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(54) POWER LINE SENSOR

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(60) Provisional application No. 60/455,832, filed on Mar. 19, 2003. Provisional application No. 60/488,700, filed on Jul. 18, 2003.

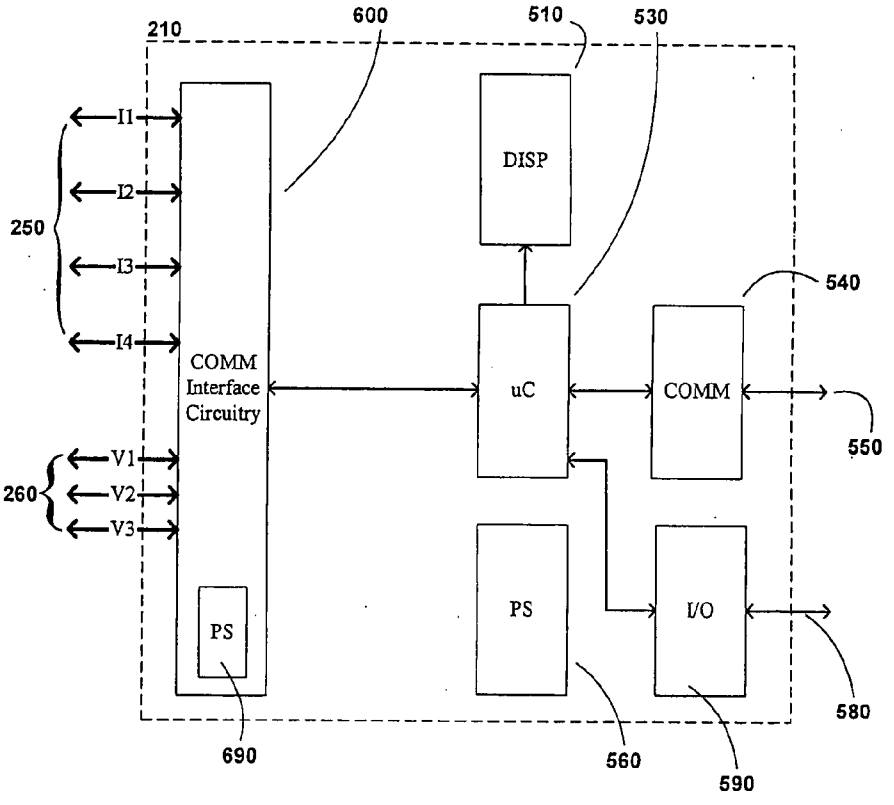
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G01R 21/00 (2006.01)

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(57) **ABSTRACT**

An apparatus for sensing the current in a power line of a power system and systems incorporating the apparatus are disclosed. The apparatus may comprise an enclosure providing a window operable to permit the passage of the power line therethrough. The apparatus may further comprise an active current transformer set within the enclosure and operative to produce a scaled version of the current. The apparatus may further comprise an amplifier coupled with the active current transformer and operative to reduce the phase shift and ratio error between the current and the scaled version of the current. The apparatus may further comprise a powering current transformer set within the enclosure and operative to receive power from the power line on a primary winding and deliver power on a secondary winding. The apparatus may further comprise power supply circuitry set within the enclosure, the power supply circuitry powered through the secondary winding from the powering current transformer and operative to supply power to the amplifier. The apparatus may further comprise at least one of secondary leads and secondary terminals extending from the enclosure, coupled with the active current transformer and operative to deliver the scaled version of the current outside of the enclosure.



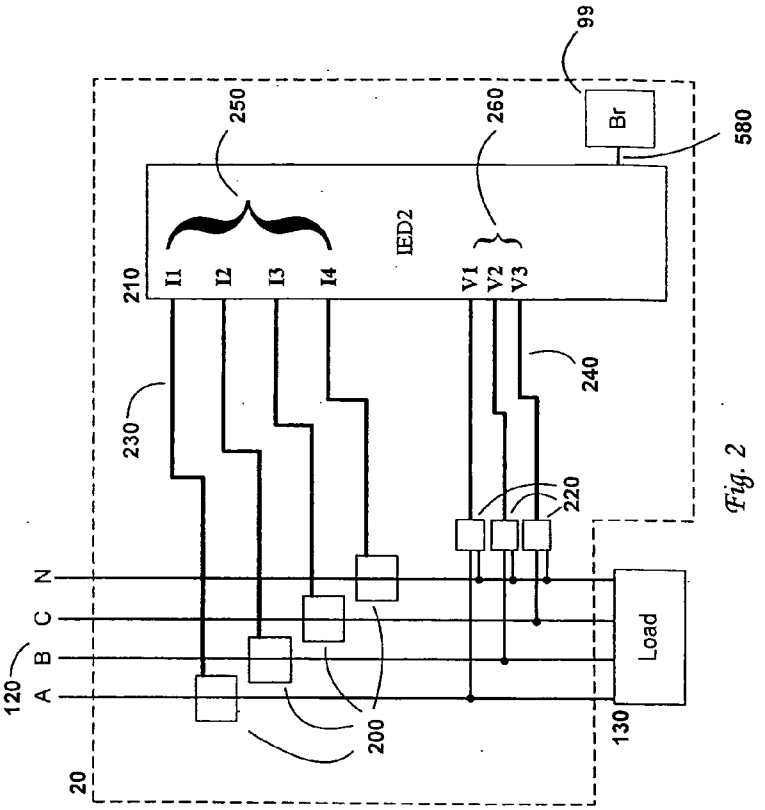

99
Br
580
250
260
IED2
210
I1
I2
I3
I4
V1
V2
V3
240
230
220
N
C
B
A
120
Load
130
200
20

Fig. 2

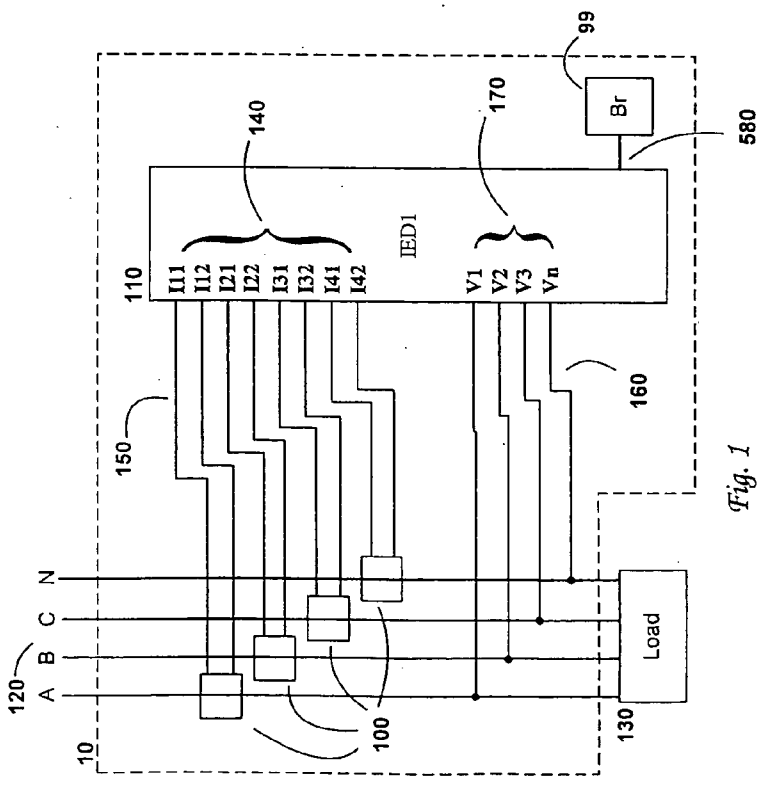

99
Br
580
140
170
IED1
110
I11
I12
I21
I22
I31
I32
I41
I42
V1
V2
V3
Vn
160
150
N
C
B
A
120
Load
130
100
10

Fig. 1

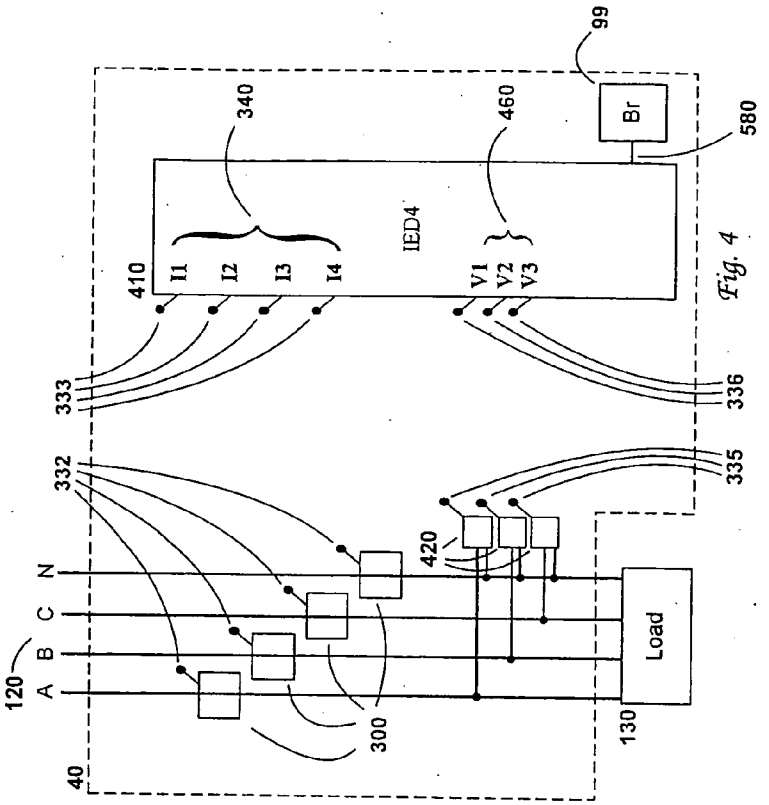

99
Br
580
340
460
IED4
410
I1
I2
I3
I4
V1
V2
V3
333
336
332
335
420
N
C
B
A
120
Load
130
300
40

Fig. 4

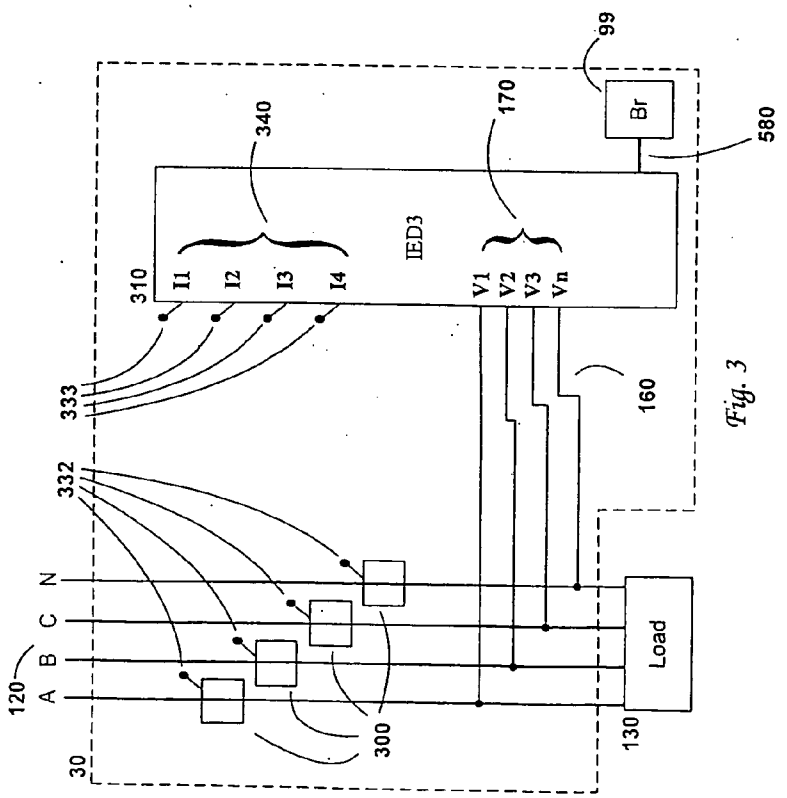

99
Br
580
340
170
IED3
310
I1
I2
I3
I4
V1
V2
V3
Vn
160
333
332
N
C
B
A
120
Load
130
300
30

Fig. 3

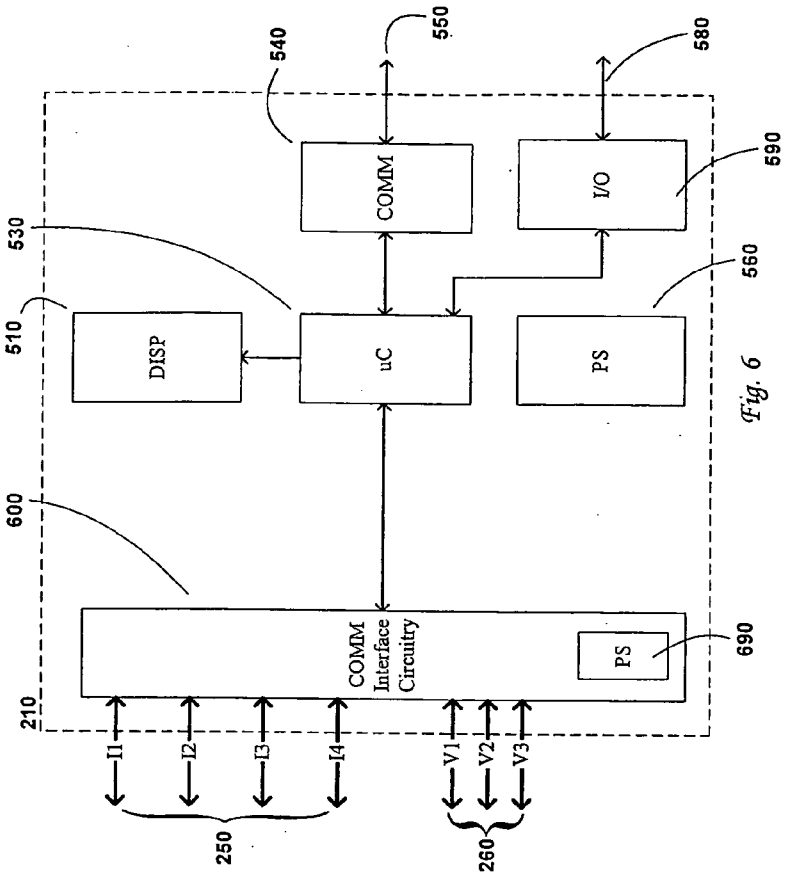

540
550
580
COMM
I/O
590
530
560
510
DISP
uC
PS
600
COMM Interface Circuitry
PS
690
210
I1
I2
I3
I4
V1
V2
V3
250
260

Fig. 6

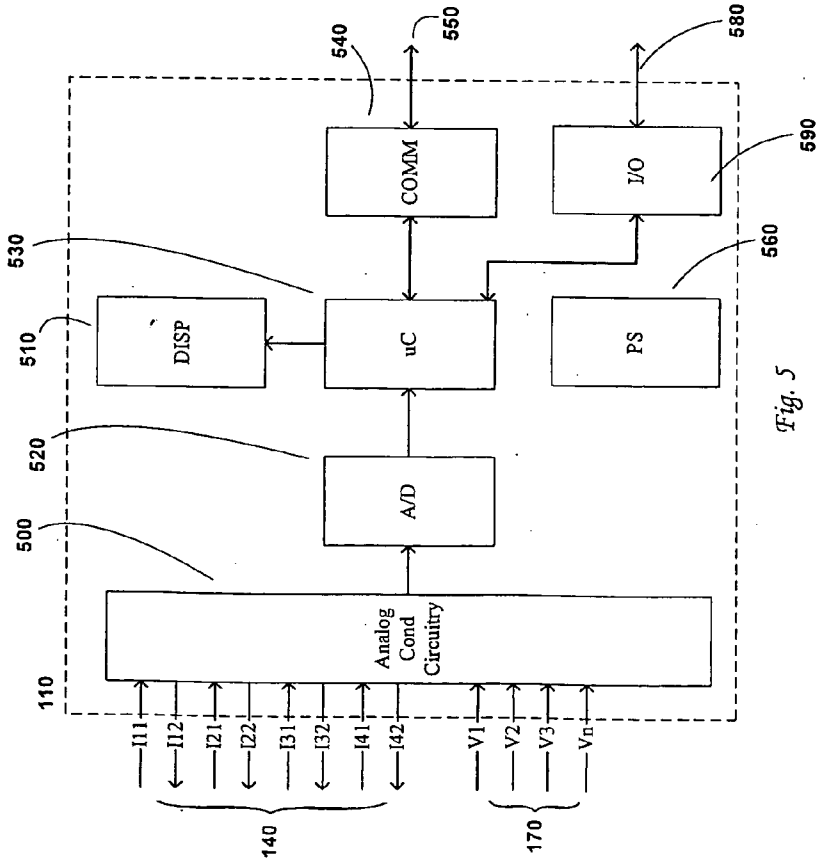

540
550
580
COMM
I/O
590
530
560
510
DISP
uC
PS
520
A/D
500
Analog Cond Circuitry
110
I11
I12
I21
I22
I31
I32
I41
I42
V1
V2
V3
Vn
140
170

