Nov. 28, 1961 H. R. COLEMAN 3,010,396

SELECTIVE FIRING APPARATUS

Filed Dec. 31, 1957 3 Sheets-Sheet 1

FIG. 1

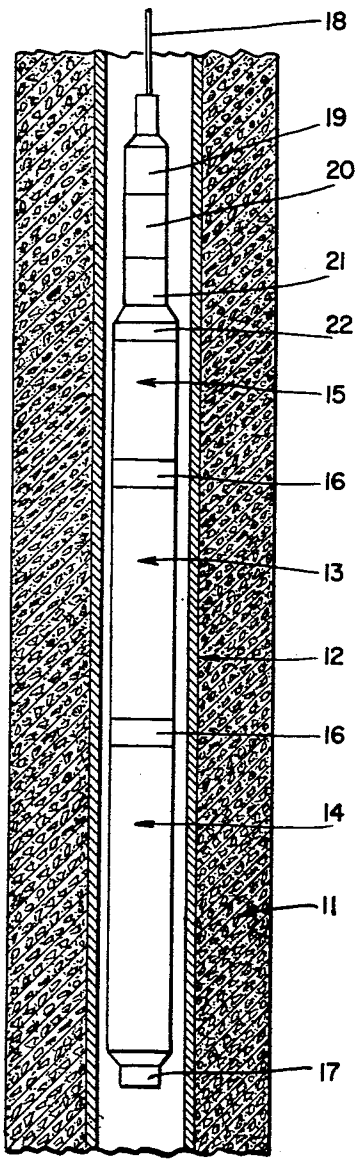
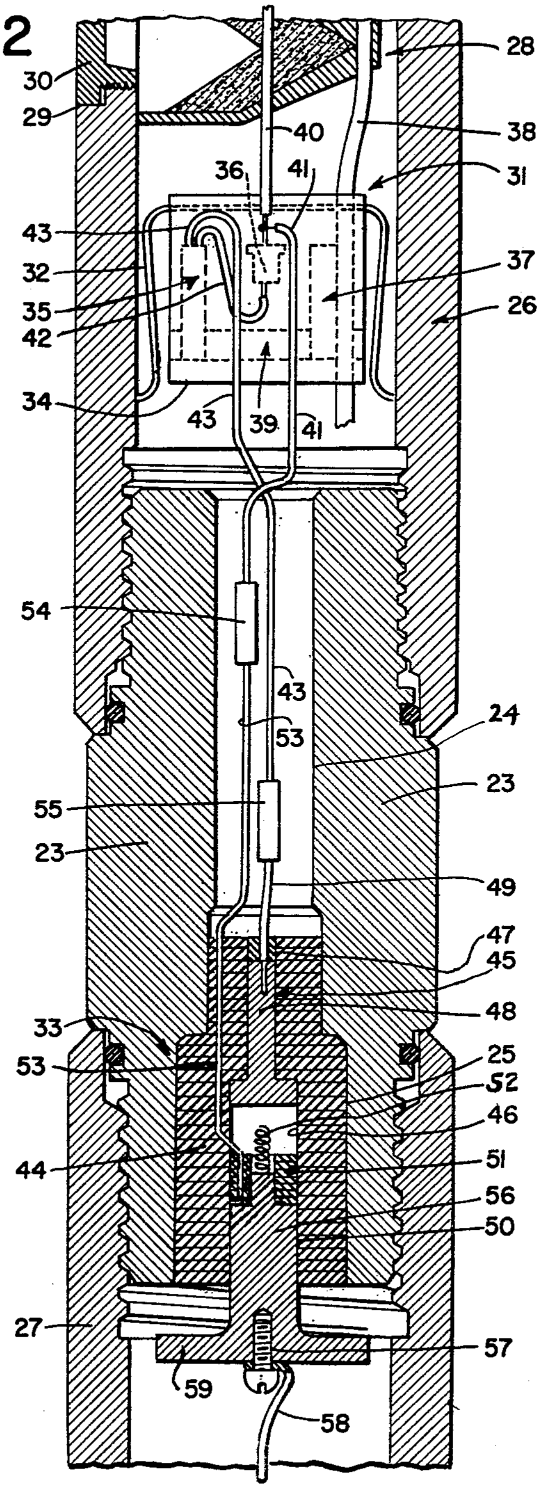


