5 to which reference is now made, varies monotonically with the current I, and is linear over a wide range of currents I.

Referring again to Figure 1, the instrument 10 can be further improved by providing a feedback winding 30 driven by the output from the current indicator 22, the magnetic field of the current in the feedback winding 30 opposing the field of the current in the cable 12. The feedback winding 30 may have many turns, so the feedback current at balance may be many times less than the current in the cable 12. The variation with time of the flux in the rings 14 is thereby maintained near the zero-current condition, which has the beneficial effect of making operation of the instrument 10 substantially independent of the magnetic circuit characteristics. Furthermore the range of currents which can be measured is increased, being limited only by the capability of supplying a balancing current to the feedback winding 30. The sensitivity of the instrument 10 with feedback is dominated by the characteristics of the feedback, and is therefore much less dependent on the magnetic characteristics of the rings 14. With such a feedback system, the current in the feedback winding 30 provides a measure of the current in the cable 12.

It should be appreciated that, in principle, feedback may be provided in this way in any instrument 10 in which the output voltage V (as shown in Figures 3a and b) has first been processed to provide a single-value output signal corresponding to a particular value of current I in the cable 12. The preferred instrument 10, as described above, integrates the induced voltage over the first and third quarters of each cycle, and also includes the feedback winding 30. Incorporation of an integrating mechanism with feedback in this way essentially makes the instrument 10 self-zeroing. With a square wave energising frequency of 750 Hz supplied to the coils 16, the instrument 10 can measure both the DC current in the cable 12, and any variations in that current, up to a frequency of about 200 Hz.

It will also be appreciated that the voltage signals may be analyzed in a variety of different ways in addition to those described above, and in particular they might instead be analyzed digitally.

Claims

1. An instrument for sensing and measuring a current in a conductor (12), the instrument (10) comprising two rings (14) of magnetic material arranged to surround the conductor (12), each ring (14) carrying an energising winding (16), the energising windings (16) being arranged to carry an alternating current (18) and arranged to magnetise the rings (14) with the same magnetising force but in opposite directions, and a sensing winding (20) connected to a current indicator (22), the sensing winding (20) being arranged to respond to the sum of the magnetic fluxes in the two rings (14), characterized in that the magnitude of the alternating current supplied to the energising windings (16) is sufficiently large to ensure that the magnetic flux density in each of the rings (14) varies in a non-linear manner with the instantaneous value of the alternating current, and that the frequency of the alternating current supplied to the energising windings (16) is at least twice that of any alternating current to be measured in the conductor (12).

2. An instrument as claimed in claim 1 wherein the rings (14) are coaxial and next to each other, separated only by the thickness of the electrical windings (16, 20) and insulation.

3. An instrument as claimed in claim 1 or claim 2 wherein the source (18) of the alternating current supplied to the energising windings (16) has a square wave variation of emf with time.

4. An instrument as claimed in any one of the preceding claims wherein the magnitude of the alternating current supplied to the energising windings (16) is sufficiently large that each ring (14) is driven from saturation in

one direction to saturation in the reverse direction in each cycle of the alternating current.

5. An instrument as claimed in any one of the preceding claims wherein the alternating current supplied to the energising windings (16) is of a frequency in the range 100 Hz to 1000 Hz.

6. An instrument as claimed in any one of the preceding claims also including a feedback winding (30) and means to generate a current in the feedback winding, arranged so that the magnetic field due to the current in the feedback winding (30) has the opposite effect to the magnetic field of the current in the conductor (12), the feedback current being such that the current indicator (22) is maintained close to the state corresponding to zero current in the conductor (12).

7. A method for sensing and measuring a current in a conductor (12), the method comprising installing two rings (14) of magnetic material around the conductor (12), each ring (14) carrying an energising winding (16), the energising windings being arranged to carry an alternating current (18), and arranged to magnetise the rings (14) with the same magnetising force but in opposite directions, and a sensing winding (20) connected to a current indicator (22), the sensing winding (20) being arranged to respond to the sum of the magnetic fluxes in the two rings (14), the method being characterized in that the magnitude of the alternating current supplied to the energising windings (16) is sufficiently large to ensure that the magnetic flux density in each of the rings (14) varies in a non-linear manner with the instantaneous value of the alternating current, and that the frequency of the alternating current supplied to the energising windings (16) is at

least twice that of any alternating current to be measured in the conductor (12).

