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(54) Title: SENSOR FOR CURRENT MEASUREMENT AND ELECTRICITY METER
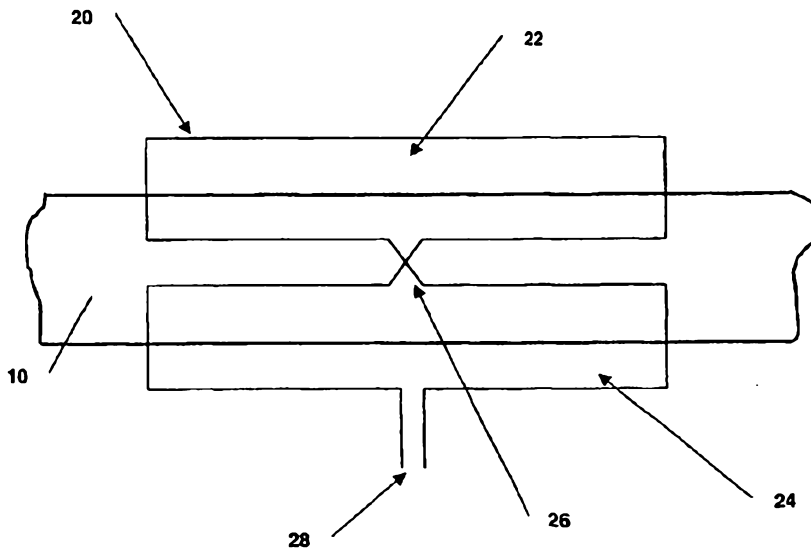
(57) **Abstract:** An electronic circuit is formed on a printed circuit board which is configured as a current to voltage converter using
a printed circuit track as a sensor (20), the sensor being placed in parallel with a primary current carrying conductor, for example,
a bus bar (10). The sensor (20) comprises two sensing coils (22, 24) arranged in a 'figure-of-eight' arrangement with a cross-over
region (26). The sensor (20) has an output (28) connecting to processing circuitry. Current flowing through the bus bar (10) induces
a magnetic field which is detected by the sensing coils (22, 24), the magnetic field being directly related to the magnitude of the
current flowing through the bus bar (10).

IMPROVEMENTS IN OR RELATING TO CURRENT MEASUREMENT

The present invention relates to improvements in or relating to current measurement.

5   Any discussion of the prior art throughout the specification should in no way be considered as an admission that such prior art is widely known or forms part of common general knowledge in the field.

In electricity meters, there are several well known techniques for measuring the current. However, in some techniques, unwanted induced voltages in connections to

10   the metering element produce undesired effects.

EP-A-0710844 teaches of a multi-coil gradiometric meter arrangement. WO 8701812 teaches of a current transformer for a static electricity counter.

It is therefore an object of the present invention to overcome or ameliorate at least one of the disadvantages of the prior art, or to provide a useful alternative.

15   In accordance with one aspect of the present invention, there is provided a current sensing arrangement comprising:-

a substantially flat current carrying conductor;

a printed circuit board placed contiguous with and lying in a plane parallel to the conductor; and

a printed circuit track formed on the printed circuit board and located on a surface thereof remote from the conductor, the printed circuit track comprising a sensor having two sensing loops arranged symmetrically about the conductor, the sensing loops being arranged symmetrically about the conductor, the sensing loops

5   being arranged in a 'figure-of-eight' configuration.

The sensing loops can be of equal dimensions.

In accordance with another aspect of the present invention, there is provided an electricity meter including a current sensing arrangement as described above.

The electricity meter may be a single phase meter or a three-phase meter.

10   Advantageously, the printed circuit track is formed on a printed circuit board carrying processing circuitry for the electricity meter.

Unless the context clearly requires otherwise, throughout the description and the claims, the words 'comprise', 'comprising', and the like are to be construed in an inclusive sense as opposed to an exclusive or exhaustive sense; that is to say, in the

15   sense of "including, but not limited to".

For a better understanding of the present invention, reference will now be made, by way of example only, to the accompanying drawing, the single figure of which illustrates a current sensing arrangement in accordance with the present invention.

20   A current carrying conductor in free space has a magnetic field around the conductor which is centred on the conductor. At any fixed point in space the magnitude of the magnetic field is directly proportional to the magnitude of the current flowing in the conductor. If a second conductor is placed alongside the current carrying conductor, the magnetic flux from the current carrying conductor

25   loop will link to the second conductor loop. If the current in the current carrying conductor, and thus its magnetic field, is time varying, a voltage is induced in the second conductor loop proportional to the rate of change of the magnetic flux and thus the alternating part of the current in the first conductor. This is a basic law of electromagnetic induction. This principle is used as a measure of the current flow in

30   a conductor.