Fig. 5

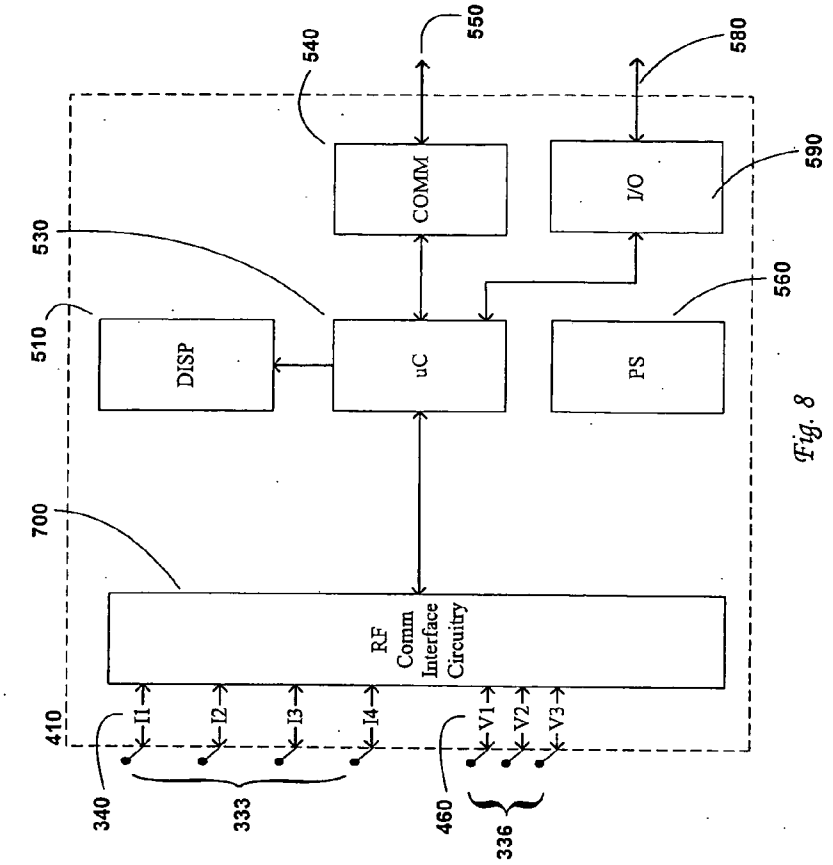

550
580
540
COMM
I/O
590
530
560
510
DISP
uC
PS
700
RF
Comm
Interface
Circuitry
410
I1
I2
I3
I4
V1
V2
V3
340
333
460
336

Fig. 8

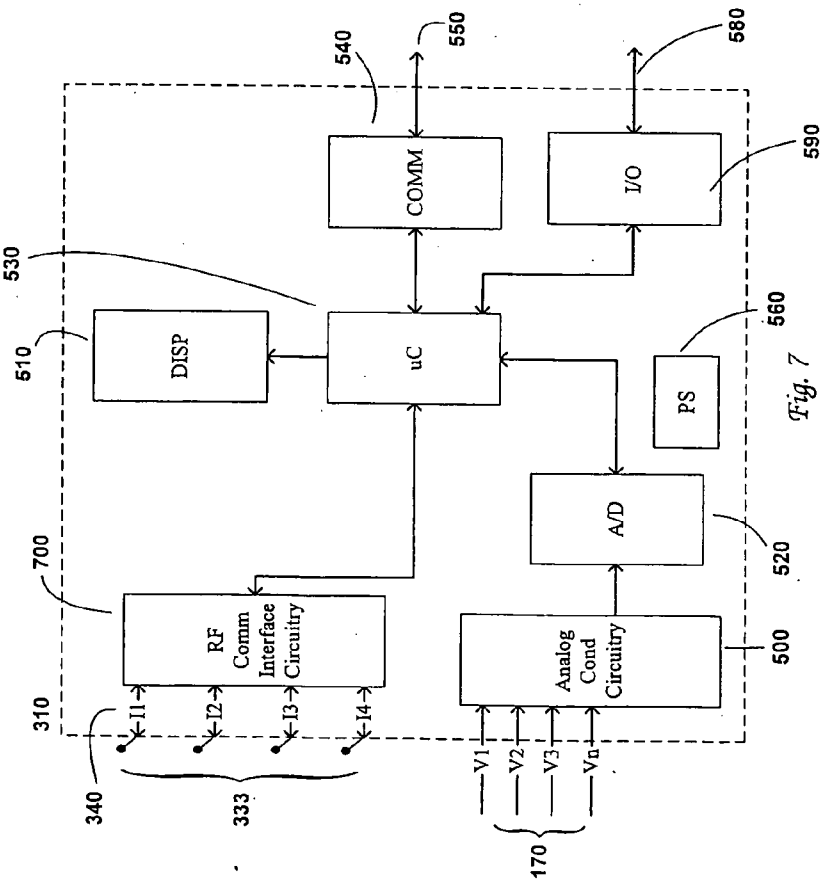

550
580
540
COMM
I/O
590
530
560
510
DISP
uC
PS
A/D
520
700
RF
Comm
Interface
Circuitry
Analog
Cond
Circuitry
500
310
I1
I2
I3
I4
V1
V2
V3
Vn
340
333
170

Fig. 7

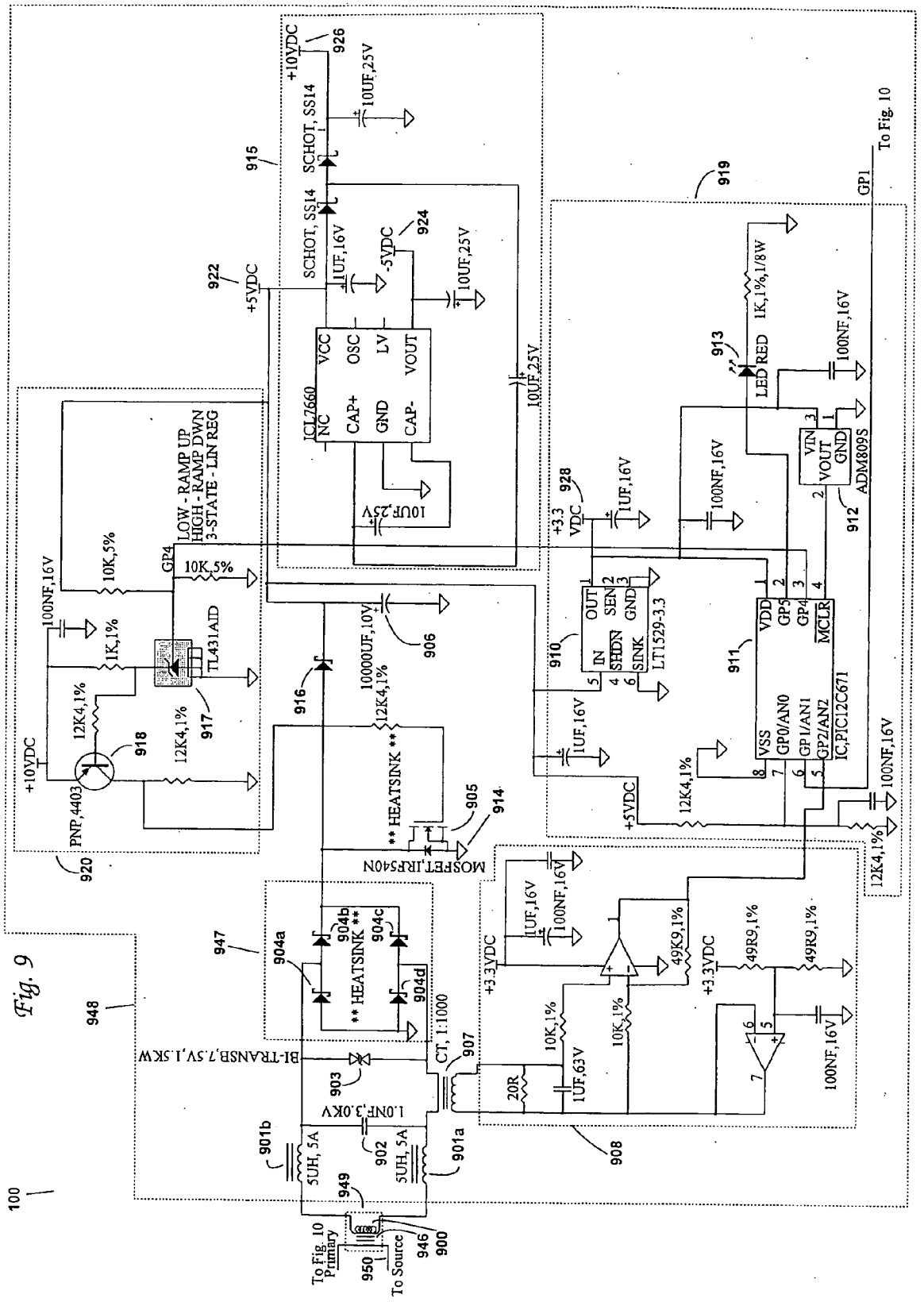

100
948
947
904a
904b
904c
904d
** HEATSINK **
BI-TRANSB,7.5V,1.5KW
903
1.0NF,3.0KV
902
901b
901a
5UH, 5A
949
946
900
950
To Fig. 10 Primary
To Source
CT, 1:1000
907
908
20R
1UF,63V
10K,1%
1UF,16V
100NF,16V
+3.3VDC
49K9,1%
49R9,1%
100NF,16V
920
PNP,4403
+10VDC
12K4,1%
918
917
TL431AID
1K,1%
100NF,16V
10K,5%
LOW - RAMP UP
HIGH - RAMP DWN
3-STATE - LIN REG
GP4
10K,5%
916
10000UF,10V
906
** HEATSINK **
12K4,1%
905
914
MOSFET,IRF540N
915
SCHOT, SS14
+10VDC
926
10UF,25V
922
+5VDC
1UF,16V
-5VDC
924
10UF,25V
ICL7660
NC
CAP+
GND
CAP-
VCC
OSC
LV
VOUT
10UF,25V
10UF,25V
919
910
IN
SHDN
SINK
OUT
SEN
GND
LT1529-3.3
928
+3.3 VDC
1UF,16V
911
VDD
GP5
GP4
MCLR
VSS
GP0/AN0
GP1/AN1
GP2/AN2
IC,PIC12C671
912
VIN
VOUT
GND
ADM809S
913
LED RED
1K,1%,1/8W
100NF,16V
100NF,16V
12K4,1%
GP1
To Fig. 10

Fig. 9

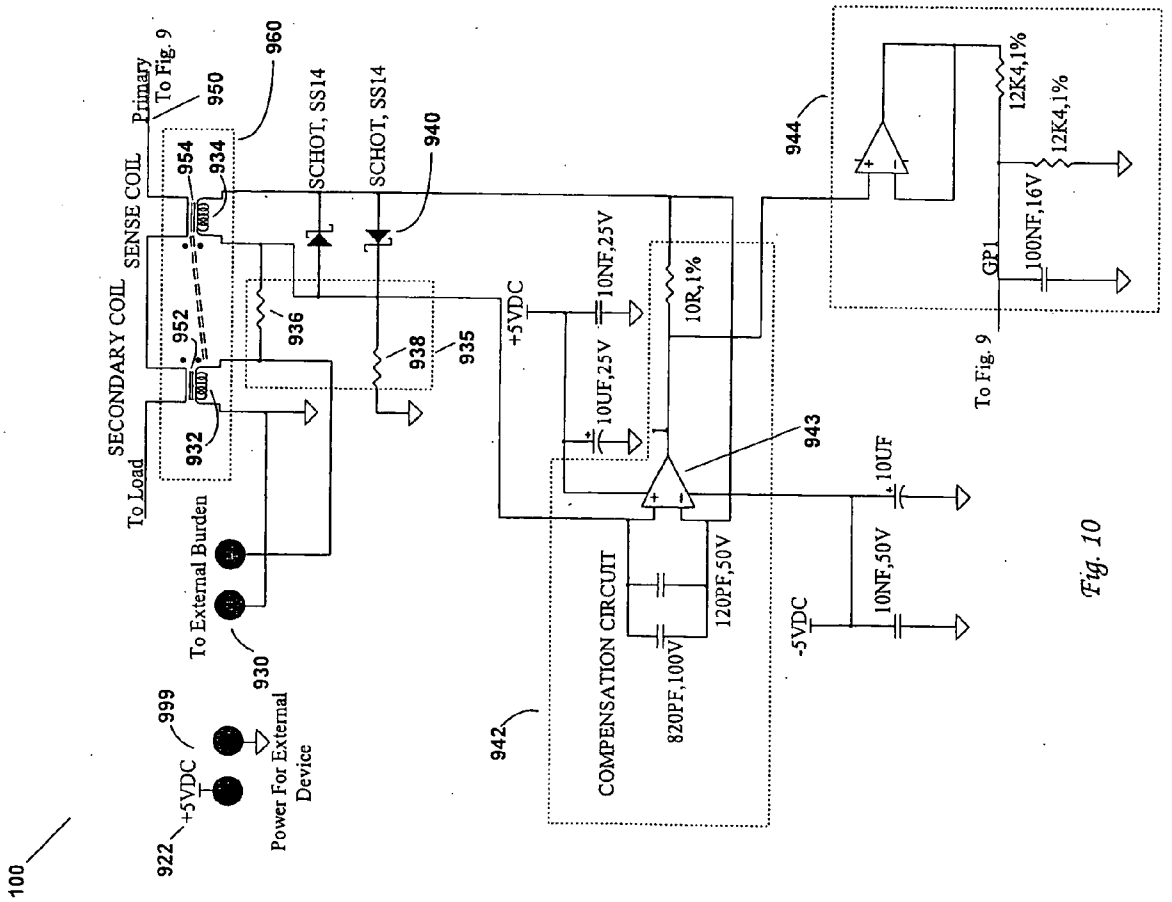

100
922
+5VDC
999
Power For External Device
930
To External Burden
To Load
SECONDARY COIL
SENSE COIL
Primary
To Fig. 9
950
960
954
934
952
932
936
938
935
SCHOT, SS14
SCHOT, SS14
940
+5VDC
10NF,25V
10UF,25V
10R,1%
942
COMPENSATION CIRCUIT
820PF,100V
120PF,50V
943
944
12K4,1%
12K4,1%
100NF,16V
GP1
To Fig. 9
10UF
10NF,50V
-5VDC