8. A method as claimed in claim 7 wherein the rings (14) also include a feedback winding (30) connected to means to generate a current in the feedback winding, and arranged so that the magnetic field due to the current in the feedback winding (30) has the opposite effect to the magnetic field of the current in the conductor (12), and the method includes maintaining the feedback current such that the current indicator (22) is maintained close to the state corresponding to zero current in the conductor (12).

9. A method as claimed in claim 7 or claim 8 wherein the current indicator (22) provides an output signal corresponding to the values of the voltage induced in the sensing windings (20) integrated over a predetermined part of each successive cycle of the alternating current supplied to the energising windings (16).

10. A method as claimed in claim 9 wherein the output signal corresponds to the said values integrated over the first and third quarters of each successive cycle.

Fig.1.

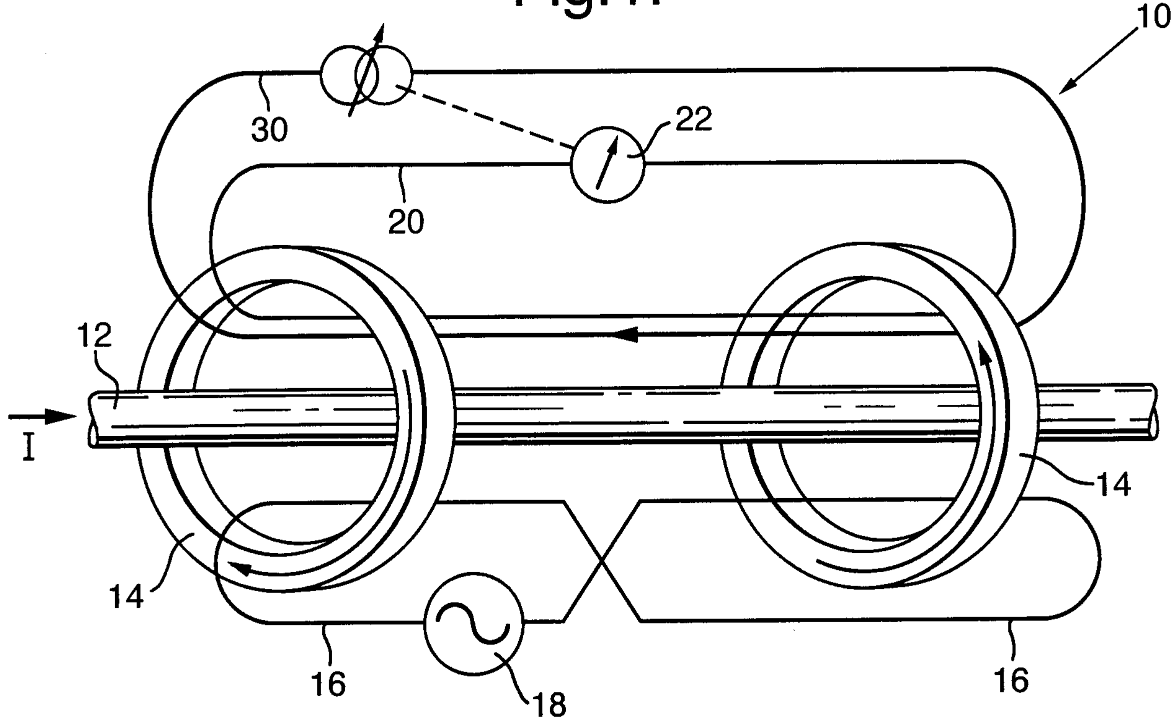


Fig.2.

