Oct. 13, 1970 P. N. MILJANIC 3,534,247

CURRENT TRANSFORMER WITH INTERNAL ERROR COMPENSATION

Filed May 15, 1968 2 Sheets-Sheet 1

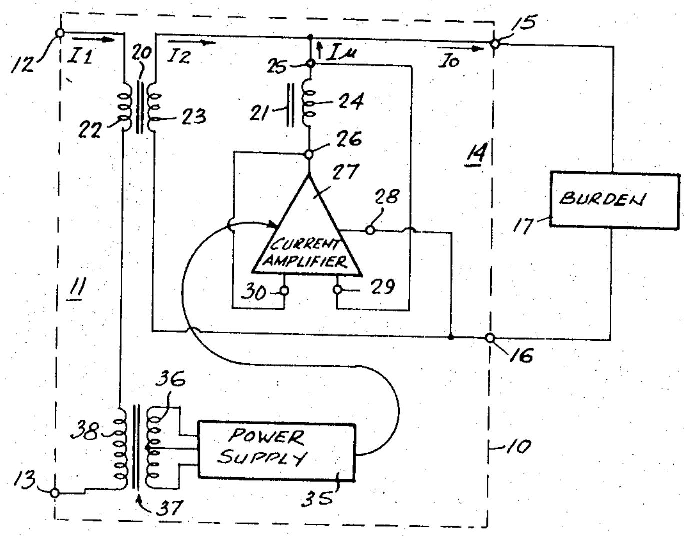

FIG. I.

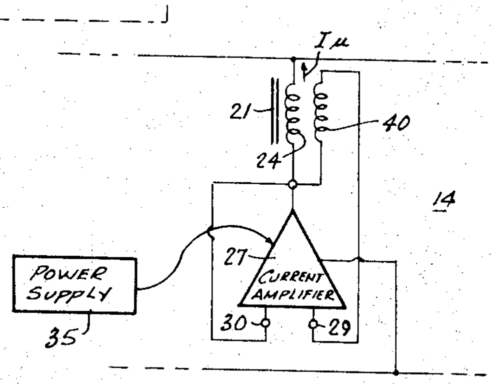

FIG. 2.

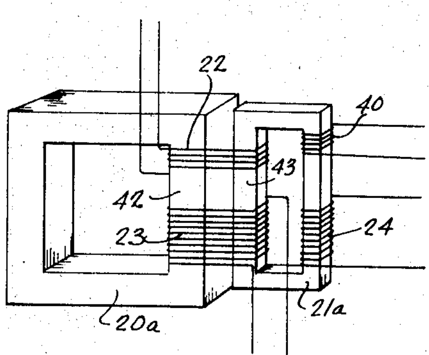

FIG. 3.

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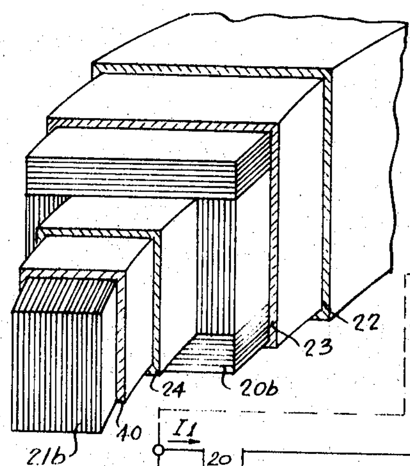

FIG. 4.

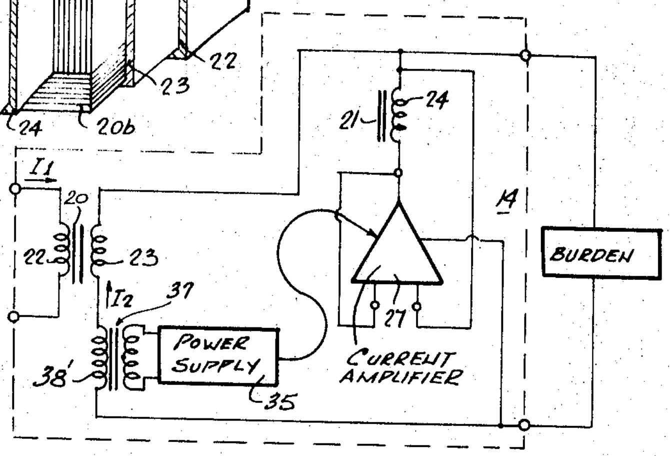

FIG. 5.