In Figure 1, a portion of a current carrying bus bar 10 is shown. A sensor 20 is arranged to overlie the bus bar 10, the sensor 20 comprising a _____

sensing loop in the shape of a 'figure-of-eight' which provides two sensing loops 22, 24 having a central cross-over region 26. Each sensing loop 22, 24 comprises a rectangular sensing loop of equal dimensions which are connected in series in the 'figure-of-eight' configuration. Each

5   sensing loop 22, 24 is approximately 50mm long (extending in the direction parallel to the bus bar 10) and approximately 30mm wide (from the cross-over region 26 to the outer edge). The sensor 20 is formed on a PCB (not shown) and is connected to an amplifier (not shown) by means of output 28.

10   The 'figure-of-eight' configuration reduces the effect of any externally induced interference. By placing the sensing loops 22, 24 in a symmetrical arrangement astride the bus bar 10, there are also has benefits in terms of sensing the current flow. The sensing loops 22, 24 are in opposition for uniform magnetic fields but they are in addition for the

15   magnetic field round the bus bar 10. The sense of the sensor 20 is opposite on opposite edges of the bus bar 10, as is the direction of the magnetic field. Thus, the output of the sensing loops 22, 24 is nearly doubled compared with the situation where only one loop is employed.

The output 28 may be connected to an amplifier (not shown)

20   which operates as a current to voltage signal conditioning stage. Alternatively, the output may be connected to a high impedance voltage amplifier (also not shown). The current to voltage signal conditioning stage allows control of the high frequency sensitivity of the sensing loops 22, 24. Equipping the high impedance voltage amplifier with an

25   appropriately selected first order filter characteristic may be used to deal with the increasing sensor loop output with rise in frequency.

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Additionally, at high frequencies, the self inductance of the
sensing loops 22, 24 will play a part. Such self inductance appears as an
inductance in series with the connection from the sensing loops 22, 24 to
the current to voltage amplifier input. The presence of this inductance

5   causes the current from the sensing loops 22, 24 into the amplifier to
become constant with frequency as the impedance of the series inductance
rises with frequency at the same rate as the induced voltage.

A number of effects can contribute to the variation of
output/current sensing performance over temperature. The ones which

10   are currently recognised are as follows:

1.   Variations in the geometry of the current carrying bus bar and
      the printed circuit board, i.e. length, spacing, etc, due to
      thermal expansion

2.   In the short circuit sense loop arrangement (with the current to

15   voltage converter amplifier) the temperature coefficient of
      resistance of the copper printed circuit track.

It is anticipated that both the above temperature effects will appear
as temperature dependent variations in the gain (scale factor) of the output
and, as such, may be readily compensated by temperature sensors in close

20   contact with the PCB track. It is not necessary for the temperature sensor
to be in contact with the bus bar 10, hence simple voltage isolation can be
maintained.

As noted above, the magnetic field at any point round the current
carrying bus bar 10 is proportional to the current flowing in the bus bar.

25   The output voltage of the PCB track (secondary) is proportional to the
rate of change of flux linking it. This results in a 90° lagging phase shift
between the primary current of the bus bar 10 and the voltage induced in

the secondary. This occurs because of the ability of the primary circuit, in

this case, the current in the bus bar 10, totally to dictate the magnetic

conditions around the bus bar 10. The back emf generated by the

inductance of the bus bar primary from the magnetic field produced by the

5   current flowing in it does not impede the flow of current in the bar in any

significant way. Neither does the secondary circuit have significant

inductive reactance in order to introduce any phase difference at the

supply frequency between the secondary voltage and current in it.

Thus, if the instantaneous primary current i is

10                          $$i = I_{max} \sin \omega t \qquad\qquad\qquad (1)$$

where I_{max} is the sinusoidal peak current in amps;

ω is the supply angular frequency in radians/sec; and

t is the time in seconds

The instantaneous flux ϕ linking the PCB track secondary loop

15   area from the instantaneous current i is

$$\phi = \Phi_{max} \sin \omega t \qquad\qquad\qquad (2)$$

where Φ_{max} is the peak total magnetic flux from the bus bar primary

linking the secondary loop in Webers

Then rate of change of change of the flux linking the secondary

20   loop area is

$$\frac{d\phi}{dt} = \Phi_{max} \omega \cos \omega t \qquad\qquad\qquad (3)$$

Thus the voltage e induced in the secondary loop is

$$e = n\Phi_{max} \omega \cos \omega t \qquad\qquad\qquad (4)$$

where n is the number of turns on the secondary loop ($n = 2$ in this case)

25   Therefore, the voltage induced in the secondary loop is sinusoidal

but phase shifted by 90° with respect to the primary current.

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The appearance of the term ω before the cosine in equation (4) indicates that the induced voltage e is proportional to frequency and thus the sensor output will rise at 6dB per octave according to the frequency of the primary current.