Fig. 10

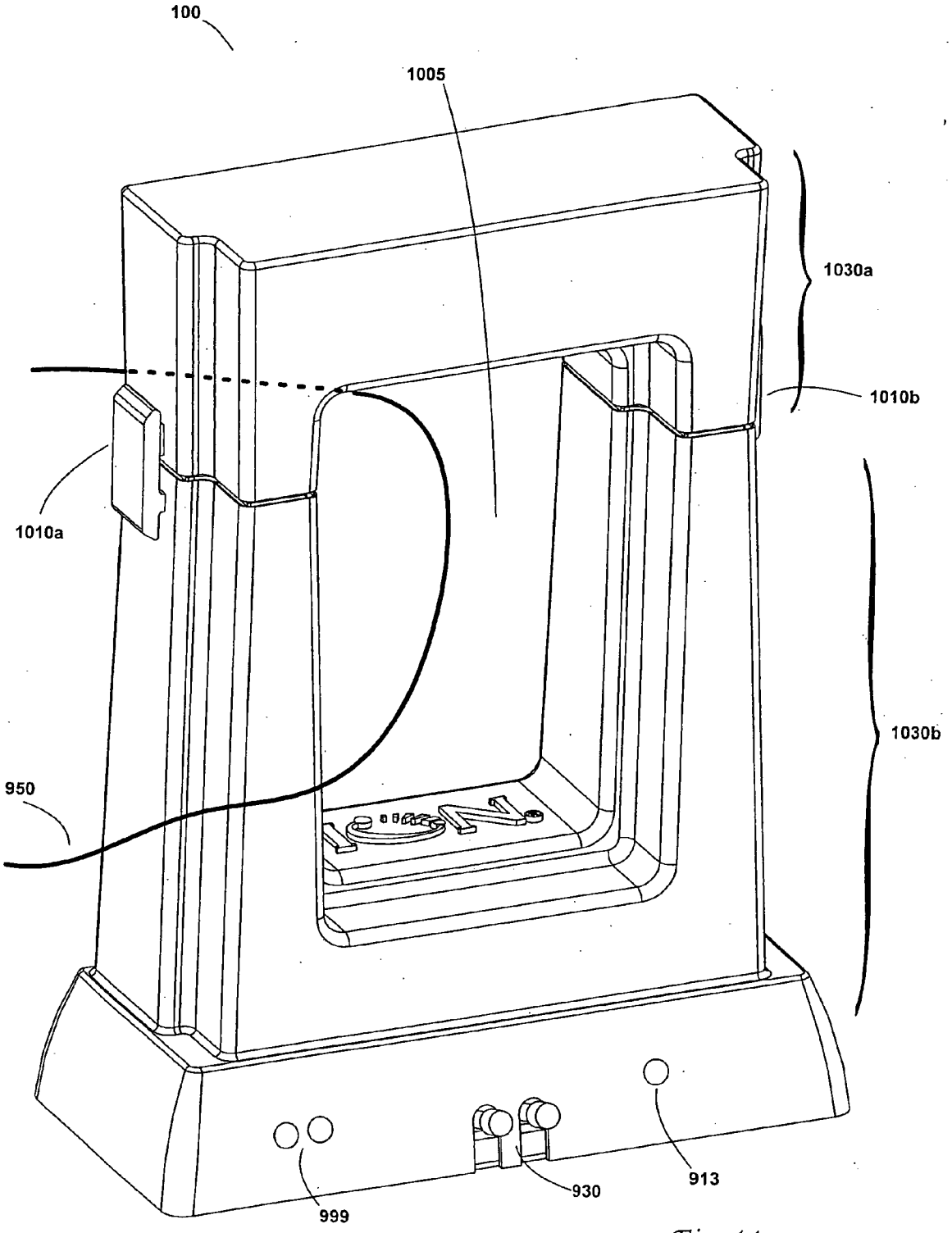


Fig. 11

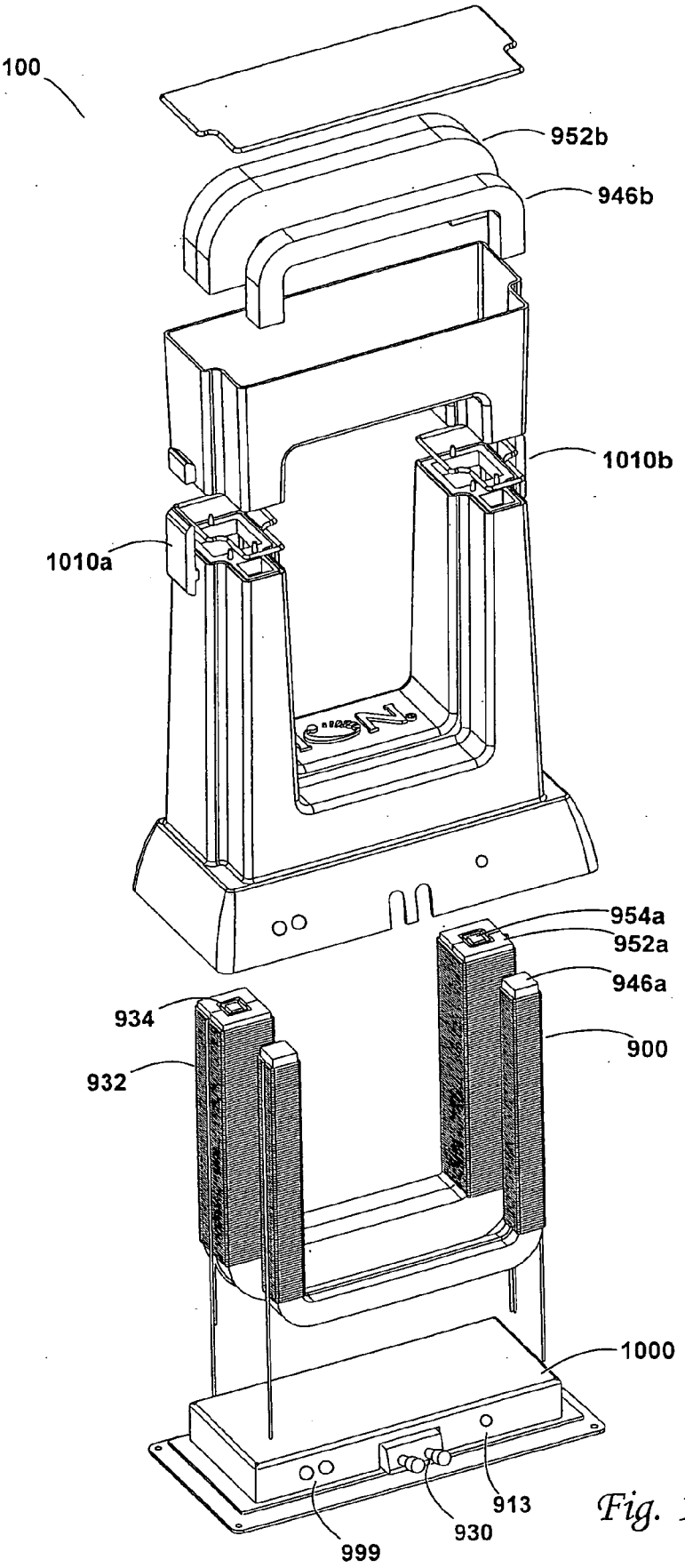

100
952b
946b
1010b
1010a
954a
952a
946a
934
900
932
1000
913
930
999

Fig. 12

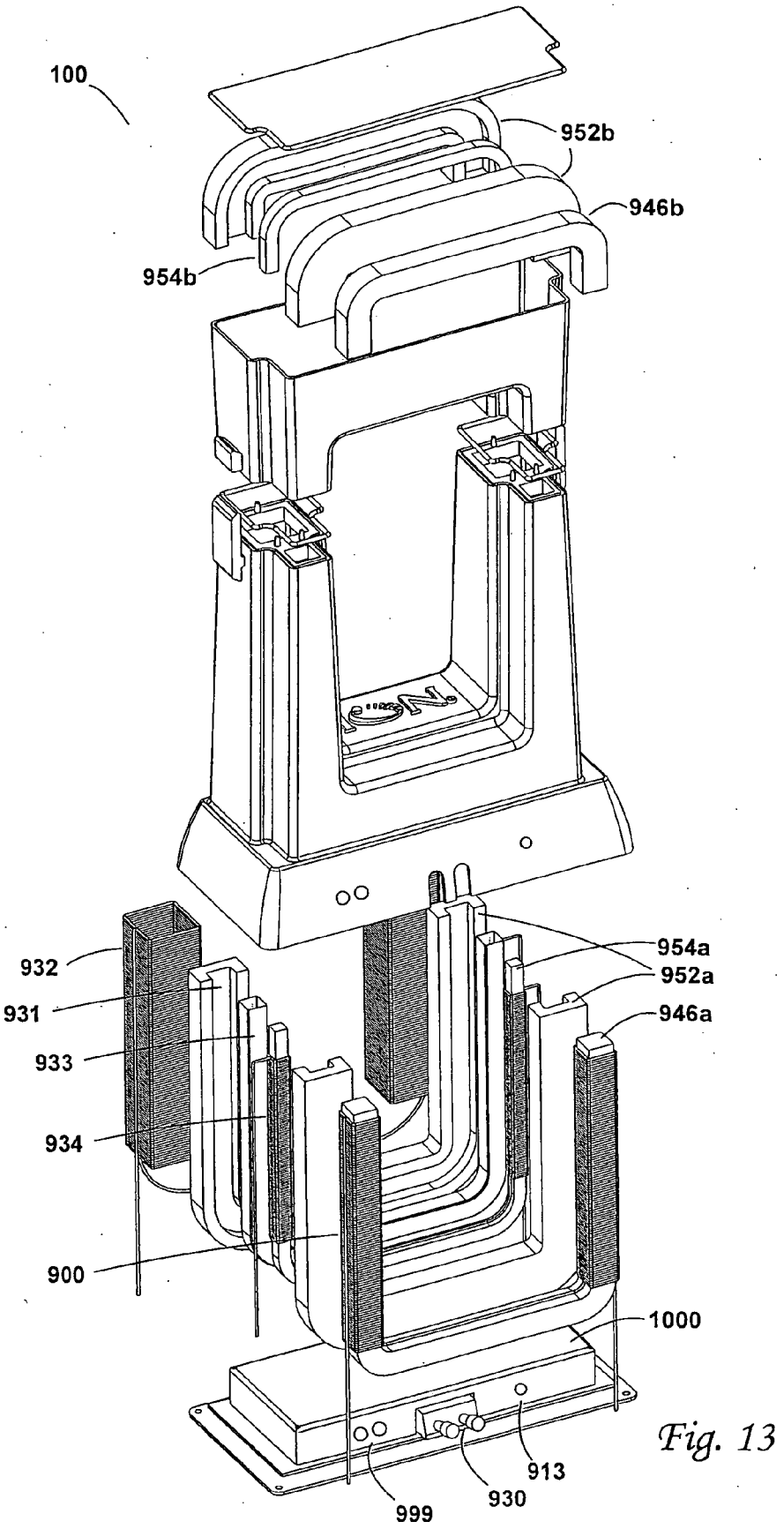

100
952b
946b
954b
954a
952a
946a
932
931
933
934
900
1000
913
930
999

Fig. 13

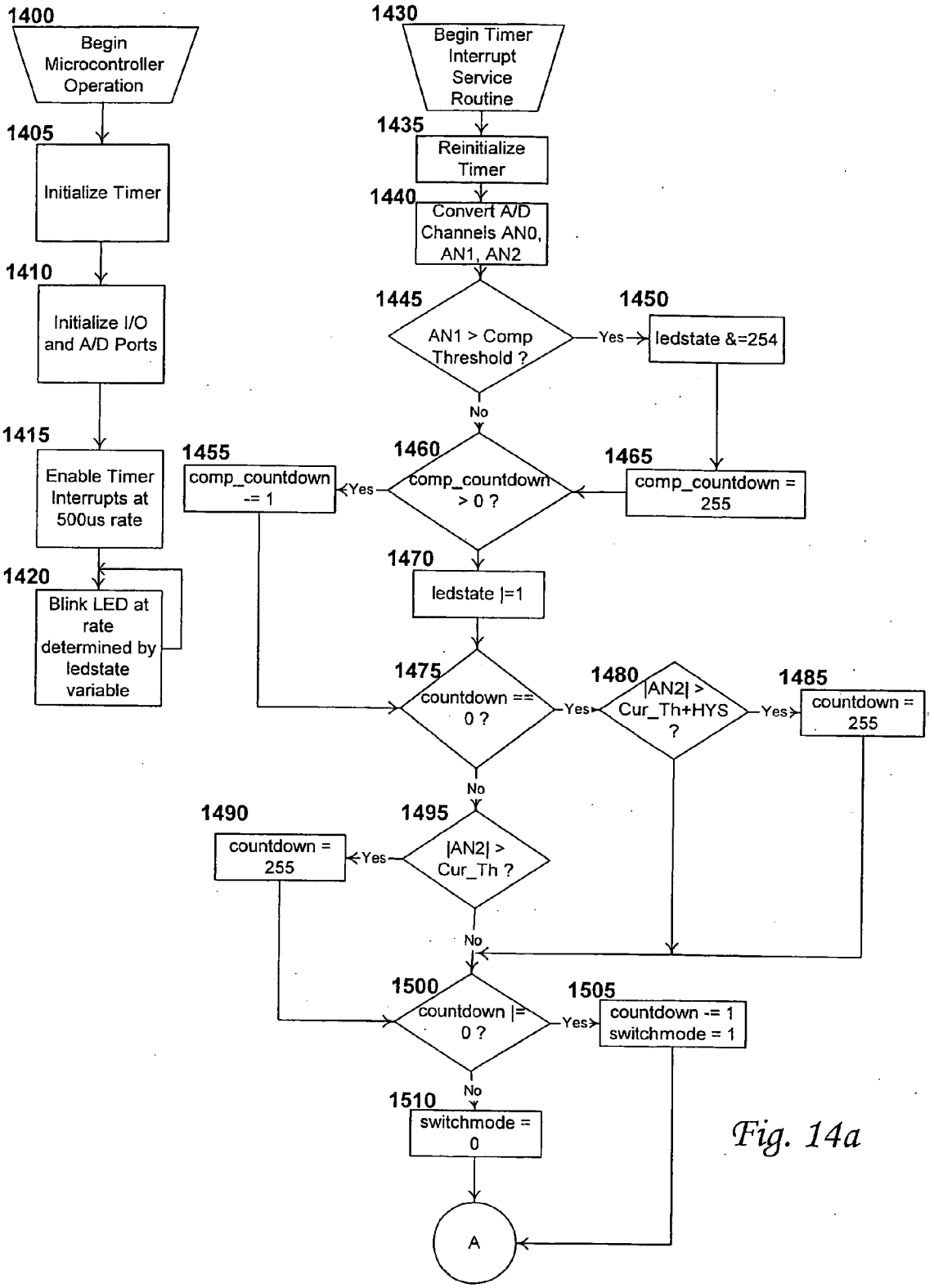

1400
Begin Microcontroller Operation
1405
Initialize Timer
1410
Initialize I/O and A/D Ports
1415
Enable Timer Interrupts at 500us rate
1420
Blink LED at rate determined by ledstate variable
1430
Begin Timer Interrupt Service Routine
1435
Reinitialize Timer
1440
Convert A/D Channels AN0, AN1, AN2
1445
AN1 > Comp Threshold ?
Yes
1450
ledstate &=254
No
1455
comp_countdown -= 1
Yes
1460
comp_countdown > 0 ?
1465
comp_countdown = 255
1470
ledstate |=1
1475
countdown == 0 ?
Yes
1480
|AN2| > Cur_Th+HYS ?
Yes
1485
countdown = 255
No
1490
countdown = 255
Yes
1495
|AN2| > Cur_Th ?
No
1500
countdown |= 0 ?
Yes
1505
countdown -= 1
switchmode = 1
No
1510
switchmode = 0
A

