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**Strack et al.**

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(54) **SYSTEM FOR MEASURING EARTH FORMATION RESISTIVITY THROUGH AN ELECTRICALLY CONDUCTIVE WELLBORE CASING**

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(\* ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 382 days.

This patent is subject to a terminal disclaimer.

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(65) **Prior Publication Data**

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**G01V 3/00** (2006.01)

(52) **U.S. Cl.** ..... **324/368; 324/355; 324/370; 324/375**

(58) **Field of Classification Search** ..... **324/355, 324/370, 375, 373, 338, 346, 368, 374**  
See application file for complete search history.

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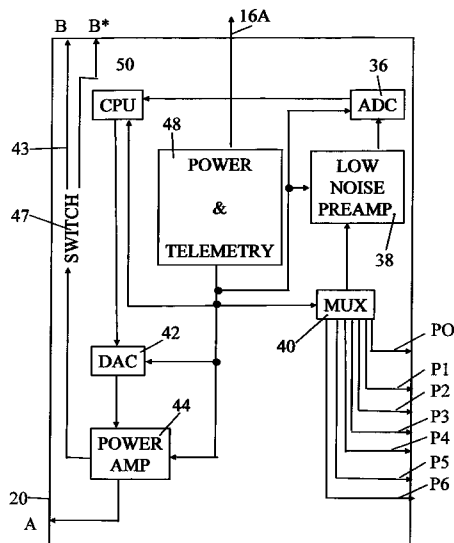
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(57) **ABSTRACT**

An instrument is disclosed for measuring resistivity of Earth formations from within a conductive pipe inside a wellbore drilled through the formations. The instrument includes a plurality of housings connected end to end and adapted to traverse the wellbore. At least one electrode is disposed on each housing. Each electrode is adapted to be placed in electrical contact with the inside of the pipe. The instrument includes a source of electrical current, a digital voltage measuring circuit and a switch. The switch is arranged to connect the source of electrical current between one of the electrodes and a current return at a selectable one of the top of the pipe and a location near the Earth's surface at a selected distance from the top of the pipe, and to connect selected pairs of the electrodes to the digital voltage measuring circuit. The pairs are selected to make voltage measurements corresponding to selected axial distances and selected lateral depths in the Earth formations.

**30 Claims, 12 Drawing Sheets**



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Page 2

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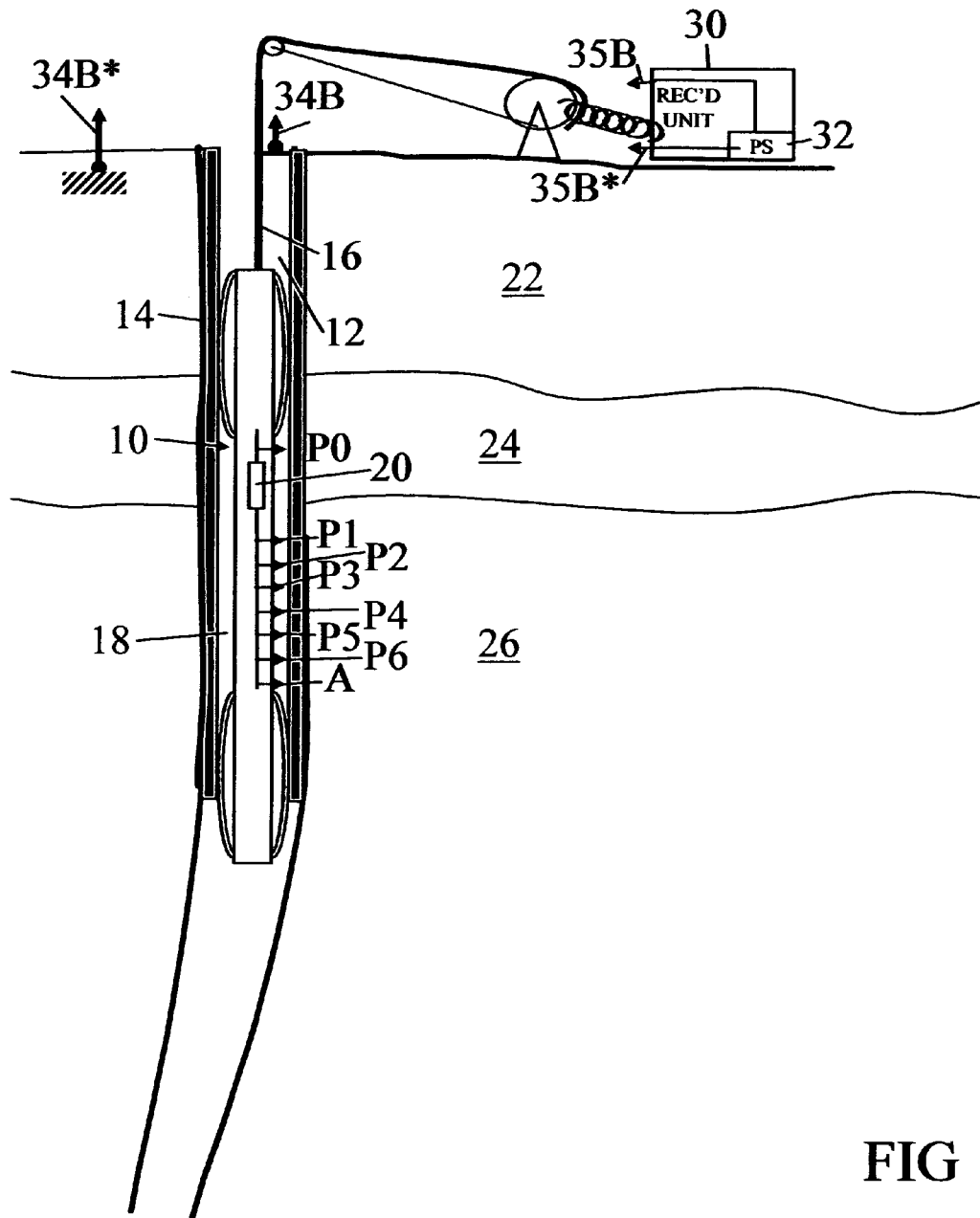


FIG 1

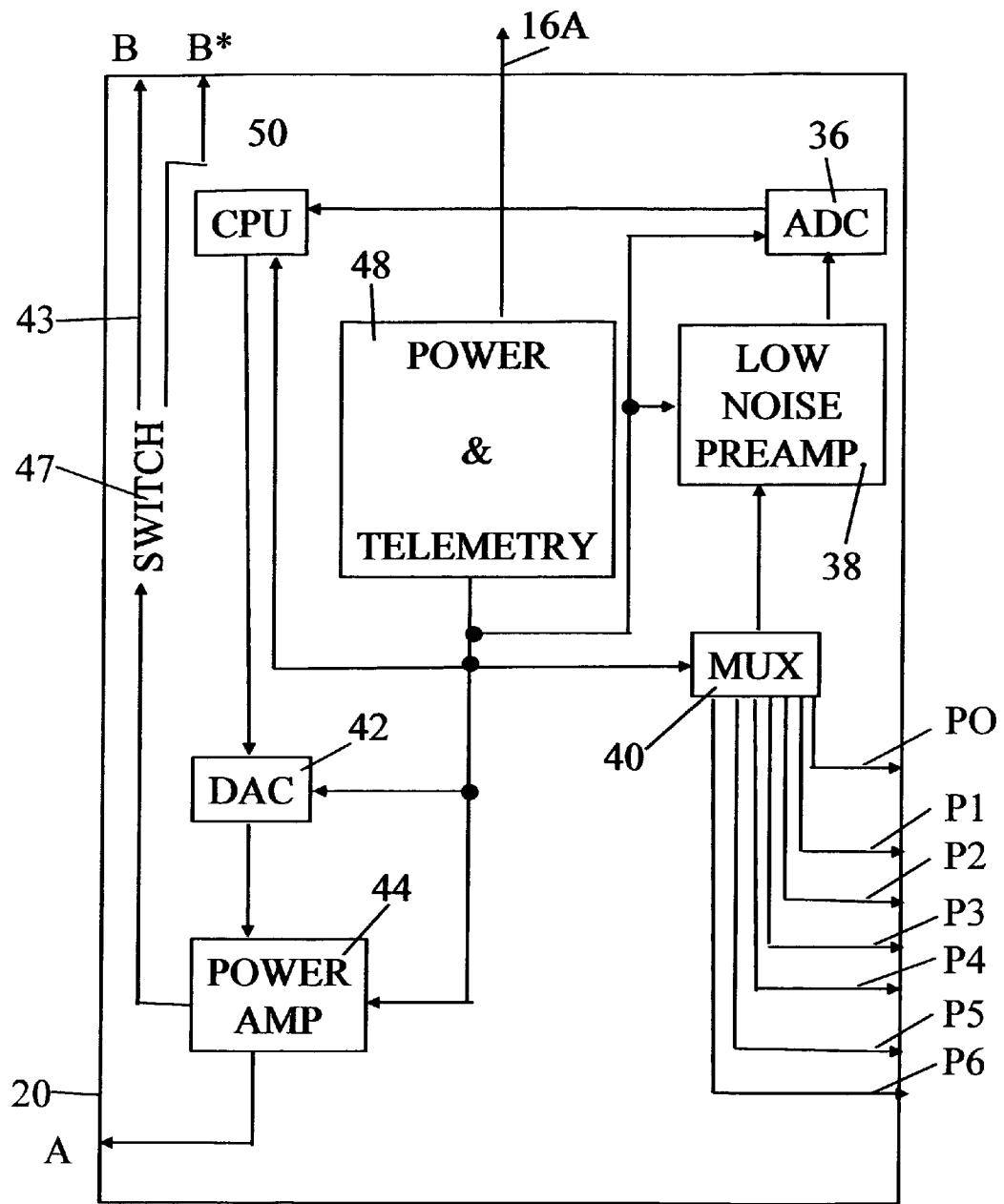
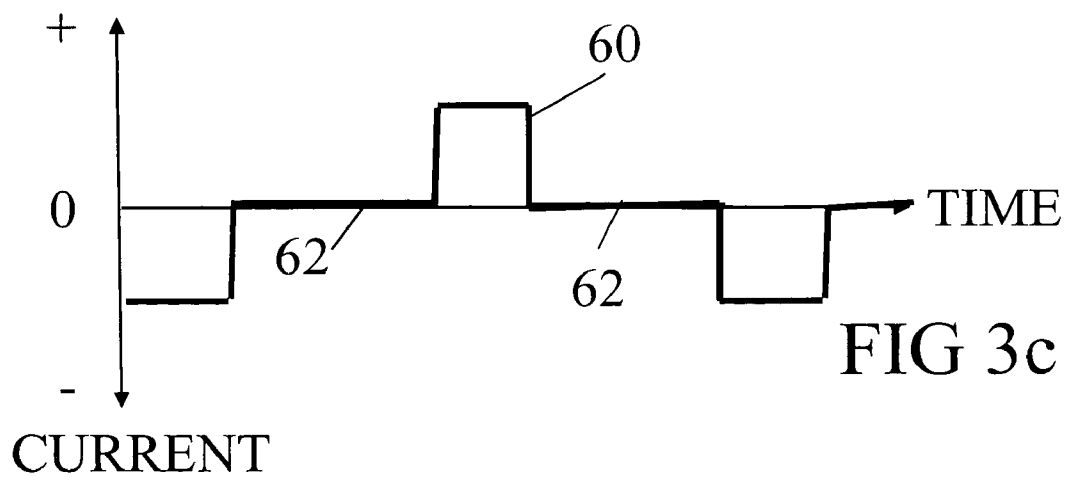
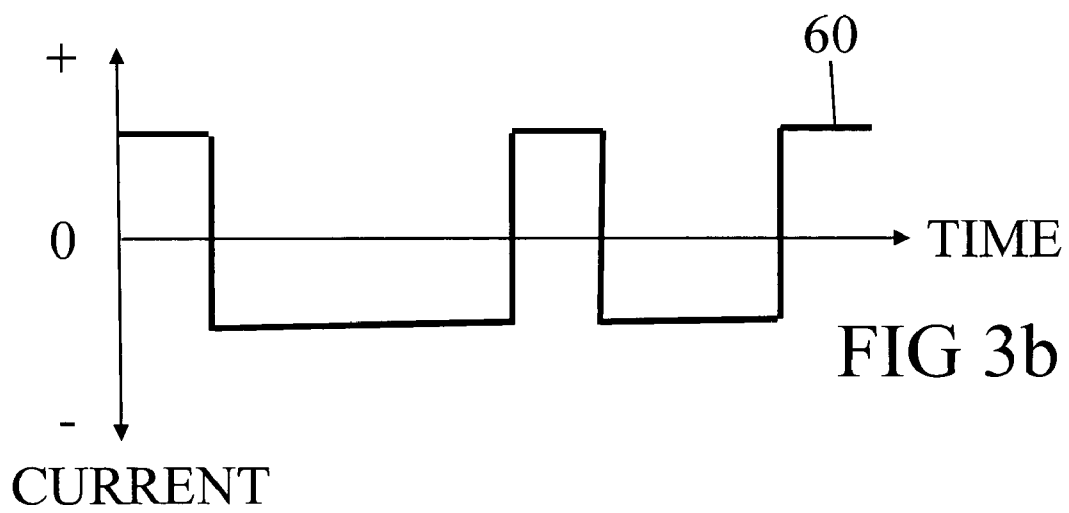
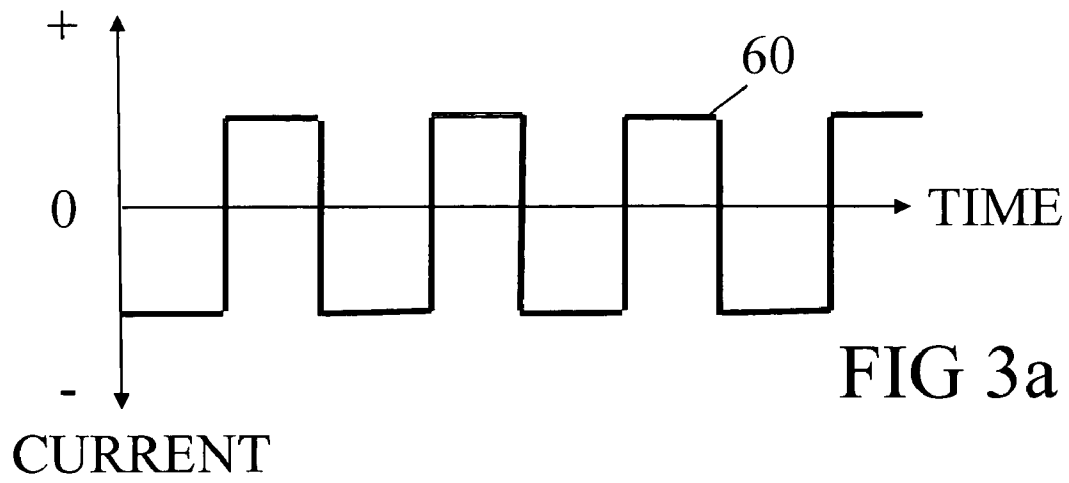
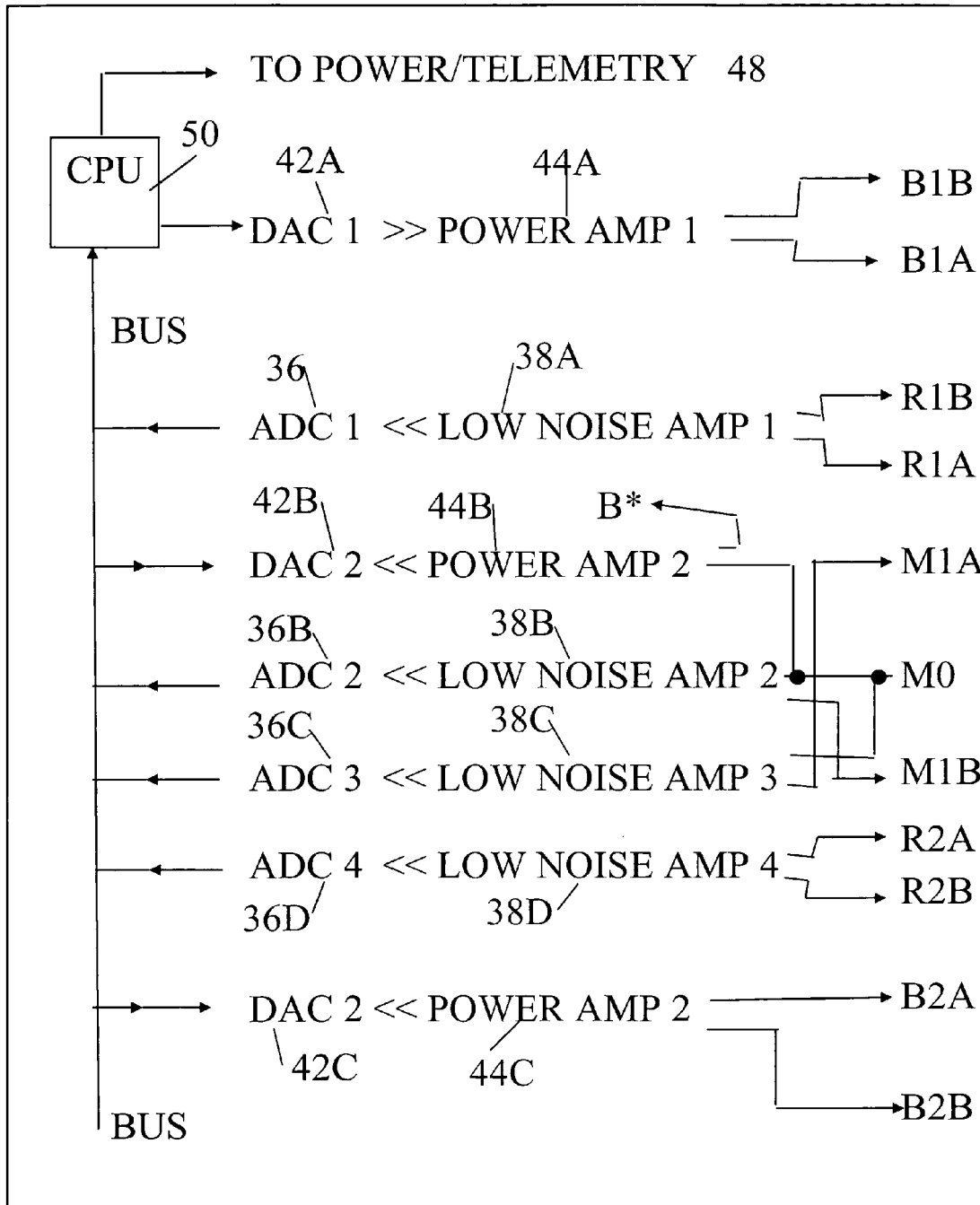


