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(54) **CLOSED-LOOP MAGNETORESISTIVE CURRENT SENSOR SYSTEM HAVING ACTIVE OFFSET NULLING**

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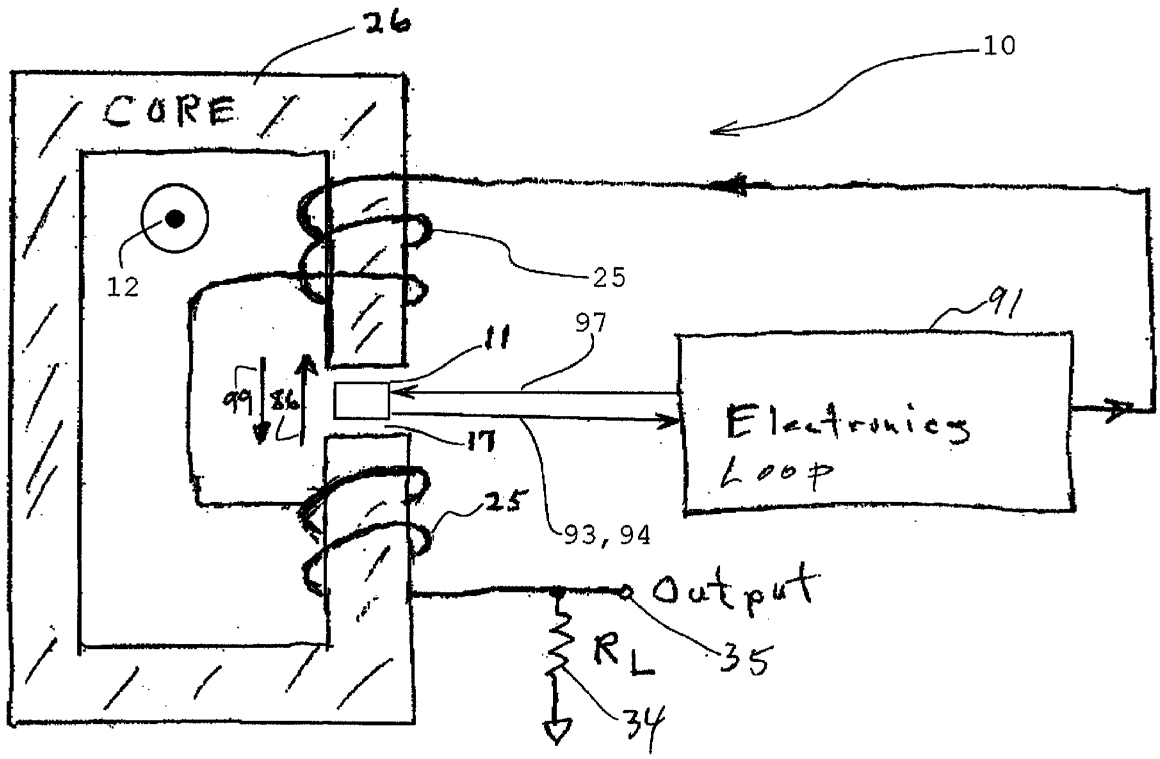
(57) **ABSTRACT**

A magnetoresistive sensor system having resistive elements changing in ohmic value in the presence of a magnetic field of a current being measured. The variant values of the elements are amplified by some electronics that inherently add offset to the resultant values. The elements themselves also add an offset. The output of the electronics is modulated and then buffered as an output. This output is demodulated and integrated. The resultant signal is fed back to the input of the electronics to null out the offsets. The output of the buffer also goes to an inductive coil that is magnetically coupled to the resistive elements to null out the magnetic field from the current being measured. The buffer output indicates the magnitude of the current being measured. An oscillator outputs a signal to actuate the modulator and the demodulator. The oscillator signal also goes to a set/reset circuit for setting and resetting the resistive elements of the magnetoresistive sensor.