FIG. 2



SELECTIVE FIRING APPARATUS

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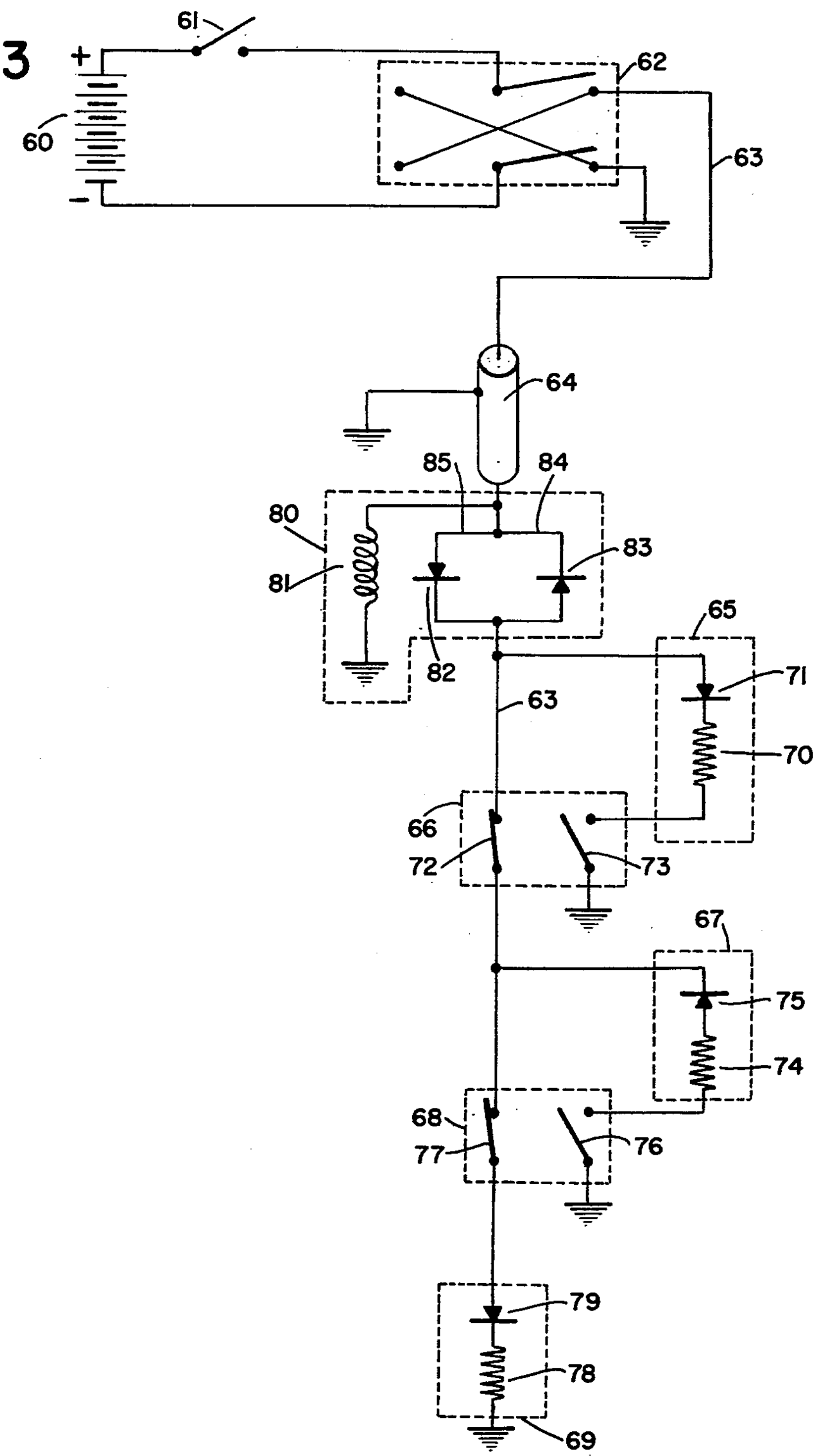
FIG.3