FIG 2





20A

FIG 4

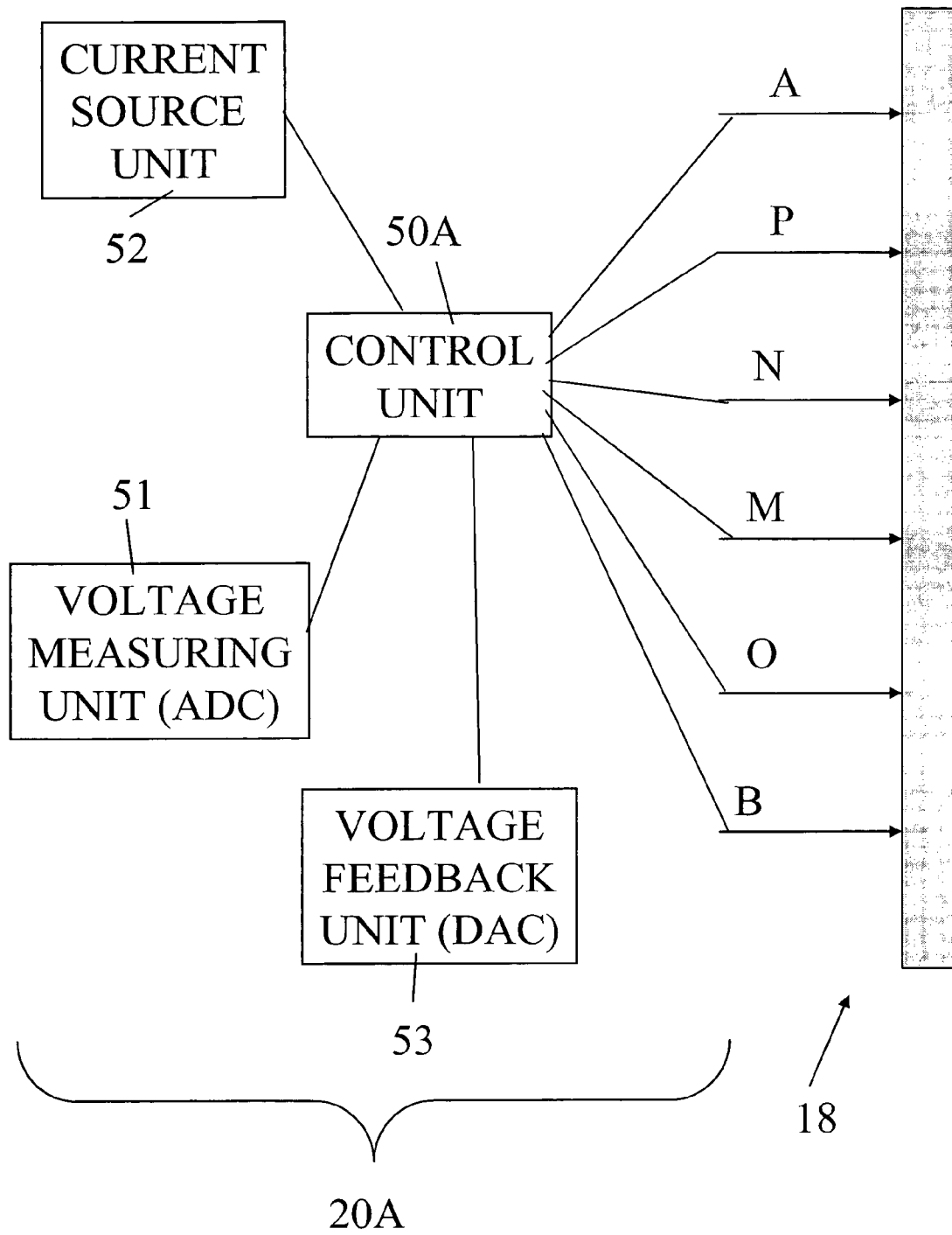


FIG 5

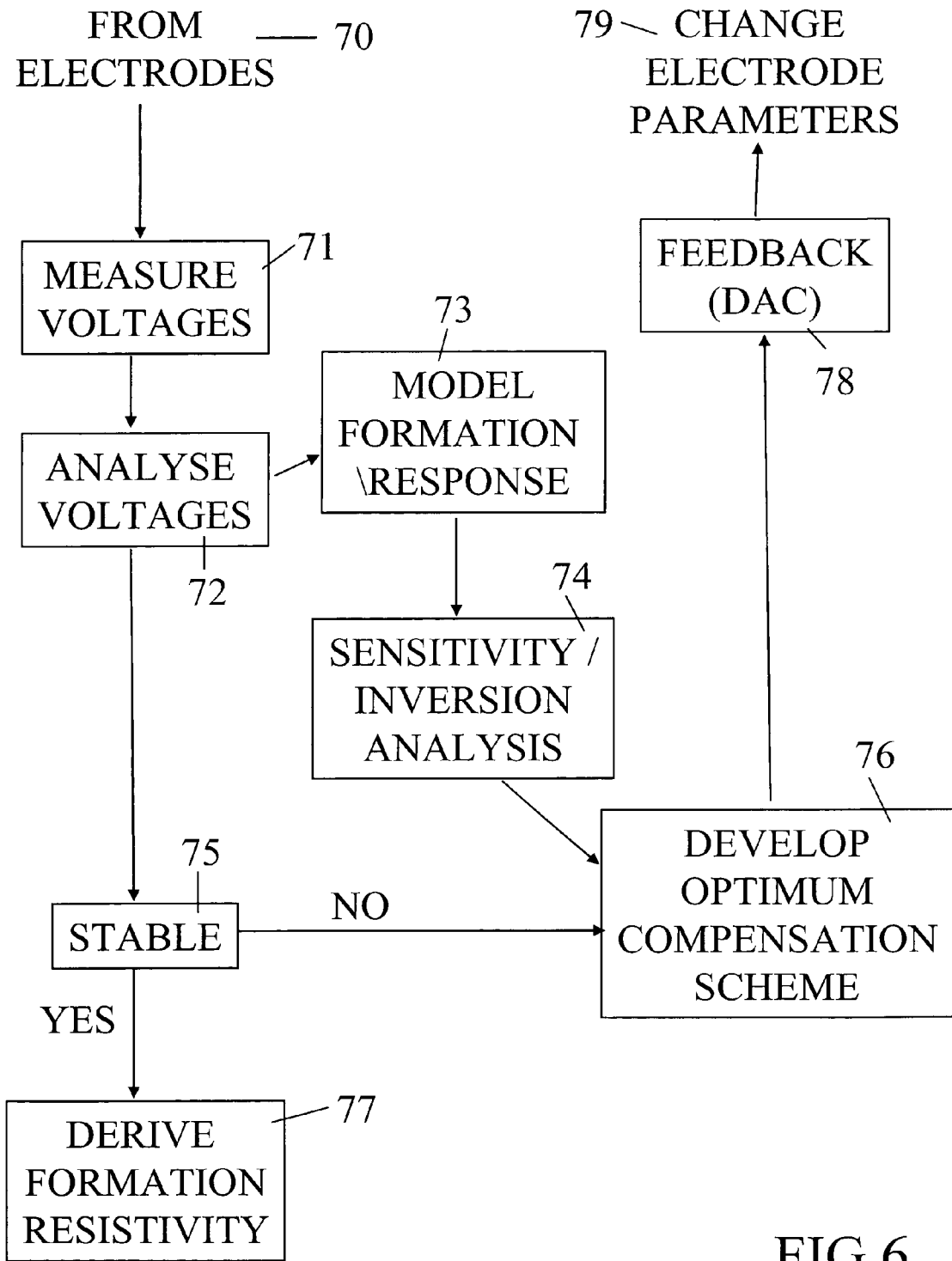


FIG 6



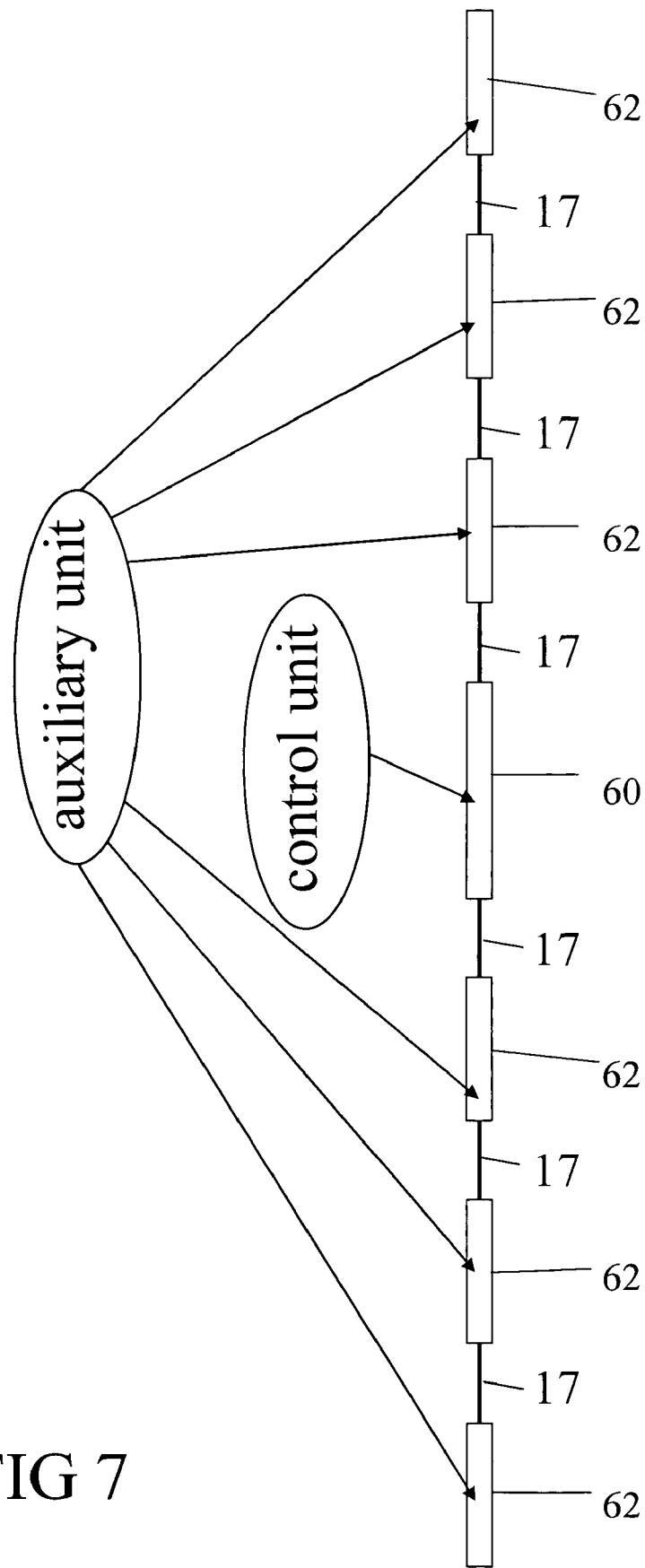


FIG 7

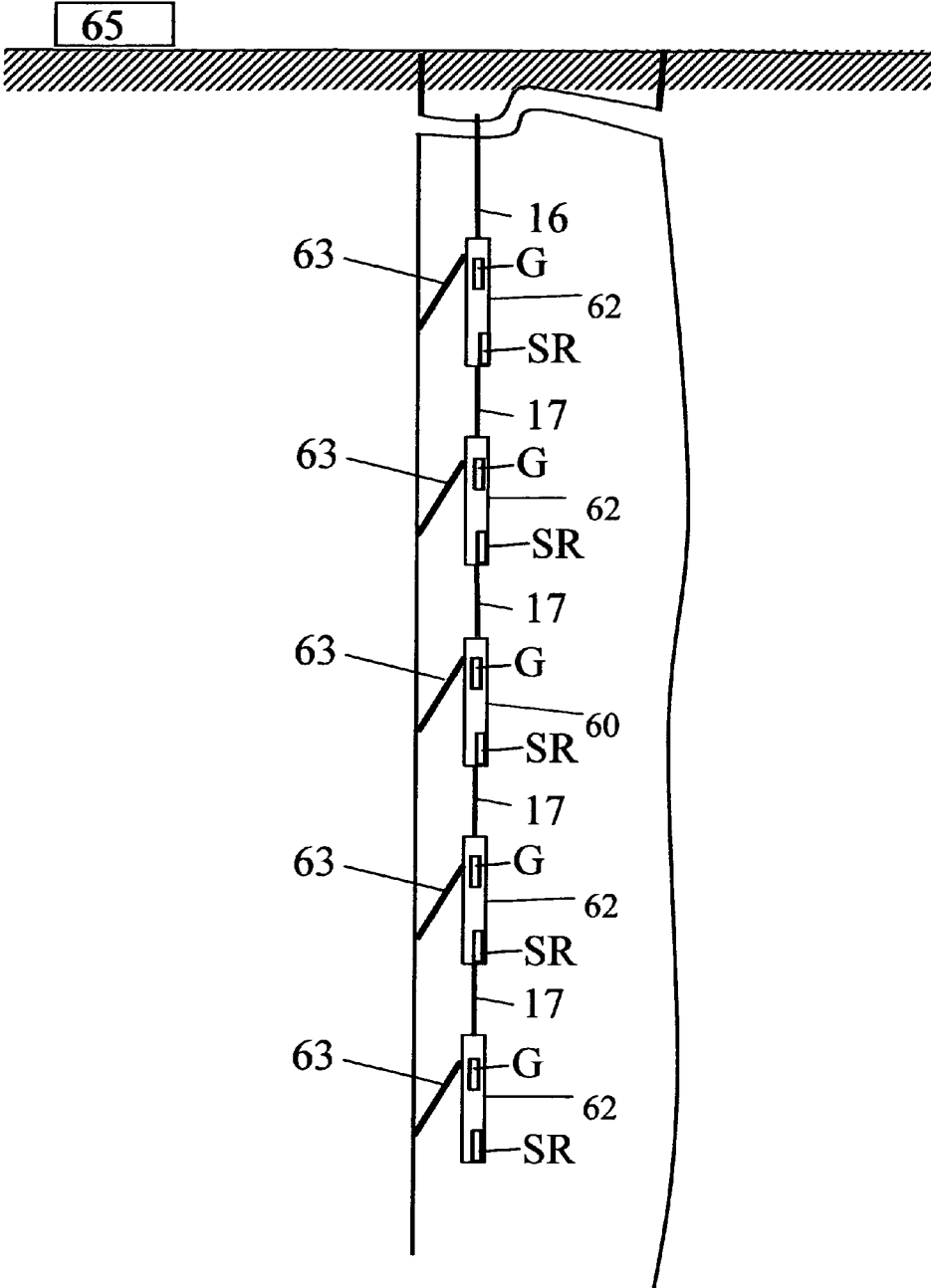


FIG 8

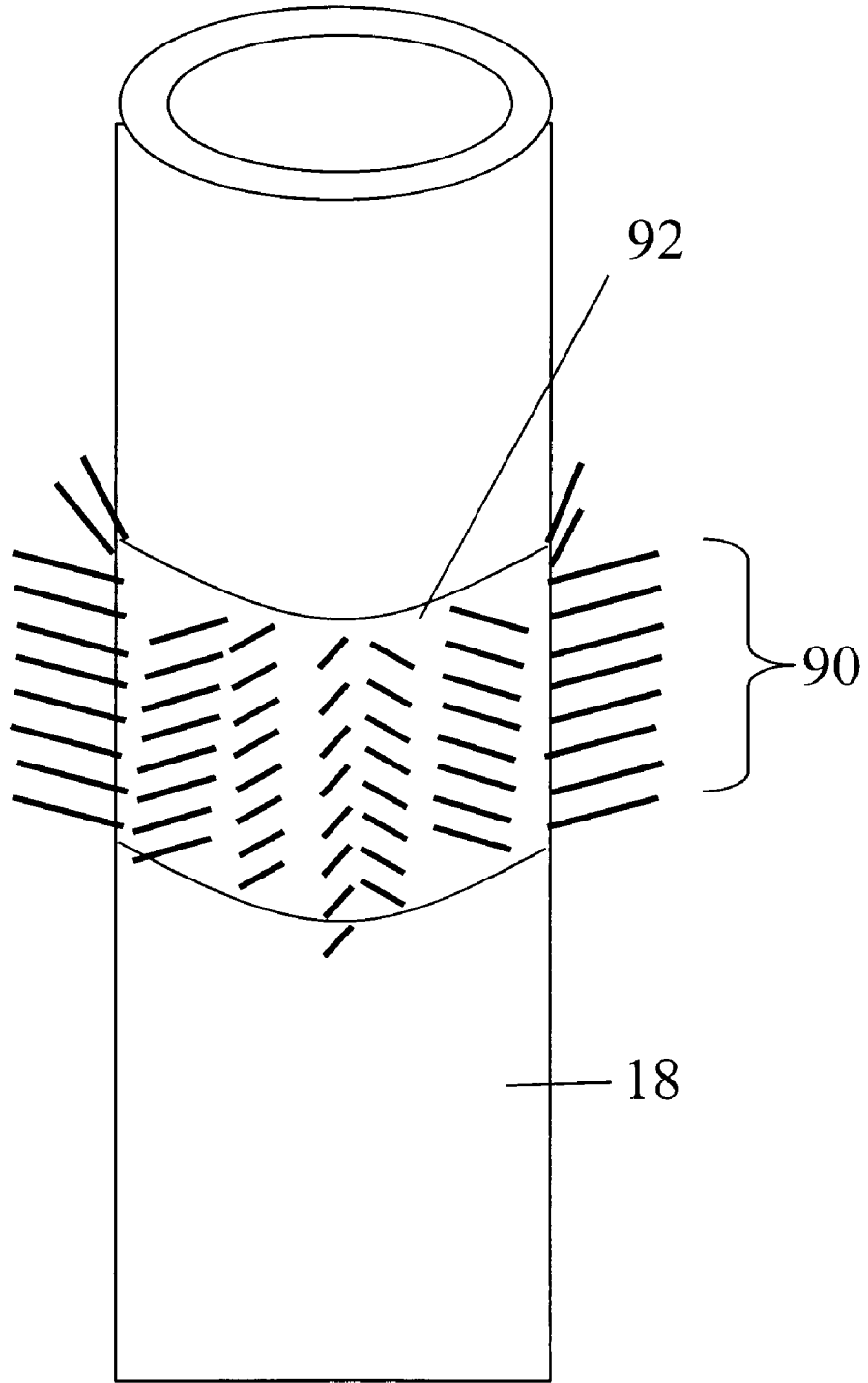


FIG 9

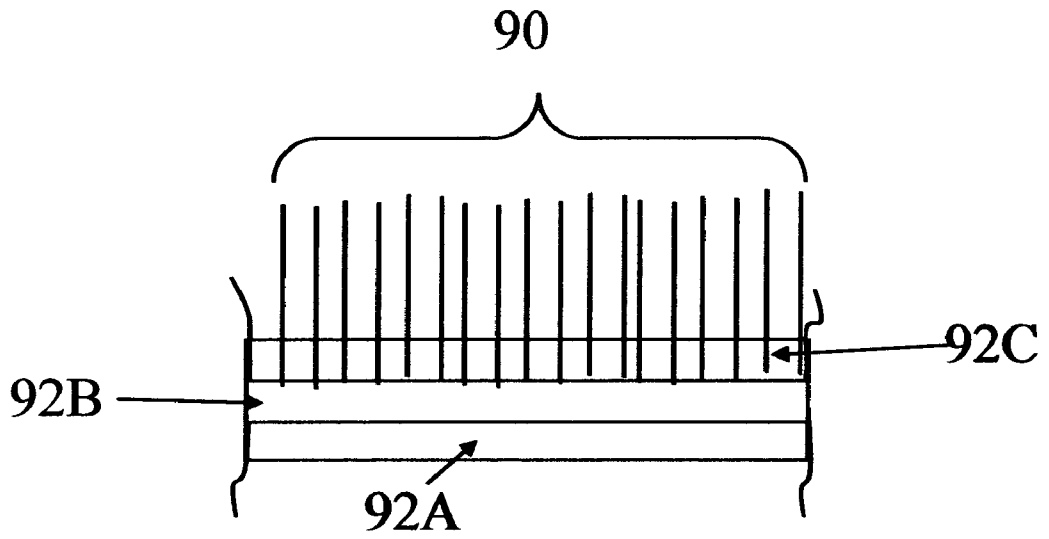


FIG 10

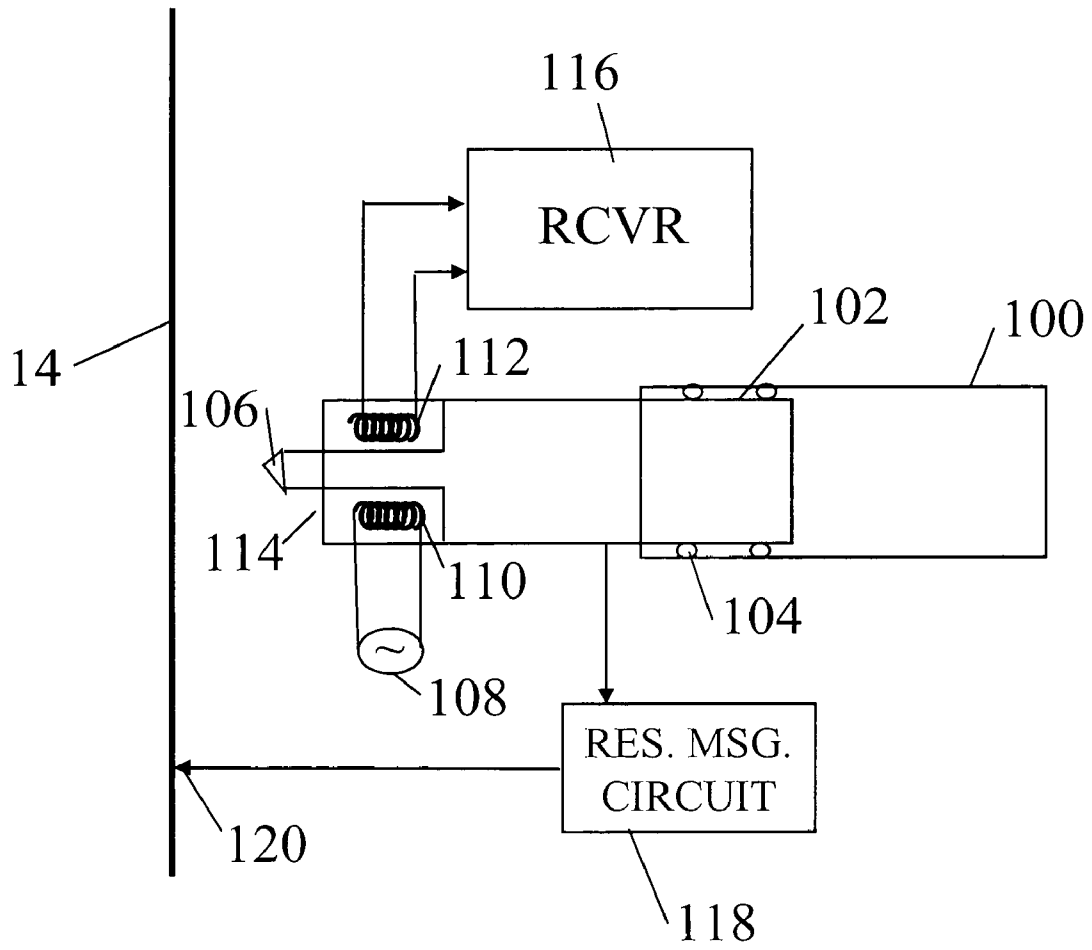


FIG 11

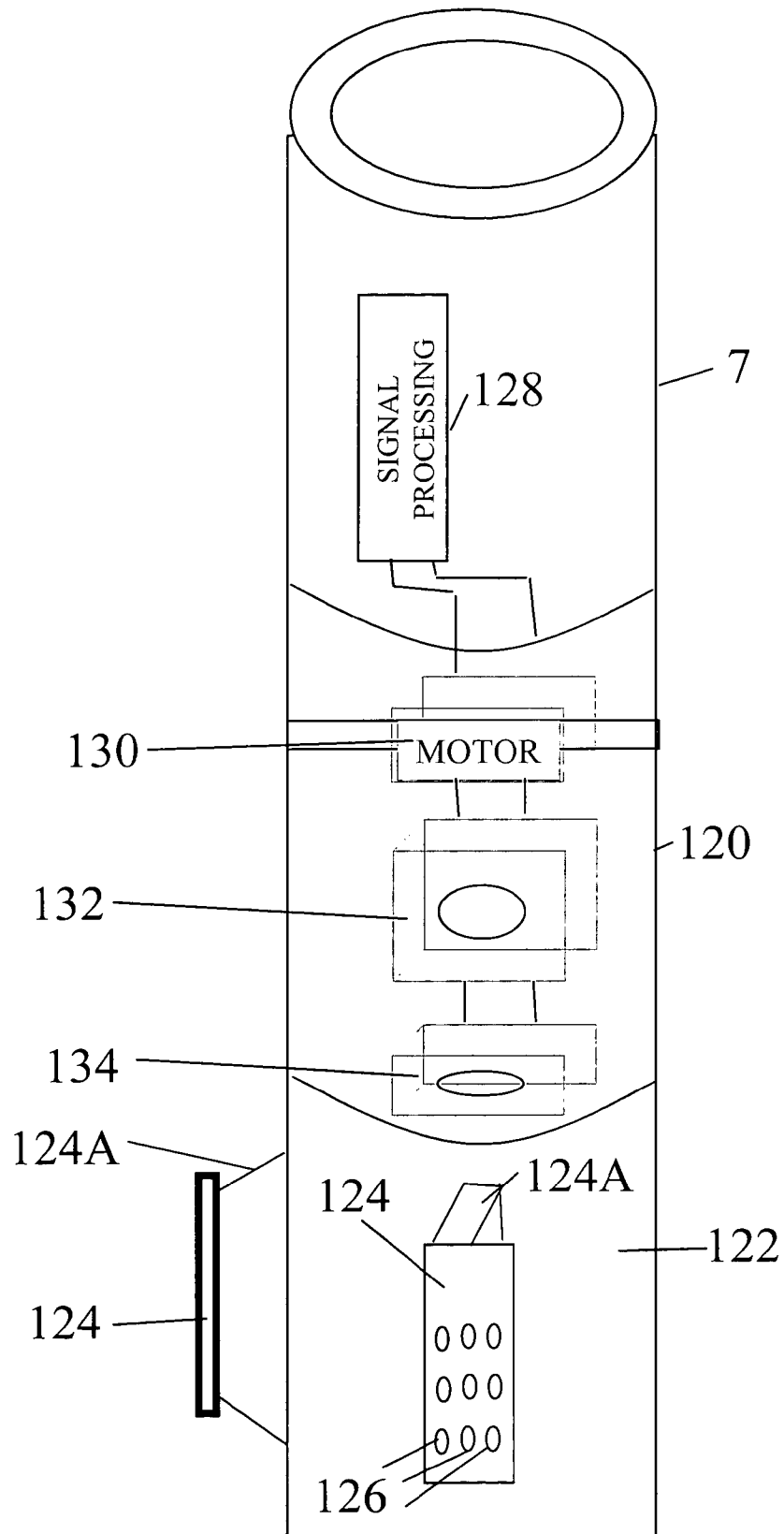


FIG 12

**SYSTEM FOR MEASURING EARTH  
FORMATION RESISTIVITY THROUGH AN  
ELECTRICALLY CONDUCTIVE WELLBORE  
CASING**

CROSS-REFERENCE TO RELATED  
APPLICATIONS

Not applicable.

STATEMENT REGARDING FEDERALLY  
SPONSORED RESEARCH OR DEVELOPMENT

Not applicable.

BACKGROUND OF INVENTION

1. Field of the Invention

The invention relates generally to the field of Earth formation electrical resistivity measuring devices. More particularly, the invention relates to wellbore instruments for measuring formation resistivity from within an electrically conductive pipe or casing.

2. Background Art

Electrical resistivity measurements of Earth formations are known in the art for determining properties of the measured Earth formations. Properties of interest include the fluid content of the pore spaces of the Earth formations. Wellbore resistivity measuring devices known in the art typically require that the Earth formations be exposed by drilling a wellbore therethrough, and that such formations remain exposed to the wellbore so that the measurements may be made from within the exposed formations.

When wellbores are completely drilled through the Earth formations of interest, frequently a steel pipe or casing is inserted into and cemented in place within the wellbore to protect the Earth formations, to prevent hydraulic communication between subsurface Earth formations, and to provide mechanical integrity to the wellbore. Steel casing is highly electrically conductive, and as a result makes it difficult to use conventional (so called "open hole") techniques to determine the resistivity of the various Earth formations from within a steel pipe or casing.

It is known in the art to make measurements for determining the electrical resistivity of Earth formations from within conductive casing or pipe. A number of references disclose techniques for making such measurements. A list of references which disclose various apparatus and methods for determining resistivity of Earth formations from within conductive casings includes: USSR inventor certificate no. 56052, filed by Alpin, L. M. (1939), entitled, The method for logging in cased wells; USSR inventor certificate no. 56026, filed by