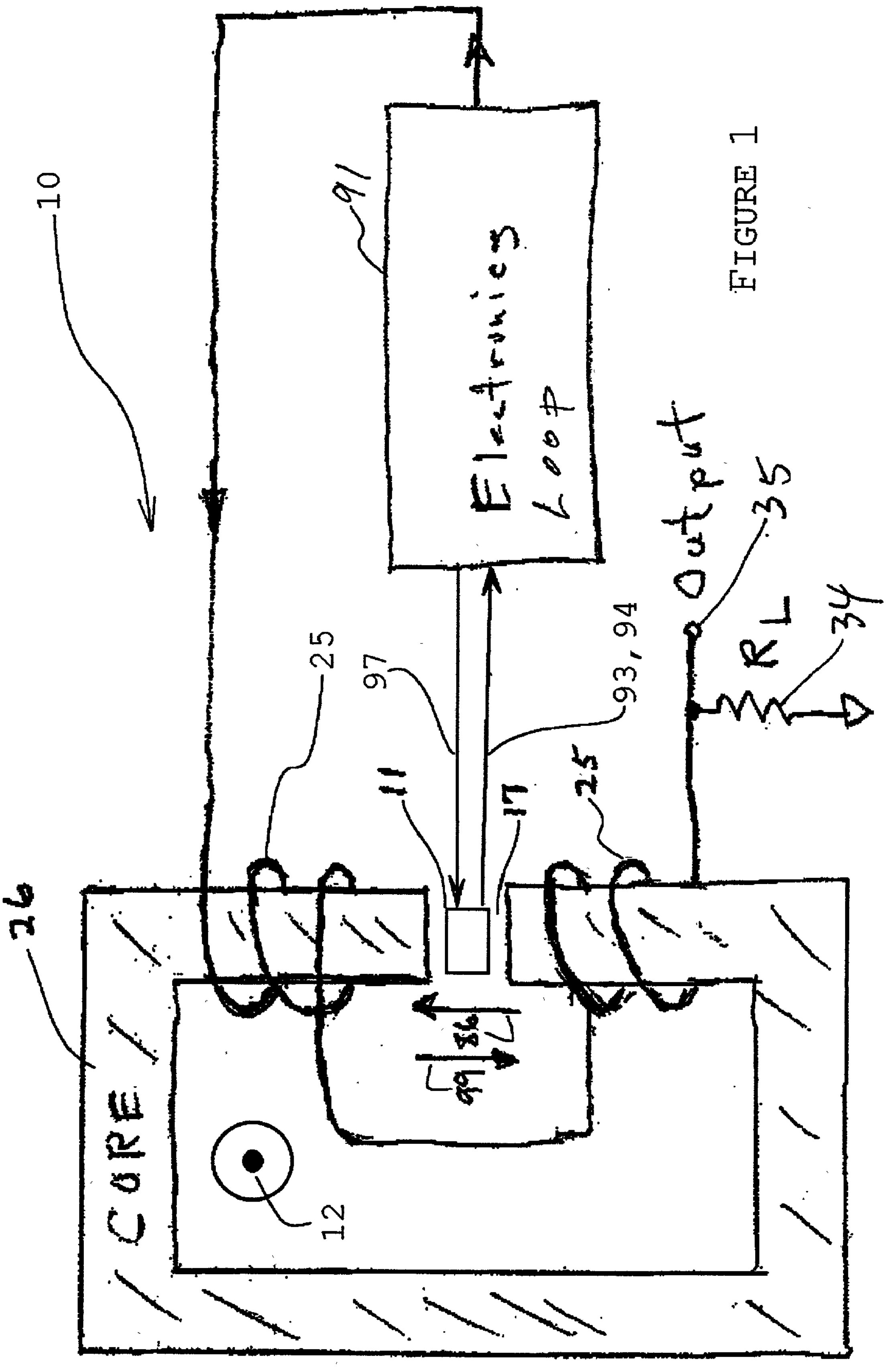

10
91
Electronics Loop
Output
35
RL
34
25
97
93, 94
11
17
25
26
36
99
CORE
12

FIGURE 1

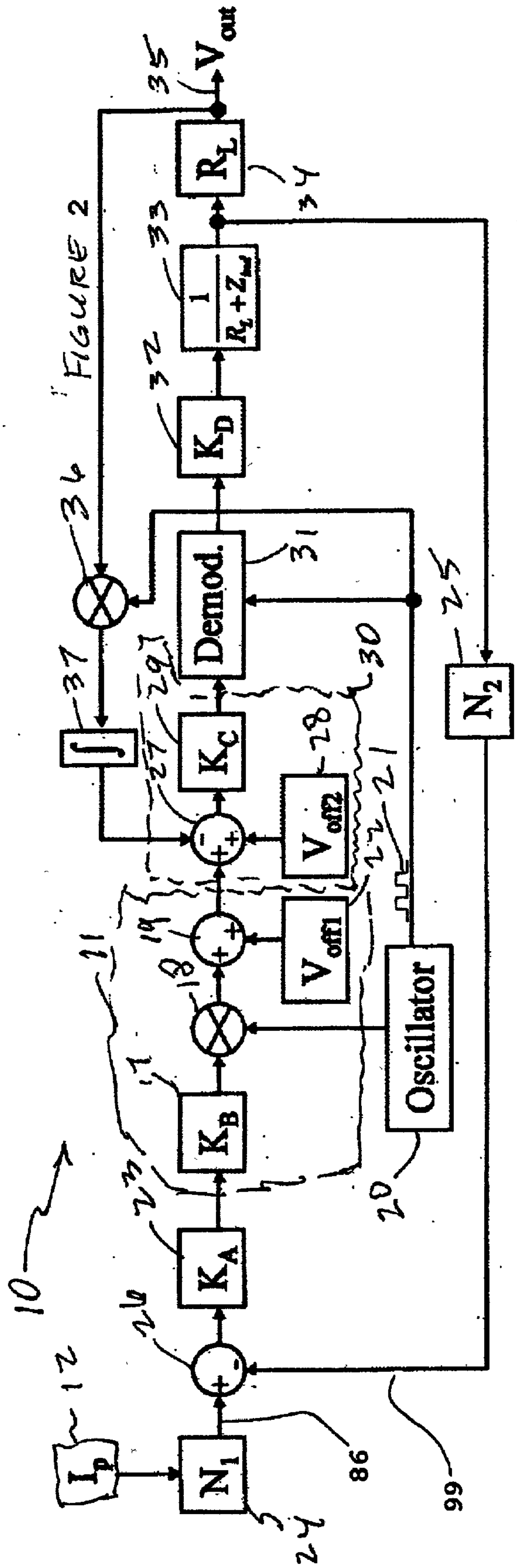


FIGURE 2
V_{out}
R_L
$\frac{1}{R_L + Z_{ind}}$
K_D
Demod.
K_C
V_{off2}
V_{off1}
Oscillator
K_B
K_A
N_1
N_2
I_p
10
11
12
17
18
19
20
21
22
23
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37
86
99