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SELECTIVE FIRING APPARATUS
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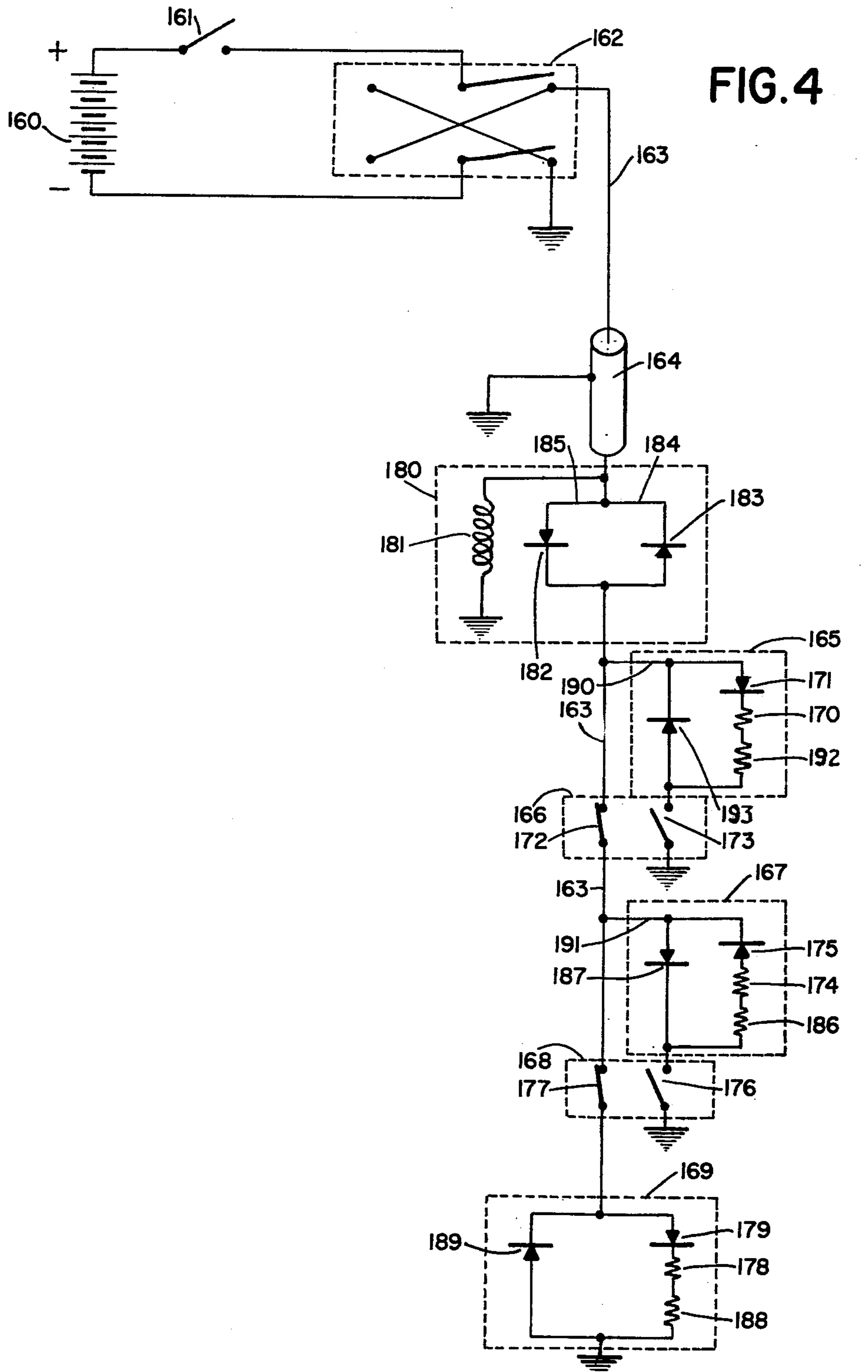

FIG. 4

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3,010,396
SELECTIVE FIRING APPARATUS

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11 Claims. (Cl. 102—21.6)

This invention relates to systems, apparatus and methods for firing explosive charges and, more particularly, to improved remotely controlled systems and apparatus for selectively and separately detonating a number of such charges. The new systems and apparatus are useful, among other purposes, for firing a plurality of charges located at various points in or adjacent to an exposed earth formation and are especially well suited for use in apparatus for perforating cased wells.

Although various systems for selectively firing a number of remote explosive charges have been developed practical applications remain for which previously available systems are not entirely satisfactory. An example of such an application is the detonation of a plurality of explosive charges in a well. It is common practice in the completion of oil, gas or water, production or injection wells to lower a steel casing into a well bore hole and anchor it in the surrounding earth formation with cement. The cased well is then perforated at a predetermined depth or depths to provide communication between the earth formation and the inside of the casing to permit fluid treatment of the formation through the casing or flow of ground fluids into the well. The perforating operation is generally carried out by lowering one or more elongated multi-shot perforating guns into the well on an electrically conductive cable and then simultaneously detonating the charges in the guns by causing an electrical impulse to flow down the cable. Perforating guns are commonly 7 or 11 feet in length and usually contain a maximum of 6 charges per foot. These charges are employed either to propel bullets through the well casing and into the surrounding earth formation or, when shaped explosive or jet charges are used, to penetrate the casing and formation by means of a high velocity metallic jet.