5   Operated into a short circuit, such as the current to voltage converter would appear, the current will depend on the open circuit voltage as defined above and also on the total resistance of the secondary loops. It is anticipated that the magnetic coupling will be sufficiently loose such that the current in the secondary loop has little effect on the

10   magnetic field linking it from the bus bar primary.

Thus, to a first approximation, the output of the current to voltage converter will be

$$E = -k \frac{n\Phi_{max}\,\omega\cos\omega t}{r} \qquad\qquad (5)$$

where E is the output voltage of the current to voltage converter in volts;

15   k is the current to voltage conversion ratio of the converter (volt/amp) and the negative sign indicates the phase inversion of such a converter; and

r is the total resistance of the loops in ohms

The above explanation avoids one critical aspect, namely, that of

20   the total flux linkages. Basic magnetic theory only defines analytically the magnetic field from conductors of infinitely small cross section and of infinite length. The field at a point on a plane normal to a current carrying wire is defined as

$$B = \mu_0 \frac{1}{2\pi r} \qquad\qquad (6)$$

25   where B is the magnetic flux density in Tesla;

μ_0 is the permeability of free space in Henrys/metre;

I is the current in the conductor in amps; and

r is the radius from the conductor in metres

Thus the magnitude of the field is inversely proportional to the

5   radius from the conductor. However, the current in the case of the bus bar

primary will be substantially uniformly distributed across its cross

sectional area. This spatially distributed current produces a spatially

distributed magnetic field. A full treatment of the magnetic field

produced by a current distributed in space is complex and is currently

10   beyond the scope of this specification.

However, an 'order of magnitude' calculation may be performed

as described below.

In order to calculate the voltage induced in a loop of known area

one must know the total flux linking the loop. To obtain an estimate for

15   the practical case, one may assume that the bus bar is of infinitely small

cross section.

Following the above approach one may calculate the integral of

the curve for the decay of field with distance from the bus bar, between

the two distances equivalent to the dimensions of the parallel parts of the

20   sense loop radially from the bus bar. This gives the value of the area

under the field versus distance decay curve in Tesla metres. Multiplying

by the dimension of the sense loop parallel to the bar gives a result in

Tesla meter^2, or Webers (Wb), the total flux. This value is used in

equation (2) above. The fact that two loops sense this flux equally

25   doubles the total flux and the resulting voltage.

For a bus bar approximately 15mm wide and approximately 2mm

thick, the calculation shows a flux of approximately 2μWb per loop

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making a total flux of approximately 4μWb. This, of course, is the rms

value and should be multiplied by √2 to obtain the peak value for use in

equation (2) above.

Using the rms value of flux and the supply angular frequency, one

5   can calculate the approximate net rms voltage induced in the loop

$$E = 4.10^{-6}\omega = 1.25\text{mV} \text{ for a 50Hz supply frequency.}$$

The output voltage of the secondary conductor loop follows the

same rules when the primary bus bar primary current is non-sinusoidal. A

situation which must be considered here is one where the primary current

10   consists only of a half wave of the supply waveform (half wave

rectification).

In the above situation, where the inductances of the loops are not

significant, the output voltage of the secondary is still proportional to the

rate of change of flux which, in turn, is proportional to the rate of change

15   of primary current. Thus, for the half wave rectified condition, the

secondary output voltage is that of a gated cosine wave. Here, the output

voltage follows the rate of change of the sine wave while it is present, but

exhibits an instantaneous transition to or from zero as the half wave

rectified current meets or leaves the zero current line.

20   As mentioned previously, the output from the secondary is directly

proportional to the supply frequency as well as the magnitude of the

primary current. Thus the output will require correction for supply

frequency deviations from the calibration frequency. The sensitivity to

frequency also applies to the harmonics of the primary current.

25   For a sinusoidal primary current the sensed voltage is directly

proportional to the magnitude of the primary current. However, following

from the above the output signal from the secondary in the case of a non-

sinusoidal primary current requires particular treatment if the true root mean square current is to be ascertained. The 'rate of change' coupling produces a situation where the harmonic content of the signal rises at 6dB per octave. The processing of the signal therefore needs to take this into

5   account.

The most obvious approach to signal processing is to convert the signal to digital format and to apply a Fourier transform to the signal to transfer it to the frequency domain. There a filter may be applied to the harmonics following which the true root mean square value of the

10   fundamental and the harmonics may be computed.

The above task may be undemanding for many digital signal processing circuits currently on the market, most of which are aimed at high speed 'real time' processing of large amounts of data. Extreme speed is probably not necessary in this situation and thus it is possible that

15   the processing may be carried out by the microprocessor which is almost certainly already part of the design.