Alpin, L. M. (1939), entitled, Process of the electrical measurement of well casing; U.S. Pat. No. 2,459,196, to Stewart, W. H. (1949), entitled, Electrical logging method and apparatus; U.S. Pat. No. 2,729,784 issued to Fearon, R. E. (1956), entitled, Method and apparatus for electric well logging; U.S. Pat. No. 2,891,215 issued to Fearon, R. E. (1959), entitled, Method and apparatus for electric well logging; French patent application no. 72.41218, filed by Desbrandes, R. and Mengez, P. (1972), entitled, Method & Apparatus for measuring the formation electrical resistivity in wells having metal casing; International Patent Application Publication no. WO 00/79307 A1, filed by Benimeli, D. (2002), entitled, A method and apparatus for determining of a formation surrounding a cased well; U.S. Pat. No. 4,796,186 issued to Kaufman, A. A. (1989), entitled, Conductivity

determination in a formation having a cased well; U.S. Pat. No. 4,820,989, issued to Vail, III, W. (1989), entitled, Methods and apparatus for measurement of the resistivity of geological formation from within cased boreholes; U.S. Pat. No. 4,837,518 issued to Gard et al. (1989), entitled, Method and Apparatus for measuring the electrical resistivity of formation through metal drill pipe or casing; U.S. Pat. No. 4,882,542 issued to Vail, III, W. (1989), entitled, Methods and apparatus for measurement of electronic properties of geological formations through borehole casing; U.S. Pat. No. 5,043,668 issued to Vail, III, W. (1991), entitled, Methods and apparatus for measurement of electronic properties of geological formations through borehole casing; U.S. Pat. No. 5,075,626 issued to Vail, III, W. (1991), entitled, Electronic measurement apparatus movable in a cased borehole and compensation for casing resistance differences; U.S. Pat. No. 5,223,794 issued to Vail, III, W. (1993), entitled, Methods of apparatus measuring formation resistivity from within a cased well having one measurement and two compensation steps; U.S. Pat. No. 5,510,712 issued to Sezginer et al. (1996), entitled, Method and apparatus for measuring formation resistivity in cased holes; U.S. Pat. No. 5,543,715 issued to Singer et al. (1996), entitled, Method and apparatus for measuring formation resistivity through casing using single-conductor electrical logging cable; U.S. Pat. No. 5,563,514 issued to Moulin (1996), entitled, Method and apparatus for determining formation resistivity in a cased well using three electrodes arranged in a Wheatstone bridge. U.S. Pat. No. 5,654,639 issued to Locatelli et al. (1997), entitled, Induction measuring device in the presence of metal