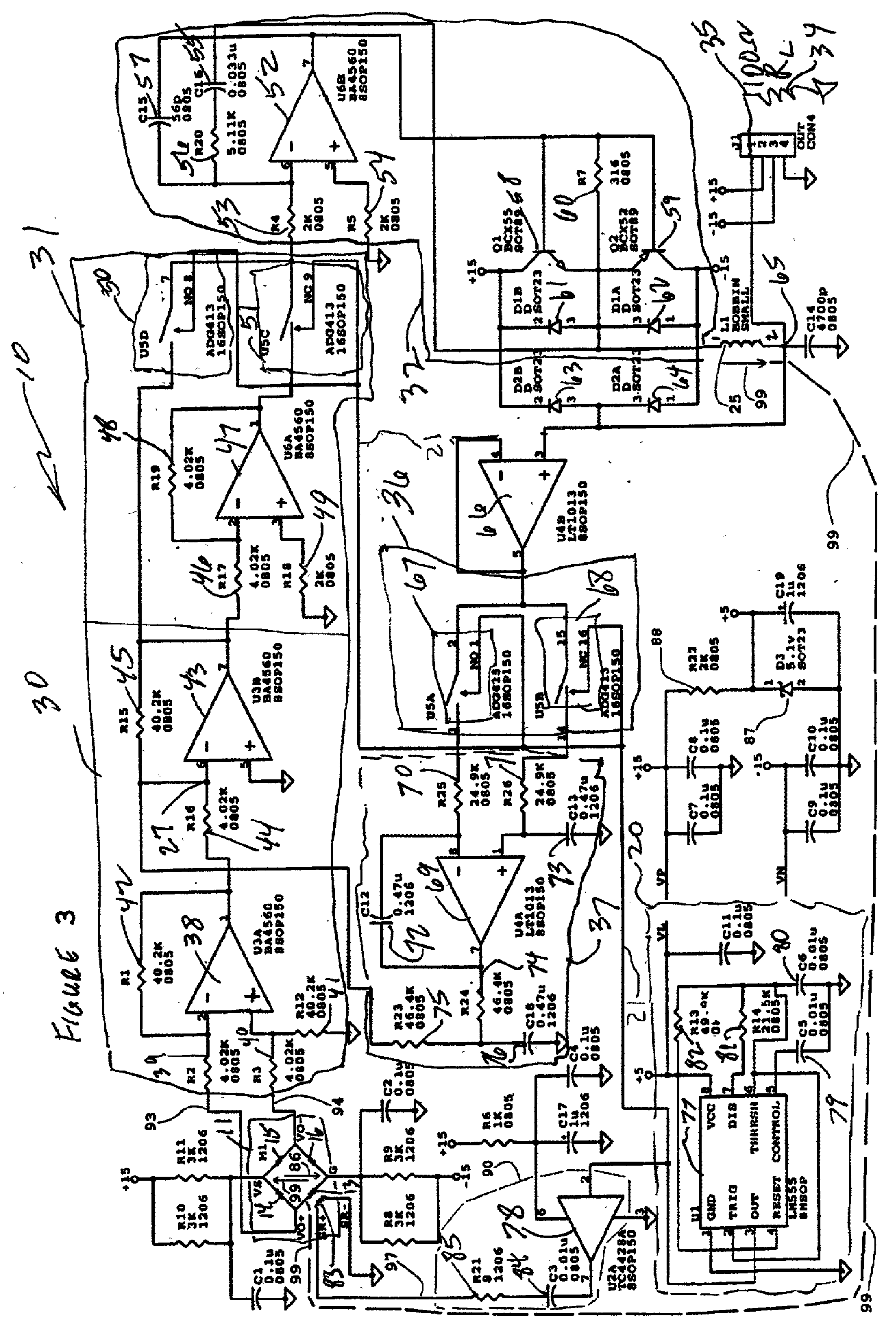

FIGURE 3

CLOSED-LOOP MAGNETORESISTIVE CURRENT SENSOR SYSTEM HAVING ACTIVE OFFSET NULLING

[0001] The invention pertains to current sensors and particularly to magnetoresistive (MR) current sensors. More particularly, it pertains to MR sensors having low offsets.

SUMMARY OF THE INVENTION

[0002] The present current sensor is a closed-loop, non-contact, fast-responding, wide-bandwidth, field nulling current sensor. This sensor reveals parameters equivalent to other closed-loop approaches such as the closed loop Hall effect current sensor in the related art. It is the use of the MR sensor having a set/reset and offset nulling loop leads to ultra low offsets and ultra low offset drifts over all conditions in current measurement. It also has very low offset drift over wide ranges of operating temperatures. Because of the ultra low offset, the sensor provides very accurate measurements of current. It has an auto-zero offset reduction circuit, which has a separate feedback path to remove offset and offset drift from the circuit. The magnetic signal and offset signals are driven to their respective nulls by independent feedback loops. The offset feedback loop is not used in Hall effect type current sensors. The transient noise and spikes caused by the set/reset circuit are greatly reduced with this new feedback scheme. The sensor has a frequency response from DC to over 150 kHz and has a response time of less than one microsecond.

BRIEF DESCRIPTION OF THE DRAWING

[0003] **FIG. 1** is an illustration of an MR closed loop current sensing system.

[0004] **FIG. 2** is a functional diagram of the MR current sensing system.

[0005] **FIG. 3** is a schematic of the MR current sensing system.

DESCRIPTION OF THE EMBODIMENT

[0006] An overview of a closed loop MR current sensor system **10** is shown in **FIG. 1**. Input primary current **12** can be in a conductor having one to N turns, where N can be any practical number. The magnetic flux **86** from current **12** of the primary current carrying conductor is concentrated by a high permeability core **26** and dropped across a gap **17** to produce a magnetic field **86**. An inductive feedback or rebalance coil **25** produces a magnetic field **99** to oppose magnetic field **86**. MR die **11** senses the difference between magnetic fields **86** and **99**. The output of MR die **11** is amplified, among other things, by an electronics loop **91**, which includes an operational amplifier electronics **30**, demodulator **31**, buffer amplifier electronics **32**, set/reset circuit **90**, modulator **36** and integrator **37**. Electronics loop **91**, along with coil **25**, drives magnetic field **86** in gap **17** to a null value with a magnetic field **99**. A path **97** provides set/reset signals to MR die **11**. Circuit **90** sets and resets or rotates the magnetic vector of MR die **11** 180 degrees at a 1 kHz rate. This technique is used to produce an ultra low offset current sensor **10**. Gap **17** is small relative to the core **26** cross-section and length to provide better accuracy and improved shielding from stray external magnetic fields.