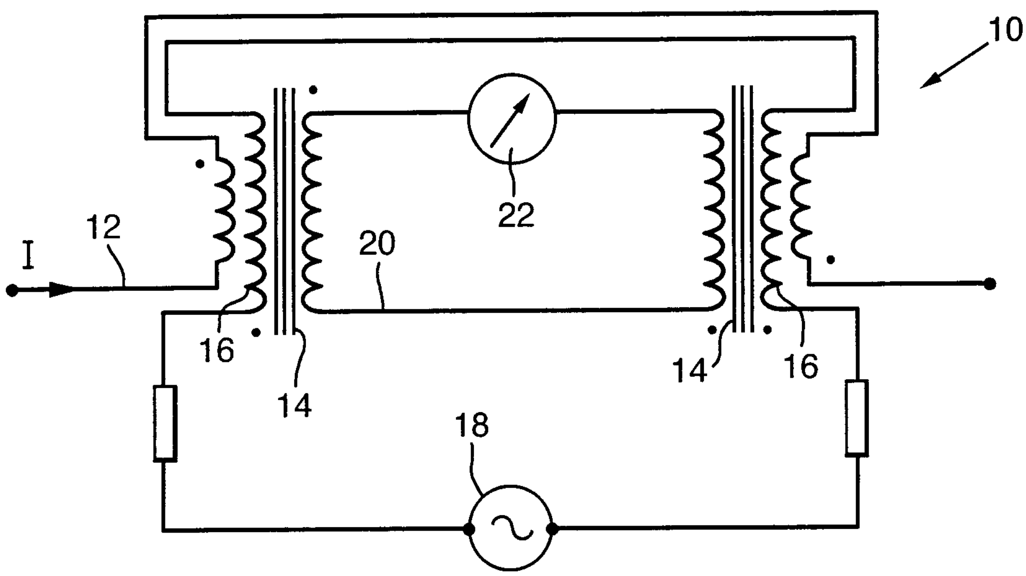


Fig.3a.

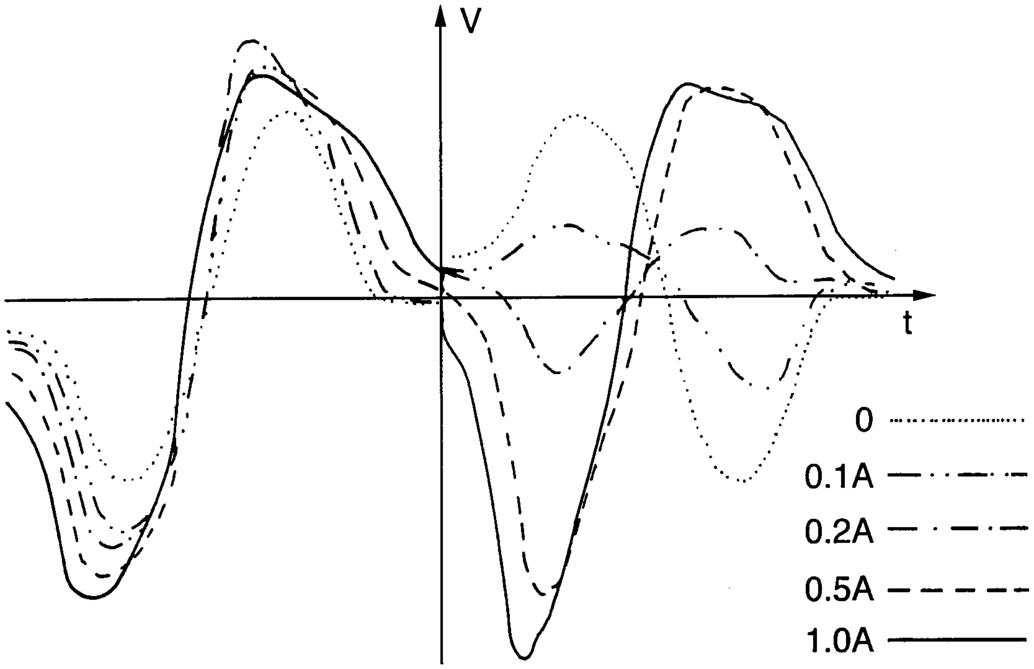


Fig.3b.