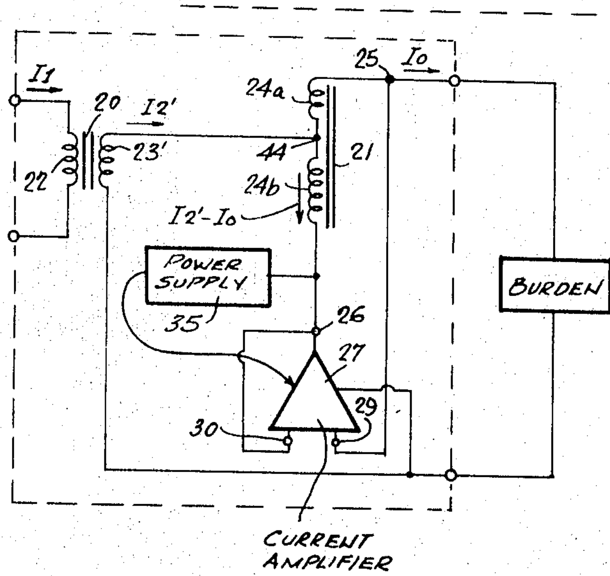

FIG. 6.

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CURRENT TRANSFORMER WITH INTERNAL ERROR COMPENSATION

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Int. Cl. G05f 7/00
U.S. Cl. 323—48 10 Claims

ABSTRACT OF THE DISCLOSURE

Due to magnetizing losses in the working core of a current transformer, the relationship between currents in the primary and secondary windings does not correspond accurately to the turns ratio. To correct for such inaccuracy, an additional core is provided for sensing the magnetic flux corresponding to the magnetizing losses. A further winding linking this core is connected in parallel with the secondary winding of the current transformer, and a feedback amplifier supplies a current through this further winding, which current creates zero residual flux in the sensing core. The power required for such correction circuit is derived from the actual currents or portions of currents forming the ratio, either through an auxiliary power supply transformer connected in series with the primary or the secondary winding of the current transformer or through the further winding, which in this case is split into two sections and acts together with the additional core as both an ampere turn sensing device and a current auto transformer.

The resulting corrected current transformer has only two input and two output terminals and thus forms a passive device requiring no auxiliary external source of power.

The present invention relates to a current transformer with internal error compensation.

The error of a current transformer, which is due primarily to the magnetizing losses in the working core, is proportionately very large when the primary and secondary windings impose only a few ampere turns on the core, as is particularly the case in the bushing-type. In order to keep the magnetizing losses low, the use of very large, high permeability cores has been proposed. Biasing or higher frequency excitation techniques have also been proposed, but all these expedients tend to be either cumbersome or expensive or both.

Features of the invention will be apparent from the following specific description which is provided by way of example only. In the accompanying drawings:

FIG. 1 shows a first embodiment of a current transformer circuit according to the invention;

FIG. 2 is a fragment of FIG. 1 showing a modification;

FIG. 3 is a diagrammatic view showing an example of a transformer used in the circuit of FIG. 1;

FIG. 4 is another example of a transformer for use in the circuit according to FIG. 1;

FIG. 5 is a second embodiment of a current transformer circuit; and

FIG. 6 shows a third embodiment of a current transformer circuit according to the invention.

Referring to FIG. 1, the current transformer circuit **10** comprises an input circuit **11** connected to input terminals **12** and **13** and an output circuit **14** connected to output terminals **15** and **16**. A burden **17**, which may be an ammeter and which does not form part of the invention, is shown connected to the output terminals **15** and **16**.

The current transformer **10** includes two magnetic cores, namely a working core **20** and a sensing core **21**.

A primary winding **22** connected to the input terminals **12** and **13** creates a magnetic flux in both the working core **20** and the sensing core **21**, and similarly a secondary winding **23** connected across the output terminals **15** and **16** links both cores **20** and **21**. A further winding **24**, which has the same number of turns as the secondary winding **23**, links only the sensing core **21**. Two examples for the physical arrangement of the two cores **20** and **21** and the three windings **22** to **24** are described below in connection with FIGS. 3 and 4.