[0007] A conceptual layout of MR sensor system **10** is shown in **FIG. 2**. System **10** has an anisotropic MR Wheatstone bridge **11** next to a conductor(s) carrying a current **12** that generates a magnetic field **86**. This magnetic field is typically concentrated across MR sensor **11** through use of a magnetic core **26**. In **FIG. 3**, MR sensor **11** is comprised of four Permalloy (NiFe) resistors **13-16** that are connected end to end, and the magnetic field **86** (B) of current **12** and **99** of rebalance coil **25** changes the resistance of resistors **13**, **14**, **15** and **16**. In the set/reset process, a high current (unrelated to the current being measured or the current being fed back) pulse is sent through the set/reset strap by a MOSFET driver **78**. This “sets” the magnetization of the Permalloy in one direction such that a positive magnetic field (generated by the conductor or feedback coil or any other field source) will cause the resistance of two resistors to increase and the other two resistors to decrease. If a pulse of equal amplitude but opposite direction is then sent through the set/reset strap, this is a “reset” condition and each resistor will change resistance opposite to the set condition. The set/reset process and the magnetization of the Permalloy are independent of the conductor with current that is being measured. Resistors **13** and **15** increase in resistance for a first direction of current **12** flow and resistors **14** and **16** decrease in the set condition. For the first direction of current **12** flow, resistors **13** and **15** decrease and resistors **14** and **16** increase in resistance in the reset condition. The resistance changes are proportional to the magnitude of the current **12** flow. Current **12** may have its magnitude measured in amperes and the magnetic field measured in Gauss. K_B **17** is a transfer function inherent to sensor **11**. Function **17** represents the effect of the magnetic field **86** of current **12** (and the field **99** generated inductive feedback coil **25**) on the resistors of sensor **11**. Modulator or multiplier **18** of **FIG. 2** is where the set/reset signal comes to sensor **11** from an oscillator **20**. The signal is a one kHz square wave **21**. The signal may be another kind of signal and/or have a different frequency. Summer **19** conceptually represents the superposition of a V_{off1} (MR offset voltage) to an output signal of sensor **11**. K_A **23** represents the transfer function for a gap in core **26**, which may be given in ampere-turns a device having N_1 **24** turns in the first winding, which is the current **12** carrying wire. N_2 **25** represents the number of turns of the second winding (inductive feedback coil), which couples the negative magnetic feedback **(99)** to sensor **11**. The feedback coil has about 1000 turns. The magnetic core superposes the magnetic fields **(99** and **86)** from the feedback coil **25** and the current **12**, therefore it is represented by summer **26**.

[0008] The output of sensor **11** goes to a summer **27** which adds an offset V_{off2} **28** of the operational amplifier electronics **30** and the voltage offset feedback to the output signal of sensor **11** to cancel the offsets. K_C **29** represents the transfer function, such as gain, of the operational amplifier electronics **30**. The output of electronics **30** goes to demodulator **31** to be demodulated. Items **46-49** are actually a part of demodulator **31**. An input signal **21** from oscillator **20** sets the demodulator **31** frequency. The demodulator sensor signal goes on to K_D **32**, which is the transfer function of the final operational or current buffer amplifier electronics **32** for sensor system **10**. It has a large gain at DC and rolls,off at above 1 kHz. The output goes to a transfer function **33** of the inverse of the sum of the load resistance R_L **34** of system **10** and the inductive impedance ($R_{ind}+j\omega L_{ind}$) of winding or coil **25**. $Z_{ind}=(R_{ind}+j\omega L_{ind})$, where Z_{ind} is the impedance of the inductive feedback coil which is the sum of the inductive coil's resistance (R_{ind}) and reactance ($j\omega L_{ind}$) where L_{ind} is the inductive coil's inductance. The output of the current sensor is given in current and is typically run through a load (R_L) to measure a voltage out. An offset feedback signal from output **35** goes to a modulator **36**. This offset feedback signal could also come from the output of **33** (tied after **32** on the schematic). Signal **21** from oscillator **20** actuates demodulator **36**. The de-modulated offset feedback signal goes to an integrator **37** that provides the integrated voltage offset feedback signal (DC) to summer **27** of operational amplifier electronics **30** with the modulated signal level at about 1 kHz filtered.