walls; U.S. Pat. No. 5,570,024 issued to Vail, III, W. (1996), entitled, Determining resistivity of a formation adjacent to a borehole having casing using multiple electrodes and resistances being defined between the electrodes; U.S. Pat. No. 5,608,323 issued to Koelman, J. M. V. A. (1997), entitled, Arrangement of the electrodes for an electrical logging system for determining the electrical resistivity of subsurface formation; U.S. Pat. No. 5,633,590 issued to Vail, III, W. (1997), entitled, Formation resistivity measurements from within a cased well used to quantitatively determine the amount of oil and gas present. U.S. Pat. No. 5,680,049 issued to Gissler et al. (1997), entitled, Apparatus for measuring formation resistivity through casing having a coaxial tubing inserted therein; U.S. Pat. No. 5,809,458 issued to Tamarchenko (1998), entitled, Method of simulating the response of a through-casing resistivity well logging instrument and its application to determining resistivity of earth formations; U.S. Pat. No. 6,025,721 issued to Vail, III, W. (2000), entitled, Determining resistivity of a formation adjacent to a borehole having casing by generating constant current flow in portion of casing and using at least two voltage measurement electrodes; U.S. Pat. No. 6,157,195 issued to Vail, III, W. (2000), entitled, Formation resistivity measurements from within a cased well used to quantitatively determine the amount of oil and gas present; U.S. Pat. No. 6,246,240 B1 issued to Vail, III, W. (2001), entitled, Determining resistivity of formation adjacent to a borehole having casing with an apparatus having all current conducting electrodes within the cased well; U.S. Pat. No. 6,603,314 issued to Kostelnicek et al. (2003), entitled, Simultaneous current injection for measurement of formation resistance through casing; and U.S. Pat. No. 6,667,621 issued to Benimelli, entitled, Method and apparatus for determining the resistivity of a formation surrounding a cased well.

United States Patent Application Publications which cite relevant art include no. 2001/0033164 A1, filed by Vinegar

et al., entitled, Focused through-casing resistivity measurement; no. 2001/0038287 A1, filed by Amini, Bijan K., entitled, Logging tool for measurement of resistivity through casing using metallic transparencies and magnetic lensing; no. 2002/0105333 A1 filed by Amini, Bijan K., entitled, Measurements of electrical properties through non magnetically permeable metals using directed magnetic beams and magnetic lenses. and no. 2003/0042016 A1, filed by Vinegar et al., entitled, Wireless communication using well casing.