It is frequently desired to perforate an extended section of a cased well. This often presents problems, however, since the widely used carrier type jet perforating guns are generally designed for not more than about 10 feet of charges due to the weight per foot of the carrier, which makes it difficult for men to handle longer guns in the field. Therefore, when it was desired to perforate a section of a well more than 10 feet in length it was previously the practice to lower a gun into the well repeatedly and retrieve it to be reloaded or replaced by a new gun after each 10-foot section of the well was perforated. The only alternative has been to connect several guns together in a string, lower them into the well, and fire them simultaneously. The latter method, while less time-consuming than the former, is not entirely satisfactory since the limitations imposed by the lowering cable, the gun coupling devices, and the well casing may not safely permit simultaneous detonation of the number of jet charges normally present in more than two 11-foot guns.

In one embodiment of the present invention there is provided a system for selectively and separately firing the individual jet perforating guns in a string of such guns. Such a system permits the perforation of a continuous extended zone or two or more separated zones on a single run into the well. This materially reduces the time required to complete a perforating operation, as compared to that required by the procedure of repeatedly running a single gun in and out of the well, and also makes it possible to eliminate the unperforated intervals previously caused by the presence of coupling devices between adjacent guns in the string. These advantages are obtained by running into the well a string containing as many guns as necessary to perforate the desired zone or zones and selectively firing the guns individually, repositioning the string in the well if necessary after firing each gun. For example, in order to eliminate unperforated intervals in an extended zone the string is repositioned after firing each gun so that the next gun to be fired overlaps the unperforated section of the well previously adjacent to the coupling device between that gun and the gun fired previously. When perforating two or more widely separated zones or increasing the perforation density in a particular zone it is only necessary to raise or lower the string in the well after firing each gun to place an unfired gun at the desired level in the well. All of these operations are carried out in a minimum of time and without placing undue stress on the casing, bore hole, cable or gun coupling devices.

Systems for selectively firing a number of perforating guns or charges have been suggested previously. For example, it has been proposed to employ several electrical selector switches and multiple electrical lead wires. Other systems comprising complex networks of electrical resistances are adapted to selectively fire perforating guns when different critical amounts of electrical current are applied. None of these systems has been found entirely practicable for use in wells, however, and most have serious limitations. For example, the multiplicity of electrical lead wires required by some adds materially to the time required to assemble a string of perforating guns in the field and inevitably multiplies the chances for equipment failure or malfunctioning. Systems employing networks of resistances for establishing critical amounts of current are also disadvantageous in many cases due to the possibility of firing all of the guns simultaneously when too large a current is accidentally applied to the system.

It is therefore, an object of the present invention to provide a reliable, mistake proof system for selectively and separately firing a plurality of remote explosive charges in a predetermined sequence.

It is yet another object of the invention to provide a system for selectively firing a plurality of well casing perforating guns which permits the use of a self-generating magnetic casing collar locator in conjunction with the firing system without affecting the selectivity of the latter.

It is another object of the invention to provide a selective firing system for a plurality of perforating guns which may be embodied in an easily assembled, ruggedly constructed, substantially mistake proof well casing perforating apparatus capable of providing safe and reliable operation under service conditions in the field.

In one illustrative embodiment of the invention there are provided one or more rectifiers associated with the individual detonators or blasting caps. If, for example, three guns are to be fired, one by one, the first and third guns each may include, in circuit with its detonator, a rectifier arranged to be selectively responsive to voltage of one polarity, and the intermediate, second gun may include a rectifier selectively responsive to voltage of the opposite polarity. There are also provided circuit means, including for example a switch, for applying to the rectifiers a voltage, the positive or negative polarity of which is controlled, step by step, in such a way as to actuate the detonators selectively in corresponding steps.

Thus there may be provided, in one embodiment, a source of voltage; control means connected to the voltage source and adapted to be switched between a first and a second condition for producing alternately an output voltage having a first characteristic and an output voltage having a second characteristic; one or more devices selectively responsive to output voltage having the first characteristic for individually firing one or a group of explosive charges associated with these individual devices; and one or more devices selectively responsive to output voltage having the second characteristic for firing other explosive charges. The voltage responsive devices are arranged in the system with those responsive to voltage of one characteristic alternating with those responsive to voltage of the other characteristic. Actuation of the control means repeatedly to its first and second conditions causes the voltage responsive devices, one by one, to detonate their respective charges, as desired.

In addition, there are described herein certain highly advantageous circuits for protecting the rectifiers referred to above against excessive inverse voltages and also circuits and a method useful for checking the apparatus to make certain that a given gun is properly armed before attempts are made to fire it. The apparatus also includes means for normally preventing the firing of any of the explosive charges except one or a group of them, for example, the one most remote from the voltage source.