[**0009**] **FIG. 3** is a schematic of sensor system **10**. Sensor **11** has the Wheatstone bridge of resistors **13-16**, connected end-to-end as described above. The bridge outputs go to the inverting and non-inverting inputs, respectively, via a conductors **93** and **94** and 4.02 K ohm resistors **39** and **40**, of differential amplifier **38** of operational amplifier electronics **30**. A 40.2 K ohm resistor **41** connects the non-inverting input to ground, and a 40.2 K feedback resistor **42** connects the output of amplifier **38** to its inverting input. The output of amplifier **38** goes to the inverting input of amplifier **43** via a 4.02 K ohm resistor **44**. The output of amplifier **43** is connected to its inverting input via a 40.2 K ohm resistor **45**. The non-inverting input of amplifier **43** is connected to ground. A resistor to ground is not necessary here (for this op-amp only) since any offset because of mis-matched input resistance is removed by the offset feedback. This removes one resistor. The output goes to the non-inverting of amplifier **47** of demodulator **31**, via a 4.02 K ohm resistor **46**. The output is connected to the inverting input via a 4.02 K ohm resistor **48**. The non-inverting input is connected to ground via a 2 K ohm resistor **49**. Operational amplifiers **38, 43** and **47** are BA4560 amplifiers, although many other models could be used.

[**0010**] An input to a first terminal of a normally open switch **50** of demodulator **31** is connected to the output of amplifier **43**. An input to a first terminal of a normally closed switch **51** is connected to the output of inverting amplifier **47**. The output terminals of switches **50** and **51** are connected to the inverting input of amplifier **52** of output buffer electronics **32**, via a 2 K ohm resistor **53**. The actuators of switches **50** and **51** of demodulator **31** are actuated with signal **21** from oscillator **20**. Switches **50** and **51** of demodulator **31** are in an ADG413 quad SPST analog switch device.

[**0011**] The non-inverting input of amplifier **52** is connected to ground via a 2 K ohm resistor **54**. The output of amplifier **52** is connected to its inverting input via a **56** picofarad capacitor **57**. This connection arrangement may be varied depending on the stability of the amplifier **52**. The output of amplifier **52** goes to the bases of NPN buffer output transistor **58** and PNP buffer output transistor **59**. The collectors of transistors **58** and **59** are connected to +15 volts and −15 volts, respectively. The emitters of transistors **58** and **59** are connected together, and are connected to the output of amplifier **52** via a 316 ohm resistor **60**. The common emitter connection of transistors **58** and **59** is the output of buffer electronics **32**. This output is connected to the inverting input of amplifier **52** via a 0.033 microfarad capacitor **55** and a 5.11 K ohm resistor **56** connected in series. A diode **61** has a cathode and an anode connected to the collector and emitter, respectively, of transistor **58**. A diode **62** has a cathode and an anode connected to the emitter and collector, respectively, of transistor **59**. Amplifier **52** is a BA4560 device; transistor **58** is a BCX55 device; and transistor **59** is a BCX52 device.

[**0012**] The output of first buffer electronics **32** is connected to a first terminal of winding **25**. Winding **25** provides the magnetic feedback to MR sensor **11** via a magnetic core **26** and gap **23**. Core **26** and gap **23** are represented in **FIG. 2** but not shown in **FIG. 3**. A second terminal of winding **25** is connected to the anode of diode **63** and the cathode of diode **64**. The cathode of diode **63** is connected to the collector of transistor **58**. The anode of diode **64** is connected to the collector of transistor **59**. Diodes **61, 62, 63** and **64** function as voltage clamps for circuit protection.

[**0013**] The second terminal of winding **25** is the current output **65** of sensor system **10**. Output **65** is connected to ground via a 4,700 picofarad capacitor. Output **65** is connected to one end of a 100 ohm RL resistor **34**. The other end of resistor **34** is connected to ground. This is the resistor used here, but the customer usually chooses this value. It can be anything from zero to one megohm, although the device does not operate over its full range of current with larger resistors. Voltage output **35** across resistor **34** is the indication of the amount of current **12** flowing through the wire proximate to MR sensor **11**. Also, output **65** is connected as an offset feedback signal to the non-inverting input of a buffer amplifier **66**. Amplifier **66** is an LT1013 device. Although the LT1013's low offset and offset drift properties are not required, it is used as this buffer versus a cheaper amplifier because it is a spare on the chip anyway.