The method of the present invention has the following advantages:

•   simplicity

•   possible implementation on the electronics PCB

20   •   low cost

•   inherent isolation from the supply voltage

•   easy adaptation to a three-phase system

THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:-

1.   A current sensing arrangement comprising:-

a substantially flat current carrying conductor;

a printed circuit board placed contiguous with and lying in a plane parallel to the conductor; and

a printed circuit track formed on the printed circuit board and located on a surface thereof remote from the conductor, the printed circuit track comprising a sensor having two sensing loops arranged symmetrically about the conductor, the sensing loops being arranged in a 'figure-of-eight' configuration.

2.   An arrangement according to claim 1, wherein the sensing loops are of equal dimensions.

3.   An arrangement according to claim 1 or 2, wherein the sensing loops are substantially rectangular.

4.   An electricity meter including a current sensing arrangement according to any one of the preceding claims.

5.   A meter according to claim 4, comprising a single phase meter.

6.   A meter according to claim 4, comprising a three-phase meter.

7.   A meter according to any one of claims 4 to 6, wherein the printed circuit track is formed on a printed circuit board carrying processing circuitry for the electricity meter.

8.   A current sensing arrangement substantially as herein described with reference to any one of the embodiments of the invention illustrated in the accompanying drawing.

9.   An electricity meter substantially as herein described with reference to any one of the embodiments of the invention illustrated in the accompanying drawing.

DATED this 28th day of March, 2003
BALDWIN SHELSTON WATERS
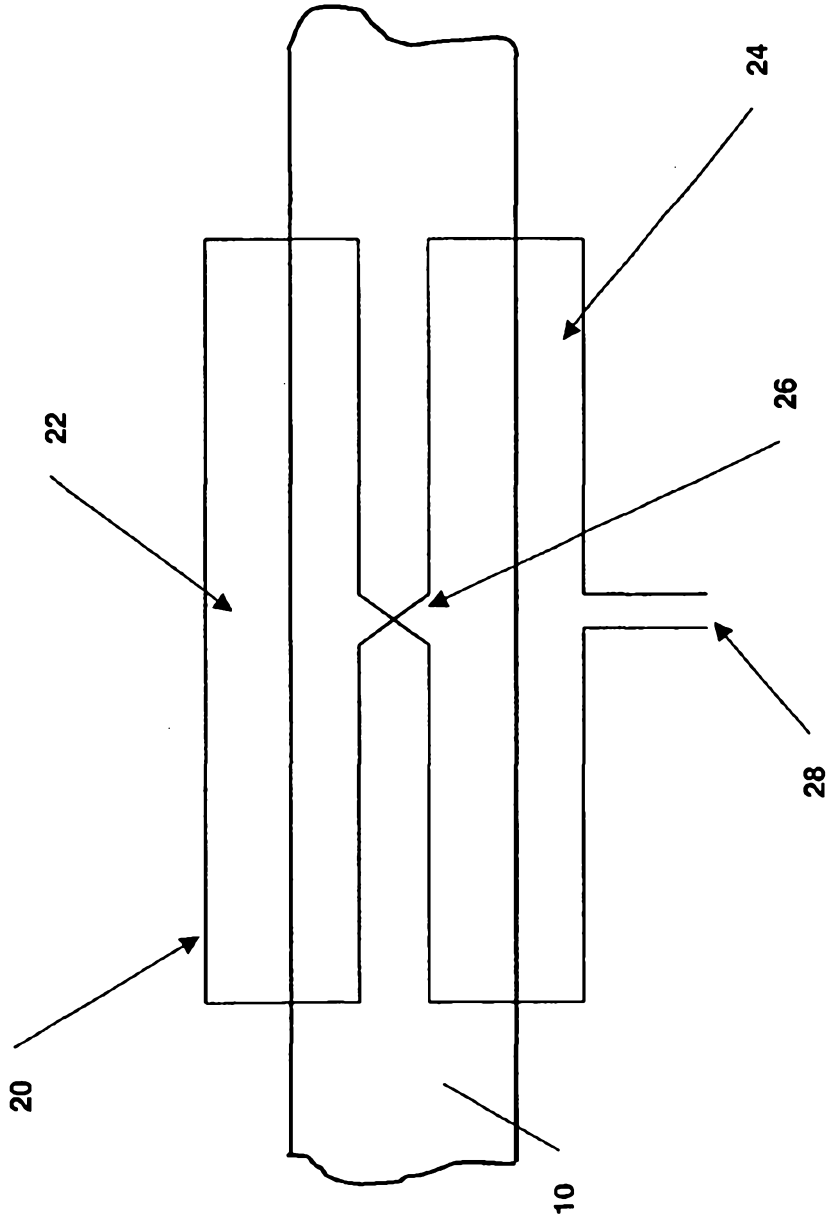Attorneys for: SIEMENS METERING LIMITED

Fig. 1