The foregoing techniques are summarized briefly below. U.S. Pat. No. 2,459,196 describes a method for measuring inside a cased wellbore, whereby electrical current is caused to flow along the conductive casing such that some of the current will "leak" into the surrounding Earth formations. The amount of current leakage is related to the electrical conductivity of the Earth formations. The '196 patent does not disclose any technique for correcting the measurements for electrical inhomogeneities in the casing.

U.S. Pat. No. 2,729,784 discloses a technique in which three potential electrodes are used to create two opposed pairs of electrodes in contact with a wellbore casing. Electrical current is caused to flow in two opposing "loops" through two pairs of current electrodes placed above and below the potential electrodes such that electrical inhomogeneities in the casing have their effect nulled. Voltage drop across the two electrode pairs is related to the leakage current into the Earth formations. The disclosure in U.S. Pat. No. 2,891,215 includes a current emitter electrode disposed between the measuring electrodes of the apparatus disclosed in the '784 patent to provide a technique for fully compensating the leakage current.

U.S. Pat. No. 4,796,186 discloses the technique most frequently used to determine resistivity through conductive casing, and includes measuring leakage current into the Earth formations, and discloses measuring current flowing along the same portion of casing in which the leakage current is measured so as to compensate the measurements of leakage current for changes in resistance along the casing. Other references describe various extensions and improvements to the basic techniques of resistivity measurement through casing.

The methods known in the art for measuring resistivity through casing can be summarized as follows. An instrument is lowered into the wellbore having at least one electrode on the instrument (A) which is placed into contact with the casing at various depths in the casing. A casing current return electrode B is disposed at the top of and connected to the casing. A formation current return electrode B\* is disposed at the Earth's surface at some distance from the wellbore. A record is made of the voltage drop and current flowing from electrode A in the wellbore at various depths, first to electrode B at the top of the casing and then to formation return electrode B\*. Current flow and voltage drop through the casing (A-B) is used to correct measurements of voltage drop and current flow through the formation (A-B\*) for effects of inhomogeneity in the casing.

If the Earth and the casing were both homogeneous, a record with respect to depth of the voltage drop along the casing, and the voltage drop through the casing and formation, would be substantially linear. As is well known in the art, casing includes inhomogeneities, even when new, resulting from construction tolerances, composition tolerances, and even "collars" (threaded couplings) used to connect segments of the casing to each other. Earth formations, of course, are not at all homogeneous, and more resistive formations are typically the object of subsurface investigation, because these Earth formations tend to be associated

with presence of petroleum, while the more conductive formations tend to be associated with the presence of all connate water in the pore spaces. Therefore, it is the perturbations in the record of voltage drop with respect to depth that are of interest in determining resistivity of Earth formations outside casing using the techniques known in the art.

The conductivity of the Earth formations is related to the amount of current leaking out of the casing into the formations. The formation conductivity with respect to depth is generally related to the second derivative of the voltage drop along A-B with respect to depth, when current is flowing between A and B\*. Typically, the second derivative of the voltage drop is measured using a minimum of three axially spaced apart electrodes placed in contact with the casing, coupled to cascaded differential amplifiers, ultimately coupled to a voltage measuring circuit. Improvements to the basic method that have proven useful include systems which create a small axial zone along the casing in which substantially no current flows along the casing itself to reduce the effects of casing inhomogeneity on the measurements of leakage current voltage drop.

In practice, instruments and methods known in the art require that the instrument make its measurements from a fixed position within the wellbore, which makes measuring formations of interest penetrated by a typical wellbore take an extensive amount of time. Further, the voltage drops being measured are small, and thus subject to noise limitations of the electronic systems used to make the measurements of voltage drop. Still further, systems known in the art for providing no-current zones, or known current flow values for measurements of voltage drop, are typically analog systems, and thus subject to the accuracy limitations of such analog systems.

Still further, it is known in the art to use low frequency alternating current (AC) to induce current flow along the casing and in the Earth formations. AC is used to avoid error resulting from electrical polarization of the casing and the electrodes when continuous direct current (DC) is used. Typically, the frequency of the AC must be limited to about 0.01 to 20 Hz to avoid error in the measurements caused by dielectric effects and the skin effect. It is also known in the art to use polarity-switched DC to make through casing resistivity measurements, which avoids the polarization problem, but may induce transient effect error in the measurements when the DC polarity is switched. Transient effects, and low frequency AC errors are not easily accounted for using systems known in the art.

#### SUMMARY OF INVENTION

One aspect of the invention is an instrument for measuring resistivity of Earth formations from within a conductive pipe inside a wellbore drilled through the Earth formations. The instrument includes a plurality of housings connected end to end and adapted to traverse the wellbore. At least one electrode is disposed on each housing. Each electrode is adapted to be placed in electrical contact with the inside of the pipe. The instrument includes a source of electrical current, a digital voltage measuring circuit and a switch. The switch is arranged to connect the source of electrical current between one of the electrodes and a current return at a selectable one of the top of the pipe and a location near the Earth's surface at a selected distance from the top of the pipe, and to connect selected pairs of the electrodes to the digital voltage measuring circuit. The pairs are selected to



make voltage measurements corresponding to selected axial distances and selected lateral depths in the Earth formations.

One embodiment of the instrument includes a focusing current source that is coupled through the switch to a selected pair of the electrodes to constrain measuring current to flow in a laterally outward path proximate the instrument.

One embodiment of the instrument includes a back up arm on one or more of the housings and a seismic receiver disposed in the one or more of the housings which includes the back up arm.

Another aspect of the invention is a method for measuring resistivity of Earth formations from within a conductive pipe inside a wellbore drilled through the Earth formations. A method according to this aspect of the invention includes inserting a plurality of housings connected end to end to a selected depth inside the pipe. At least one electrode on each housing is placed in electrical contact with the inside of the pipe. Electrical current from a measuring current source is passed through at least one of the electrodes into the pipe. A return from the measuring current source is switched between one of the electrodes and a current return at a selectable one of the top of the pipe and a location near the Earth's surface at a selected distance from the top of the pipe. Voltages are digitally measured across selected pairs of the electrodes. The pairs of electrodes are selected to make voltage measurements corresponding to selected axial distances and selected lateral depths in the Earth formations.

Other aspects and advantages of the invention will be apparent from the following description and the appended claims.

#### BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 shows an example resistivity measurement through casing apparatus according to the invention being used in a cased wellbore.

FIG. 2 shows a circuit systems of the example apparatus of FIG. 1 in more detail.

FIGS. 3A through 3C show different examples of current waveform for making through casing resistivity measurements according to the invention.

FIG. 4 shows an example instrument for measuring resistivity through a conductive pipe which includes current focusing systems.

FIG. 5 shows an alternative embodiment of an apparatus including a selectable array of electrodes on a sonde mandrel.

FIG. 6 shows a flow chart of operation of an instrument such as shown in FIG. 4 adapted to automatically optimize control of electrode usage according to a model based instrument response.

FIG. 7 shows a system for measuring resistivity through conductive pipe including a central control unit and a plurality of "satellite" units.

FIG. 8 shows an embodiment as in FIG. 7 including seismic receivers in one or more of the central control unit and the satellite units.

FIG. 9 shows one embodiment of an electrode for making electrical contact with the interior surface of a conductive casing.

FIG. 10 shows a cut away view of the electrode shown in FIG. 9.

FIG. 11 shows a system for estimating quality of contact between an electrode and the conductive pipe.

FIG. 12 shows an additional portion of one embodiment of an apparatus used to evaluate the condition of the interior surface of the pipe.

#### DETAILED DESCRIPTION

One embodiment of a well logging instrument used to measure resistivity of Earth formations from within a wellbore, when the wellbore has a conductive pipe or casing within is shown schematically in FIG. 1. The instrument 10 may include a sonde or similar mandrel-type housing 18. The housing 18 is preferably made from an electrically non-conductive material, or has such non-conductive material on its exterior surface. The housing 18 is adapted to be inserted into and withdrawn from the wellbore 14, by means of any well logging instrument conveyance known in the art. In the present example, the conveyance can be an armored electrical cable 16 extended and retracted by a winch 28. Other conveyances known in the art may be used, including coiled tubing, drill pipe, production tubing, etc. Accordingly, the conveyance is not intended to limit the scope of the invention.

The wellbore 14 is drilled through various Earth formations, shown schematically at 22, 24 and 26. After the wellbore 14 is drilled, a conductive pipe 12 or casing is inserted into the wellbore 14. If the pipe 12 is a casing, then the casing 12 is typically cemented in place within the wellbore 14, although cementing the pipe or casing is not necessary to operation of the instrument 10. While the embodiment shown in FIG. 1 is described in terms of a "casing" being inserted and cemented into a drilled wellbore, it should be understood that other types of electrically conductive pipe, such as drill pipe, coiled tubing, production tubing and the like may also be used with an instrument according to the invention. In one particular example, the pipe 12, rather than being casing, may be drill pipe that has become stuck in the wellbore 14, whereupon the instrument 10 is lowered into the stuck drill pipe on an armored electrical cable 16 to make measurements as will be further explained.

The armored electrical cable 16 includes one or more insulated electrical conductors (not shown separately) and is arranged to conduct electrical power to the instrument 10 disposed in the wellbore 14. Electrical power can be conducted from, and signals from the instrument 10 can be transmitted to, a recording unit 30 disposed at the Earth's surface using the electrical conductors on the cable 16. The recording unit 30 may also be used to record and/or interpret the signals communicated thereto from the instrument 10 in the wellbore 14. The recording unit 30 may include an electrical power supply 32 used to make measurements for determining resistivity of the various Earth formations 22, 24, 26. In the present description, any electrical power supply used to enable making the measurements corresponding to formation resistivity will be referred to as a "measuring current source." The power supply 32 may also be used merely to provide electrical power to various measurement and control circuits, shown generally at 20 in FIG. 1, in the instrument 10. The functions provided by the various circuits in the instrument will be further explained below with reference to FIG. 2.

Still referring to FIG. 1, a measuring current return electrode 34B\* is provided at the Earth's surface at a selected distance from the wellbore 14. The measuring current return electrode 34B\* is typically inserted into formations proximate the Earth's surface so as to provide an electrically conductive path to the Earth formations 22, 24, 26 penetrated by the wellbore 14. The measuring current return electrode 34B\* provides, in particular, a current path through the Earth formations 22, 24 26 for electrical measuring current to flow from a source electrode A on the

instrument **10**. The current return electrode **34B\*** may be connected, as shown in FIG. **1**, either to circuits **35B\*** in the recording unit **30**, or alternatively may be connected to one of the electrical conductors (not shown separately) in the cable **16**. A casing current return electrode **34B**, shown

5 connected to the top of the pipe or casing **12**, provides a return path for electrical measuring current caused to flow from the current source electrode A on the instrument **10**, to the top of the casing **12**. The casing current return electrode **34B** may be coupled to circuits **35B** in the recording unit **30**, or may be coupled to one of the conductors (not shown) in the cable **12** for return to the circuits **20** in the instrument **10**.

The instrument **10** includes a plurality of electrodes, shown at A, and P0 through P6 disposed on the sonde mandrel **18** at axially spaced apart locations. The electrodes A, P0-P6 are electrically isolated from each other by the non-conductive material disposed on the exterior of, or forming, the sonde mandrel **18**. Each of the electrodes A, P0-P6 is mechanically and electrically adapted to make good electrical contact with the casing **12**. Various types of casing-contact electrodes are known in the art and include brushes, hydraulically actuated "spikes", spiked wheels and similar devices. The electrodes A, P0-P6 are each coupled to a selected portion of the electronic circuits **20** in the instrument **10**.

During operation of the instrument **10** when conveyed by armored cable, the cable **16** is extended by the winch **28** so that the instrument **10** is positioned at a selected depth in the wellbore **14**. Electrical power is passed through the casing **12** and through the Earth formations **22, 24, 26** by selective connection between the source electrode A at one end of the current path, and either the casing return **34B** or formation return **34B\***, respectively, at the other end of the current path. Measurements are made of the voltage extant between a reference potential electrode, shown as electrode P0 in FIG. **1**, and one or more potential measurement electrodes, P1-P6 in FIG. **1**. Depending on the type of electrodes used, for example, brushes or spiked contact wheels, it may be possible, in some embodiments, for the instrument **10** to be moved slowly along the wellbore **14** as the measurements are being made. Other types of electrode, such as hydraulically actuated spikes, may require that the instrument **10** remain essentially stationary during any one measurement sequence. As the voltage measurements are made, whether the instrument **10** is stationary or moving, the instrument **10** is gradually withdrawn from the wellbore **14**, until a selected portion of the wellbore **14**, including formations of interest, **22, 24, 26**, have voltage measurements made corresponding to them, both using the casing current return **34B** and the formation current return **34B\***.

One embodiment of the electronic circuits **20** is shown in greater detail in FIG. **2**. The present embodiment of the circuits **20** may include a central processing unit (CPU) **50**, which may be a preprogrammed microcomputer, or a programmable microcomputer. In the present embodiment, the CPU **50** is adapted to detect control commands from within a formatted telemetry signal sent by the recording unit (**30** in FIG. **1**) to a telemetry transceiver and power supply unit **48**. The telemetry transceiver **48** also performs both formatting of data signals communicated by the CPU **50** for transmission along a cable conductor **16A** to the recording unit (**30** in FIG. **1**) and reception and conditioning of electrical power sent along the conductor **16A** for use by the various components of the circuits **20**. The CPU **50** may also be reprogrammed by the command signals when such are detected by the telemetry transceiver **48** and conducted to the CPU **50**. Reprogramming may include, for example,

changing the waveform of the measure current used to make the previously explained voltage drop measurements. Reprogramming may also include changing the magnitude of the measure current, and may include changing a sample rate of voltage drop measurements, among other examples. Still other forms of reprogramming will be explained with reference to FIGS. **4** through **6**.