[**0014**] The output of amplifier **66** is connected to its inverting input and to input terminals of a normally open switch **67** and a normally closed switch **68**. Switches **67** and **68** are of modulator **36**. Actuators of switches **67** and **68** are actuated by signal **21** from oscillator **20**. The output terminals of switches **67** and **68** are connected to the inverting and non-inverting inputs of an amplifier **69** of integrator **37** via 24.9 K ohm resistors **70** and **71**, respectively. Amplifier **69** is an LT1013 device. A 0.47 microfarad capacitor connects the output of amplifier **69** to its inverting input. A 0.47 capacitor **73** connects the non-inverting input of amplifier **69** to ground. The output of amplifier **69** is connected to a summer **27** point at the non-inverting input of amplifier **43**, via 46.4 K ohm resistors **74** and **75**. The inter-connection of resistors **74** and **75** is connected to ground through a 0.47 microfarad capacitor **76**. The signal from amplifier **69** to the summer **27** point is a voltage offset signal that is used for nulling out offset signals (V_{off1}) **22** in MR sensor **11** and offset signals (V_{off2}) of amplifier electronics **30**.

[**0015**] Demodulator **31** and modulator **36** have normally open switches **50** and **67**, and normally closed switches **51** and **68**. The switches, as noted above, are paired off in demodulator **31** and modulator **36**. In each pair, one switch is open and one switch is closed at any one given time period. All of the four switches **50, 51, 67** and **68** are actuated by clock pulse **21**. Since the sensed signal was modulated in MR sensor **11** at one kHz, demodulator **31** demodulates the signal back down to DC (and modulates DC signals up to one kHz). Switches **67** and **68** take one kHz square wave **21** and alternately switch the incoming signal to the non-inverting and the inverting inputs of operational amplifier **69**. This in effect modulates any DC signal and demodulates a one kHz signal. Amplifier **69** then acts as an integrator to pass the DC signal as feedback to operational amplifier electronics **30**. Resistors **74** and **75** and capacitor **76** also act to filter this voltage.

[**0016**] The set/reset mechanism **90** for MR sensor **11** is initiated by a signal **21** from oscillator **20**. Oscillator **20** consists of an LM555 chip **77** with a terminal **1** to ground. A terminal **2** is connected to threshold terminal **6** that is connected to ground via a 0.01 microfarad capacitor **80** and to VCC (+5 volts DC) via a 49.9 K ohm resistor **82**. An output terminal **3** provides about one kHz square wave output **21**. Also, chip **77** has a reset terminal **4** connected to the input of a high speed MOSFET driver **78**, and control terminal **5** connected to ground via a 0.01 microfarad capacitor **79**. Discharge terminal **7** is connected to terminal **6** via a 21.5 k ohm resistor **81**. VCC terminal **8** is connected to +5 volts DC.

[**0017**] The output of set/reset driver **78** is connected to set/reset coil or strap **83** of MR sensor **11**, via a 0.01 microfarad capacitor **84** and an eight ohm resistor **85** connected in series. Associated with the power supply, there is a 5.1 volt Zener diode **87** and 2 K resistor **88** tied between ground and +15 volts. This creates a 5 volt supply for the switches **67**, **68**, **50** and **51** (through Vp) and device **77**. The approach creates a 5 volt supply, and improves performance over the tying those pins to +15 volts. Basically, this configuration decreases the "glitches" on the output each time the set or reset occurs, for the price of two low-cost components.

[**0018**] Although the invention has been described with respect to a specific preferred embodiment, many variations and modifications will become apparent to those skilled in the art upon reading the present application. It is therefore the intention that the appended claims be interpreted as broadly as possible in view of the prior art to include all such variations and modifications.

1. A magnetoresistive current sensor system comprising:

a magnetoresistive sensor having an output;

operational amplifier electronics having an input connected to the output of said magnetoresistive sensor, and having an output;

a demodulator having an input connected to the output of said operational amplifier electronics, and having an output;

output buffer having an input connected to the output of said demodulator, and having an output;

a coil, magnetically coupled to said magnetoresistive sensor and connected to the output of said output buffer;

a modulator having an input connected to the output of said output buffer; and

an integrator having an input connected to the output of said modulator and having an output connected to said operational amplifier electronics.

