

June 1, 1965

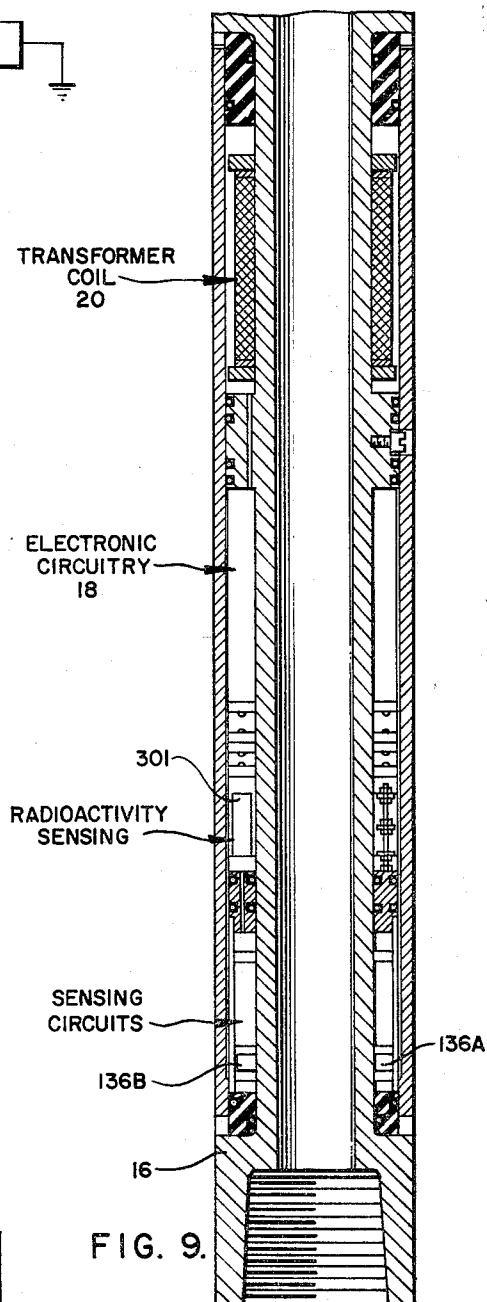
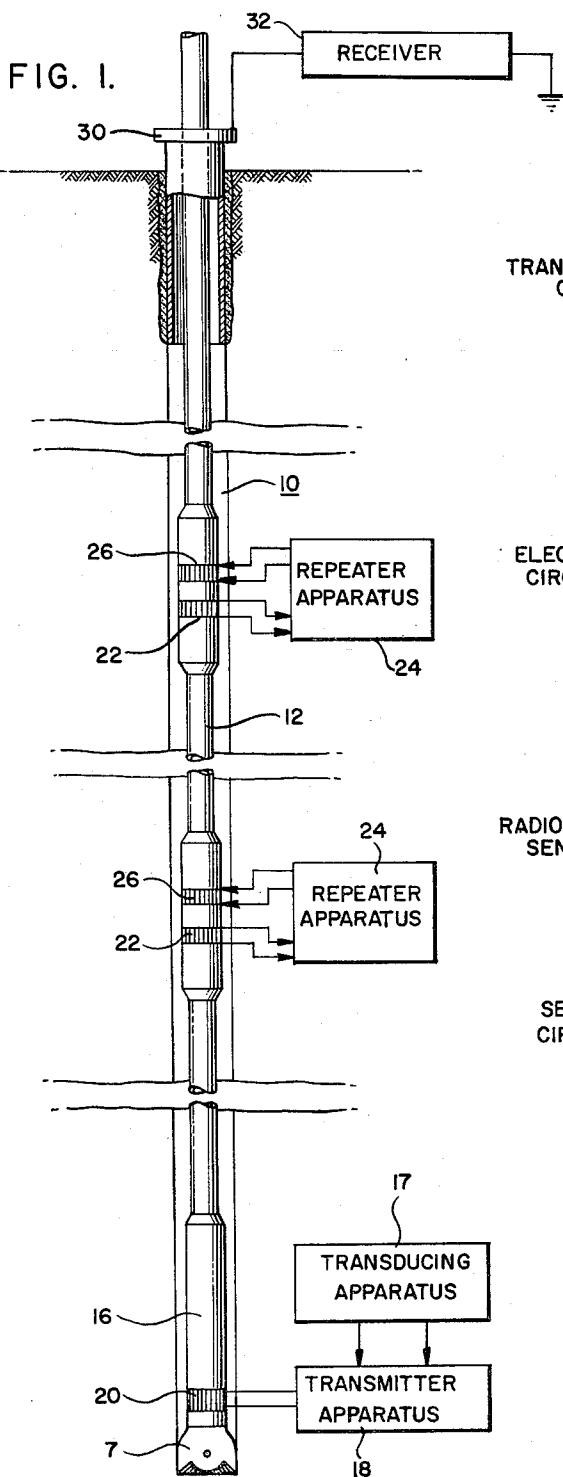
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3,186,222

WELL SIGNALING SYSTEM

Filed July 28, 1960

4 Sheets-Sheet 1



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WELL SIGNALING SYSTEM

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4 Sheets-Sheet 3

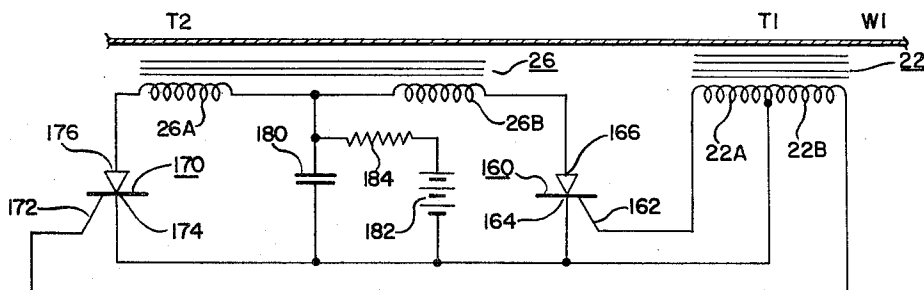


FIG. 4.