While the embodiment shown in FIG. **2** includes an electrical telemetry transceiver **48**, it should be clearly understood that optical telemetry may be used in some embodiments, and in such embodiments the telemetry transceiver **48** would include suitable photoelectric sensors and/or transmitting devices known in the art. In such embodiments, the cable **16** should include at least one optical fiber for conducting such telemetry signals. One embodiment of an armored electrical cable including optical fibers therein for signal telemetry is disclosed in U.S. Pat. No. 5,495,547 issued to Rafie et al. Other embodiments may use optical fibers to transmit electrical operating power to the instrument **10** from the recording unit **30**. The cable disclosed in the Rafie et al. '547 patent or a similar fiber optic cable may be used in such other embodiments to transmit power to the instrument over optical fibers.

The CPU **50** may include in its initial programming (or may be so programmed by reprogramming telemetry signals) a digital representation of various current waveforms used to energize the Earth formations (**22, 24, 26** in FIG. **1**) and the casing (**12** in FIG. **1**) for determining the resistivity of the Earth formations (**22, 24, 26** in FIG. **1**). The digital representation includes information about the frequency content, the shape of the waveform and the amplitude of the current to be conducted through the formations and casing. The digital representation can be conducted to a digital to analog converter (DAC) **42**, which generates an analog signal from the digital representation. The analog signal output of the DAC **42** is then conducted to the input of a power amplifier **44**. The power amplifier **44** output is connected between the current source electrode A and a switch **47**. The switch **47** is under control of the CPU **50**. The switch **47** alternates connection of the other output terminal of the power amplifier **44** between the casing return electrode B and the formation return electrode B\*, or other current electrodes in other electrode arrangements. Alternatively, the other output terminal of the power amplifier **44** may be connected to one of more cable conductors (either **16A** or other electrical conductor), and the switching between casing return and formation return may be performed within the recording unit (**30** in FIG. **1**). Yet another alternative omits the DAC **42** and the power amplifier **44** from the circuits **20**, and provides measuring current and switching features using the power supply (**32** in FIG. **1**) in the recording unit (**30** in FIG. **1**) and appropriate conductors (not shown) in the cable (**16** in FIG. **1**). In the latter example embodiment, measuring current may be conducted to the source electrode A using one or more cable conductors, such as **16A** in FIG. **2**.

In the present embodiment, voltage measurements can be made between the potential reference electrode P0 and a selected one of the potential measuring electrodes P1-P6. The one of the voltage measuring electrodes from which measurements are made at any moment in time can be controlled by a multiplexer (MUX) **40**, which itself may be controlled by the CPU **50**. The output of the MUX **40** is connected to the input of a low noise preamplifier or amplifier **38**. The output of the preamplifier **38** is coupled to an analog to digital converter (ADC) **36**. The ADC **36** may be a sigma delta converter, successive approximation reg-

ister, or any other analog to digital conversion device known in the art, that preferably can provide at least 24 bit resolution of the input signal. Digital signals output from the ADC 36 represent the measured potential between the reference electrode P0 and the MUX-selected one of the voltage measuring electrodes P1-P6. One possible advantage of using the MUX 40 and single preamplifier 38 as shown in FIG. 2 is that the analog portion of the voltage measuring circuitry will be substantially the same irrespective of which voltage measuring electrode P1-P6 is being interrogated to determine potential drop with respect to electrode P0. As a result, measurement error caused by differences in preamplifier 38 response may be reduced or eliminated. Preferably, the ADC 36 is a twenty-four bit device capable of accurately resolving measurements representing voltage differences as small as one nanovolt ( $1 \times 10^{-9}$  volts). Alternatively, each measurement electrode P1-P6 could be coupled to one input terminal of a separate preamplifier (not shown in the Figures) for each electrode P1-P6, thus eliminating the MUX 40 from the analog input circuitry.

Digital words representing the voltage measurements can be conducted from the ADC 36 to the CPU 50 for inclusion in the telemetry to the recording unit (30 in FIG. 1). Alternatively, the CPU 50 may include its own memory or other storage device (not shown separately) for storing the digital words until the instrument (10 in FIG. 1) is removed from the wellbore (14 in FIG. 1). In some embodiments, a sample rate of the ADC 36 is in the range of several kilohertz (kHz) both to provide both a very large number of voltage signal samples, preferably at least one thousand, per cycle of current waveform, and to be able to sample transient effects when switched DC is used as a current source to make resistivity measurements. In such embodiments, a switching frequency of the switched DC can be in a range of about 0.01 to 20 Hz, thus enabling the ADC 36 to make preferably at least one thousand, and as many as several thousand, voltage measurement samples within each cycle of the switched DC.

In the present embodiment, the ADC 36 operates substantially continuously, to provide a relatively large number of digital signal samples for each cycle of the current source waveform. In the present embodiment, such substantially continuous operation of the ADC 36 may provide the advantage of precise, prompt determination of any DC bias in the voltage measurements. Such DC bias must be accounted for in order to precisely determine formation resistivity from the voltage measurements. In systems known in the art which do not operate voltage measuring devices substantially continuously, it is necessary to determine DC bias by other means. See, for example, U.S. Pat. No. 5,467,018 issued to Rueter et al.

The measuring current waveform, as previously explained, may be generated by conducting waveform numerical values from the CPU 50, or other storage device (not shown) to the DAC 42. Referring now to FIGS. 3A through 3C, several types of current waveforms particularly suited to making through-casing (or through electrically conductive pipe) resistivity measurements will be explained. FIG. 3A is a graph of current output of the power amplifier (44 in FIG. 2) with respect to time. The current waveform 60 in FIG. 3A is a low frequency (0.01 to 20 Hz) square wave, which may be generated using switched DC, or by conducting appropriate numbers representing such a waveform to the DAC (42 in FIG. 2). The waveform 60 in FIG. 3A is periodic, meaning that the waveform is substantially con-

stant frequency within a selected time range, and has 100 percent "duty cycle", meaning that current is flowing substantially at all times.

Another possible current waveform is shown at 60 in FIG. 3B. The current waveform in FIG. 3B is a random or pseudo random frequency square wave, also having 100 percent duty cycle. As with the previous embodiment (FIG. 3A), the embodiment of current waveform shown in FIG. 3B may be generated by conducting appropriate digital words from the CPU (50 in FIG. 2) to the DAC (42 in FIG. 2). Random switching will be advantageous to avoid aliasing or other adverse effects related to periodic data sampling.

Another possible waveform is shown at 60 in FIG. 3C. The current waveform 60 in FIG. 3C is a periodic square wave having less than 100 percent duty cycle. Less than 100 percent duty cycle can be inferred from time intervals, shown at 62, in which no current is flowing. As with the previous embodiment (FIG. 3A), the embodiment of current waveform shown in FIG. 3C may be generated by conducting appropriate digital words from the CPU (50 in FIG. 2) to the DAC (42 in FIG. 2). Using less than 100 percent duty cycle may be advantageous to save electrical power where measured voltage drops are sufficiently large to make possible a reduction in the number of voltage samples measured. Using less than 100 percent duty cycle may also enable determination of some transient effects, by measuring voltage drops across the various electrodes (P0 b between P1-P6 in FIG. 1) during a short time interval after the current is switched off. Such induced potential (IP) effects may be related to fluid composition within the pore spaces of the Earth formations (22, 24, 26 in FIG. 1). Using less than 100 percent duty cycle may also enable better determination of any DC bias, by using the times with no current flow 62 as measurement references.

The foregoing examples shown in FIGS. 3A, 3B and 3C are not the only current waveforms that may be generated using the CPU/DAC combination shown in FIG. 2. As will be readily appreciated by those skilled in the art, substantially any frequency and waveform type may be generated, including for example sinusoidal waveforms, by conducting appropriate digital words to the DAC (42 in FIG. 2). In some embodiments, the digital words may be stored in the CPU (50 in FIG. 2). In other embodiments, the digital words themselves, or a command which activates selected waveform digital words, may be transmitted from the recording unit (30 in FIG. 1) to the instrument (10 in FIG. 1) over the cable (16 in FIG. 1). In other embodiments, the waveform may be a pseudo random binary sequence (PRBS).

Referring once again to FIG. 2, some embodiments may include one or more of the following features, either programmed into the CPU 50, or programmed into a surface computer in the recording unit (30 in FIG. 1). Some embodiments may include automatic editing of voltage measurements made across the one or more electrode pairs, P0 between any one of P1-P6. For example, if a particular digital voltage sample represents a number outside of a selected range, the sample may be discarded, and an interpolated value may be written to storage in the CPU 50, or transmitted to the recording unit (30 in FIG. 1) for the outlying sample value. Alternatively, if voltage measurements do not increase monotonically as the spacing between P0 and the various measurement electrodes P1-P6 is increased, the anomalous voltage samples may be discarded; interpolated or otherwise not written directly to storage. Other embodiments may include stacking of voltage measurement words corresponding to the same electrode pair

11

(P0 between any of P1-P6) at substantially the same depth in the wellbore to improve the signal to noise ratio of the measurements significantly.

Referring once again to FIG. 1, still other embodiments may include permanent installation of an array of electrodes, such as shown in FIG. 1 at A and P0 through P6 inside the casing 16. A cable or similar device may be used to make electrical connection to the Earth's surface from inside the wellbore 14 at a selected depth proximate a petroleum bearing reservoir, for example, formation 24 in FIG. 1. Measurements may be made at selected times during the life of the wellbore 14 to determine movement of a water contact (not shown in FIG. 1) with respect to time. In such permanent emplacements of electrodes A, P0-P6, the circuits 20 may be disposed at the Earth's surface, or may themselves be disposed in the wellbore 14, just as for the cable conveyed instrument described earlier herein.

Operating the instrument may be performed in a number of different ways, of which several will be explained herein. In a regular measurement mode, the instrument 10 may be moved to a selected depth in the wellbore 14 at which measurements are to be made. First, the circuits 20 are operated, either by internal programming of the CPU (50 in FIG. 2) or by command transmitted from the recording unit (30 in FIG. 1) first to enable measuring voltage drop caused by current flow entirely along the casing 12. To make casing voltage drop measurements, the power amplifier (44 in FIG. 2) is connected between the current source electrode A on the instrument 10 and casing current return electrode 34B coupled to the top of the casing (12 in FIG. 1) at the Earth's surface. Voltage measurements between P0 and any one or more of P1 through P6 are then made. The output of the power amplifier (44 in FIG. 2) is then switched to return the measuring current at measuring current return electrode 34B\* at the Earth's surface. Another set of voltage measurements between P0 and the same ones of P1 through P6 are made. The instrument 10 may then be moved a selected axial distance along the wellbore 14, and the measuring process can be repeated. Values of voltage difference made between P0 and any one or more of P1 through P6 can be converted mathematically into a second derivative, with respect to depth in the wellbore 14, of the measured voltage drop. The values of such second derivative are related to the depth-based current leakage into the Earth formations 22, 24, 26, and are thus related to the electrical conductivity of each of the formations 22, 24, 26. Advantageously, an instrument configured substantially as shown in FIGS. 1 and 2 does not require measurement of voltage drop across cascaded differential amplifiers (all of which would be analog) to determine the second derivative of voltage drop with respect to depth.

Performance of an instrument according to the invention may be improved by providing focusing current systems to axially constrain the flow of measuring current through the various Earth formations. An example instrument which includes focusing current systems is shown schematically in FIG. 4. The principle of measurement of the example instrument shown in FIG. 4 is described in U.S. Pat. No. 2,729,784 issued to Fearon, incorporated herein by reference. The instrument in FIG. 4 includes an array of electrodes disposed at selected locations along the instrument mandrel or housing (18 in FIG. 1). The electrodes may be similar in mechanical and electrical configuration to the electrodes described above with reference to FIG. 1. The electrodes are adapted to make electrical contact with the pipe or casing (12 in FIG. 1) in the wellbore (14 in FIG. 1).

12

The electrodes in the embodiment of FIG. 4 include two pairs of focusing current electrodes, shown at B1A, B1B and B2A, B2B, approximately equally spaced on either axial side of a central measuring current source electrode M0. Reference potential measuring electrodes R1A, R1B and R2A, R2B are disposed, respectively, between each focusing current electrode pair B1A, B1B; B2A, B2B, and the measuring current source electrode M0. Each focusing current electrode pair B1A, B1B and B2A, B2B is connected across the output of a corresponding focusing current power amplifier 44A, 44C, respectively. In the present embodiment, the focusing current is generated by driving each power amplifier 44A, 44C using the output of a corresponding DAC 42A, 42C. Each DAC 42A, 42C can be connected to a bus or other similar data connection to the CPU 50. As in the embodiment explained above with reference to FIG. 2, the embodiment shown in FIG. 4 may include digital words stored or interpreted by the CPU 50 which represent the focusing current waveform to be generated by each power amplifier 44A, 44C and conducted to the casing (12 in FIG. 1). Aspects of the waveform which may be controlled include amplitude, phase, frequency and duty cycle, among other aspects.