One end **25** of the further winding **24** is connected to the output terminal **15**, while the other end of the winding **24** is connected to a first output terminal **26** of a current amplifier **27**, the second output terminal **28** of which is connected to the output terminal **16** of the output circuit **14**. Thus, the series connection of the winding **24** and the current amplifier **27** is connected in parallel with the secondary winding **23** and with the burden **17**. A control input terminal **29** of the current amplifier **27** is connected to the end **25** of the winding **24**, while the other control input terminal **30** of the amplifier **27** is connected to the other end of the winding **24** and thereby to the output terminal **26** of the amplifier **27** itself. Ideally, the current amplifier **27** has an infinite input impedance and infinite gain. In more precise terms, the transconductance between the input voltage and the output current of the amplifier **27** ideally approaches infinity.

The power required for the amplifier **27** is taken from a power supply **35** the input of which is formed by the secondary winding **36** of a power supply transformer **37**. In the embodiment of FIG. 1, the primary winding **38** of the power supply transformer **37** is connected in series with the primary winding **22** of the input circuit **11**.

To describe the principle of operation of the current transformer circuit shown in FIG. 1, it is assumed that the input circuit **11** carries a primary current I1, the secondary winding **23** carries a secondary current I2, the turns ratio between the primary and secondary windings **22** and **23** is *l:n* and the output current I*o* is the current flowing through the burden **17**. The relationship between the primary current I1 and the secondary current I2 is given by the following equation:

$$I2=\frac{I1}{n}-I\mu \qquad (1)$$

wherein $I\mu$ is the magnetizing current covering the losses in the working core **20**. No such losses occur in the sensing core **21**, since the operation of the circuit is such as to create zero residual flux in this core, as will be understood from the following description.

The residual zero magnetic flux in the sensing core **21** can be conceived as composed of a positive magnetic flux $+F\mu$ and a magnetic flux $-F\mu$ of equal value and opposite phase. The positive magnetic flux $+F\mu$ corresponds to the difference between the ampere-turns created by the primary current I1 through the primary winding **22** linking the sensing core **21** and the ampere-turns created by the secondary current I2 through the secondary winding **23** linking the sensing core **21**, and therefore equals the magnetizing losses mentioned above. This positive magnetic flux $+F\mu$ induces a voltage across the winding **24** which voltage appears at the input terminals **29** and **30** of the amplifier **27** which in turn feeds a current through the winding **24**. Due to this feedback connection of the amplifier **27** and due to the fact that the amplifier has a very high gain, ideally infinite gain, the current through the winding **24** will create the above-mentioned negative flux $-F\mu$ so that the residual flux in the sensing core **21** approaches zero and thus the voltage induced in the winding **24** similarly approaches zero. Since the number of turns of the winding **24** equals that of the secondary winding **23**, the current creating the negative magnetic flux $-F\mu$ is equal to the magnetizing current $I\mu$. If the number of turns of the winding **24** were smaller than that of the secondary winding **23**, the same result could be achieved by a resistance network appropriately dividing the current flowing through the winding **24**.

The resulting current Io led to the burden **17** equals the sum of the secondary current $I2$ and the magnetizing current $I\mu$, giving

$$Io=I2+I\mu \quad (2)$$

and with respect to Equation 1

$$Io=I1/n \quad (3)$$

so that the output current Io is proportional to the primary current I divided by the turns ratio n between the secondary and primary windings **23, 22**, as desired.

The power required for the current amplifier **27** is equal to the burden voltage across the output terminals **15** and **16** multiplied by the magnetizing current $I\mu$ and is usually below one watt. In the embodiment of FIG. 1, the power supply **35** is coupled to the input circuit **11** and forms part of the current transformer circuit **10**.

In this circuit the winding **24** serves two functions: firstly it carries the output current of the amplifier **27**, which creates the negative magnetic flux $-F\mu$ in the sensing core **21**, and secondly it senses the residual flux in the sensing core **21** to supply the input voltage for the amplifier **27**. Due to the finite gain of the amplifier **27**, and also due to the voltage drop across the winding **24**, the current $I\mu$ added to the secondary current $I2$ is slightly smaller than the magnetizing current.