2. The sensor system of claim 1, wherein:

a first offset voltage is at the output of said magnetoresistive sensor;

a second offset voltage and the first offset voltage are at the output of said operational amplifier electronics; and

an offset voltage feedback signal from the output of said integrator nulls out the first and second offset voltages.

3. The sensor system of claim 2, wherein:

a magnetic signal, having a magnitude, from said coil to said magnetoresistive sensor, magnetically nulls out a magnetic field sensed by said magnetoresistive sensor; and

the magnitude of the coil's magnetic signal is indicative of a magnitude of the magnetic field sensed by said magnetoresistive sensor.

4. The sensor system of claim 3, further comprising:

at least one conductor proximate to said magnetoresistive sensor; and

wherein said at least one conductor conducts a current that radiates the magnetic field sensed by said magnetoresistive sensor.

5. The sensor system of claim 4,, wherein the magnitude of a signal at the output buffer is indicative of the magnitude of the current.

6. The sensor system of claim 4, further comprising:

a set/reset circuit connected to said magnetoresistive sensor; and

an oscillator outputting a clock signal; and wherein:

the clock signal goes to said set/reset circuit;

said set/reset circuit sets and resets said magnetoresistive sensor;

the clock signal goes to said demodulator to actuate said demodulator; and

the clock signal goes to said modulator to actuate said modulator.

7. The sensor system of claim 4, wherein;

said magnetoresistive sensor is a Wheatstone bridge of resistors; and

said resistors are Permalloy (NiFe) resistors.

8. A magnetoresistive sensor system comprising:

a magnetoresistive sensor;

a conductor proximate to said magnetoresistive sensor;

a first amplifier connected to said magnetoresistive sensor;

a demodulator connected to said first amplifier;

a second amplifier connected to said demodulator;

a coil, coupled to said magnetoresistive sensor and connected to said second amplifier;

a modulator connected to said second amplifier; and

an integrator connected to said modulator and to said first amplifier.

9. The sensor system of claim 8, wherein said integrator outputs a first signal to null out an offset voltage, if any, of said magnetoresistive sensor.

10. The sensor system of claim 9, wherein said integrator outputs a second signal to null out an offset voltage, if any, of said first amplifier.

11. The sensor of claim 10, wherein:

said coil couples a magnetic signal to said MR sensor to null out a magnetic field of a current in said conductor, sensed by said magnetoresistive sensor; and

a magnitude of the magnetic signal is indicative of a magnitude of the current in said conductor.

12. The sensor of claim 11, further comprising:

a set/reset circuit connected to said magnetoresistive sensor; and

an oscillator connected to said modulator, said demodulator, and said set/reset circuit.

13. A magnetoresistive current sensor system comprising:

a magnetoresistive sensor;

an amplifier connected to said magnetoresistive sensor;

a modulator connected to said amplifier;

a buffer connected to said modulator;

a modulator connected to said buffer;

an integrator connected to said modulator and said amplifier; and

an inductive device coupled to said magnetoresistive sensor and connected to said buffer.

14. The system of claim 13, further comprising:

a set/reset circuit connected to said magnetoresistive sensor; and

a signal generator connected to said modulator, demodulator and set/reset circuit.

15. A means for sensing current with offset nulling, comprising:

sensor means for magnetoresistively sensing a magnetic field;

amplifier means for amplifying signals from said sensor means;

modulator means for modulating signals from said amplifier means;

buffer means for buffering signals from said modulator means;

demodulator means for demodulating signals from said buffer means; and

integrator means for integrating signals from said demodulator means, and adding integrated signals to said amplifier means.

16. The means for sensing current of claim 15, wherein the integrated signals null out offsets from said sensor means.

17. The means for sensing current of claim 16, wherein the integrated signals null out offsets from said amplifier means.

18. The means for sensing current of claim 17, further comprising magnetic feedback means for providing signals from said buffer means to said sensor means to null out the magnetic field sensed by said sensing means.

19. The means for sensing current of claim 18, further comprising a set/reset means for setting and resetting said sensor means.

20. The means for sensing current of claim 19, further comprising a generator means for generating a signal for said modulator means, demodulator means and set/reset means.

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