Each pair of reference potential measuring electrodes R1A, R1B and R2A, R2B is coupled across the input terminals of a respective low noise preamplifier 38A, 38B, or low noise amplifier, similar to the preamplifier described with reference to FIG. 2. Each low noise preamplifier 38A, 38B has its output coupled to an ADC 42A, 42B. The ADC 42A, 42B outputs are coupled to the bus or otherwise to the CPU 50. In the present embodiments, the ADCs 42A, 42B are preferably 24 bit resolution devices, similar to the ADC described with reference to FIG. 2. In the present embodiment, potential difference measurements are made across each pair of reference potential electrodes R1A, R1B and R2A, R2B, respectively. The CPU 50 receives digital words representing the measured potential across each reference electrode pair R1A, R1B and R2A, R2B, respectively. The magnitude of the focusing current output by each power amplifier 44A, 44C can be controlled by the CPU 50 such that the measured potential across each pair of reference potential electrodes R1A, R1B and R2A, R2B, respectively, is substantially equal to zero. The CPU 50 may cause such adjustments to be made by, for example, changing the amplitude or changing the duty cycle of the power amplifier 44A, 44B outputs, or both. Changes to amplitude and/or duty cycle may be made to either or both power amplifier 44A, 44B. Other methods for changing or adjusting the power output of each focusing current power amplifier 44A, 44C will occur to those skilled in the art. The purpose of making such focusing current magnitude adjustments so as to maintain substantially zero potential across the reference electrodes R1A, R1B and R2A, R2B, respectively, is to assure that there is a region within the casing (12 in FIG. 1) where substantially no net current flows along the casing in either an upward or downward direction.

The embodiment of FIG. 4 can include a digitally controlled measuring current source. The source consists of, in the present embodiment, a measuring current DAC 42B coupled to the bus or otherwise to the CPU 50. Measuring current is generated by conducting waveform words to the DAC 42B, which converts the words into a driver signal for a measuring current power amplifier 44B coupled at its input to the DAC 42B output. Measuring current output from the measuring current power amplifier 44B is coupled to the measuring current source electrode M0, and maybe returned at the Earth's surface, at return electrode 34B\*, or alterna-

tively at casing current return 34B. Measuring potential electrodes M1A, M1B are disposed on either side of the measuring current source electrode M0. Each measuring potential electrode M1A, M1B, and the source electrode M0 is coupled across the input of a respective measuring potential low noise amplifier 38B, 38C. The output of each measuring potential low noise amplifier 38B, 38C is coupled to a respective ADC 36B, 36C, wherein digital words representing the value of measured potential across each respective pair of measure potential electrodes M1A, M0 and M1B, M0 are conducted to the CPU 50 for processing. The measuring potential ADC 44B is also preferably a 24 bit resolution device. Resistivity of the Earth formations outside the casing is related to the potential across the measuring potential electrodes and the magnitude of the measuring current. Waveform, frequency and duty cycle of the measuring current may be controlled in a substantially similar manner as explained with reference to the embodiment of FIG. 2.

Possible advantages of a system as shown in FIG. 4 include more accurate control over focusing current properties than was previously possible, making measurements of potential across the measuring electrodes M1A, M1B more accurate.

Another embodiment of an instrument according to the invention is shown schematically in FIG. 5. The instrument includes an array of electrodes disposed on the instrument housing 18 at axially spaced apart locations. The electrodes are designated A, B, P, O, N and M. The electrodes are coupled through a switching system, designated "control unit" 50A (which may be associated with for form part of a controller similar in design to CPU 50 from FIG. 2). The control unit 50A selects which electrodes are coupled to which one or selected circuits. The circuits include a current source 52. The current source 52 may be a digital synthesizer, and may include a DAC and power amplifier (not shown separately). The circuits may include a voltage (or potential) measuring circuit 51, which may include a low noise preamplifier and ADC (not shown separately) as explained with reference to FIG. 2. The circuits may also include a voltage feedback unit 53, which may be similar in configuration to the focusing current source explained with reference to FIG. 4.

To perform various types of measurements, the instrument shown in FIG. 5 can select the measuring and focusing current sources to be applied to, and voltage measurements to be made across, selected ones of the electrodes and selected electrode pairs. Examples of various modes of measurement, and the electrodes used to make measurements in each of the modes, are explained in the following table:

| Measurement Mode               | Current source and return electrodes  | Potential measured across electrodes |
|--------------------------------|---|--------------------------------------|
| Downhole, completely contained | A, B  | M and N; O and P                     |
| Deep penetrating resistivity   | B, current return is at Earth's surface away from top of casing (return 34B*) | M and N; O and P                     |
| Fast measurement               | M and N   | A and B; O and P                     |
| Mixed                          | Mix sources   | Mix pairs                            |

In the above table, the "Current source and return electrodes" column represents the electrodes coupled to the measuring current source 52. Potential measurement is made

across electrode pairs as indicated in the "Potential measured across electrodes" column.

Various configurations of an instrument according to the invention which include a suitably programmed CPU (50 in FIG. 2) may provide substantially real-time automatic control of selection of the various electrodes for the purposes as explained above with reference to FIG. 4, namely axial spacings of the voltage measuring electrodes, and the spacing of and amount of focusing current supplied to various focusing electrodes. A generalized flow chart showing one embodiment of a system programmed to perform the foregoing functions is shown in FIG. 6. At 70, initially configured electrodes, current sources and voltage measuring circuits emit measuring current, focusing current and make voltage measurements, respectively. Initial configuration may be set by the system operator, or may be preprogrammed. Preprogrammed or operator-selected initial configuration may be based on parameters such as expected thickness of the various Earth formations and expected resistivities of the various Earth formations, among other parameters. At 71, voltages are measured, at least for one pair of voltage measuring electrodes. In configurations which include reference potential electrodes, for example as explained with reference to FIG. 4, such reference potentials may also be measured. At 72 the measured voltages are analyzed. Analysis may include determining a magnitude of voltage drop along the casing to determine casing resistance, and may include determining voltage drop of leakage current into the formations. Analysis may include determination of polarization direction for reference potential measurements which are not substantially equal to zero. At 75, the analysis is used to determine if the response obtained represents a stable set of formation resistivity calculations. If the response is stable, at 77, the voltage measurements are used to determine formation resistivity, typically, as previously explained, by determining a second derivative, with respect to depth, of the magnitude of leakage current corrected for casing resistance variation in the vicinity of where the measurements are made.

At 73, the voltage measurements may be used to develop a model of the resistivity distribution around the outside of the wellbore (14 in FIG. 1) proximate the instrument (10 in FIG. 1). Methods for determining a model of the Earth formations are disclosed, for example, in U.S. Pat. No. 5,809,458 issued to Tamarchenko (1998), entitled, Method of simulating the response of a through-casing resistivity well logging instrument and its application to determining resistivity of earth formations. At 74, the model is subjected to a sensitivity analysis. The model, using appropriate sensitivity analysis, may be used, at 76, to determine an optimum arrangement of focusing current electrodes. If the determined optimum focusing current electrode arrangement is different from the initial or current configuration, the configuration is changed, at 79, and focusing current parameters are changed at 78 to provide the model with the optimum sensitivity response.

A different embodiment which may be used to investigate relatively long axial spans between electrodes, as well as shorter axial spans, is shown schematically in FIG. 7. The embodiment in FIG. 7 includes a plurality of "satellite" or auxiliary instrument units, shown generally at 62, coupled to each other axially by cable segments 17. Any number of auxiliary units 62 may be used in a particular implementation. Each auxiliary unit 62 may include one or more electrodes made as previously explained and adapted to make electrical contact with the casing (12 in FIG. 1). Each auxiliary unit 62 may include one or more current sources,

15

configured as explained with reference to FIG. 2, and one or more voltage measuring circuits, also configured as explained with reference to FIG. 2. The length of the cable segments 17 is not a limitation on the scope of the invention, however, it is contemplated that the length of the cable segments is typically about 1 to 1.5 meters.

The auxiliary units 62 may be disposed axially on either side of, and electrically connected to, a central control unit 60. The central control unit 60 may include a central processor, similar in configuration to the CPU explained with reference to FIG. 2. The control unit 60 may operate the various auxiliary units 62 to perform as current source electrodes and/or current return electrodes for either or both measuring current or focusing current, these currents as explained with reference to FIG. 4. The various electrodes on the auxiliary units 62 may also be configured to make voltage measurements of either or both measuring current and focusing current, also as explained with reference to FIG. 4. In some embodiments, the central control unit 60 may itself include one or more current sources (not shown separately) and one or more voltage measuring circuits (not shown separately). The central control unit 60 may also include a telemetry transceiver, similar in configuration to the transceiver explained with reference to FIG. 2, and adapted to communicate measurement signals to the Earth's surface in a selected telemetry format, and to receive command signals from the Earth's surface, along the cable 16. Alternatively, the control unit 60 may include recording devices, as explained with reference to FIG. 2, to store measurements until the instrument is withdrawn from the wellbore (14 in FIG. 1).

The embodiment shown in FIG. 7 may be electronically configured, in some instances, to provide focusing currents across a very long axial span, for example, by selecting innermost auxiliary units (those axially closest to the control unit 60) to provide a focusing current source electrode, and outermost auxiliary units 62 (those axially most distant from the central unit 60) to provide a focusing current return electrode. As will be readily appreciated by those skilled in the art, such a long axial span for focusing current may provide a relatively large radial (lateral) "depth of investigation" of the measuring current, because such measuring current is constrained to flow laterally a larger distance than when the focusing current traverses a smaller axial span.

A possible advantage of the control unit 60/auxiliary unit 62 arrangement shown in FIG. 7 is that the various electrodes may be selectively configured and reconfigured electronically, by the central control unit 60, to make a wide range of different radial depth and axial resolution measurements of Earth formation resistivity outside of a conductive pipe. More specifically, the electrical connections between the one or more electrodes on each of the auxiliary units 62 may be individually addressable by the circuitry in the central control unit 60. While the configuration shown in FIG. 7 could conceivably be adapted to a single, elongated instrument housing, it will be readily appreciated by those skilled in the art that a set of axially shorter units (60, 62) interconnected by flexible cable segments 17 may be more readily inserted into and withdrawn from a wellbore, particularly if the wellbore is not substantially vertical or includes places of relatively high trajectory tortuosity ("dog leg severity").

Another embodiment is shown in FIG. 8. The embodiment of FIG. 8 includes a central control unit 60 configured as explained with reference to the embodiment of FIG. 7, and includes a plurality of auxiliary units 62, also configured as explained with reference to the embodiment of FIG. 7.

16

The auxiliary units 62 are connected end to end to each other and to the central control unit 60 by cable segments 17. The entire array of auxiliary units 62 and central control unit 60 can be conveyed into and out of the wellbore by the cable 16 or other conveyance known in the art.

In the present embodiment, any one or more of the central control unit 60 and the auxiliary units 62 may include a seismic receiver SR disposed within the housing. The housing of the one or more units which includes a seismic receiver SR preferably includes a selectively extensible back-up arm 63 for urging the respective housing into contact with the interior surface of the pipe or casing (12 in FIG. 1). The seismic receiver may be a single sensor element (not shown separately), or may be a plurality of sensor elements arranged along different sensitive axes. The sensor element may be a geophone, accelerometer or any other seismic sensing device known in the art. A suitable arrangement of actuating mechanism for the back up arm(s) 63, and seismic sensors is shown in U.S. Pat. No. 5,438,169 issued to Kennedy et al. and incorporated herein by reference. The one or more of the units having the seismic receiver SR therein preferably includes circuits (not shown separately) for converting signals detected by the one or more sensing elements into appropriately formatted telemetry for recording in the central unit 60 and/or for transmission to the Earth's surface in a selected telemetry format.

In operation, the embodiment of FIG. 8 may be moved to a selected depth in the wellbore, and the one or more back up arms 63 may be extended to urge the associated unit's housing into contact with the casing. A seismic energy source 65 disposed at the Earth's surface may be actuated at selected times and the signals detected by the one or more seismic receivers SR is recorded (indexed with respect to time of actuation of the source 65) for interpretation. The extension of the back up arm(s) 63, actuation of the source 65 and signal recording may be repeated at different selected depths in the wellbore.

Similarly, measurements of voltage drop and current amplitude may be made using the one or more auxiliary units 62 as the array is positioned at each one of a plurality of selected depths in the wellbore, while seismic data recordings are being made. Voltage measurements may also be made while the array is moving through the wellbore, depending on the type of electrodes used on each one of the units 60, 62.

While the embodiment shown in FIG. 8 includes seismic receivers SR and a back up arm 63 in each one of the central control unit 60 and the auxiliary units 62, it should be clearly understood that any one or more of the units 60, 62 may include a seismic receiver and back up arm.

A possible advantage of using a back up arm 63 in each of the units 60, 62 as shown in FIG. 8 is that each back up arm 63 may serve both the purpose of providing good mechanical contact between the unit housing and the casing to enhance acoustic coupling therebetween, and to provide back-up force such that the electrodes (see FIG. 2) may be urged into firm contact with the interior of the casing to enhance electrical contact therebetween. An combination through-casing resistivity measuring and borehole seismic instrument configured as shown in FIG. 8 may provide the advantage of substantial time saving during operation, because both seismic surveys and resistivity measurements may be made in a single insertion of the instrument into the wellbore. Such time savings may be substantial in cases where conveyance other than by gravity are used, for example, well tractors or drill pipe.