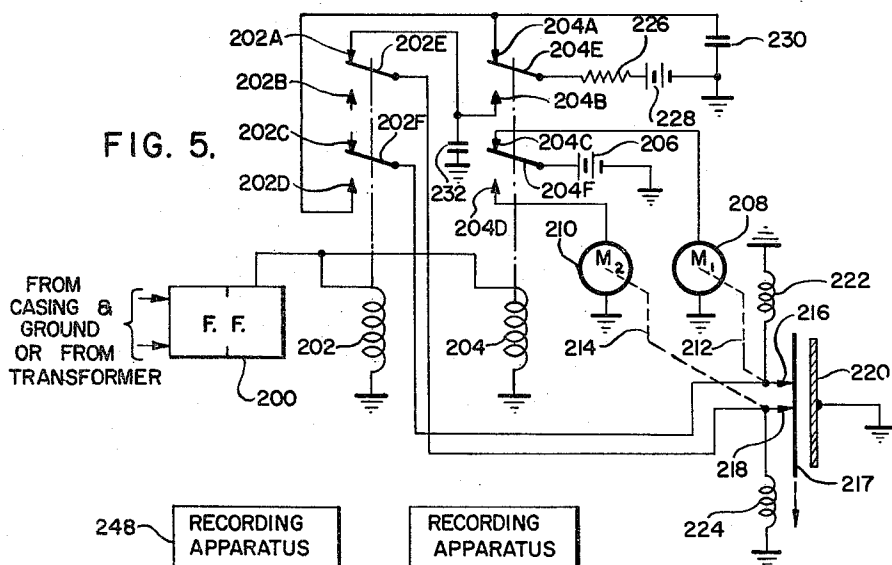
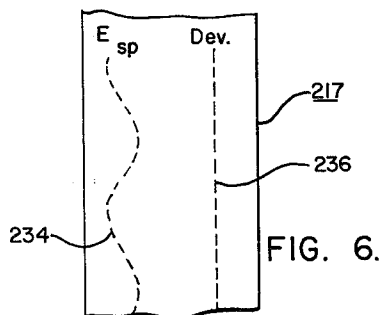
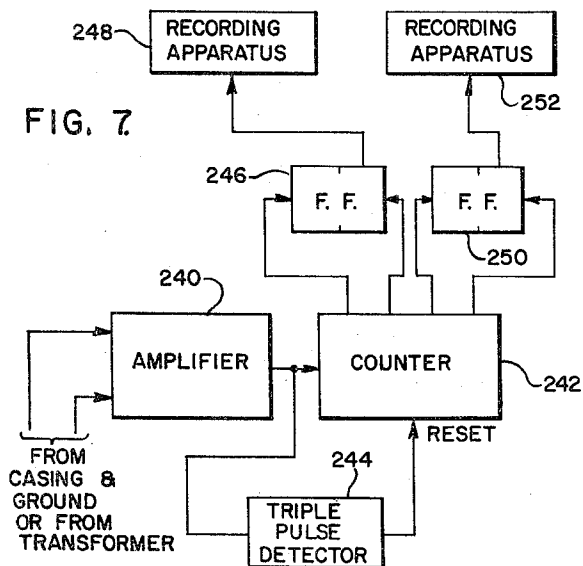


FIG. 7.



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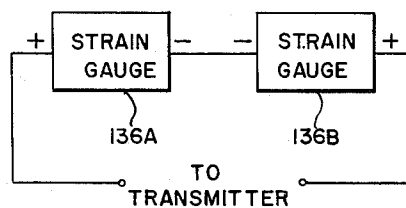
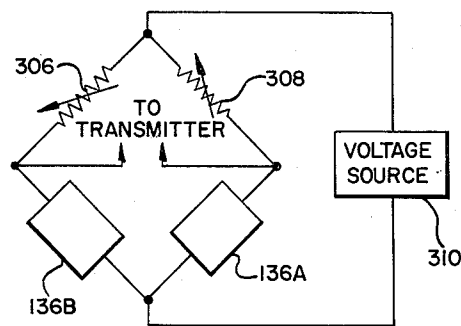
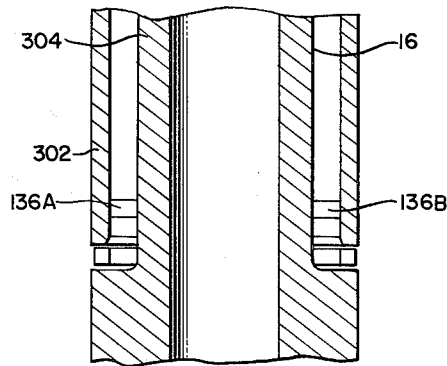
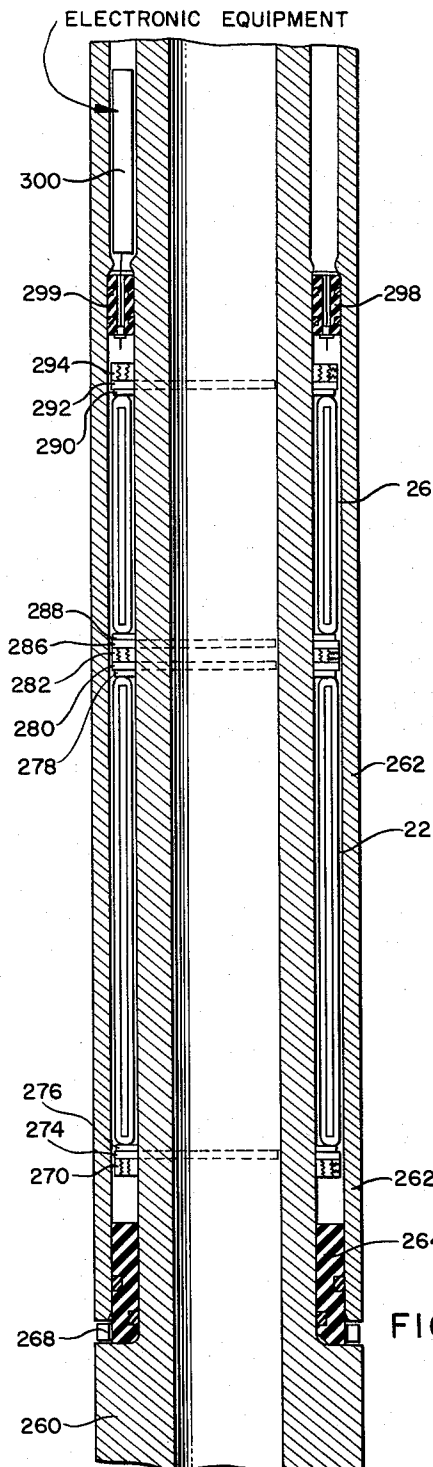
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WELL SIGNALING SYSTEM

4 Sheets-Sheet 4



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3,186,222

WELL SIGNALING SYSTEM

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Filed July 28, 1960, Ser. No. 45,857
12 Claims. (Cl. 73-151)

This invention relates to a well signaling system and, more particularly, to improvements therein.

The desirability of having available at the surface of a well, while it is being drilled, information concerning conditions at and in the vicinity of the drill at the bottom of the well has long been established. A considerable number of well signaling systems have been developed for the purpose of transmitting the information measured at the bottom of the well to the surface. The transmission of data from the bottom to the top of the well has not proved to be an easy task. The rotating metal drill string causes the generation of noise signals which adds to the problems attendant those of signal transmission. A considerable number of expedients have been tried. For example, cables have been lowered to the drilling string to contact the bit. The extremely rapid flow of fluid down the well with high mud pressures caused by mud pumps having on the order of hundreds of horsepower, cause terrific strain on such a line, cause stretch, and consequently slack in the line. The abrasive muds wear the line rapidly, and very high pressure differentials along the length of the drill pipe make this process quite impractical.

Another method which has been tried has been to signal, by pressure, pulses on the drill string set up by a pulsing device on the bottom. This has proven to be an economic failure and to be unreliable because of its extreme complexity and high noise level on a drilling rig.

Still another method has been to use a fixed conductor and a series of connections at each joint down the well. These have also not been successful. The trouble with using joints may be appreciated from the fact that in an average drilling string of 10,000 feet there are somewhere on the order of 250 joints, or connections, that must be made up. This means 250 places for shorts or open circuits; consequently, this, again, has not proven successful. Industry still very much desires a process of logging-while-drilling, because the most important time to obtain lithological information from the drilling well is while that formation is uncontaminated and fresh and immediate contact is made with the virgin formation, at which time one may withdraw the drill pipe and test that formation for productivity, or even spot oil in it immediately as it is open, to prevent water from reaching the clays in the oil sands and blocking all future production. This inability of the oil-drilling industry to realize what it is drilling through has probably cost the oil industry on the order of hundreds of millions of dollars a year, and it is entirely probable that the drilling rate per rig could double if a successful method of logging-while-drilling and deviation-determination-while-drilling entered the field. While the industry has spent millions of dollars trying to develop apparatus for logging-while-drilling and while large numbers of patents have been issued on logging-while-drilling over the last thirty years, not one commercially successful logging-while-drilling apparatus has been obtained.