In the modified circuit according to FIG. 2, an auxiliary winding **40** with any convenient number of turns is provided to link only the sensing core **21** and is connected to the amplifier input terminals **29** and **30**. In this embodiment, the detection of the residual flux in the sensing core **21** is performed by the auxiliary winding **40** and the negative magnetic flux $-F\mu$ is created by the winding **24**. This functional separation reduces current loss in the winding **24** and also avoids voltage loss across the input terminals **29** and **30** of the amplifier **27** due to the voltage drop at the current carrying winding **24**.

FIG. 3 shows a first example for the physical embodiment of the magnetic cores and the arrangement of the various windings thereon. According to this example, both the working core **20** and the sensing core **21** take the shape of annular laminated magnet cores **20***a* and **21***a* disposed adjacent each other and separated from each other by an air gap sufficient to avoid magnetic cross-coupilng. Usually, the cross-section of the sensing core **21***a* will be much smaller than that of the working core **20***a*. The primary and secondary windings **22** and **23** are wound around the adjacent limbs **42** and **43** thereby linking both cores **20***a* and **21***a*, whereas the further winding **24** and—if present—the auxiliary winding **40** are wound only around the sensing core **21***a*.

In the second example shown in FIG. 4, the working core and the sensing core take the shape of toroidal laminated magnetic cores **20***b* and **21***b*, with the sensing core **21***b* nested inside the working core **20***b*. FIG. 4 shows only a short part of the complete torus. The primary and secondary windings **22** and **23** are wound on the exterior of the working core **20***b*, thereby linking the working core **20***b* as well as the sensing core **21***b*. The further winding **24** and—if present—the auxiliary winding **40** are wound around the exterior of the sensing core **21***b* but are disposed inside the working core **20***b*, thereby only linking the sensing core **21***b*. A transformer according to the example of FIG. 4 is described in more detail in U.S. Pat. No. 3,153,758 to N. L. Kusters et al. issued Oct. 20, 1964.

The second embodiment of a current transformer circuit according to the invention shown in FIG. 5 differs from the one shown in FIG. 1 in that the primary winding **38′**

of the power supply transformer **37** is disposed in the output circuit **14** and is connected in series with the secondary winding **23** of the current transformer. In this connection, the power supply transformer **37** imposes an additional load on the current transformer and therefore increases the current $I\mu$ due to increased magnetizing losses, which current has to be furnished by the further winding **24**. The circuit of FIG. 5, however, has an advantage from the design point of view. The size of the power supply transformer **37** can be reduced, because its primary winding **38′** carries the secondary current $I2$ rather than the much heavier primary current $I1$.

Instead of using one further winding **24** for both creating the negative magnetic flux in the sensing core **21** and sensing the residual flux in this core, the modification of FIG. 2 could be applied in the circuit of FIG. 5 using an auxiliary sensing winding **40**. As is obvious, the physical embodiment of the working core **20** and the sensing core **21** and the arrangement of the windings on these cores can be made according to the example shown in FIG. 3 or to that shown in FIG. 4.

In the circuits of FIGS. 1 and 5, the amplifier output power is positive, i.e. the amplifier is supplying power that is added to the power supplied through the secondary winding **23**. In a third embodiment shown in FIG. 6, the amplifier output power is negative, as will be understood from the following description.

According to FIG. 6, the turns ratio between the secondary and the primary windings **23′** and **22** is n' which is slightly smaller than the nominal transformer ratio n. Hence the secondary current $I2'$ is larger than the corresponding secondary current $I2$ in the circuits of FIG. 5:

$$I2'=I2\left(\frac{n}{n'}\right) \quad (4)$$

The further winding is split into two sections **24***a* and **24***b* connected in series with each other, and the secondary winding **23′** is connected to the junction point **44** of the two sections **24***a* and **24***b*. The number of turns of the section **24***b* equals that of the secondary winding **23′**. The total number of turns of both sections **24***a* and **24***b* corresponds to the nominal transformer ratio, leaving for the section **24***a* a number of turns which is related to the number of turns of the primary winding **22** by the ratio $(n-n')$. The power supply **35** is directly connected to the output terminal **26** of the amplifier **27**, thereby forming together with the amplifier **27** an active impedance which absorbs the portion of the secondary current $I2'$ that exceeds the desired output current Io. In other words, the power is supplied by means of the current $I2'-Io$ flowing through the winding section **24***b* to the power supply **35**. This assumes that the current $I2'$ is without error and that there are no voltage drops due to internal impedances. If the current $I2'$ is in error, the amplifier **27** will force an additional current into the section **24***b* to correct for such error.