Fig. 14a

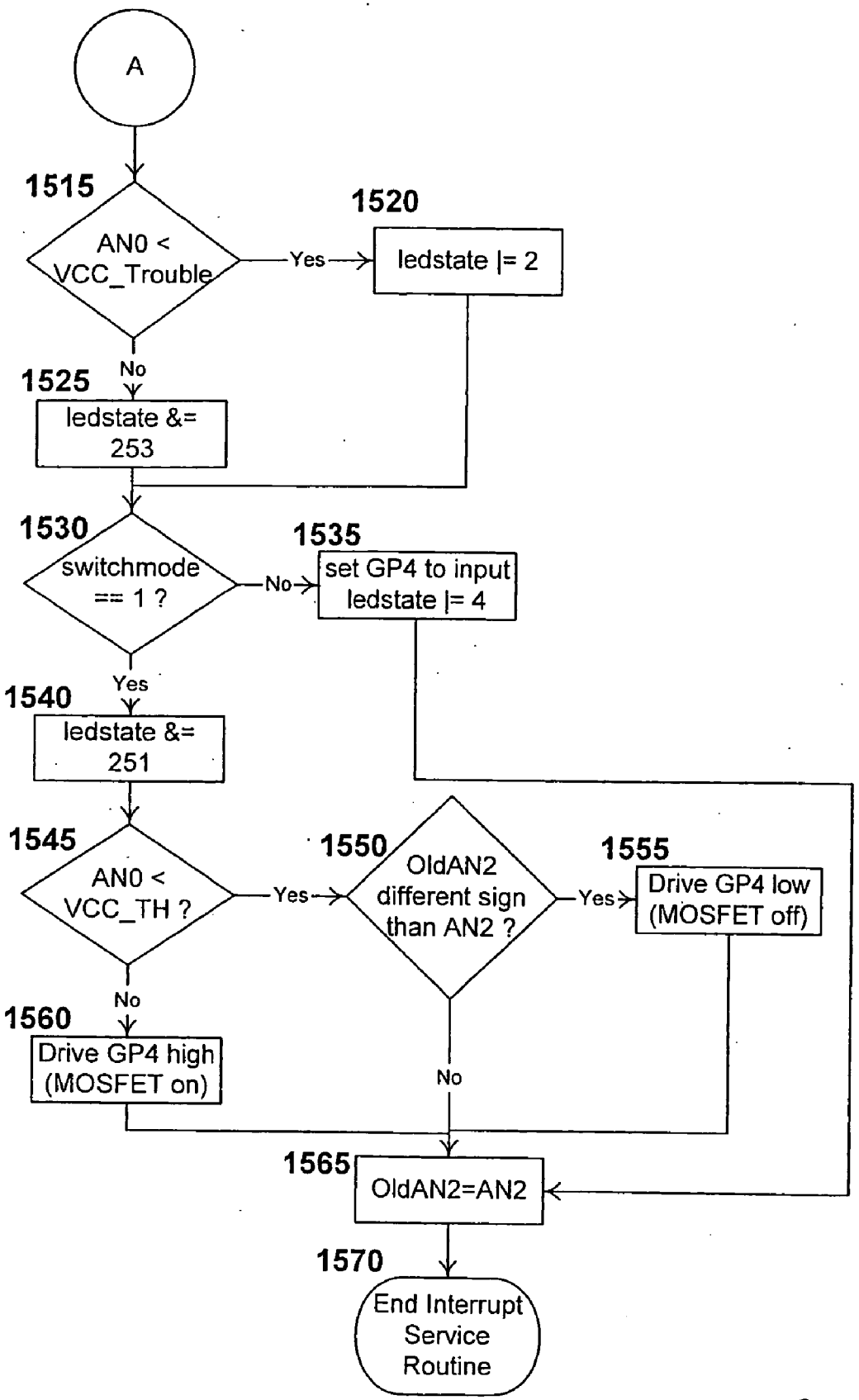

A
1515
AN0 < VCC_Trouble
Yes
1520
ledstate |= 2
No
1525
ledstate &= 253
1530
switchmode == 1 ?
No
1535
set GP4 to input
ledstate |= 4
Yes
1540
ledstate &= 251
1545
AN0 < VCC_TH ?
Yes
1550
OldAN2 different sign than AN2 ?
Yes
1555
Drive GP4 low (MOSFET off)
No
1560
Drive GP4 high (MOSFET on)
No
1565
OldAN2=AN2
1570
End Interrupt Service Routine

Fig. 146

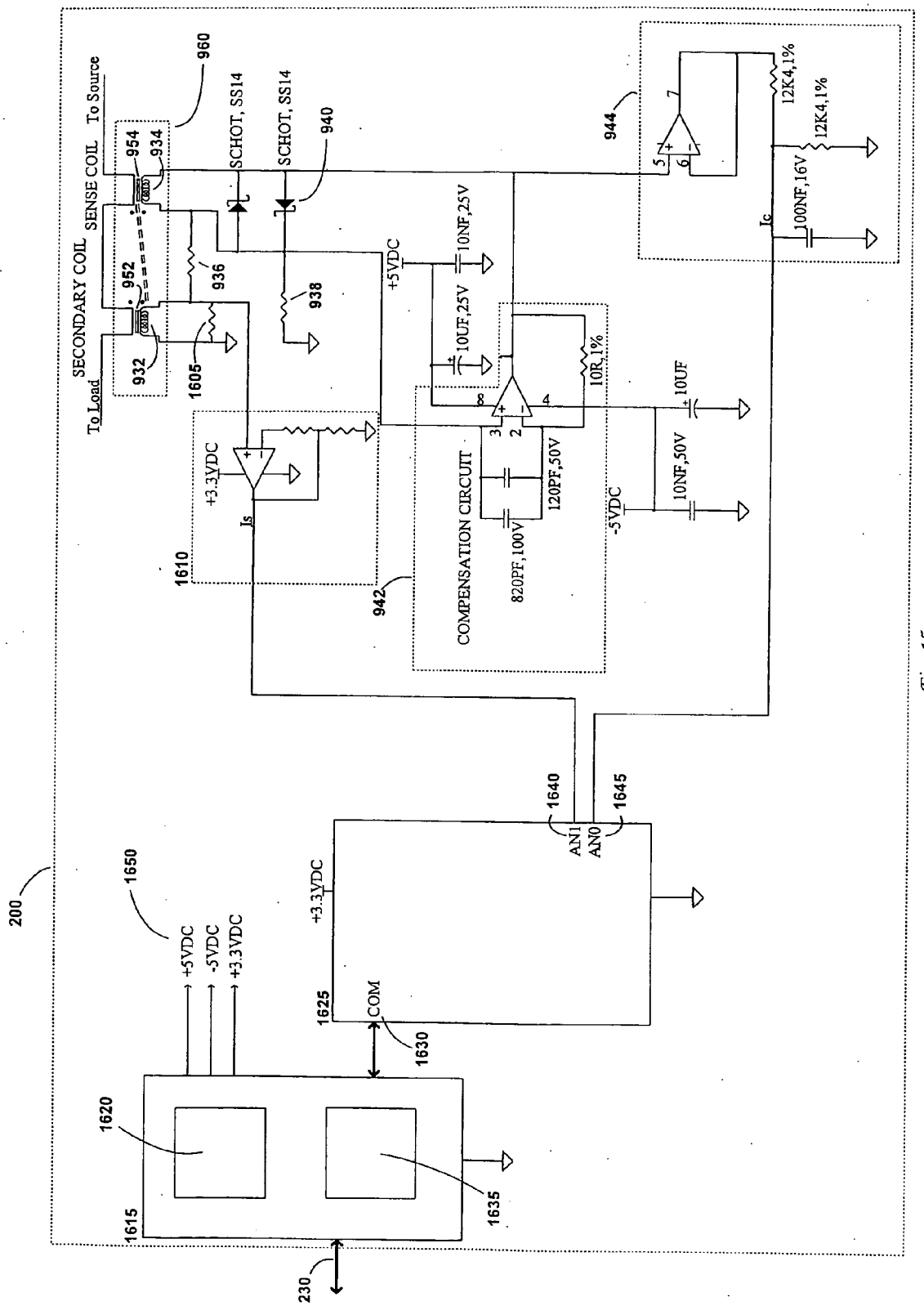

200
960
954
934
SCHOT, SS14
SCHOT, SS14
940
944
12K4,1%
12K4,1%
SECONDARY COIL
SENSE COIL
To Source
To Load
952
932
936
938
1605
+5VDC
10NF,25V
10UF,25V
100NF,16V
Ic
10R,1%
10UF
10NF,50V
+3.3VDC
Is
1610
942
COMPENSATION CIRCUIT
820PF,100V
120PF,50V
-5VDC
1640
1645
AN1
AN0
1650
+5VDC
-5VDC
+3.3VDC
+3.3VDC
1625
COM
1630
1620
1615
1635
230

Fig. 15

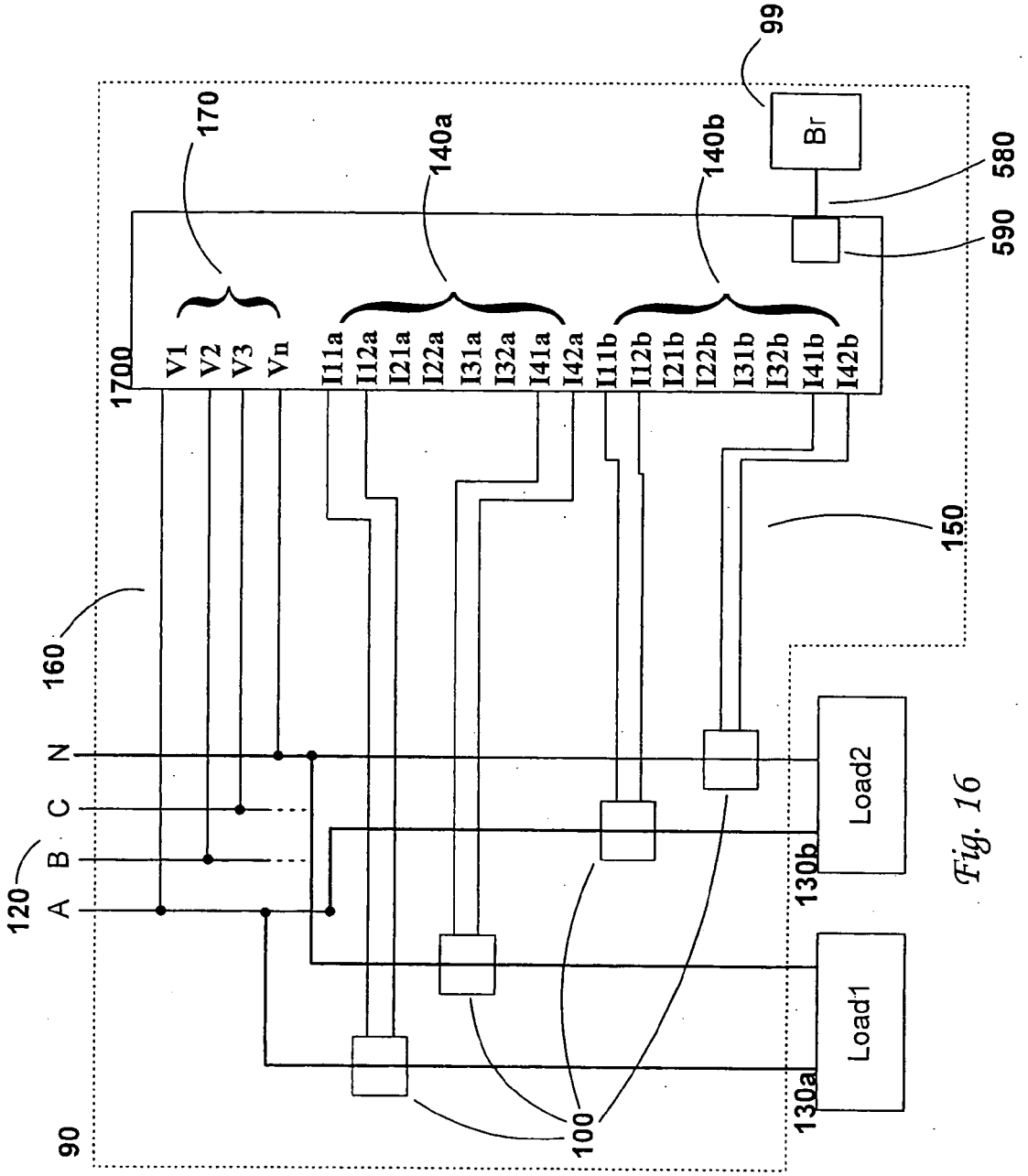

99
Br
580
590
170
140a
140b
1700
V1
V2
V3
Vn
I11a
I12a
I21a
I22a
I31a
I32a
I41a
I42a
I11b
I12b
I21b
I22b
I31b
I32b
I41b
I42b
150
160
N
C
B
A
120
Load2
130b
Load1
130a
100
90

Fig. 16

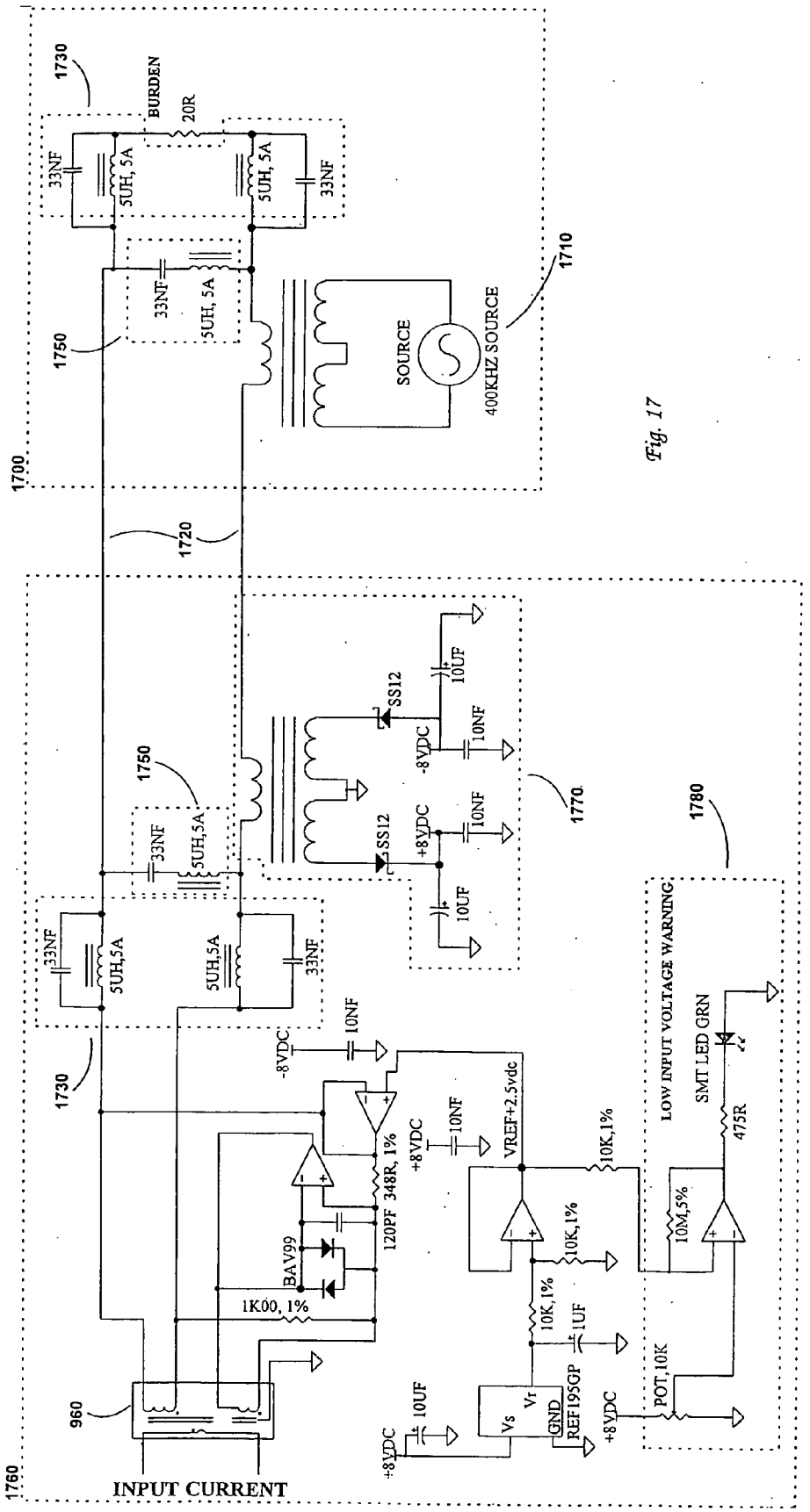

1730
BURDEN
20R
33NF
5UH, 5A
5UH, 5A
33NF
1750
33NF
5UH, 5A
SOURCE
400KHZ SOURCE
1710
1700
1720
1750
33NF
5UH,5A
SS12
10UF
-8VDC
10NF
+8VDC
10NF
SS12
10UF
1770
1780
33NF
5UH,5A
5UH,5A
33NF
1730
-8VDC
10NF
+8VDC
10NF
VREF+2.5vdc
10K,1%
LOW INPUT VOLTAGE WARNING
SMT LED GRN
475R
120PF 348R, 1%
BAV99
1K00, 1%
10K,1%
10K,1%
10M,5%
1UF
960
10UF
Vs
Vr
GND
REF195GP
+8VDC
POT,10K
+8VDC
1760
INPUT CURRENT