An object of this invention is to provide a practical and operative well-logging system.

Another object of this invention is to provide a well signaling system wherein the effects of noise signals are obviated.

Yet another object of this invention is to provide a well signaling system which is simpler than those employed heretofore.

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Still another object of the present invention is to provide a novel transmission system for well logging which is more economical to operate than any of those employed heretofore.

One important bit of data which is sought to be transmitted, from the bottom of the well to the top, is the weight applied by the drill string on the drill bit. The reason is that it has been found that excessive weight on the drill bit can cause the drill stem to flex, whereby drilling will take place at an angle to the vertical. A crooked well is extremely costly to the oil industry, since it produces serious wear on both the drilling and producing equipment, making it impractical to produce some otherwise productive wells, and sometimes causes the total loss of a valuable oil well. Often a hole already drilled is subsequently lost because the hole is so crooked that the drill string will not re-enter the hole.

Although it is desirable not to apply excessive weight to the drill bit because of the possibility of drilling a crooked hole, on the other hand, the drilling of the hole does require a sufficient weight to be applied for obtaining the maximum efficiency. All the devices which have been produced heretofore attempt, not very successfully, to solve the problem of preventing a crooked hole by measuring the weight on the drill bit.

Yet another object of this invention is the provision of an arrangement whereby an indication is achieved at the bottom of the well, which can be transmitted to the top of the well, as to when a drill bit is about to make a crooked hole whereby preventive measures may be taken.

Still another object of this invention is the provision of a simple and improved sensing arrangement which indicates when the drill bit deviates from a straight hole.

These and other objects of this invention may be achieved in a transmission system which transmits pulses wherein the time between successively transmitted pulses of opposite polarity is a measure of the quantity sought to be transmitted. Repeater stations for these pulses are provided along the drill string. Further, a sensing arrangement for determining when a crooked hole is about to occur is achieved by placing two sensing devices, such as strain gages, crystals, or electromagnetic transducers, on opposite sides of the pipe close above the drill bit to indicate the lateral stress on the pipe. The electrical outputs of these sensing elements may be balanced by opposing one against the other, whereby whenever the pipe begins to bend as the result of starting to travel in a path other than the vertical path there is a difference in compression which is measured by the sensing elements and which provides a resultant signal, indicating that a crooked hole is about to be drilled. This enables the drill operator to take the necessary steps to avoid the drilling of such crooked hole.

The novel features that are considered characteristic of this invention are set forth with particularity in the appended claims. The invention itself, both as to its organization and method of operation, as well as additional objects and advantages thereof, will best be understood from the following description when read in connection with the accompanying drawings, in which:

FIGURE 1 is a drawing illustrating an arrangement for transmitting data from the bottom of the well to the top in accordance with this invention;

FIGURE 2 is a schematic circuit diagram of a transmitter in accordance with this invention;

FIGURE 3 is a block diagram of another type of transmitter in accordance with this invention;

FIGURE 4 is a circuit diagram of a repeater station in accordance with this invention;

FIGURE 5 is a block schematic diagram of a receiver in accordance with this invention;

FIGURE 6 illustrates recordings illustrative of what is obtained with the use of the invention;

FIGURE 7 is a block diagram illustrating another receiver in accordance with this invention;

FIGURE 8 is a section through a drill string showing repeater and transmitter component placement therein;

FIGURE 9 is a schematic section through the drill string attached to the drill bit illustrating transducer disposition. In addition, FIGURE 9 illustrates the placement of sensing elements to detect the deviation of the drill string from the vertical in accordance with this invention;

FIGURE 10 illustrates another placement for sensing elements to detect drill-string deviation from vertical; and

FIGURES 11 and 12 are schematic drawings showing circuit arrangements of the deviation-measuring apparatus in accordance with this invention.

In FIGURE 1 there is a representation of a well 10 with a string of drill pipe 12 lowered therein in order to drill the hole deeper in accordance with the customary rotary drilling practice. The usual derrick and mud circulation system and other features attendant to these types of wells are not shown to preserve clarity in the drawing. It will be assumed that by some means, either by actual contact of the drill with the earth or by a conducting material, such as drill mud, there is electrical contact between the conducting drill pipe 12 and the earth itself. In the lower end of the drill string is the drill collar section 16. This section serves to apply weight to the drill bit 7 and to stiffen the lower section of the drill pipe so that a straighter hole may be bored. A portion of the wall of the drill collar is hollowed out, as will be shown in greater detail hereinafter, in order that the well-logging apparatus, including the deflection-sensing equipment and transmitter in accordance with this invention, will be protected and maintained at the bottom of the well.

In accordance with this invention, signals from transducing apparatus 17, which convert phenomena sought to be logged into such signals, are applied to transmitting apparatus 18. The transmitting apparatus 18 is connected to a transformer winding 20. The transformer winding 20, which surrounds the drill casing, serves as the primary of a transformer whose secondary comprises the conductive drill pipe 12, the drill mud, not shown, and the earth. The output of the transmitter may be transmitted by electromagnetic induction and appears as a flow of current up the drill string, which may be detected by a receiving transformer winding 22, which has its output connected to the repeater apparatus 24. The output of the repeater apparatus 24 is applied to an output transformer winding 26 to be again transmitted up the drill string, thus adding to or reinforcing the signal already going up the drill pipe. While only two are shown, the receiving-transformer winding, repeater apparatus, and output-transformer winding are periodically provided, as often as is required along the drill string, for insuring transmission of clear signals to the surface. Thus, the two repeater arrangements shown are by way of exemplification, and not to be construed as a limitation. For picking up the transmitted signals, a receiver 32 is provided which is conductively coupled between the drill string and the earth.

As will be shown hereinafter, this invention, in operation, transmits powerful pulses of alternate polarity at spaced intervals. The duration of these intervals is determined by the quantity sought to be transmitted from the bottom of the well. In view of this mode of operation, substantially no power is required except during the transmission of the pulse. The actual pulse width is made short, so that the actual power drain during the pulse-transmission interval is a minimum and pulse amplitude is a maximum during transmission.

Reference is now made to FIGURE 2, which shows a circuit diagram of a transmitter in accordance with this invention.

Let it be assumed that it is desired to transmit from the

bottom of the well such quantities as the deviation of the drill pipe from the vertical, employing a "pipe-deviation transducer" 34, to be subsequently described herein, and the earth's self potential, using an "earth's self-potential transducer" 36, a number of arrangements for which are described, shown, and claimed in an application for patent by this inventor, entitled "Means and Techniques for Logging Well Bores," Serial No. 670,326, filed July 5, 1957, now Patent No. 3,079,549 and also in Patent No. 2,568,241. One embodiment of a transmitter, in accordance with this invention, will include two pairs of input terminals, one pair 38A, 38B of which are respectively connected to the collector and emitter of a transistor 39, the current-conducting ability of which is controlled by the signal applied from the pipe-deviation transducer 34. The other pair 40A, 40B of terminals are respectively connected to the collector and emitter of a transistor 41, the current-conducting ability of which is controlled by signals received from the earth's self-potential (SP) transducer 36.