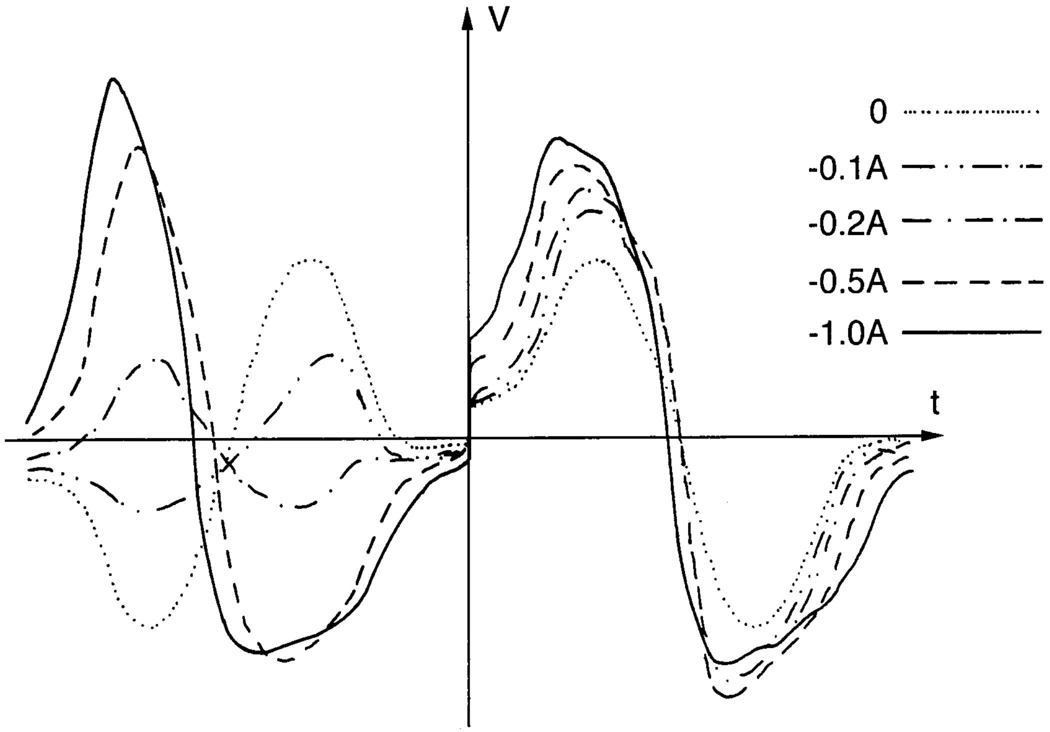
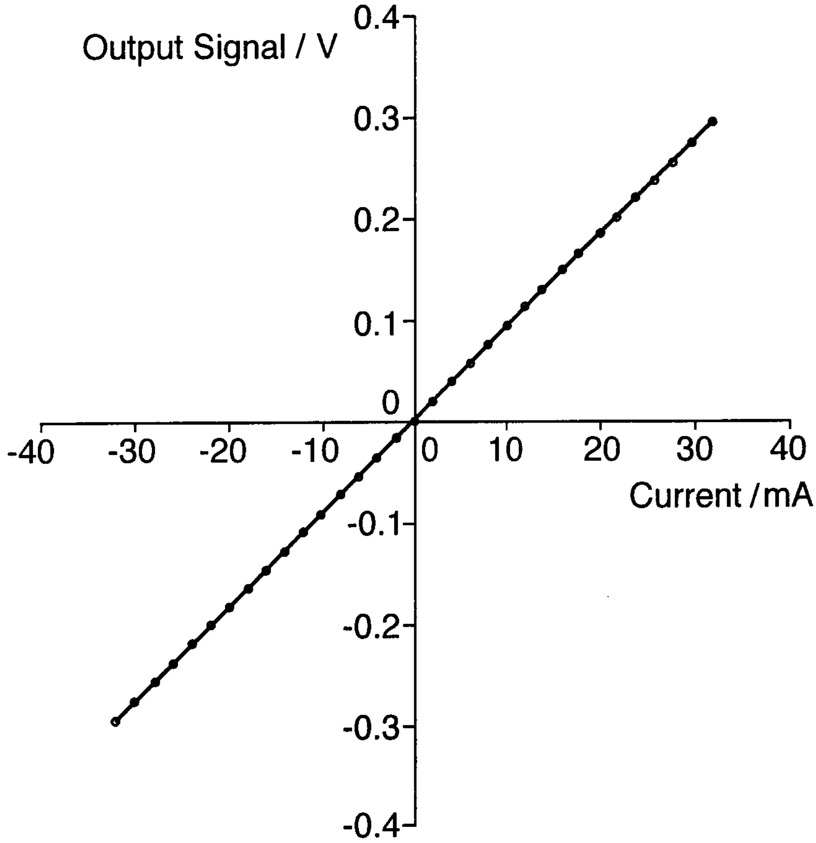