Fig. 17

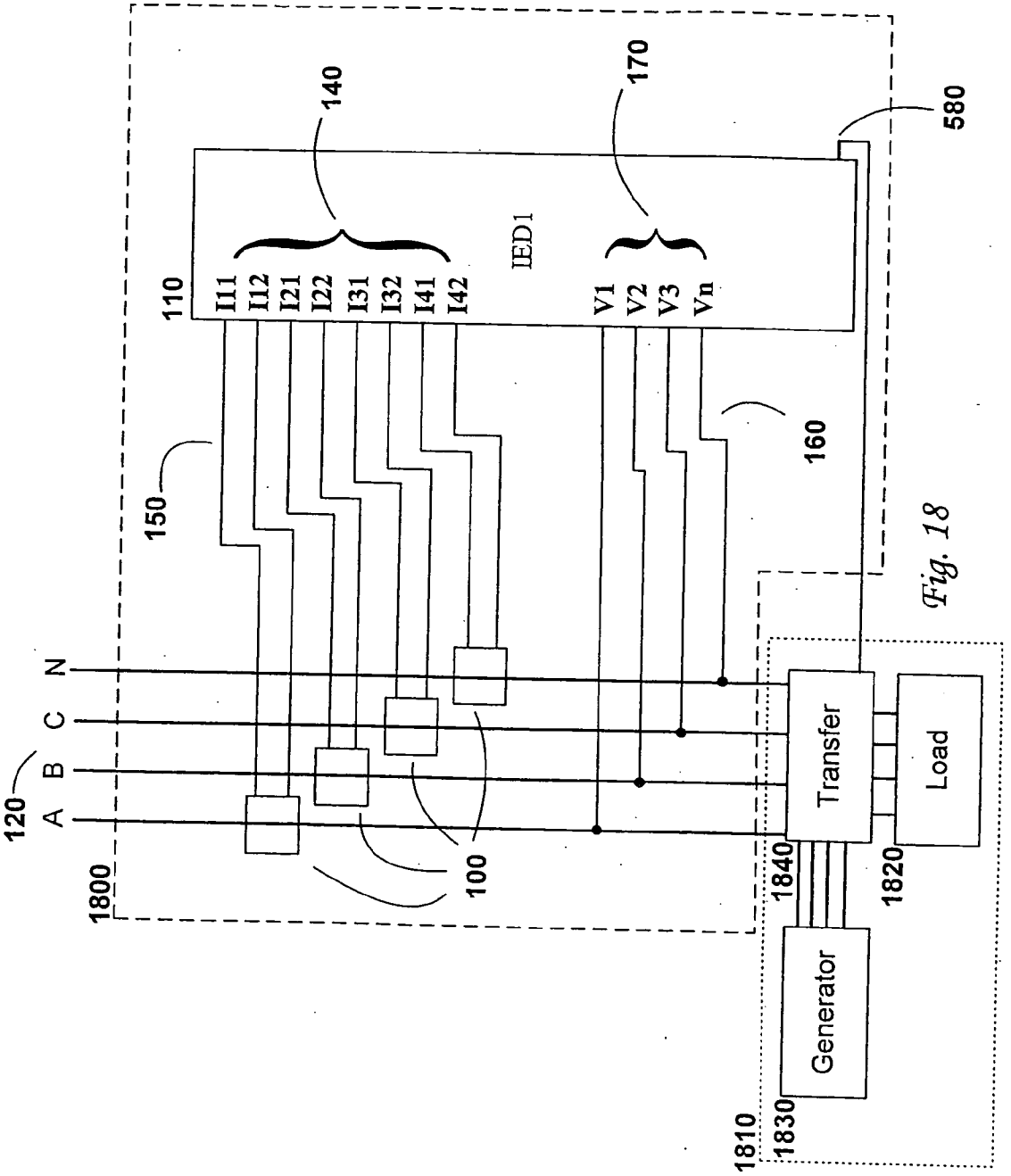

140
170
580
IED1
110
I11
I12
I21
I22
I31
I32
I41
I42
V1
V2
V3
Vn
160
150
120
A
B
C
N
100
1800
Transfer
Load
Generator
1840
1820
1810
1830

Fig. 18

POWER LINE SENSOR

RELATED APPLICATIONS

[0001] The present patent document claims the benefit of the filing date under 35 U.S.C. §119(e) of Provisional U.S. Patent Application Ser. No. 60/455,832, filed Mar. 19, 2003, (Attorney Ref. No. 6270/099) and Provisional U.S. Patent Application Ser. No. 60/488,700, filed Jul. 18, 2003 (Attorney Ref. No 6270/115) which are hereby incorporated by reference.

[0002] The following co-pending and commonly assigned U.S. Provisional Patent Application has been filed on the same date as the present application. This application relates to and further describes other aspects of the embodiments disclosed in the present application and is herein incorporated by reference:

[0003] U.S. Provisional Pat. Application Ser. No. _____, "Non-intrusive energy sensor with wireless communications", (Attorney Ref. No. 6270/116).

BACKGROUND

[0004] The invention relates generally to the field of current sensors used for monitoring current in power systems. More specifically the invention relates to a self powered or remotely powered current sensor device providing an output signal.

[0005] Intelligent Electronic Devices (IEDs) comprise, but are not limited to digital power/energy meters, protective relays, power quality measurement devices, fault recorders or other devices capable of interfacing to electric power lines and calculating at least one power parameter. Power parameters include, but are not limited to rms current, rms voltage, kW, kVAR, kVA, frequency, harmonics, kWh, kVARh, kVAh, symmetrical components, etc.

[0006] Current transformers are used to monitor the current flowing in power system conductors. Generally, current transformers consist of two types. The first type is the closed (toroidal or rectangular) type. The second type is the clamp-on type. The closed type consists of a toroidal or substantially rectangular section of magnetic material with a "window" or opening through the middle. The current transformers have at least one secondary transformer winding that is wound around the material and through the window. A primary winding normally consists of a power line in a power system passing through the window that forms a single transformer turn. The winding ratio of the transformer is then the ratio of the primary to secondary turns. Clamp-on type current transformers are of substantially the same shape as closed type current transformers with the addition of a split in the magnetic material such that the transformer can be placed around the primary winding without having to "thread" the primary winding through the window. This allows installation of the clamp-on type current transformer on power system cables without disconnecting the power system cables from their source or load.

[0007] Standard current transformers suffer from errors in both ratio and phase shift mainly due to the magnetization current required to excite the magnetic material of the core. These effects limit the accuracy of the current transformer and dynamic range of current the transformers are able to sense. This is especially the case with clamp-on type current transformers due to the magnetic flux leakage caused by the split in the magnetic material.

[0008] An active or compensated current transformer circuit that corrects for such errors is described in U.S. Pat. No. 3,534,247 to Miljanic entitled "Current Transformer with Internal Error Compensation." This circuit minimizes phase shift and ratio error during current transformation using a compensation amplifier. Powering the compensation amplifier from an additional current transformer is included in the active current transformer circuit. The presence of a separate powering current transformer means that additional wires are present beyond those providing the secondary current. This may make the device undesirable for installation in locations such as switchgear cabinets due to the high voltages present.

[0009] A second active current transformation approach is described in U.S. Pat. No. 4,841,236 to Miljanic et al. entitled "Current Ratio Device." This approach provides additional isolation over the approach of the U.S. Pat. No. 3,534,247 through the inclusion of an isolated additional secondary winding which provides advantages for uses in high accuracy metrology applications. In general the accuracy of the approach of the U.S. Pat. No. 3,534,247 is more than adequate for most power system monitoring applications.

[0010] A self powered current monitor for monitoring current in an electric power system is described in U.S. Pat. No. 6,018,700 to Edel entitled "Self-Powered Current Monitor." This circuit provides power for amplification circuitry, a microprocessor, etc. that is derived from the power line that is being monitored. The circuit includes a burden reducing circuit. The burden reducing circuit allows current monitoring to be performed with the same magnetic core that is powering the circuitry. The monitoring function of this circuit is not continuous or in alternate embodiments the burden of the power supply reduces the accuracy of the current transformation. Accordingly, this approach is difficult to use with accurate advanced power monitoring devices that continuously sample the current waveform in order to provide accurate power calculations and power quality functionality.

[0011] Intelligent Electronic Devices ("IEDS") are available from multiple manufacturers. These IEDs commonly have current sensing inputs which accept current inputs from standard current transformers in the 5 Amp range. These current sensing inputs are typically two terminals. Two cables extend from the current transformers for connection to the terminals. Additional wiring of power supplies or separate powering cores as required by the previously described active current transformers is undesirable due to increased cost of installation, compliance with electrical codes, etc.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] FIG. **1** depicts a block diagram of a first embodiment of a plurality of current sensors of the present invention in a first embodiment of a power monitoring system of the present invention.

[0013] FIG. **2** depicts a block diagram of a second embodiment of the current sensors of the present invention in a second embodiment of the power monitoring system of the present invention.

[0014] FIG. **3** depicts a block diagram of a third embodiment of the current sensors of the present invention in a third embodiment of the power monitoring system of the present invention.

[0015] FIG. **4** depicts a block diagram of the third embodiment of the current sensors of the present invention in a fourth embodiment of the power monitoring system of the present invention.

[0016] FIG. **5** depicts a block diagram of the internal circuitry of a first embodiment of an IED of the present invention.

[0017] FIG. **6** depicts a block diagram of the internal circuitry of a second embodiment of the IED of the present invention.

[0018] FIG. **7** depicts a block diagram of the internal circuitry of a third embodiment of the IED of the present invention.

[0019] FIG. **8** depicts a block diagram of the internal circuitry of a fourth embodiment of the IED of the present invention.

[0020] FIGS. **9** and **10** depict schematic diagrams of the electronic circuitry of a first embodiment of the current sensor of the present invention.

[0021] FIG. **11** depicts a perspective view of a first embodiment of the current sensor of the present invention in assembled condition.

[0022] FIG. **12** depicts a perspective view of a first embodiment of the current sensor of the present invention in semi-exploded condition.

[0023] FIG. **13** depicts a perspective view of a first embodiment of the current sensor of the present invention in exploded condition.

[0024] FIGS. **14***a* and **14***b* depict the operation of the code of a microcontroller of the present invention in flow chart form.

[0025] FIG. **15** depicts a schematic diagram of the electronic circuitry of a second embodiment of the current sensor of the present invention.

[0026] FIG. **16** depicts a block diagram of the first embodiment of the current sensors of the present invention in a fifth embodiment of the power monitoring system of the present invention.

[0027] FIG. **17** depicts a schematic diagram of an example power supply circuit for the first embodiment of the current sensor.

[0028] FIG. **18** depicts a block diagram of a power monitoring and control system for an IPP.

DETAILED DESCRIPTION OF THE PRESENTLY PREFERRED EMBODIMENTS

[0029] Herein, the phrase "coupled with" is defined to mean directly connected to or indirectly connected through one or more intermediate components. Such intermediate components may include both hardware and software based components.

[0030] The present invention relates to a current sensor and a power monitoring and control system that includes the sensor. The current sensor can replace a traditional current transformer in that it appears to the user and is usable the same way as a conventional current transformer while providing increased accuracy and dynamic range. For improved compatibility with standard current transformers the current sensor may have only two leads exiting its enclosure, and is intended to surround a current carrying conductor and sense the current flowing in the conductor. The current sensor may have at least one of decreased phase shift, decreased ratio error, decreased size and increased dynamic range when compared to typical current transformers. In addition, the current sensor may be self-powered.

[0031] In an alternate example, the current sensor may provide a digital communication link exiting its enclosure instead of analog current leads. This communication link can be used with intelligent electronic devices (IEDs) that do not have analog current and/or voltage inputs to implement a power monitoring and control system. The communication link may be wired, wireless or fiber optic. In this example the current sensor may be self powered, or powered over the cabling of the communication link.

[0032] Referring now to FIG. **1**, an example of a plurality of current sensors is shown in a power monitoring system **10**. In this first example, each of the current sensors will be referred to as an analog sensor **100** since the outputs from the analog sensor **100** contain secondary current in analog form. A plurality of analog sensors **100** are coupled with power lines **120** which deliver power to a load **130** in a power system. The illustrated power lines **120** and load **130** are part of a three phase power system however; single phase, phase-to-phase or any other power system configuration is possible in other examples. The analog sensors **100** produce a scaled version of the current flowing in the power lines **120**. The scaled version is provided to a plurality of current inputs **140** of an IED **110** through current conductors **150**.

[0033] The IED **110** may also have a plurality of voltage inputs **170** which are coupled with the power lines **120** through voltage conductors **160** in order that the IED **100** can sense the voltage on the power lines **120**. Those skilled in the art will appreciate that depending on the voltage on the power lines **120** it may be necessary to install potential transformers (PTs) between the power lines **120** and the voltage inputs **170** in order that the voltage supplied to the voltage inputs **170** is within the specifications of the IED **110**. The IED **110** may be any device(s) capable of providing monitoring, recordation, relaying, or any other power system related functionality using the current information provided by the current sensor. The model ION7350 Digital Power Meter manufactured by Power Measurement Ltd. located in Saanichton, B.C., Canada, represents one embodiment of the IED **110**.

[0034] Referring now to FIG. **2**, a second example of the current sensors is shown in a power monitoring system **20**. This second embodiment of the current sensor will be referred to as a digital sensor **200** as the outputs from the sensor contain secondary current information in digital form. Digital sensors **200** are coupled with power lines **120**, which deliver power to a load **130** in a power system. The digital sensors **200** communicate packets containing data

indicative of the current flowing in power lines **120**. The communication packets may be delivered to a plurality of current communications ports **250** of an IED **210** through current communications cabling **230**. Current communications cabling **230** may be wire, fiber optic cabling and/or any other medium capable of transmitting data.

[**0035**] The IED **210** may also have a plurality of voltage communications ports **260** which are coupled with a respective plurality of digital voltage sensors **220**. The digital voltage sensors **220** include circuitry operative to sample at least one voltage and communicate the sample. The digital voltage sensors **220** are coupled with the power lines **120** and produce voltage communications packets containing data indicative of the voltage on the power lines **120**. The communications packets are received by the voltage communications ports **260** over voltage communications cabling **240**. Voltage communications cabling **240** may be wire, fiber optic cabling and/or any other medium capable of transmitting data. Those skilled in the art will appreciate that separate communications ports for each voltage or current may not be necessary depending on the communications architecture used. In addition, digital sensors **200** and digital voltage sensors **220** may be combined into single enclosures with a single communications port where installation requirements allow.

[**0036**] Referring now to FIGS. **3** and **4**, additional examples of the current sensors of the present invention are shown in power monitoring systems **30** and **40**. These examples of the current sensor will be referred to as a wireless sensor **300** since the outputs are communicated through a plurality of antennas **332** to a plurality of respective current receiving antennas **333** on IEDs **310** and **410**. Wireless sensors **300** are coupled with power lines **120** which deliver power to a load **130** in a power system. The wireless sensors **300** communicate wireless packets containing data indicative of the current flowing in power lines **120** through one or more wireless radio frequency (RF) channels. The wireless packets may be delivered to the current receiving antennas **333** which are coupled with a plurality of current RF communications ports **340** of the IEDS **310**, **410**. Control and other data necessary to enable the communications may flow from the current receiving antennas **333** to the antennas **332** on the wireless sensors **300** which include wireless transceivers. Wireless sensors **300** and IEDs **310**, **410** may form part of an RF mesh network.

[**0037**] IED **310** has voltage inputs **170** similar to those of IED **110**. IED **410** has a plurality of wireless voltage sensors **420**. The wireless voltage sensors **420** are coupled with antennas **335** to voltage receiving antennas **336**. Voltage RF communications ports **460** receive the data from the wireless voltage sensors **420**. The wireless voltage sensors **420** are coupled with the power lines **120** and produce wireless packets containing data indicative of the voltage on the power lines **120**. Those skilled in the art will appreciate that separate antennas and communications ports for each voltage or current may not be necessary depending on the communications architecture used. In addition, wireless sensors **332** and wireless voltage sensors **420** may be combined into single enclosures with a single antenna.