Terminals 38A, 40A are connected to a capacitor 42, and also to the emitter 46 of a unijunction transistor 48, which also has base-1 and base-2 electrodes, respectively 50, 52. The base-1 electrode 50 is connected through a resistor 54 to the capacitor 42. The base-1 electrode is connected through a resistor 56 to the control electrode 60 of a silicon-controlled rectifier 58. The silicon-controlled rectifier also has a cathode 62 and an anode 64. The cathode 62 is connected through a resistor 66 to resistor 54 and capacitor 42. A capacitor 68 is connected between the control electrode 60 and resistor 54. The anode 64 of silicon-controlled rectifier 58 is connected through a diode 70 to input terminal 40B and through a resistor 72 to a battery 74. Base-2 of the unijunction transistor 48 is connected to the battery 74 through a resistor 76.

Base-1 of the unijunction transistor 48 is connected through a resistor 78 to the control electrode 82 of a second silicon-controlled rectifier 80, which also has a cathode electrode 84 and an anode electrode 86. The cathode electrode 84 of silicon-controlled rectifier 80 is connected through a resistor 88 to the negative terminal of battery 74, as are also resistors 54 and 66, and capacitor 68. The anode electrode 86 is connected through a resistor 90 to the positive side of battery 74. It is also connected through a diode 92 to terminal 38B, and through a capacitor 94 to anode 64 of silicon-controlled rectifier 58. A capacitor 96 couples control electrode 82 to the positive side of the battery 74.

A third silicon-controlled rectifier 100 has a control electrode 102 connected to the cathode 62 of the first silicon-controlled rectifier 58. The cathode 104 is connected to the positive terminal of a bias battery 105. The anode 106 is connected to one end of a winding 108A, which is one-half of a center-tapped transformer winding 108 having another half 108B, and a center tap 110. The center tap 110 is connected through a resistor 112 to the positive terminal of the battery 74 and through a capacitor 114 to the negative terminal of the battery.

A fourth silicon-controlled rectifier 116 has its control electrode 118 connected to the cathode 84 of the second silicon-controlled rectifier 86. Its cathode 120 is connected to the positive terminal of the bias battery 105, and its anode is connected to the end of winding 108B. A capacitor 124 is connected between the anodes 122 and 86 of silicon-controlled rectifiers 80 and 116. Similarly, capacitor 124' is connected between anodes 106 and 64 of silicon-controlled rectifiers 100 and 58.

The transformer windings 108A, 108B are wound on a laminated core 126, which is toroidal in shape and which surrounds the drill pipe. These windings are wound on the core to pass through the toroidal aperture. Thus, the winding 108 comprises the primary of a transformer, of which the secondary comprises the pipe drill string and the earth. The winding 108 corresponds to the winding

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20 represented in FIGURE 1. The transducing apparatus 17 in FIGURE 1 corresponds to the transducers 34 and 36 in FIGURE 2. The transmitter apparatus 18 in FIGURE 1 is represented by the circuitry in FIGURE 2.

For a description of the operation of the circuit shown in FIGURE 2, let it first be assumed that, upon the first application of potential by battery 74 to the circuit, capacitor 96 applies a positive pulse to the control electrode 82 of the second silicon-controlled rectifier 80, rendering it conductive and dropping the potential of its anode 86. Capacitor 68 simultaneously applies a negative pulse to the control electrode 60 of the first silicon-controlled rectifier 58, holding it nonconductive. When the second silicon-controlled rectifier 80 is rendered conductive, capacitor 42 commences to charge up from the battery 74 controlled by the transducer 36 over a path which includes resistor 72, diode 70, terminal 40B, the transistor 41, terminal 40A, to capacitor 42. Since the amount of charging current allowed to flow through transistor 41 is determined by the amplitude of the earth's self-potential transducer signal, the time required to elapse before unijunction transistor 48 will conduct depends upon the signal potential received from the transducer 36.

When capacitor 42 reaches a potential sufficiently high to enable unijunction transistor 48 to conduct, the capacitor 42 is discharged over a path through the emitter 46, base-1 50, and resistor 54. As a result, a positive pulse is applied to the control electrodes 60, 82 through the respective resistors 56, 78. However, since silicon-controlled rectifier 80 is already conducting, silicon-controlled rectifier 58 can and does respond by becoming conductive. Capacitor 94 discharges through silicon-controlled rectifier 58 which reduces the potential at anode 86, which cuts off silicon-controlled rectifier 80.

When capacitor 52 has discharged below the potential required to maintain unijunction transistor 48 conductive, it again begins to charge up, this time over a path including resistor 90, diode 92, terminal 38B, transistor 39, and terminal 38A. This time the interval required for capacitor 42 to charge up to a potential required to render unijunction transistor 48 conductive again depends upon the signal voltage of the pipe deviation transducer. When the unijunction transistor 48 conducts again, it operates to switch conduction between the silicon-controlled rectifiers again. Thus, the intervals of conduction of the first and second silicon-controlled rectifiers is determined by the amplitudes of the signals being produced by the transducers. Effectively, the operation of the circuit described thus far is that of a bistable-state flip-flop circuit which is driven from one to the other of its stable states at a rate determined by the amplitude of two separate signals derived from two separate transducers. The remainder of the circuit in FIGURE 2 emits a positive and then negative pulse into the pipe drill string each time a transfer of conduction between the two silicon-controlled rectifiers 58, 80 occurs. It is also within the scope of this invention for certain purposes to replace transducers 34 and 36, respectively, with variable resistances and to eliminate transistors 39 and 41. The variable resistances are respectively connected between terminals 38A, 38B and 40A, 40B. The resistance of these variable resistances is then varied in accordance with the quantity being measured, thus varying the timing of the unijunction transistors. For example, a pressure transducer can directly vary the timing of these transistors, thus eliminating transistors 39 and 41.

A capacitor 114 is charged up from battery 74 through resistor 112. When silicon-controlled rectifier 58 is rendered conductive, its cathode 62 goes positive, thus applying an enabling pulse to the control electrode 102 of silicon-controlled rectifier 100, which is connected thereto. This enables capacitor 114 to discharge over a path including winding 108A and silicon-controlled rectifier 100. Thus, a pulse of one polarity is applied to the pipe drill string. Similarly, when silicon-controlled rectifier 80 is

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first rendered conductive, its cathode goes positive, thereby applying an enabling signal to control electrode 118, whereby silicon-controlled rectifier 116 can discharge capacitor 114, and a pulse of opposite polarity to said one polarity is applied to said pipe drill string. Each of the silicon-controlled rectifiers 100, 116 becomes non-conductive upon discharge of capacitor 114, since this drops the voltage across them below the conduction-sustaining value. In the event both silicon-controlled rectifiers 100, 116 are turned on initially, capacitor 124 assists in reducing the potential at anode 122, in the manner described for capacitor 94, to turn off silicon-controlled rectifier 80. Bias battery 105 assists in turning off silicon-controlled rectifiers 100 and 116.