17

The embodiment shown in FIG. 8 may also include a gravity sensor, shown generally at G, in one or more of the central control unit 60 and the auxiliary units. The one or more gravity sensors G may be a total gravitational field sensor, or a differential gravity sensor. Suitable types of gravity and differential gravity sensors are disclosed, for example, in U.S. Pat. No. 6,671,057 issued to Orban. An instrument configured as shown in FIG. 8 including resistivity, gravity and seismic sensors may be used, for example, in fluid displacement monitoring of subsurface reservoirs.

One embodiment of an electrode system for making electrical contact with the interior of a casing is shown in FIG. 9. The electrode system includes an electrical insulating layer 90 coupled to the exterior surface of the instrument housing 18. A plurality of resilient, electrically conductive wires 90 are mechanically coupled to the insulating layer 92 so as to protrude laterally outward from the exterior of the housing 18 and insulating layer 92. The wires 90 are all in electrical contact with each other. The wires 90 are preferably made from a corrosion resistant, high strength and "spring like" alloy, and have a length such that a free diameter traversed by the wires 90 is slightly larger than the expected maximum internal diameter of the pipe or casing (14 in FIG. 1) in the wellbore to be surveyed. The wires 90 will thus be urged into a scratching or scraping contact with the interior of the pipe or casing. While some of the wires 90 may not penetrate scale, deposits or corrosion present on the interior of the pipe, some of the wires 90 are likely to make such penetration and thus provide good electrical contact to the pipe or casing.

One possible configuration for the wires 90 so as to be in electrical contact with each other and insulated from the exterior surface of the housing is shown in FIG. 10. The wires 90 are bonded to an electrically conductive substrate 92B. The substrate 92B is insulated from the exterior surface of the housing (18 in FIG. 9) by a lower insulation layer 92A. The substrate 92B may be covered on its exterior surface by an upper insulating layer 92C to prevent electrical contact between the housing (18 in FIG. 9) and the substrate 92B. The wires 90 thus act as a single electrode at the location of the substrate 92B and insulating layers 92A, 92C.

One embodiment of a system for estimating quality of contact between extensible/retractable type electrodes and the interior surface of the pipe is shown in FIG. 11. The electrode 106 in FIG. 11 in extended and retracted by a piston 102 disposed in a hydraulic cylinder 100. Alternatively, a solenoid or other similar electromagnetic device may be used to extend and retract the electrode 106. The piston 102 in the present embodiment is sealed with respect to the cylinder 100 by o-rings 100 or the like. Disposed proximate the contact tip of the electrode 106 is an insulating mandrel 114 which includes an electromagnetic transmitter antenna 110 and an electromagnetic receiver antenna 112. The antennas 110, 112 can be wire coils. The transmitter coil 110 is coupled to a source of alternating current (AC) 108. The AC source 108 preferably has a frequency selected to make a voltage induced in the receiver coil 112 related to a distance between the coils 110, 112 and the pipe or casing 14. The voltage is determined by a voltage measuring circuit 116 coupled to the receiver coil 112. Additionally, a resistance measuring circuit, which can be a direct current (DC) or preferably and AC type, is electrically coupled between the electrode 106 and the pipe 14. The pipe connection may be at the Earth's surface, or through a different one of the electrodes on the instrument (10 in FIG. 1). Quality of electrical contact is determined when the voltage detected by the voltage measuring circuit 116 remains steady, indicating

18

no further movement of the electrode 106 toward the pipe 14, and the resistance measured by the resistance circuit 118 reaches a minimum.

As will be readily appreciated by those skilled in the art, sometimes the condition of the interior of the pipe in the wellbore is such that it may prove difficult or even impossible to provide sufficient electrical contact between the electrodes on the instrument and the conductive pipe. Much operating time can be consumed in attempts to make such electrical contact in sections of the pipe which are sufficiently deteriorated or covered in mineral and/or hydrocarbon deposits so as to make electrical contact poor at best. One embodiment of an apparatus according to the invention may include one or more types of wellbore imaging device to assist the system operator in determining whether any particular portion of a wellbore pipe is unlikely to provide a sufficient basis for good electrical contact. One example of a wellbore imaging subsystem is shown in FIG. 12. The imaging subsystem 7 may include any one or all of the embodiments of wellbore wall imaging devices shown therein. The imaging subsystem 7, and additional ones of the imaging subsystem, may in some embodiments be contained in one or more of the auxiliary units 62, the central unit 60, or in a single housing system such as shown in FIG. 1.

The imaging subsystem 7 may be contained in a housing having therein a conventional strength and load bearing portion 122, and an acoustically and/or optically transparent window section 120. The transparent window section 120 may include therein an optical video camera 134, and an ultrasonic transducer 132 either or both of which may be coupled to a motor 130 for rotating the camera 134 and transducer 132 to enable imaging over the entire interior circumference of the pipe. Output of the camera 134 and transducer 132 may be coupled to conventional signal processing circuits 128 disposed, preferably, in the housing 122.

A portion of the housing may include one or more electrically insulating contact pads 124, coupled to the housing 122 by extensible arms and linkages, shown generally at 124A. The linkages 124A may be of any type known in the art for extending a pad or contact device laterally outward from the housing 122. Each of the one or more pads 124 may include a plurality of spaced apart electrodes 126 for making galvanic resistance measurements therebetween or with reference to a selected potential point, such as the housing 122. Imaging devices for making electrical and ultrasonic images of the interior surface of a wellbore, including a pipe, are disclosed in U.S. Pat. No. 5,502,686 issued to Dory et al., incorporated herein by reference. Video imaging devices for use in a wellbore are disclosed in U.S. Pat. No. 5,134,471 issued to Gendron et al., also incorporated herein by reference. Various embodiments of a through-pipe resistivity measurement apparatus according to the invention may include any one or more, or all of the imaging systems shown in FIG. 12.

During operation, the system operator may observe a visual representation, such as by a graphic print or video display, of measurements made by the one or more imaging systems shown in FIG. 12. If the system operator determines that a particular portion of the wellbore is likely to be difficult to establish good electrical contact, the operator may instead move the instrument (10 in FIG. 1) to a different portion of the wellbore. Alternatively, a record of the measurements made by the one or more imaging systems may be made with respect to depth in the wellbore, along with the measurements of potential as explained previously herein. Image representations may then be used in combination with



19

the potential measurements to evaluate whether the potential measurements are more likely representative of the true resistivity of the Earth formations outside the pipe, or whether such potential measurements are more likely to have been materially affected by the condition of the interior of the pipe. Such imaging can therefore improve the quality of interpreted results by providing a way to resolve ambiguous measurements where pipe condition is suspected to have affected the potential measurements.

While the invention has been described with respect to a limited number of embodiments, those skilled in the art, having benefit of this disclosure, will appreciate that other embodiments can be devised which do not depart from the scope of the invention as disclosed herein. Accordingly, the scope of the invention should be limited only by the attached claims.

What is claimed is:

1. An instrument for measuring resistivity of Earth formations from within a conductive pipe inside a wellbore drilled through the formations, comprising:

a plurality of housings connected end to end, the housings adapted to traverse the interior of the pipe;

at least one electrode on each housing, each electrode adapted to be placed in electrical contact with the interior of the pipe;

a source of electrical measuring current;

at least one digital voltage measuring circuit;

at least a first switch arranged to selectively connect the source of electrical measuring current between one of the electrodes and a current return at a selectable one of the top of the pipe and a location near the Earth's surface at a selected distance from the top of the pipe; at least a second switch arranged to connect selectable pairs of the electrodes to the digital voltage measuring circuit, the pairs selectable to make voltage measurements corresponding to selectable, variable axial distances between the electrodes and corresponding lateral depths in the Earth formations;

means for extending at least one of the electrodes laterally outward from the respective housing associated therewith, a resistance measuring circuit operatively coupled between the at least one electrode and the pipe;

an electromagnetic transmitter antenna and an electromagnetic receiver antenna disposed proximate a contact end of the at least one electrode;

a source of alternating current electrically coupled to the transmitter antenna; and

a receiver circuit electrically coupled to the receiver antenna, whereby a quality of contact between the electrode and the conductive pipe is determinable by comparison of a resistance measured by the resistance measuring circuit to a voltage detected by the receiver circuit.

2. The instrument of claim 1 wherein the digital voltage measuring circuit comprises at least a twenty four bit resolution analog to digital converter.

3. The instrument of claim 2 wherein the analog to digital converter has a sampling rate of at least one thousand times a frequency of electrical current used to energize the one of the electrodes coupled thereto by the at least first switch.

4. The instrument of claim 1 wherein the measuring current source comprises a digital waveform synthesizer.

5. The instrument of claim 1 wherein the measuring current source is adapted to generate switched direct current.

6. The instrument of claim 1 wherein the measuring current source is adapted to generate switched direct current having less than a one hundred percent duty cycle.

20

7. The instrument of claim 1 wherein the measuring current source is adapted to generate alternating current having a selected frequency and waveform.

8. The instrument of claim 1 wherein the measuring current source is adapted to generate a pseudo random binary sequence.

9. The instrument of claim 1 wherein the digital voltage measuring circuit is adapted to determine a direct current bias present on the electrodes coupled thereto by operating substantially continuously.

10. The instrument of claim 1 wherein at least one of the housings comprises:

a back-up arm for selectively urging the at least one of the housings into contact with the interior of the pipe, and a seismic receiver for detecting seismic signals from a seismic source.

11. The instrument of claim 1 wherein each of the housings comprises therein:

a back-up arm for selectively urging the housing into contact with the interior of the pipe; and

a seismic receiver for detecting seismic signals from a seismic source, the at least one electrode on each of the housings adapted to make electrical contact with the pipe when each of the housings is urged into contact with the interior of the pipe.

12. The instrument of claim 1 further comprising at least one gravity sensor disposed in one of the plurality of housings.

13. The instrument of claim 1 wherein the at least one electrode on at least one of the plurality of housings comprises a plurality of laterally extending, resilient, electrically conductive wires, the wires in electrical contact with each other and insulated from the at least one of the housings, the wires traversing a free diameter larger than a maximum expected internal diameter of the pipe.

14. The instrument of claim 13 wherein the wires are bonded to an electrically conductive substrate.

15. The instrument of claim 1 further comprising at least one imaging device adapted to generate a representation of a visual appearance of at least part of an interior surface of the pipe.

16. The instrument of claim 15 wherein the imaging device comprises one of ultrasonic imager, electrical imager and optical imager.

17. A method for measuring resistivity of Earth formations from within a conductive pipe inside a wellbore drilled through the formations, comprising:

inserting a plurality of housings connected end to end to a selected depth inside the pipe;

causing at least one electrode on each housing to be placed in electrical contact with the inside of the pipe; passing electrical current from a measuring current source through at least one of the electrodes into the pipe;

switching a current return point for the measuring current source between another one of the electrodes and a current return point at a selectable one of the top of the pipe and a location near the Earth's surface at a selected distance from the top of the pipe;

digitally measuring voltages across selectable pairs of the electrodes, the selectable pairs of electrodes to make voltage measurements corresponding to selectable, variable axial distances between the electrodes and corresponding lateral depths in the Earth formations; and

switching a focusing current source through selected pairs of the electrodes, and controlling an output of the



21

focusing current source to constrain current flowing from the measuring current source between the one of the electrodes switched thereto and the return near the Earth's surface to a path substantially laterally outward from the wellbore in the lateral proximity of the wellbore.

18. The method of claim 17 wherein the digitally measuring voltages is performed to at least twenty four bit resolution.

19. The method of claim 17 wherein the digitally measuring is performed at a sampling rate of at least one thousand times a frequency of electrical current generated by the measuring current source.

20. The method of claim 17 wherein the measuring current is digitally synthesized.

21. The method of claim 20 wherein the digitally synthesizing comprises synthesizing switched direct current.

22. The method of claim 21 wherein the switched direct current has less than a one hundred percent duty cycle.

23. The method of claim 20 wherein the digitally synthesizing includes generating alternating current having a selected frequency and waveform.

24. The method of claim 20 wherein the digitally synthesizing includes generating a pseudo random binary sequence.

25. The method of claim 17 further comprising controlling the focusing current to maintain a selected voltage drop across a pair of reference potential electrodes, the reference

22

potential electrodes switchably selected from the plurality of electrodes.

26. The method of claim 17 further comprising determining a direct current bias present on the ones of the electrodes used to measure voltage by substantially continuously digitally measuring the voltage on the electrodes.

27. The method of claim 17 further comprising selectively urging at least one of the housings into contact with the interior of the pipe and detecting seismic energy originating from a seismic energy source.

28. The method of claim 17 further comprising measuring a galvanic property and an electromagnetic property of an electrical current conducted between at least one of the electrodes and an interior of the pipe, the properties related to a degree of electrical contact and physical proximity between the at least one of the electrodes through which the current is passed and an interior of the pipe.

29. The method of claim 17 further comprising measuring a property related to a visual appearance of the interior of the pipe to determine suitability of the interior of the pipe at the position of measuring the property of establishing electrical contact between the electrodes and the pipe.

30. The method of claim 29 wherein the measuring the property comprises one of ultrasonic imaging, electrical imaging and optical imaging.

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