[**0038**] Referring now to FIG. **5**, a block diagram of the internal circuitry of an example of the IED **110** is shown. Current and voltage signals enter current and voltage inputs **140** and **170**, respectively. Analog conditioning circuitry **500** may convert the relatively high current and voltage signals to lower voltage signals (proportional to the high current and voltage signals) appropriate for input to analog to digital converter (A/D) **520**. The analog conditioning circuitry **500** may also perform any other conditioning, scaling, processing, etc. needed to provide signals compatible with the internal circuitry of the IED **110**. Microcontroller **530** receives an output from the A/D **520** that is a digital representation of the current and voltage signals. The microcontroller **530** may be any form of processing computer device capable of executing instructions to control the overall operation of the IED **110**. Microcontroller **530** may compute various power parameters such as rms current, rms voltage, kW, kVAR, kVA, frequency, harmonics, kWh, kVARh, kVAh, etc. based on the current and voltage signals and may store these computations in internal or external memory. Microcontroller **530** may provide at least some of the power parameters to display **510** and through communications interface circuitry **540** to communications bus **550**. Communications bus **550** may be coupled with a computer or other device with communication capability that may retrieve power parameters from the IED **110** and transmit or receive other information useful in the operation of the IED **110**. Power supply **560** provides power to the various circuits in IED **110**. Power supply **560** may be provided with power from power lines **120** (FIG. **1**) or any other appropriate power source.

[**0039**] Referring now to FIG. **6**, a block diagram of the internal circuitry of an example of the IED **210** is shown. Data indicative of current and voltage enters current communications ports **250** and voltage communications ports **260** respectively. Communications interface circuitry **600** receives the data and makes the data available to microcontroller **530**. Communications interface circuitry **600** may comprise any circuitry operative to send and receive data in a packetized form. Microcontroller **530** may compute various power parameters such as rms current, voltage, kW, kVAR, kVA, frequency, harmonics, kwh, kVARh, kVAh, etc. based on the current and voltage signals, and may store the results of computations in internal or external memory. Microcontroller **530** provides at least some of the power parameters to display **510** and through communications interface circuitry **540** to communications bus **550**. Communications bus **550** may be coupled with a computer that retrieves the power parameters from the IED **210**, and transmits or receives other information useful in the operation of the IED **210**. Power supply **560** provides power to the various circuits in IED **210**. Power supply **560** may be provided with power from power lines **120** or any other appropriate power source. Communications interface circuitry **600** also may contain power multiplexing circuitry **690** that multiplexes power on the current communications ports **250** and thus communications cabling **230** (FIG. **2**) such that the digital sensors **200** may receive operational power from the IED **210**.

[**0040**] Referring now to FIG. **7**, a block diagram of the internal circuitry of an example of the IED **310** is shown. Voltage signals enter the voltage inputs **170** as previously described for IED **110** (FIG. **5**). Wireless packets containing secondary current information are received through current receiving antennas **333**, and current RF communications ports **340** into RF communications interface circuitry **700**. RF communications interface circuitry **700** comprises any

appropriate circuitry operative to transmit and/or receive data over a wireless channel. RF communications interface circuitry **700** provides data indicative of the current received through current RF communications ports **340** to microcontroller **530**. The analog conditioning circuitry **500** may provide analog voltage information to the microcontroller **530** via the A/D converter **520** as previously discussed. Microcontroller **530** may compute various power parameters such as rms current, voltage, kW, kVAR, kVA, frequency, harmonics, kWh, kVARh, kVAh, etc. based on the current and voltage signals. Microcontroller **530** may provide at least some of the power parameters to display **510** and through communications interface circuitry **540** to communications bus **550**. Communications bus **550** may be connected to a computer which retrieves the power parameters from the IED **310** and may send or receive other data necessary for operation of the IED **310** or system. Power supply **560** provides power to the various circuits in IED **210**. Power supply **560** may be provided with power from power lines **120** or any other appropriate power source.

[**0041**] Referring now to FIG. **8**, a block diagram of the internal circuitry of an example of the IED **410** is shown. Wireless packets containing current information are received in a similar manner to IED **310** described above. Wireless packets containing voltage information are received through voltage receiving antennas **336**, and voltage RF communications ports **460** into RF communications interface circuitry **700**. RF communications interface circuitry **700** provides data indicative of the current and voltage to microcontroller **530**. Microcontroller **530** may compute various power parameters such as rms current, voltage, kW, kVAR, kVA, frequency, harmonics, kWh, kVARh, kVAh, etc. based on the current and voltage signals and may store the result of these computations in internal or external memory. Microcontroller **530** may provide at least some of the power parameters to display **510** and through communications interface circuitry **540** to communications bus **550**. Communications bus **550** may be coupled with a computer that retrieves the power parameters from the IED **410** and may send or receive other data necessary for operation of the IED **410**. Power supply **560** provides power to the various circuits in IED **410**. Power supply **560** may be provided with power from power lines **120** or any other appropriate power source.

[**0042**] In FIGS. **9-13** and the following description, a particular example of the analog sensor **100** will be described. This particular example functions as a 1000:5 current sensor indicating that a 1000 A primary current will be transformed to a 5 A secondary current. It will be appreciated that with appropriate modifications (such as core sizes, turns ratios, component values and component types) other current transfer ratios are possible including, but not limited to, nominal primary currents from 50 to 20,000 Amps and nominal secondary currents between 1 and 20 Amps. In addition, it will be appreciated that with modifications evident from the preceding discussion, the other examples of the current sensors can be realized including the digital sensor **200** and wireless sensor **300**.

[**0043**] Referring now to FIGS. **9** and **10**, schematic diagrams of an example of the electronic circuitry of the analog sensor **100** of the present invention are shown. It will be noted by those skilled in the art that although specific values and parts for many components have been indicated, the invention is not limited to those particular values or parts. The analog sensor **100** includes a powering current transformer (CT) **949**. The illustrated powering CT **949** comprises a power core **946** and a power coil **900**. A primary winding **950** passes through the power core **946** upon installation of the analog sensor **100**. The power coil **900** may have a determined number of turns of a particular gauge of wire, such as 200 turns of 14 AWG gauge wire. The core materials of power core **946** may be formed from laminations, such as, 0.007 inch M2 Grade silicon steel laminations, ferrite material such as FerroxCube 3E6 ferrite material, or any other type of appropriate core material. The power core **946** may be magnetized by primary current flowing in the primary winding **950** to produce an output current from the power coil **900**.

[**0044**] Output current from the power coil **900** is provided to power supply circuitry **948**. Within the power supply circuitry **948**, the output current passes through a first and second inductor **901***a* and **901***b*, a power coil sensing CT **907** and a bridge rectifier **947** formed by a plurality of diodes **904***a*, **904***b*, **904***c*, **904***d*, such as the illustrated Schottky diodes. A capacitor **902** and transorb **903** may be provided for transient protection of the circuitry.

[**0045**] A secondary current produced by power coil sensing CT **907** passes into current monitoring circuitry **908**. The current monitoring circuitry **908** may be any circuit that provides a voltage signal that is proportional to the current flowing through power coil **900**. The voltage signal is provided to microcontroller circuitry **919**.

[**0046**] Microcontroller circuitry **919** may comprise circuitry for the operation of a microcontroller **911** such as a linear regulator **910**. The microcontroller **911** may be any processor capable of processing the given inputs and outputs at an appropriate rate. Instructions in the form of code that is stored in a memory device (in the illustrated embodiment within the microcontroller) may be executed by the microcontroller **911** to perform the described functionality. One example microcontroller **911** is the model PIC12C671 manufactured by Microchip Technology Inc. located in Chandler, Ariz., U.S.A. The voltage signal provided by the current monitoring circuitry **908** may be fed to an A/D input of the microcontroller **911**.

[**0047**] During operation, rectified current flowing from the bridge rectifier **947** may split between a MOSFET **905** and a diode **916** (such as a Schottky diode) during a linear regulation mode. When conducting, the MOSFET **905**, or shunt switch, operates as a shunt to carry at least a portion of the output current of the power coil **900** to ground via a ground connection **914**. The diode **916**, operates to provide at least a portion of the output current of the power coil **900** to power the circuitry of the analog sensor **100** as herein described. It will be appreciated that other semiconductor device(s) capable of switching current on and off and modulating current may also be usable with appropriate circuit modifications in place of the MOSFET **905**, including bipolar transistors, SCRs, TRIACs, etc. In addition, device(s) other than a Schottky diode may be used to perform the function of the diode **916**.

[**0048**] Alternatively, during operation substantially all of the rectified current may flow through one of the MOSFET **905** or the diode **916** during a switched regulation mode. Selection of an operating mode may be controlled by the

microcontroller **911**. In the linear regulation mode, voltage regulation is performed by shunt regulation circuitry **920**. In switched regulation mode, voltage regulation is performed by microcontroller **911**. Shunt regulation circuitry **920** is a regulator that may be any circuit capable of performing as a voltage regulator in the linear regulation mode, and capable of being directed by the microcontroller during the switched regulation mode as described herein.

[**0049**] During the switch regulation mode, the path of the output current flow is controlled through the shunt regulation circuitry **920**. When microcontroller **911** drives line GP**4** high (approximately 3.3 VDC in the illustrated example), MOSFET **905** is activated by the shunt regulation circuitry **920** to conduct. In the illustrated example, the shunt regulation circuitry **920** includes a shunt regulator **917** and a transistor **918**. The shunt regulator **917** may be a linear shunt regulator such as a TL431 from Texas Instruments of Dallas Tex. In other examples, any other circuit components and/or devices may perform the described functionality. In the example configuration, when line GP**4** is driven high, shunt regulator **917** turns transistor **918** on. Activation of transistor **918** activates the MOSFET **905** to turn on completely (by applying approximately 10 VDC to the gate of the MOSFET in the illustrated example) and virtually all current from the bridge rectifier **947** is shunted through MOSFET **905** to ground **914**. XXX

[**0050**] When the microcontroller **911** drives line GP**4** low (approximately 0 VDC in the illustrated example), shunt regulator **917** turns transistor **918** off. Deactivation of transistor **918** in turn deactivates the MOSFET **905** by applying about 0 VDC to the gate of the MOSFET **905** in the illustrated example. When the MOSFET **905** is turned off (or open), and is non-conducting, virtually all current from the bridge rectifier **947** flows through diode **916**. Microcontroller **911** may selectively switch line GP**4** between high and low states to maintain regulation of a supply rail **922**, as will be described herein. The switching of the MOSFET **905** between an on state (conducting) and an off state (non-conducting), or an open and a closed state, is referred to as the switched regulation mode. Those skilled in the art will appreciate that the term "on" or "closed" means that a relatively large, or a maximum, amount of current flows through the device while the term "off" or "open" means that a relatively small, or a minimum, amount of current flows through the device.

[**0051**] During the linear regulation mode, the microcontroller **911** converts line GP**4** into an input (allows it to float). In the illustrated example, line GP**4** floats to a voltage of approximately half of the supply rail **922**. This causes shunt regulation circuitry **920** to operate in the linear regulation mode. In the linear regulation mode, transistor **918** dynamically modulates the gate voltage of MOSFET **905** to regulate the division of the current flow through MOSFET **905** and diode **916**. The current flow through the MOSFET **905** is dynamically regulated by dynamically adjusting the conductivity of the MOSFET **905** between being on (or fully closed) and being off (or fully open).

[**0052**] Regulation of the current flow divided between MOSFET **905** and diode **916** allows the supply rail **922** to be substantially maintained at a determined supply rail voltage, such as about +5 VDC. It will be noted that when primary current is first applied to the analog sensor **100**, the circuitry will operate in the linear regulation mode until the microcontroller **911** comes out of reset and begins executing code. The circuitry will operate in linear regulation mode since the GP4 line is configured as an input during microcontroller **911** startup. This ensures that the supply rail voltage on the supply rail **922** will ramp up when power is first applied.

[**0053**] Current flowing through diode **916**, flows into the supply rail **922**. In switched regulation mode, the majority of this current charges energy storage device **906** when the MOSFET **905** is turned off. Energy storage device **906** may be any energy storage device, such as a bulk capacitor and/or a 1 Farad Supercapacitor such as the Model PB5R0V105 manufactured by PowerStorm, a division of Cooper Technologies, located in Boynton Beach, Fla. The Supercapacitor is designed to allow the analog sensor **100** to continue operation for a significant period of time when the current in primary winding **950** is too low to provide sufficient power for operation.

[**0054**] The supply rail **922** is provided to switched capacitor circuitry **915**. The switched capacitor circuitry **915** generates a negative rail voltage on a negative rail **924** and a positive rail voltage on a positive rail **926** of about −5 VDC and +10 VDC, respectively, in the illustrated example. The supply rail **922** also provides power to microcontroller circuitry **919**, compensation circuitry **942** and compensation overload detection circuitry **944** (FIG. **10**). The negative rail **924** similarly provides power to compensation circuitry **942** and compensation overload detection circuitry **944**. The positive rail **926** is used to drive the gate of the MOSFET **905** using the shunt regulation circuitry **920**.

[**0055**] Microcontroller circuitry **919** may include a linear regulator **910** that produces a determined controller voltage, such as 3.3 VDC on a controller voltage rail **928** to power the microcontroller **911** and current monitoring circuitry **908**. An example linear regulator is an LT1529-3.3 made by Linear Technology Corporation of Milipitas Calif. In addition, a voltage monitor **912** may be included to ensure that the microcontroller **911** does not execute instructions when the controller voltage rail **928** is not at the proper controller rail voltage. An example voltage monitor is an ADM809S made by Analog Devices Inc. of Norwood Mass. An indicator LED **913** may provide diagnostic information to the user of the analog sensor **100**. Those skilled in the art will appreciate that other forms of indicating diagnostic information may also be usable.

[**0056**] Primary winding **950** also passes through active CT **960** (FIG. **10**). The active CT **960** comprises a sense coil **934** that is wound on a sense core **954**, and a secondary coil **932** that is wound on the combination of a secondary core **952** and the sense core **954**. The secondary coil **932** of the active CT **960** is coupled with the burden terminals **930** which may be coupled with an external burden or load (such as, for example, an input of an IED). Upon magnetization of the secondary core **952** with the primary winding **950**, the secondary coil **932** may supply a secondary current to the burden. Secondary coil **932** may have 200 turns of 14 AWG wire. Secondary core **952** may comprise 0.007 inch M2 grade silicon steel laminations or FerroxCube 3E6 ferrite material (many other core materials are also usable). Sense coil **934** may have 200 turns of 18 AWG wire. Sense core **954** may comprise 0.007 inch silicon steel laminations or

FerroxCube 3E6 ferrite material (many other core materials are also usable). Upon magnetization of the primary core **952**, the sense coil **934** may supply a sense current to a current divider **935** that may be included in the analog sensor **100**.

[**0057**] The illustrated current divider **935** includes divider resistors **936** and **938**. In other examples, the current divider **935** may be any other device(s) or circuit capable of dividing current. Diodes **940** (such as Schottky diodes) provide transient protection for the circuitry. When the divider resistors **936** and **938** are included, the current flowing through the sense coil **934** may be divided between the combination of divider resistor **936** and secondary coil **932** and divider resistor **938**. This allows for a ratiometrically determined smaller number of windings in sense coil **934** than in secondary coil **932**, while still allowing compensation as later described. This current divider **935** provides the ability to make adjustments to the compensation current in order to maintain current transformer compensation under conditions where the effective turns ratio between the sense coil **934** and secondary coil **932** is less than unity. This may happen if the sense coil **934** and secondary coil **932** are intentionally wound with a differing number of turns or if magnetization effects cause the effective turns ratio to be other than indicated by the number of turns.

[**0058**] Alternatively, divider resistors **936** and **938** may not be provided. Divider resistor **936** may be replaced with a short and divider resistor **938** may be replaced with an open. As a result, the effective turns ratio between sense coil **934** and secondary coil **932** may be set to unity.

[**0059**] Compensation circuitry **942** may replace magnetization current lost in the transformation through secondary core **952**. The compensation circuitry **942** may include a compensation amplifier **943** that operates to maintain the voltage across sense coil **934** at about zero with a compensation current. The compensation current is provided to maintain the voltage at about zero by replacing the magnetization current (e.g. losses) of the secondary core **952**. Replacement of the magnetizing current significantly reduces the phase shift and amplitude error during the transformation from primary current to secondary current flowing within the secondary coil **932**. For further details of the operation of the active CT **960** and compensation amplifier **942** refer to U.S. Pat. No. 3,534,247 entitled "Current Transformer with Internal Error Compensation." Other active current compensation architectures may also be usable to compensate for magnetic losses in the secondary core **952** without departing from the spirit and scope of the present invention.

[**0060**] With all standard metering burdens defined in the IEEE C57.13-1993 standard, the active CT **960** may maintain a ratio error of less than about 0.1% and a phase shift of less than about 0.05 degrees between the primary and secondary current over a current range from at least 20 to 1000 Amps. In other words, the ratio error and phase shift may be maintained while the apparatus is operating over a dynamic range of 50 to 1 of the primary current to the secondary current. With core material and other optimizations this dynamic range may be increased to 100 to 1 or better.