The silicon-controlled rectifiers 100 and 116 are alternately enabled to discharge capacitor 114 through the transformer windings 108A, 108B at intervals determined by the amplitude of the signals derived from transducers 36, 34, whereby pulse signals of opposite polarity are transmitted with the information desired being represented by the interval between these pulses. Although transmission can be performed using unipolar pulses, this is to be considered within the scope of this invention; the reason successive pulses of opposite polarity are used is because it is desired to transmit successive pulses at high-power levels. The transformer cores would soon saturate with unidirectional pulses unless a very, very large amount of iron in the core were used. When successive pulses of opposite polarity are used, then the full extent of the core hysteresis characteristics is used, and much less iron in the core is necessary for transmitting power. Using pulse spacing to carry intelligence eliminates the effects of noise and amplitude modulation.

Thus far there has been described an embodiment of the invention for transmitting signals from two transducers at the bottom of a well to the surface. Those skilled in the art, with the teachings provided herein, will be able to transmit one or more than two signals from the bottom of a well, without departing from the spirit and scope of this invention. For example, FIGURE 3 illustrates a block schematic diagram of an arrangement for transmitting more than two signals from the bottom of a well. This includes a typical pulse-position-modulator arrangement, also known as "PPM," which drives a flip-flop circuit or bistable-state circuit 130, which drives an opposite polarity pulse transmitter 132. This latter circuit will be recognized as that portion of FIGURE 2 which includes the silicon-controlled rectifiers 100, 116, the transformer winding 108, and the capacitor 114.

Assume, for the purpose of exemplification, that it is desired to transmit from the bottom of a well, while it is being drilled, information from an earth's self-potential transducer 134, a pipe-deviation transducer 136, an earth's resistivity transducer 138, and an earth's radioactivity transducer 140. An oscillator 142 drives a sawtooth generator 144. The output of the sawtooth generator drives a counter 146 and is also applied to a voltage comparator 148. The counter outputs, consisting of the sampling frequency, are applied to channel-input circuits 150 and channel-collector circuits 152 which comprise gate circuitry, which gates are successively enabled, in response to the output of the counter, to successively sample the outputs of each of the transducers 134-140 and to serialize these outputs. These outputs are applied to the voltage comparator 148.

The input to the voltage comparator 148 will comprise a train of pulses having amplitudes representative of the different transducer-output signals. The voltage comparator 148 converts these amplitude-modulated pulses into pulse-width modulated pulses. The pulse-width modulated pulses are applied to differentiator and clipper circuits 154, wherein these are differentiated and clipped and thus converted to pulse-position modulation pulses. These are then applied to a mixer 156.

The last count of the counter 146 is applied to a triple pulse generator 153, which generates three closely spaced pulses in response thereto. These are inserted in the pulse-position pulse train by the mixer 155. The output of the mixer is applied to the flip-flop circuit 130, to drive it from one to the other stable state in response to each successive pulse. Each of the flip-flop circuit bistable outputs is applied to the opposite-polarity pulse generator 132 to alternately trigger it to generate opposite-polarity pulses, which may be in the manner described wherein silicon-controlled rectifiers 100 and 116 were alternately triggered for this purpose. Thus, the output of the opposite-polarity pulse transmitter 132, which is transmitted up the pipe drill string, will consist of a train of seven pulses of alternate polarity which is repeated. The spacing between the last three pulses of a train is closer than that of the remaining pulses and is always constant. The spacing between the last of these three pulses and the first of the succeeding four pulses, as well as the spacing between the remaining three of these succeeding four pulses, represents the amplitudes of the respective signals derived from the four transducers 134-140.

The portion of the block diagram bearing reference numerals 142 through 156 is illustrative of an encoder of PPM signals, which are well-known in the communication art. For example, see pages 98-101 in a text entitled "Telemetry Systems," by Borden and Mayo-Weils, published in 1959 by the Reinhold Publishing Corp. The flip-flop circuit 130 is of a type well known in the art. The transmitter 132 has been described in connection with FIGURE 2.

FIGURE 4 is a circuit diagram of the repeater apparatus 24 and the receiving-transformer winding 22 and transmitting-transformer winding 26. The receiving-transformer winding is center tapped, thus having two halves, respectively 22A, 22B. The transmitting-transformer winding is also center tapped, having two halves 26A, 26B. These transformer windings are of the same general type as those described for the transmitter, being toroidal in form and placed around the pipe drill string to which they are inductively coupled. One end of the winding 22A is connected to the control electrode 162 of a first silicon-controlled rectifier 160. The opposite end of the transformer winding 22B is connected to the control electrode 172 of a second silicon-controlled rectifier 170. The center tap of the winding 22 is connected to cathodes 164, 174 of the silicon-controlled rectifiers, respectively 160, 170. The opposite ends of the center-tap windings 26A, 26B are respectively connected to the anodes 176, 166 of the silicon-controlled rectifiers 170, 160. The center tap of the winding 26 is connected to a capacitor 180, the other end of which is connected to the cathodes 164, 174 of the silicon-controlled rectifiers. Across the capacitor 180 there is connected a battery 182 in series with a charging resistor 184.

A voltage from a transmitted pulse is induced in the detecting winding 22. This voltage is applied with opposite polarity to both control electrodes 162, 172 of the silicon-controlled rectifiers. However, only the one of these which receives a positive voltage in excess of the critical firing voltage of the silicon-controlled rectifiers will be enabled to conduct. Thus, since the polarity of the transmitted pulse is alternately positive and negative, first one and then the other of the silicon-controlled rectifiers is enabled to conduct in response thereto. Capacitor 180 charges up through resistor 184 from battery 182 between the times the capacitor is discharged. Thus, the application of a proper polarity pulse to the control electrode of the silicon-controlled rectifier 160 will enable the capacitor 180 to discharge through the winding 26B. The application of a positive pulse to the control electrode of the silicon-controlled rectifier 170 enables the discharge of the capacitor 180 through the winding 26A. In this manner the polarity and the pulse spacing of the pulses retransmitted by the repeater is maintained identical with

that received. It will be appreciated that no standby power is required by the repeater station. It operates only when called upon and in response to pulses of opposite polarity. As many of these repeater stations as are required may be employed. They insure that the pulses spaced by the meaningful intervals are of a sufficiently high level that they are not masked or distorted by noise. The amplitude of these pulses and to a large extent their shape are not significant. What is significant is that pulses occur which exceed the noise levels and which demark data intervals.

FIGURE 5 is a block schematic of a receiver (32 in FIGURE 1) in accordance with this invention for receiving information from the transmitter shown in FIGURE 2. The data represented by the interval between two transmitted pulses may be identified by the polarity of either of these pulses. Although pulse polarities alternate, there is a fixed association between the polarity of a pulse generated by the transmitter and a transducer signal. Thus, by way of illustration, the earth's self-potential data is represented by the interval between a positive and a negative pulse, and the pipe-deviation data is represented by the interval between the negative pulse terminating the self-potential data interval and a succeeding positive pulse. This association is maintained by the repeater stations.

The receiver shown in FIGURE 5 includes a flip-flop or bistable-state circuit 200 which is connected to be driven from one to the other of its stable states by the alternative positive and negative polarity pulses. The input to the flip-flop circuit is derived by way of suitable amplifying and filtering equipment either from a pickup transformer winding, such as 30 in FIGURE 1, or from a connection between the pipe casing and ground. One output of the flip-flop circuit is connected to energize two relay coils 202, 204. Relay coil 202 is part of a fast-acting relay having double-pole, double-throw contacts, respectively contacts 202A, 202B with swinger 202E, and contacts 202C, 202D with swinger 202F. Relay coil 204 is part of a slower-acting relay having double-pole, double-throw contacts, respectively contacts 204A, 204B, swinger 204E, and contacts 204C, 204D with swinger 204F.