The control mechanism of the winding **24***a*, **24***b* which acts as an auto-transformer in combintaion with the amplifier **27** and the power supply **35** is basically the same as in the circuit according to FIG. 5. As can easily be understood, the positive magnetic flux $+F\mu$ in the sensing core **21** has not changed, since the magnetization of the working core **20** is assumed to be the same which results in the same magnetizing losses. The negative magnetic flux $-F\mu$ created by the further winding sections **24***a* and **24***b* can be expressed by the following equation

$$-F\mu\alpha Io(N-n')-(I2'-Io)n' \quad (5)$$

wherein the term $Io(n-n')$ represents the ampere turns in the section **24***a* and the term $(I2'-Io)n$ represents the ampere turns in the section **24***b*. By simplifying Equation 5 and also substituting in it $I2$ for $I2'$ in accordance with Equation 4, the negative magnetic flux $-F\mu$ in the sensing core **21** becomes

$$-F\mu\alpha n(Io-I2) \qquad (6)$$

or in the light of Equation 2

$$-F\mu\alpha n.I\mu \qquad (7)$$

Remembering that the turns ratio of the winding **24** in the circuit of FIG. 5 equals n, the expression given in Equation 7 also represents the negative magnetic flux created by the further winding **24** in the embodiment of FIG. 5, which flux has been explained as causing zero residual flux in the sensing core **21**.

Again and still referring to FIG. 6, instead of connecting the input terminals **29** and **30** of the amplifier **27** to the ends **25** and **26** of the winding **24**_a_, **24**_b_, an auxiliary winding **40** with any convenient number of turns can be provided as shown in FIG. 2. As before, the physical arrangement of the working and sensing cores and the various windings can be made in accordance with FIG. 3 or 4 with the additional feature of an intermediate tap on the further winding **24**.

I claim:

1. A current transformer comprising:

(a) a first core;

(b) a second core magnetically separate from said first core;

(c) a primary winding linking both said cores to create a first magnetic flux in said first core and a second magnetic flux in said second core;

(d) a secondary winding linking both said first and said second cores;

(e) output terminals for connection to an external burden and connected across said secondary winding;

(f) a further winding linking said second core, said further winding being connected across said output terminals;

(g) means for generating current through said further winding for creating in said second core a magnetic flux substantially equal and opposite to said second flux; and

(h) means for supplying power to said current generating means, said power supply means having input means connected in series with one of said windings;

(i) wherein said current generating means includes amplifier means having input means and output means, said output means being connected in series with said further winding and said output means being connected to sense any residual magnetic flux in said second core.

2. A current transformer as in claim **1**, wherein said power supply input means includes a transformer having its primary winding connected in series with one of said windings linking both said cores.

3. A current transformer as in claim **2**, wherein the primary winding of said power supply transformer is connected in series with the primary winding of said current transformer.

4. A current transformer as in claim **2**, wherein the primary winding of said power supply transformer is connected in series with said secondary winding.

5. A current transformer as in claim **2**, wherein the number of turns of said further winding is equal to the number of turns of said secondary winding.

6. A current transformer as in claim **1**, wherein said further winding includes a first section and a second section connected in series to said first section, said first section being connected in parallel with said secondary winding, and wherein said power supply input means is connected to said first section.

7. A current transformer as in claim **6**, wherein the number of turns of said first section is equal to the number of turns of said secondary winding.

8. A current transformer as in claim **1**, wherein said amplifier input means is connected across said further winding.

9. A current transformer as in claim **1**, further comprising an auxiliary winding linking said second core, and wherein said amplifier input means is connected across said auxiliary winding.

10. A current transformer as in claim **1**, wherein said second core is nested within said first core, said primary and secondary windings being wound onto said first core and said further winding being wound onto said second core.

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U.S. Cl. X.R.

324—43, 55; 336—155