[**0061**] Compensation overload detection circuitry **944** provides a scaled version of the voltage output from compensation circuitry **942** on line GP**1** to the microcontroller **911** (FIG. **9**). This allows the microcontroller **911** to detect when the compensation amplifier **943** is driving a voltage too near its power supply rail and thus may no longer be compensating for the total amount of secondary core **952** magnetization current. Microcontroller **911** may then initiate an indication to the user of this condition such as, by using LED **913**.

[**0062**] The analog sensor **100** includes auxiliary power terminals **999**. The auxiliary power terminals **999** allow a user to power an auxiliary device from at least one of the power rails generated within the analog sensor **100**. External devices may include IEDs, communication devices, etc. In the illustrated example, the supply rail **922** is powering the auxiliary power terminals **999**. In other examples, multiple auxiliary power terminals may be included in the analog sensor **100** each powered by a different one of the available power rails.

[**0063**] For manufacturing and cost reasons it is desirable to make the secondary core **952** and sense core **954** out of the same material. Alternatively, sense core **954** may be made of a material with a higher initial permeability than the secondary core **952**. The higher initial permeability provides an advantage when the primary current is low since the reluctance of the sense core **954** may prevent operation at lower primary current levels with lower initial permeability materials. However, the sense core **954** material may have much lower flux handling capability than the other cores since the compensation circuitry **942** maintains the flux in the sense core near zero as previously discussed. An acceptable alternate higher initial permeability sense core **954** material is Magnetic Alloy 2714A manufactured by Honeywell International Metglase Solutions in Conway, S.C., U.S.A.

[**0064**] As an alternate example, secondary core **952** and secondary coil **932** of active CT **960** can replace the powering CT **949**. In this example, the powering CT **949** is removed and the resultant open ends of inductors **901***a* and **901***b* are connected in series with the external burden **930**. Also in this example, an isolated DC/DC converter may be installed on the positive rail **926** in switched capacitor circuitry **915** to provide isolated power for the circuitry shown in FIG. **10**. In addition, line GP**1** can no longer connect directly between the circuitry of FIG. **9** and FIG. **10**, and the ground connections **914** of FIG. **9** are isolated from the ground connections of FIG. **10**. The arrangement provides for a reduction in the number of magnetic cores, but increases the electronic circuitry complexity and may reduce performance due to the active CT **960** performing two functions.

[**0065**] Microcontroller Operation

[**0066**] Referring now to FIGS. **14***a* and **14***b*, example operation of the firmware code of microcontroller **911** is shown. When the microcontroller code begins operation (block **1400**) an internal timer is initialized (block **1405**). The code then initializes I/O and analog to digital converter (A/D) ports (block **1410**). The internal timer is initialized to interrupt at a determined rate, such as a 500 microsecond rate (block **1415**). The microcontroller **911** then goes into a loop where it blinks the LED **913** connected to the GP5 port at a rate determined by an "ledstate" variable (block **1420**). The remainder of the microcontroller **911** functionality is implemented in a timer interrupt service routine.

[0067] When the timer interrupt service routine begins (block **1430**) the timer is reinitialized to interrupt at the expiration of the determined rate (block **1435**). An A/D conversion is performed on the signals present on channels AN**0**, AN**1** and AN**2** (block **1440**). This provides samples of the state of the supply rail **922** line, the compensation circuitry **942** output, and the current monitoring circuitry **908**, respectively. AN**0** and AN**1** are treated as positive unsigned numbers. AN**2** is treated as a signed number (and thus voltages around one half of 3.3 VDC input to AN**2** result in A/D output values that are large positive or negative numbers for example.)

[0068] If AN**1** is above a compensation threshold (for example 4.0 volts) this is an indication that the compensation circuitry **942** may not be compensating the active CT **960** properly (block **1445**). This may happen if the primary current is too high, the external burden is too large or there is too large of an air gap in one of the cores of the analog sensor **100**. In this case, the "ledstate" variable is bitwise ANDed with a determined value, such as 254 to clear the least significant bit (block **1450**). This will be detected at block **1420** and the LED **913** will be blinked with a predetermined on/off pattern to indicate to the user that the compensation may not be working properly. Then a "comp_countdown" variable is set to 255 (block **1465**). Due to the fact that the output from the compensation amplifier **943** is an AC signal, if a peak over the threshold is detected at block **1445**, the "comp_countdown" variable ensures that the "ledstate" variable does not have its least significant bit set until there has been no peak above the compensation threshold for 255 executions of the timer interrupt. This equates to about 7.6 line frequency cycles at 60 Hz or 6.4 line frequency cycles at 50 Hz. If the "comp_countdown" variable is greater than zero (block **1460**) execution continues at block **1475**. Otherwise, the least significant bit of the "ledstate" variable is set (block **1470**).

[0069] If a variable "countdown" is zero (block **1475**) the absolute value of AN**2** is compared to a current threshold minus a hysteresis constant (block **1480**). Adjustment of the hysteresis constant changes the response time of the system. If the absolute value of AN**2** is less than this amount the variable "countdown" is set to 255 (block **1485**). If the variable "countdown" is not equal to zero at block **1475**, the absolute value of AN**2** is compared to a current threshold without hysteresis (block **1495**) and if the absolute value of AN**2** is less than this amount, the variable "countdown" is set to 255 (block **1490**).

[0070] If "countdown" is not equal to zero (block **1500**) "countdown" is decremented and a variable "switchmode" is set (block **1505**). Otherwise, variable "switchmode" is cleared (block **1510**). The function of blocks **1475** to **1510** is to set the variable "switchmode" if the code was in the switched regulation mode previously and the output current from the power coil **900** is still high enough to remain there, or if the code was not in the switched regulation mode, change to the switched regulation mode if the output current has risen to a value equal to the amount required to stay in switched mode plus an amount of hysteresis. The amount of hysteresis may be, for example, 4 A/D counts. Due to the fact that the signal going into AN**2** is an AC signal, the "countdown" variable provides for detection of the peak output current in a similar fashion as the "comp_countdown" variable described above. (In this case smaller absolute value of analog to digital conversion results mean larger current flow.)

[0071] If AN**0** is less than a VCC Trouble threshold (block **1515**) this is an indication that the circuitry is unable to keep the supply rail **922** at a high enough level for reliable operation. In this case, the second bit of the "ledstate" variable is set (block **1520**) such that the LED **913** can be blinked at a rate indicating to the user that there is a problem (at block **1420**). Otherwise, the second bit of the "ledstate" variable is cleared (block **1525**). The supply rail **922** is +5 VDC in the illustrated embodiment.

[0072] If the "switchmode" variable is set to 1 (block **1530**) the analog sensor **100** is in the previously discussed switched regulation mode and the third bit of the "ledstate" variable is cleared (block **1540**). AN**0** is then compared to a VCC regulation threshold (block **1540**). The VCC regulation threshold is set to a determined level such that the ripple in the supply rail **922** is acceptable for operation of the circuitry of the analog sensor **100**. If AN**0** is not below this threshold, line GP**4** is driven high (block **1560**) to turn the MOSFET **905** on. When the MOSFET **905** is turned on, most of the current provided from the power coil **900** flows through the MOSFET **905**. Otherwise if AN**0** is below the VCC regulation threshold, the previous value of AN**2** is compared to the present value (block **1550**). If the previous value and the present value are different in sign, line GP**4** is driven low (block **1555**). This turns the MOSFET **905** off and most of the current from the power coil **900** flows through diode **916**. If the previous value and present value of AN**2** are the same sign, the drive state of line GP**4** is not changed. This means that the switching off of MOSFET **905** happens near a zero crossing of the current in the power coil **900** which reduces transients generated on the primary winding **950**. Transients may otherwise propagate to the active CT **960**, or cause misoperation of test equipment being used by a customer the operation of the analog sensor **100**.

[0073] At block **1565**, the old value of AN**2** is recorded for the next entry into the timer interrupt service routine and the timer interrupt service routine terminates (block **1570**).

[0074] If at block **1530**, the switchmode variable is not set to 1, the GP4 input is set to be an input (floating) and the third bit of the ledstate variable is set and execution continues at block **1565**. The circuitry of the analog sensor **100** thus enters the linear regulation mode as described previously.

[0075] It will be appreciated that the microcontroller **911** is implementing at least one comparison function in the preceding description and therefore, the microcontroller **911** could be at least partially replaced by devices and/or circuits employing a comparator.

[0076] Referring now to FIG. **11**, a perspective view of an example of the analog sensor **100** in assembled condition is shown. This example of the analog sensor **100** has split cores. The split core allows for routing of the primary winding **950** through a window **1005** without disconnection of the primary winding **950** from the source or load **130**. Routing through the window **1005** may be accomplished by first unlatching a first latch **1010***a* and a second latch **1010***b*, and then separating a top half of the enclosure **1030***a* from a bottom half of the enclosure **1030***b*.

[0077] In other examples, other forms of split core configurations may be implemented for the analog sensor **100**. The primary winding **950** may be positioned within the window **1005**. In addition, the top half of and the bottom half **1030***b* may be aligned with each other and the latches **1010***a*, **1010***b* may be re-latched. In the illustrated example, burden terminals **930**, auxiliary power terminals **999** and LED **913** are disposed on the bottom portion of the analog sensor **100**. In other examples, the burden terminals **930**, auxiliary power terminals **999** and LED **913** may be positioned anywhere else on, or near the analog sensor **100**. It will be appreciated that the various windings described herein may be wound on bobbins that are then slipped over the appropriate core.

[0078] Referring now to FIG. **12**, a semi-exploded perspective view of the example of the analog sensor **100** depicted in FIG. **11** is shown. Electronics enclosure **1000** houses the electronic circuitry shown in FIGS. **9** and **10**. Power core **946**, sense core **954** and secondary core **952** are split horizontally (as shown in the diagram) into a first section and a second section, respectively. The first and second sections are illustrated as elements **946***a* and **946***b*, **954***a* and **954***b*, and **952***a* and **952***b*. Power coil **900** may be wound on the first section of the power core **946***a*. Sense coil **934** (more easily visible in FIG. **13**) may be wound on the first section of the sense core **954***a*. Secondary coil **932** may be wound on the first section of the secondary core **952***a*. A portion of each of the power coil **900**, sense coil **934** and secondary coil **932** enter the electronic enclosure **1000**. It will be noted that splitting the analog sensor **100** provides for ease of installation, but may compromise accuracy to some extent (although not nearly to the extent that splitting the core affects the accuracy of standard current transformers due to the active magnetization current replacement employed). Non-split version examples of the present invention are also contemplated.

[0079] Referring now to FIG. **13**, a further exploded perspective view of the example analog sensor **100** depicted in FIG. **11** is shown. The first and second sections of the secondary core **952***a*, **952***b* are further split vertically. The first and second sections of the secondary core **952***a*, **952***b* are further split to allow the insertion of the sense coil **934** and sense core **954** within a channel or groove **931** formed within the secondary core **952**. The sense coil **934** is wound on the first section of sense core **954***a* before the sense core **954** is inserted within the secondary core **952**. The first section of the secondary core **952***a* is then wound with the secondary coil **932**. The analog sensor **100** is then assembled, potted with an appropriate potting compound such as type XR6 1470/XHD 1471 manufactured by Crosslink Technology Inc. located in Toronto, Ontario, Canada and then cut to form a top half of the enclosure **1030***a* and bottom half of the enclosure **1030***b*. At least one of the secondary coil **932** and the sense coil **934** may be shielded from extraneous magnetic and/or electric fields with a shield **933**. In other examples, other component configurations and/or construction techniques may be used to achieve the functionality of the analog sensor **100**.

[0080] Referring now to FIG. **15**, a schematic diagram of an example of the digital sensor **200** is shown. For purposes of brevity, the remaining discussion will focus on differences with the previously described analog sensor **100** (FIGS. **8** and **9**). A burden amplifier **1610** amplifies the voltage dropped across a burden **1605** that is coupled in parallel with the secondary coil **932** of the active CT **960**. An amplified voltage signal produced by the burden amplifier **1610** is applied to one analog to digital converter input **1640** of a microcontroller **1625**. A second analog to digital converter input **1645** is connected to the output of the compensation overload detection circuitry **944**. The microcontroller **1625** samples the amplified voltage signal and transmits the samples through a communications port **1630** to communications cabling **230** via a communications transceiver **1635** that is included in communications interface circuitry **1615**. Communications may be performed over the communications cabling **230** according to a standard communication protocol, such as the IEEE 802.3af standard. The communications cabling **230** may also provide power to the digital sensor **200**. The power is extracted from the communications cabling **230** by a power supply interface circuitry **1620** included in communication interface circuitry **1615**. The power supply interface circuitry **1620** provides various power rails **1650** for operation of the digital sensor **200**. If the microcontroller **1625** detects (through analog to digital converter input **1645**) that the compensation circuitry **942** is not compensating the active CT **960** completely, the microcontroller **1625** may transmit a message indicative of this fact over communications cabling **230**. It will be appreciated that in this example the digital sensor **200** receives power from an IED or other device over communications cabling **230**. Alternatively, the digital sensor **200** may be powered from the current flowing in at least one of the power lines **120** in a similar fashion and with similar circuitry as the analog sensor **100**.

[0081] Referring now to FIG. **16**, another example of a power monitoring and control system **90** is illustrated. The power monitoring system may include an IED **1700**, current conductors **150**, voltage conductors **160**, analog sensors **100**, breaker **99** and I/O lines **580**. The IED **1700** of this system comprises at least 2 sets of current inputs **140***a*, **140***b* and at least one set of voltage inputs **170**. Otherwise this IED **1700** is similar to the IED **110**. The at least 2 sets of current inputs **140***a*, **140***b* allow the IED **1700** to monitor power consumption parameters of at least 2 loads **130***a*, **130***b*. This means that the IED **1700** can be installed in an electrical cabinet, switchgear enclosure, etc. and monitor multiple loads thus reducing the overall cost of the monitoring and control system. Note that similar systems for monitoring more than one load are possible by adding additional current inputs to the IEDS **110**, **210**, **310**, and **410**.

[0082] The IED **1700** may be programmed with the impedance of the wiring between where its voltage inputs **170** connect to the power lines **120**, and where the analog sensors **100** are located. Since the IED **1700** knows the current that is flowing to each particular load **130***a*, **130***b*, it may determine at least an approximation of the voltage at the load through Ohm's law and calculate power parameters based on the actual voltage seen by the load rather than that seen directly by the IED **1700**. This may be an especially valuable configuration for an application such as tenant sub-metering.

[0083] The IEDs **110**, **210**, **310**, **410**, **1700** in FIGS. **1**, **2**, **3**, **4** and **16** may contain I/O interface circuitry **590** which can control a breaker **99** through I/O lines **580** to switch various loads on and off. This switching may be based on

various power parameters being monitored by the IED **1700** that fall outside preset thresholds.

[**0084**] Self Powered Rogowski Coil

[**0085**] As an alternate example, the active CT **960** of the various current sensors described may be replaced with a Rogowski coil. In this case, the circuitry of the sensor can be changed to accept the output of the Rogowski coil and render either an analog or digital representation of the primary current. Rogowski coils have the advantage of non-saturating operation. In this configuration, the powering CT **949** is retained to provide power to the electronic circuitry. The active CT **960** and Rogowski coil are two alternative types of current transducers.

[**0086**] Protocol

[**0087**] It will be noted that the protocol used over the digital or wireless communication links between the sensors and the IEDs may be TCP/IP and may comply with the ITMEL Instrument Transducer-Meter Communication Ethernet Link as defined in the standard of the same name which is hereby incorporated by reference. The determinism and error checking capabilities of IPV6 may be used to ensure timely delivery of current and voltage sample information.

[**0088**] Other protocols that may be supported include Modbus®, DNP, ION, XML, SMTP, DHCP, DNS, HTTP, HTML. The sensors may be self describing using a protocol such as XML. This allows for amplitude/phase correction factors, scales, load curves, phase curves, etc. to be transferred to an IED or computer over communications. This may include calibration curves as described in U.S. Pat. No. 6,671,635 entitled "Systems for Improved Monitoring Accuracy of Intelligent Electronic Devices" which is herein incorporated by reference. The ED or computer may then use this information to improve accuracy.