As flip-flop 200 is operated from one to the other of its stable states by the alternate polarity input pulses, it will alternately energize and de-energize the relay coils 202, 204. Of course, the intervals between such energization and de-energization are directly determined by the intervals between the pulses driving flip-flop 200. Relay coil 202 operates its contacts from the normally open to the normally closed state at a sufficiently higher rate than does relay coil 204 to effectuate a normally open state while relay 204 is still operated and a closed or operated state while relay 204 is still in its normally open state and before it can begin to operate. Alternative to using two relays 202, 204, a single magnetic latching relay of the four-pole double-throw type may be used.

Swinger 204F is connected to a source of potential 206. Contact 204C is connected to a first constant-speed motor 208. Contact 204D is connected to a second constant-speed motor 210. The source of potential 206 is thus used to alternately drive either the first or second motor, depending upon the stable state of flip-flop 200. The first and second motors each drives a shaft, respectively 212, 214, on which is mounted a stylus, respectively 216, 218. These styli are supported to be driven from either side of a center line on paper 217, which has the characteristic that it can be marked by an electric current passing there-through to a backing plate 220. Such paper is known commercially as "Teledeltos." A spring 222 is used to return the stylus 216 to the paper center line when the motor 208 is no longer driven. A spring 224 is used to return the stylus 218 to the paper center line when motor 210 is no longer excited.

Swinger 204E is connected through a resistor 226 to a source of potential 228. This is used to charge a capacitor 230 connected to contact 204A when the swinger is closed

thereon in the normally open relay position. The source of potential 228 can charge capacitor 232 when the swinger 204 is closed on contact 204B in the relay-operated position.

Contact 204B is connected to contact 202A. Contact 204A is connected to contact 202D. Swinger 202E is connected to stylus 218. Swinger 202F is connected to stylus 216.

In operation, upon flip-flop 200 being triggered to the stable state at which the relay coils are not excited, the state shown in FIGURE 5, capacitor 230 commences to charge up and motor 208 is excited. Motor 208 drives stylus 216 away from the center line until the flip-flop circuit 200 is driven to its other stable state, wherein it applies excitation to the relay coils. Swingers 202E and 202F are switched before swingers 204E and 204F commence to move. As a result, capacitor 230 is connected to discharge through stylus 216 at the furthestest position to which it has been moved from the center line by the motor, thus marking the paper at this point. Swingers 204E and 204F then move to the other pair of contacts, respectively 204B and 204D. This starts the charging of capacitor 232, starts motor 210 moving stylus 218, and enables spring 222 to restore stylus 216 to the paper center line. The paper may be advanced at any desired rate, for example synchronously with the speed of drilling.

When flip-flop 200 is again driven to its initial stable state, relay coil 202 is de-energized and its contacts return to their normally open position before relay coil 204 contacts can do so. This enables capacitor 232 to be discharged by stylus 218 through the paper at the position to which it has been moved from the center line. Thereafter, swingers 204E and 204F return to their normally open position, whereby motor 208 is energized and capacitor 230 commences to be charged up.

FIGURE 6 illustrates markings of a type which may be on paper 215. The distance of the marking from the center line represents the amplitude of the transducer signal originally transmitted since the mark is placed on the paper at a distance from the center line. Thus the markings 234 represent the earth's self-potential, and the markings 236 represent the drill pipe deviations.

FIGURE 7 is a block diagram of a receiver which may be employed on the surface to receive and display a multiplicity of signals from transducers, transmitted, for example, by the transmitter shown in FIGURE 3. An amplifier 240 receives, rectifies, and amplifies the signals transmitted up the pipe string. As before, the input to the amplifier may be derived from a transformer winding on the pipe string, or from a brush contacting the pipe and from a terminal buried in the ground. The amplifier output is used to drive a counter 242 and a triple-pulse detector 244. The triple-pulse detector may be an integrating circuit, which, in the presence of the triple pulses, can provide an output to reset the counter 242 to establish synchronism with the counter 146 at the bottom of the well. The first two counter outputs thereafter successively act to drive a flip-flop circuit from its one stable state to its other stable state, then to its one stable state again. The flip-flop 246 drives recording apparatus 248. The flip-flop 246 and recording apparatus 248 are intended to represent the receiver shown in FIGURE 5. Responsive to the third and fourth count of the counter 242 are a flip-flop 250 and recording apparatus 252. These also are intended to represent the receiver shown in FIGURE 5. Thus, the counter 242 successively energizes the receiving apparatus for responding to successive pairs of transducer signals, which are now represented by the intervals between advancing count outputs of the counter.

FIGURE 8 is a cross section of a pipe drill string indicating a preferred placement which may be used for the apparatus required for a repeater. An exterior portion of the pipe wall 260 is hollowed out and an outer wall 262 is provided to surround this hollowed-out portion. All the required apparatus is placed in the space obtained.

The two transformers 22 and 26 are immersed in oil. An insulator 264 bears an O-ring on its inner and outer peripheries, and thus is a floating compensating member between walls 260 and 262, which compensates for pressure differences caused by the expansion of oil inside the annulus or for pressure external to the tool. A rubber ring 265 seals the opening at the bottom against iron filings or cuttings. A first positioning ring 270 is locked onto the wall 260 with set screws to prevent its vertical motion. In ring 270 there also are vertical set screws which bear against plate 274 in such a way as to cause it to bear against plastic ring 276 to clamp the core of the transformer in place. To hold the transformer winding 22 in place, a second plastic ring 278 is positioned at the top of the winding on which a plate 280 is placed, similar to the plate 274. Bearing down on this is another positioning ring 282, which is locked in position to the wall with set screws similar to ring 270.

Another plate 286 is positioned on the ring 282, on which is the plastic ring 288. The transmitting winding 26 rests on this. A last plastic ring 290, plate 292, and positioning ring 294 secure the transformer winding in place. An insulating ring 298 bears O-ring seals, which seal off the oil from the space for the transformer windings. The ring 298 is forced against shoulders in walls 260, 262 by the pressure of the oil. The ring 298 contains feed-through openings 299, as do the ring structures between the transformer windings, to enable connecting wires to pass through to the circuit and battery equipment 300.

The required circuit and battery equipment 300 for the repeater may be positioned in the space 300 above the O-ring 298. Feed-through connections may be employed to pass through suitable openings in the supporting and spacing ring structure to connect the transformers to the required circuits.

FIGURE 9 schematically represents a preferred arrangement for mounting transducer and transmitter apparatus on the drill collar within the cavity provided therefor. As described for FIGURE 8, an exterior portion of the pipe wall is hollowed out and surrounded by an outer wall to protect the equipment in the annular cavity formed thereby. Means are provided, as before, for sealing off this cavity. In the lower-most portion of the cavity, closest to the bit end are placed transducers or sensing circuits which measure, for example, earth resistivity, earth self-potential, and, as will be explained later herein, pipe deviation. Above these transducers in a separate portion of the cavity provided therefor are positioned transducers for radioactive sensing 301. Above this, in a separate portion of the cavity, is the transmitter circuitry 18. Above the transmitter circuitry is the transmitter-transformer coil 20. It will be understood that the transducers are connected to the transmitter circuit as previously described and the transmitter circuit to the transmitter-transformer by wire connections which pass through "feed through" openings in the insulators separating the separate cavity portions.