Fig.4.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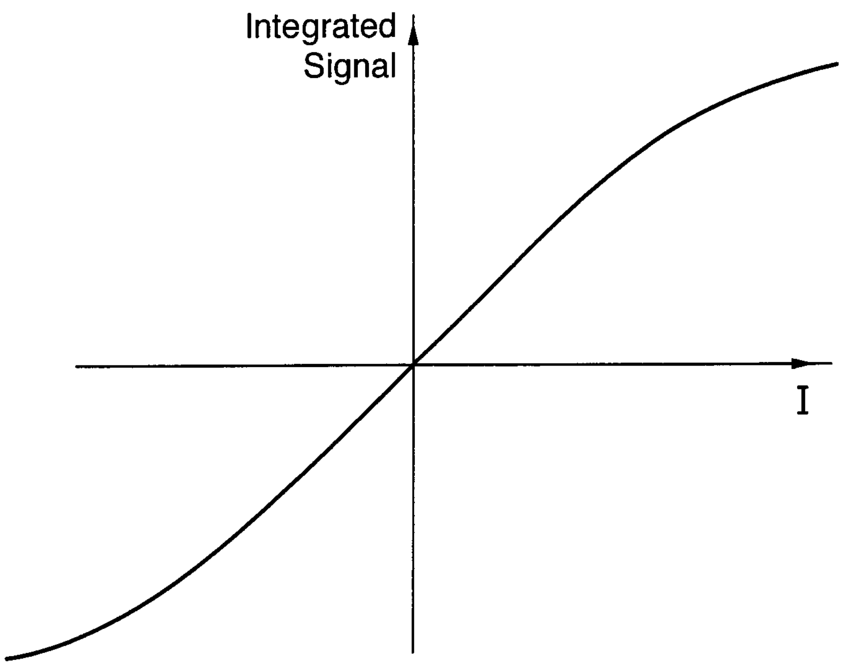
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-40
-30
-20
-10
0
10
20
30
40
Current /mA

Fig.5.


Integrated Signal
I

INTERNATIONAL SEARCH REPORT

International Application No
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A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 B61L1/18 G01R19/20 G01R15/18

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01R B61L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

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C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 356 171 A (UNIV BRITISH COLUMBIA) 28 February 1990 (1990-02-28) abstract; claims 4-6; figures column 2, line 14 - line 25 column 3, line 23 - line 51 column 4, line 49 -column 5, line 8 column 6, line 10 - line 28 ---	1-10
X	CH 419 338 A (UNIV. SOUTHAMPTON ET AL.) 28 February 1967 (1967-02-28) page 2, line 111 - line 118 page 3, line 15 - line 21; figures ---	1-10
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[X] Further documents are listed in the continuation of box C.

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INTERNATIONAL SEARCH REPORT

International Application No
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	RIPKA P ET AL: "PRECISE DC CURRENT SENSORS" PROCEEDINGS OF THE INSTRUMENTATION AND MEASUREMENT TECHNOLOGY CONFERENCE (IMTC),US,NEW YORK, IEEE, 4 June 1996 (1996-06-04), pages 1479-1483, XP000642756 ISBN: 0-7803-3313-6 figure 5 ---	1-10
X	DE 39 40 932 A (DOERR ULRICH ;PERSCH RAINER (DE); SCHMIDT WOLFGANG (DE)) 13 June 1991 (1991-06-13) abstract; figures column 2, line 57 -column 3, line 8 ---	1-10
A	US 5 501 417 A (CAPAN RONALD R) 26 March 1996 (1996-03-26) abstract; figures 4,6-9 ---	1
A	FR 2 731 974 A (ROBERT JEAN) 27 September 1996 (1996-09-27) abstract; figure 3 -----	1

1

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/GB 00/01398

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
EP 0356171	A	28-02-1990	US	4914381 A	03-04-1990
			JP	2124470 A	11-05-1990
CH 419338	A		NONE		
DE 3940932	A	13-06-1991	NONE		
US 5501417	A	26-03-1996	US	5501416 A	26-03-1996
			AU	685928 B	29-01-1998
			AU	2026295 A	25-01-1996
			CA	2149841 A	16-01-1996
			US	5622339 A	22-04-1997
			US	5791602 A	11-08-1998
FR 2731974	A	27-09-1996	NONE		