[**0089**] In addition, the digital sensor **200** (FIG. **2**) may communicate to the IED **210** over power line carrier rather than dedicated communication lines.

[**0090**] Also, the wireless sensor **300** (FIG. **3**) may transmit and receive at least some communication from communication satellites.

[**0091**] Timesync

[**0092**] It will be noted that an accurate time reference may be needed by the digital sensor **200** and wireless sensors **300** and **400** in order that sample times can be communicated to the appropriate IED with an accurate time reference for the time of the current and/or voltage sample. The digital sensor **200** or wireless sensor **300** and **400** may receive time synchronization with a global positioning system (GPS) receiver, a receiver capable of receiving very low frequency signals such as those from the NIST radio stations WWVB and/or WWVH or through an appropriate communications protocol over a respective communications link. This protocol may comprise the network time (NTP) protocol.

[**0093**] Once an IED has received time synchronized current and/or voltage samples, the IED can rebuild the waveform of the power system voltages/currents and enable functions such as waveform capture, harmonics analysis, sag/swell detection, transient detection, fast Fourier transforms, etc.

[**0094**] Instead of communicating with an IED, the digital sensor **200** and wireless sensors **300** and **400** may communicate directly with a computer. The computer may then emulate at least partially the operation of the IED.

[**0095**] The sensor may be programmed with a fixed TCP/IP, Ethernet or other address. When the sensor is equipped with a GPS receiver, this allows the determination of the location of the sensor. In addition to time synchronization, the sensor may then communicate both its address and location to the IED and/or a computer. This allows for the automatic determination of the location of the sensor. If many sensors are simultaneously installed by a user in multiple locations, the software in the IED and/or computer can automatically determine which data is coming from which location in the power system using the address and the location communicated. The location and/or time synchronization may also be provided to the sensor over a wireless telephone network utilizing control channels, GSM, TDMA, CDMA, CDPD, etc.

[**0096**] If multiple digital sensors **200** or wireless sensors **300** are installed in different locations in a power system, they may be used to perform traveling wave fault detection since each has an accurate time reference. For instance if a fault occurs at one end of a power system, the affect on the waveform of the power signal will propagate through the power system at a given rate. The sensors that are closer to the fault will see the affect on the waveform earlier than those farther away.

[**0097**] IPP Monitoring

[**0098**] Due to the wide dynamic range of the current sensors, they may be used in Independent Power Producer (IPP) monitoring applications. IPPs usually generate a large amount of power (and thus a large current flows through the sensors), but when they are not generating, they consume a much smaller amount of power (perhaps more than an order of magnitude less). Therefore, it is important to accurately measure the current (which is one of the parameters that power is determined from) in both the consumption and generation condition. The wide range of the current sensors allows for revenue accurate monitoring in both conditions. For instance when combined with an accurate IED, the current sensors of the present invention may allow for a determination of a power parameter such as kWh within 0.2% at power factors of 0.8 or lower. This may result in the combination of the accurate IED and the current sensor meeting the accuracy requirement of an international standard such as IEC60687 which normally would not take an external current transformer into account.

[**0099**] Referring now to FIG. **18**, a power monitoring and control system **1800** for an IPP **1810** is shown. This system uses the analog sensors **100** and IED **110**, but similar systems may be implemented using the digital sensor **200**, wireless sensor **300** and IEDs **210**, **310** and **410**. The IPP has both a load component **1820** and a generation component **1830**. A transfer switch **1840** may determine whether the IPP is in generation or consumption condition. The transfer switch **1840** may be controlled by an I/O line **580** of the IED **110**.

[**0100**] CVT

[**0101**] The analog sensor **100** may operate as a current to voltage transformer (CVT) if an internal burden is installed

across the burden terminals **930**. The analog sensor then will provide a voltage output rather than a current output.

[**0102**] Breaker or Protective Relay

[**0103**] The sensor may also function as a circuit breaker or protective relay with the addition of circuit opening device or relaying circuitry that is controlled by the microcontroller **1625**. The microcontroller **1625** may execute protective relaying algorithms such as I^2T and interrupt the flow of electricity if a threshold is exceeded.

[**0104**] Hybrid Device

[**0105**] Any or all of the functionality of the IEDs **110**, **210**, **1700** may be integrated into the current sensor or voltage sensor to provide a hybrid unit capable of calculating power parameters. As described earlier, the current and/or voltage sensors may be combined to provide a single unit capable of calculating power parameters such as kVA, kwh, etc. for at least one phase of the power system.

[**0106**] Switchyard

[**0107**] The current sensors may be used in a switchyard application on medium voltage or high voltage transmission lines. In this case it may be necessary for the physical shape of the sensor to be substantially circular or spherical to prevent corona discharge. The wireless sensor **300** may be especially advantageous in this application due to the fact that there is no physical connection between it and the IED or computer it is communicating with.

[**0108**] Alternate Powering Arrangements

[**0109**] IED **110** may alternately supply power to analog sensor **100** by multiplexing a higher frequency (eg., 500 kHz) signal onto current conductors **150**. The energy at this higher frequency may be extracted by the analog sensor **100**. The lower frequency (eg., 50 or 60 Hz) signal from the analog sensor **100** is extracted from the current conductors **150** by the IED **110** using appropriate filtering.

[**0110**] An example of this method of powering the analog sensor is shown in the example circuit schematic illustrated in FIG. **17**. IED end circuitry **1700** may be integrated into IED **110** or be provided as a separate device (without the burden). IED end circuitry **1700** multiplexes power from a higher frequency source such as 400 kHz source **1710** onto lines **1720**. Appropriate filtering circuitry **1730** is provided to block the higher frequency signal from burden **1740** and high frequency bypass circuitry **1750** provides a path for current at the higher frequency to flow. Sensor end circuitry **1760** extracts power from the high frequency current flowing in lines **1720** using power extraction circuitry **1770**. Sensor end circuitry **1760** contains appropriate filtering circuitry **1730** and high frequency bypass circuitry **1750** similar to that in IED end circuitry **1700**. Low input voltage warning circuitry **1780** is provided to warn a user if sufficient voltage is not available in sensor end circuitry **1760**. This may be due to lines **1720** being too long, having too much inductance, etc. The remainder of the circuitry of sensor end circuitry **1760** includes an active CT **960** and support circuitry similar to that previously described. It will be noted that filtering circuitry **1730** will pass current at frequencies substantially within a first range (eg. below 4 kHz) while the high frequency bypass circuitry **1750** will pass current at frequencies substantially within a second range (eg. above 400 kHz). The power extraction circuitry **1770** will extract power at frequencies substantially within the second range.

[**0111**] IED **210** may alternately supply power to digital sensor **200** if current communications cabling **230** is fiber optic cable by injecting optical power at the IED **210** end of the cable. The digital sensor **200** then uses appropriate photovoltaic detection circuitry to extract operating power from the optical power injected.

[**0112**] Wireless sensor **300** may alternately be supplied power by an appropriate microwave power transmitter. The wireless sensor **300** then may have a microwave power receiver to receive this power.

[**0113**] It is intended that the foregoing detailed description be regarded as illustrative rather than limiting, and that it be understood that it is the following claims, including all equivalents, that are intended to define the spirit and scope of this invention.

1.-**84**. (canceled)

85. An apparatus for sensing the current in a power line of a power system, the apparatus comprising:

an enclosure providing a window operable to permit passage of said power line therethrough;

an active current transformer set within said enclosure and operative to produce a scaled version of said current;

a compensation circuit coupled with said active current transformer and operative to compensate for magnetic losses in said active current transformer;

a powering current transformer set within said enclosure and operative to receive power from said power line on a primary winding and deliver power on a secondary winding; and

power supply circuitry set within said enclosure and coupled with said secondary winding, said power supply circuitry operative to supply regulated power to power said compensation circuit as a function of power received from said secondary winding.

86. The apparatus of claim 85, further comprising a burden set within said enclosure and at least one of secondary leads and secondary terminals extending from said enclosure, said at least one of secondary leads and secondary terminals coupled with said active current transformer and operative to deliver said scaled version of said current outside of said enclosure, and said burden is coupled across said at least one of secondary leads and secondary terminals and is operative to provide a voltage representative of said scaled version of said current.

87. The apparatus of claim 85, wherein said compensation circuit is operative to compensate for magnetic losses by being operative to reduce a phase shift and ratio error between said current and said scaled version of said current.

88. The apparatus of claim 87, wherein said compensation circuit is configured so that an absolute value of said phase shift is below 0.05 degrees when said apparatus is operated over a dynamic range of 50 to 1 of said current to said scaled version of said current.

89. The apparatus of claim 87, wherein said compensation circuit is configured so that said ratio error is below 0.1% when said apparatus is operated over a dynamic range of 50 to 1 of said current to said scaled version of said current.

90. The apparatus of claim 85, wherein said compensation circuit is configured to generate a compensation current which zeros a flux in a sense coil included in said active current transformer.

91. The apparatus of claim 90, further comprising:

a secondary coil included within said active current transformer;

a current divider coupled to said secondary coil;

wherein said current divider is configured to feed a portion of said compensation current into said secondary coil to compensate for losses of said active current transformer.

92. The apparatus of claim 85, wherein said power supply circuitry comprises:

a shunt coupled with said secondary winding and operative to carry at least a portion of an output current of said secondary winding.

93. The apparatus of claim 92, wherein said power supply circuitry further comprises:

a regulator coupled with said shunt and operative to regulate a flow of current through said shunt.

94. The apparatus of claim 92, further comprising:

a microcontroller operative to sense said output current, and operate said shunt in a linear regulation mode, or a switched regulation mode in response to a magnitude of said output current.

95. The apparatus of claim 86, further comprising a detector operative to detect when said compensation circuit is unable to reduce said phase shift and ratio error by an expected amount.

96. The apparatus of claim 85, wherein said power supply circuitry is operative to provide power to power a device external to said apparatus.

97. The apparatus of claim 85, further comprising a wireless transceiver set within said enclosure, said wireless transceiver operative to transmit at least one digital sample proportional to said scaled version of said current for receipt by a device external to said enclosure.

98. The apparatus of claim 97, further comprising a receiver set within said enclosure, said receiver operative to receive time synchronization information, said wireless transceiver operative to transmit at least one digital sample that is time synchronized based on said synchronization information.

99. The apparatus of claim 98, wherein said transceiver is operative to transmit said at least one digital sample over a first wireless channel, and said receiver is operative to receive time synchronization information over a second wireless channel.

100. The apparatus of claim 85, further comprising a microprocessor and a compensation overload detection circuit powered from said regulated power, wherein said compensation overload detection circuit is operative to provide said microprocessor with an indication in response to failure of said compensation circuit to compensate for all of said magnetic losses.

101. The apparatus of claim 85 wherein said active current transformer comprises a sense core and a secondary core; said sense core mounted within a groove formed in said secondary core.

102. The apparatus of claim 85, wherein said active current transformer comprises said powering current transformer.

103. The apparatus of claim 85, wherein said power supply circuitry comprises:

a bridge rectifier coupled with said secondary winding, said bridge rectifier operative to provide a rectified output current from an output current of said secondary winding;

a shunt coupled with said bridge rectifier and operative to selectively shunt said rectified output current from said secondary winding;

an energy storage device operative to receive a portion of said rectified output current that is not shunted by said shunt; and

a regulator operative to sense a voltage of said energy storage device and turn said shunt off in response to said voltage being below a first threshold, and turn said shunt on in response to said voltage being above a second threshold.

104. The apparatus of claim 103, further comprising a switched capacitor circuit coupled with said energy storage device, said switched capacitor circuit operative to generate a predetermined magnitude of negative supply voltage and a predetermined magnitude of positive voltage from said determined voltage of said energy storage device.

105. The apparatus of claim 103, wherein said regulator comprises a microcontroller, said apparatus further comprising:

a sense current transformer coupled to said secondary winding, said sense current transformer operative to provide a sense signal to a current monitoring circuit included in said compensation circuit;

wherein an output of said current monitoring circuit is coupled to an input of said microcontroller and said microcontroller is operative to sense zero crossings in said output and turn said shunt off near said zero crossings.

106. The apparatus of claim 105, wherein said voltage powers said microcontroller.

107. The apparatus of claim 85, wherein said power supply circuitry comprises a shunt switch coupled between a ground connection and said regulated power, said shunt switch selectable to be one of open or closed during a switched regulation mode, and a conductivity of said shunt switch operable to be dynamically modulated during a linear regulation mode.

108. The apparatus of claim 85, wherein said power supply circuitry comprises a first switch and a second switch coupled with a supply rail, said first switch selectively enabled to provide a conductive path to ground and said second switch selectively enabled to conduct when a voltage at said first switch is greater than a voltage of said supply rail.

109. An apparatus for sensing the current in a power line of a power system, the apparatus comprising:

an enclosure providing a window operable to permit passage of said power line therethrough;

an active current transformer set within said enclosure and operative to produce a scaled version of said current;

said current containing frequency components substantially within a first range of frequencies;

a compensation circuit coupled with said active current transformer and operative to reduce a phase shift and ratio error between said current and said scaled version of said current;

a powering current transformer set within said enclosure and operative to receive power from said power line on a primary winding and deliver power on a secondary winding; and

power supply circuitry set within said enclosure, said power supply circuitry operative to extract power from a power source within a second range of frequencies, said power supply circuitry further operative to supply regulated power to power said compensation circuit.

110. The apparatus of claim 109, further comprising a high frequency bypass coupled with said power supply circuitry and said power source, said high frequency bypass operative to pass said power at said second range of frequencies.

111. The apparatus of claim 109, further comprising filtering circuitry coupled with said active current transformer and said power source, said filtering circuitry operative to pass said first range of frequencies for receipt by said active current transformer.

112. The apparatus of claim 109 wherein said first range of frequencies is 4 kHz and below and said second range of frequencies is 400 kHz and above.

113. The apparatus of claim 109, wherein said first range of frequencies covers a frequency range at lower frequencies than said second range of frequencies.

114. The apparatus of claim 109, further comprising at least one of secondary leads and secondary terminals extending from said enclosure, said at least one of secondary leads and secondary terminals coupled with said active current transformer and operative to deliver said scaled version of said current in a form of digital data.

115. The apparatus of claim 109, further comprising at least one of secondary leads and secondary terminals extending from said enclosure, said at least one of secondary leads and secondary terminals coupled with said active current transformer and operative to deliver said scaled version of said current in a form of a scaled current signal.

116. A method of sensing current in a power line of a power system, the method comprising:

receiving a primary current from a power line on a primary winding of a powering current transformer;

delivering power on a secondary winding of said power current transformer, said delivered power comprising a supply voltage and a supply current;

producing a scaled version of said primary current with an active current transformer;

compensating for magnetic losses in said active current transformer with a compensation circuit; and

supplying regulated power with a power supply circuit to power said compensation circuit, said power supply circuit coupled with said secondary winding and supplied said supply voltage and said supply current therefrom.

117. The method of claim 116, wherein said regulated power comprises a supply rail voltage and an output current, and supplying regulated power with a power supply circuit to power said compensation circuit comprises sensing said output current, and operating a shunt in one of a linear regulation mode, or a switched regulation mode in response to a magnitude of said output current.

118. The method of claim 117, wherein operating said shunt in said switched regulation mode comprises selectively switching said shunt switch between opened and closed to regulate said supply rail voltage in response to said output current being one of at or above a determined threshold, said shunt switch coupled between said supply rail voltage and ground.

119. The method of claim 117, wherein operating said shunt in said linear regulation mode comprises modulating a conductivity of said shunt switch to regulate said supply rail voltage when said output current is below a determined threshold.

120. The method of claim 116, wherein producing a scaled version of said primary current with an active current transformer comprises:

magnetizing a secondary core of said active current transformer with said power line to supply a secondary current to a burden; and

compensating for magnetization losses in said secondary core with a compensation circuit that is powered with said supply rail voltage.

121. The method of claim 116, further comprising dividing a compensation current generated by said compensation circuit between said supply current and a divider resistor.

122. The method of claim 116, further comprising monitoring said compensation circuit to detect when compensation for magnetization losses is insufficient.

123. The method of claim 122, further comprising indicating to a user when said compensation for magnetization loses is insufficient.

124. The method of claim 116, further comprising providing an external device with power from said supply voltage.

125. The method of claim 116, wherein compensating for magnetization losses in said active current transformer with a compensation circuit further comprises reducing a phase shift and ratio error between said primary current and said scaled version of said primary current.

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