FIGURE 9 also illustrates in more detail the placement of the pipe deviation-measuring apparatus 136. The deviation-measuring apparatus actually comprises two similar strain gages 136A, 136B, which are mounted on the pipe close above the bit and on opposite portions thereof to detect, not the strain caused by the weight on the pipe as has been done in the prior art heretofore, but to indicate when any bend occurs in the pipe. When the drill bit, due to a boulder or some other rock formation, is caused to glance to one side and thus to depart from a vertical orientation, the drill collar will begin to bend, causing a compression in the drill string on one side and a stretch or extension on the other side. This can be sensed by the transducers 136A, 136B and can be used to indicate to the drill operator that his hole is beginning to go crooked. At this time, the drill operator can remove the weight of the drill string and take precautionary

measures to enable him to straighten out the hole. Although the sensing elements mentioned heretofore are called strain gages, other known forms of sensing elements may be employed, such as the electromagnetic type or the piezoelectric type, which provide output voltages which vary with the stress applied thereto. Thus, the term, strain gage, should be considered as covering stress and strain types of indicating transducers.

Two or more strain gages may be employed around the drill string at the location indicated or may also be placed, as shown in FIGURE 10, between the outside shell 302 and the mandrel 304 of the drill collar 16 to sense the compression and stretching which occur between mandrel and shell as the drill rotates on a deviation path. The sensing elements 136A, 136B are shown positioned in location. FIGURES 11 and 12 illustrate two possible variations of the electrical circuit employed with the sensing elements. A Wheatstone bridge arrangement, as shown in FIGURE 11, may be employed with strain gages, for example. These strain gages 136A, 136B are shown connected as two arms of a bridge; the other two arms consist of resistors 306, 308, which are variable. Voltage from a source 310 is applied across the bridge, and resistors 306 and 308 are varied to establish a balance condition for the normal operational stresses and strains which occur when the drill is cutting a vertical hole. At that time, the voltage to the transmitter is substantially zero, since the bridge is balanced. Should the drill begin to go off vertical, then the bridge is unbalanced and a voltage indicative of this fact is applied to the transmitter from which it is transmitted to the surface, in the manner previously described.

If the sensing element is of a type which develops a voltage without the necessity for an outside voltage source, such as the electromagnetic type, or even with the type which employs an outside source, as shown in FIGURE 12, the voltage developed by the two sensing elements 136A, 136B may be connected in bucking fashion. Thus, the output to the transmitter is the algebraic sum of the two voltages. Under conditions of drilling, where the bit is cutting a vertical hole, this sum is substantially zero. When a deviation from vertical occurs, then the pipe bends and an output voltage indicative of that fact is transmitted to the surface of the well.

The significance of the deviation-determining apparatus is that a driller with this type of an arrangement need not be concerned with the weight on the bit. He can apply as much weight as the pipes will stand without bending, to drill as rapidly as possible. Such rapid drilling can continue for most of the time drilling is necessary, since, as soon as the drill bit deviates from a straight line or hole, an immediate electrical indication is sent to the surface. At that time, the driller may take the weight off of the bit and thereafter proceed with the necessary precautions until the object or force at the bottom of the well, which has tried to shunt the bit from its desired course, is overcome.

There has accordingly been described and shown herein a novel and useful well-logging apparatus and deviation-indicating apparatus. The well-logging apparatus may be constructed of all solid state components and thus occupy a minimum of space. It draws a minimum of power, since it is only on during the transmission of a pulse. It transmits power on the order of one percent of the time or less, as contrasted with previous systems which were using battery power all the time. Because energy is not wasted in transmitting a continuous signal, it is possible to generate a signal of a power amplitude one hundred or more times as strong with the same battery life. Because much larger signals are transmitted, it is much easier to override the background noise set up by the drilling apparatus. Furthermore, by reason of the fact that the repeaters transmit pulses which are synchronized with the transmitter output, all the repeater and transmitter outputs are additive, thus greatly increas-

ing the net output signal. This may be contrasted with previous systems wherein each repeater regenerates the signal received anew, and indeed with a different carrier, and thus no reinforcing or additive effects are obtained. Further, and of considerable significance, with respect to reducing complexity and enabling an economy in apparatus and power, the signals are transmitted unchanged up the drill string.

I claim:

1. A system for transmitting a signal generated by a transducer in a well hole to the surface comprising means coupled to said transducer for generating a pulse of substantially uniform amplitude and of one polarity followed by a pulse of an opposite polarity after an interval representative of said transducer signal, means for transmitting to the surface said uniform amplitude and undirectional pulse of one polarity followed by said opposite polarity uniform amplitude including a transformer having a saturable core pulse while maintaining the interval therebetween, means on the surface for receiving said uniform amplitude pulse of one polarity followed by said uniform amplitude pulse of opposite polarity, means to which the output of said means for receiving is applied for providing an indication of said transducer signal from the interval between said received uniform amplitude pulse of one polarity followed by said uniform amplitude pulse of opposite polarity.

2. A system for inductively transmitting the signals from a first and second transducer from the bottom of a well hole to the surface comprising a first capacitor, means for charging said first capacitor up to a predetermined voltage at a rate alternately responsive to the amplitude of a signal from said first transducer and then to the amplitude of a signal from said second transducer, a second capacitor, means for charging said second capacitor, a transformer having a tapped winding, means for coupling said second capacitor between the tap on said transformer winding and the ends of said transformer winding, means actuated each time said first capacitor attains its predetermined voltage for alternately discharging said second capacitor first through the portion of said transformer winding at one side of said tap and then through the portion of said transformer winding at the other side of said tap to produce alternate polarity pulses spaced by intervals representative alternately of the signals of said first and said second transducer.

3. Apparatus for transmitting signals from a plurality of transducers located at the bottom of a well hole up a pipe drill string to the surface comprising means for generating a train of pulses having a spacing between pulses thereof representative of the amplitude of the signal from a different one of said transducers, a transformer winding inductively coupled to said pipe drill string, said transformer winding being center tapped, a capacitor, means for charging said capacitor, means connecting one side of said capacitor to said center tap of said transformer winding, first nonconductive rectifier means coupling said other side of said capacitor to one of the ends of said transformer winding, second nonconductive rectifier means coupling said other side of said capacitor to the other of the ends of said transformer winding, and means responsive to said pulse train for rendering said first and second nonconductive rectifier means alternately conductive for alternately discharging said capacitor through the halves of said transformer winding on either side of said center tap for transmitting up said pipe drill string alternate polarity pulses spaced at intervals representative of said transducer signals.

4. Apparatus for receiving signals from transducers at the bottom of a well hole transmitted up a pipe drill string to the surface as a pulse train having alternate opposite polarity pulses having a spacing between pulses representative of one of the signals from one of said transducers, said apparatus comprising means coupled to said pipe drill string for receiving said pulse train, a

flip-flop circuit having two stable states and being driven from one to the other responsive to successive pulses in said train received by said means for receiving said pulse train, and means responsive to said flip-flop circuit being driven from one to the other of its stable states for indicating the length of time said flip-flop was in said stable state to thereby present an indication of the signals from said transducers.

5. A system for transmitting the signals generated by a plurality of transducers in a well hole to the surface comprising means for generating a train of pulses including a center-tapped transformer winding, a first capacitor having one side connected to the center tap of said transformer winding, a separate controlled switching means coupled between each end of said transformer winding and the other side of said first capacitor, and means for charging up said first capacitor; means to which the signals from said transducers are applied for establishing the interval between successive pulses in said pulse train to be representative of the signal from sequentially different ones of said transducers, said means for establishing including means for controlling the charging of a second capacitor to a predetermined level at a rate determined by the amplitude of one of said transducer signals, means coupled to said second capacitor for applying said transducer signals in sequence to said means for establishing, and means for alternately rendering conductive each of said separate controlled switching means for discharging the first capacitor connected thereto alternately through each of the halves of said center-tapped transformer winding; and means for transmitting to the surface said pulse train having intervals between successive pulses representative of the signal from sequentially different ones of said transducers.

6. A system for inductively transmitting the signals from a first and second transducer from the bottom of a well hole to the surface comprising a transmitter including a first capacitor, means for charging said first capacitor to a predetermined voltage at a rate alternately responsive to the amplitude of a signal from said first transducer and then to the amplitude of a signal from said second transducer, a second capacitor, means for charging said second capacitor, a transformer having a tapped winding, means for coupling said second capacitor between the tap on said transformer winding and the ends of said transformer winding, means actuated each time said first capacitor attains its predetermined voltage for alternately discharging said second capacitor first through the portion of said transformer winding at one side of said tap and then through the portion of said transformer winding at the other side of said tap to produce alternate polarity pulses spaced by intervals representative alternately of the signals of said first and said second transducer; a repeater station disposed between said transmitter and the surface and including means for receiving said alternate polarity pulses, a transformer having a tapped winding, a third capacitor, means for charging said third capacitor, means for coupling said third capacitor between the tap on said transformer winding and the ends of said transformer winding, and means responsive to said alternate polarity pulses for alternately discharging said third capacitor first through the portion of said transformer winding at one side of said tap and then through the portion of the winding at the other side of said tap to regenerate and retransmit said alternate polarity pulses.

7. Apparatus for transmitting signals from a plurality of transducers located at the bottom of a well hole up a pipe drill string to the surface comprising a transmitter including means for generating a train of pulses having a spacing between pulses thereof representative of the amplitude of the signal from a different one of said transducers, a transformer winding inductively coupled to said drill string, said transformer winding being center tapped, a first capacitor, means for charging said first capacitor,

means connecting one side of said first capacitor to said center tap of said transformer winding, first controlled rectifier means coupling said other side of said first capacitor to one of the ends of said transformer winding, second controlled rectifier means coupling said other side of said first capacitor to the other of the ends of said transformer winding, and means responsive to said pulse train for rendering said first and second controlled rectifier means alternately conductive for alternately discharging said first capacitor through the halves of said transformer winding on either side of said center tap for transmitting up said pipe drill string alternate polarity pulses spaced at intervals representative of said transducer signals; and a repeater station disposed between said transmitter and the surface and including a receiving transformer inductively coupled to said drill string to receive pulses being transmitted therein, a retransmitting transformer inductively coupled to said drill string having a center tapped winding, a second capacitor, means connecting one side of said second capacitor to said transformer center tap, first and second controlled rectifier means respectively coupling the other side of said second capacitor to the respective opposite ends of said retransmitting transformer, and means coupling said receiving transformer to said first and second controlled rectifiers to render said first rectifier conductive responsive to pulses of one polarity and said second rectifier conductive responsive to pulses of the opposite polarity.

8. In apparatus for oil well logging, while drilling, with a continuous metallic pipe drilling string, a transmitter inductively coupled to said pipe drilling string and disposed at the bottom of said oil well for generating and transmitting successive pulses of alternate polarity each having substantially uniform amplitude, each pulse having a duration that is relatively short compared to the time interval between two successive pulses, said time interval between each two successive pulses being representative in predetermined sequence of different physical data to be transmitted, and amplifier stations disposed along said oil well, each being inductively coupled to said pipe drilling string and including an amplifier responsive to transmitted uniform amplitude pulses having an amplitude exceeding a predetermined threshold level, said amplifier in each repeater station developing an amplified uniform amplitude output pulse in response to a pulse exceeding said threshold level.

9. In apparatus for well logging, while drilling, with a continuous metallic pipe drilling string, a transmitter inductively coupled to said pipe drilling string and disposed at the bottom of said oil well for generating and transmitting successive pulses of alternate polarity, each pulse having a duration that is relatively short compared to the time interval between two successive pulses, said time interval between each two successive pulses being representative in predetermined sequence of different physical data to be transmitted, repeater stations disposed along said oil well, each being inductively coupled to said pipe drilling string and including an amplifier responsive to transmitted pulses having an amplitude exceeding a predetermined threshold level, said amplifier in each repeater station developing an amplified output pulse in response to a pulse exceeding said threshold level, and means in said transmitter and in each of said amplifiers for rendering said transmitter and amplifiers incapable of generating or amplifying a pulse for a predetermined interval immediately after generating or amplifying a pulse.

10. In apparatus for well logging, while drilling, with a continuous metallic pipe drilling string, a transmitter inductively coupled to said pipe drilling string and disposed at the bottom of said oil well for generating and transmitting successive pulses of alternate polarity, each pulse having a duration that is relatively short compared to the time interval between two successive pulses, said time interval between each two successive pulses being representative in predetermined sequence of different physical

data to be transmitted, repeater stations, each being inductively coupled to said pipe drilling string and including an amplifier responsive to transmitted pulses for developing an amplified output pulse in response to a transmitted pulse, and means in said transmitter and in each of said amplifiers for rendering said transmitter and amplifiers incapable of generating or amplifying a pulse for a predetermined interval immediately after generating or amplifying a pulse.

11. In apparatus for well logging while drilling employing a drill bit on a conductive drill string, said drill string including a transformer winding disposed therein, means for applying an electric current to said transformer winding to establish an electric field about said drill string and about said drill bit, said electric field being focused by said conductive drill string in a direction ahead of said drill bit into the formation of the well, a sensing transducer disposed in said drill string for developing pulse-position modulated pulses of substantially uniform amplitude representative of earth resistivity encountered by said electric field ahead of said drill bit, and means for transmitting said uniform amplitude pulses to the surface.

12. In apparatus for well logging while drilling employing a drill bit on a metallic drill string, a sensing transducer disposed in said drill string near said drill bit, means disposed in said drill string near said drill bit for generating a train of electrical pulses and coupled to said transducer, each of said pulses having substantially uniform amplitude, the time intervals between two successive pulses being representative of data sensed by said sensing transducer, a transformer winding coupled to said pulse generating means disposed in said drill string and coupled thereto, said transformer winding in response to a uniform amplitude pulse impressed thereon developing an electric field about said drill string, said electric field extending

ahead of said drill bit, said sensing transducer sensing earth resistivity encountered by said electric field in the formation of the well ahead of said drill bit to control said pulse generating means, and a plurality of stations spaced from each other along said drill string and disposed in said drill string, each of said stations including amplifier means responsive to each uniform amplitude pulse of said pulse train for transmitting from station-to-station a uniform amplitude output pulse toward the surface.

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