Other features of the invention will appear in the course of the following detailed description of a typical embodiment thereof taken in conjunction with the accompanying drawings in which:

FIG. 1 is a diagrammatic elevational view in section of a cased well bore hole containing a string of perforating guns;

FIG. 2 is an axial cross-sectional fragmentary view showing portions of two adjacent carrier type jet perforating guns and an intermediate coupling device;

FIG. 3 is a diagrammatic representation of a system of the invention and the electrical circuit included therein.

FIG. 4 is a diagrammatic representation of another system of the invention and the electrical circuit included therein.

In FIG. 1, a string of perforating guns is shown positioned in a well penetrating an earth formation **11**. The well is lined with steel well casing **12**. The string of guns is made up of two relatively long perforating guns **13** and **14** and a shorter gun **15** joined at their ends by means of coupling devices **16**. The lower end of gun **14** is sealed against well fluids by means of bull plug **17**. The string of guns is supported in the well on cable **18** which may be a conventional single conductor, reverse concentric cable or any other suitable electrical conductor. The cable **18** is connected to a cable head **19** which serves to retain the cable and insulate its central conductor from any fluid present in the well. A self generating magnetic casing collar locator **20** is connected between cable head **19** and a contact sub **21** which is connected in turn to the upper gun **15** of the string through top sub **22**. Although three perforating guns are shown in the drawing any convenient number may be employed in the present invention.

In FIG. 2 a cylindrical steel coupling device **23** having an axial bore **24** terminating in a machined recess **25** at the lower end of the coupling device serves to connect two carrier type jet perforating guns **26** and **27** (only the lower end of gun **26** and the upper end of gun **27** being shown). It will thus be seen that FIG. 2 represents a portion of a string of guns like the string of FIG. 1. It is apparent that the coupling device **23** in the string of guns in FIG. 2 serves the same function as the coupling devices **16** in the string of guns in FIG. 1. A shaped explosive or jet charge **28** is shown positioned to fire through a port **29** in the lower end of gun **26**. Port **29** is closed with a soft metal plug **30** which serves to seal the port to prevent entry of desensitizing well fluids but does not, however, seriously interfere with the jet when the charge is fired. A voltage polarity selective detonator assembly **31** is positioned in the lower end of gun **26** by means of spring wire retainer **32**. Explosively actuated switch assembly **33** is press fitted into the recess **25** in the lower end of coupling device **23**.

The voltage polarity selective detonator assembly **31** comprises an electrically insulating casing **34** containing an electrical blasting cap **35** or other suitable detonator, a rectifier **36**, a primacord initiating booster charge **37** and a length of primacord or other suitable fuse **38** which runs through the detonator assembly and the length of gun **26** adjacent to the bases of the plurality of jet charges **28** therein. Silicon rectifiers are preferred for use in well treating systems or apparatus since they are relatively small and have superior high temperature characteristics. Other types of rectifiers are, however, also suitable for use in the systems of the invention. A passageway **39** in insulating casing **34** ensures contact of the explosive wave front from the detonator **35** with the booster charge **37**. A main electrical conductor **40** in electrical contact with the central conductor of the cable **18** runs through the gun **26** and into the detonator assembly **31** where it is electrically connected to rectifier **36**. An electrical lead wire **41** is connected to main conductor **40** ahead of rectifier **36** and is led through and out of the casing **34**. Electrical lead wire **42** electrically connects the detonator or blasting cap **35** with the rectifier **36**. Electrical lead wire **43** connected to blasting cap **35** is led through and out of the casing **34**.

Explosively actuated switch assembly **33** comprises an insulating body member **44** which is press fitted into the recess **25** in coupling device **23**. Body member **44** is provided with an axial bore **45** opening into an enlarged recess **46**. An insulating plug **47** having a small axial hole therein is snugly fitted into the upper end of bore **45** of body member **44**. A stationary metal electrical contact member **48** is press fitted into the remainder of bore **45** of body member **44**. An electrical lead wire **49** is led through the axial hole in insulated plug **47** and one end is electrically connected to lead wire **43** which is connected to the main conductor **40** through blasting cap **35** in the detonator assembly **31**. The other end of electrical lead **49** makes electrical contact with stationary contact member **48**. A movable steel electrical contact member **50** having a shaft portion **56** adapted to slide into the enlarged recess **46** in insulating body member **44** is shown in an initial position. The end of the shaft portion **56** of movable contact member **50**, which is positioned within the recess **46**, is adapted to engage an insulating and wire shearing plug **51** having an axial bore therein to receive a spring wire electrical contact **52** connected at one end to movable contact member **50**. One end of an electrical lead wire **53** is connected to lead **41** which is in turn connected to the main conductor **40** ahead of the rectifier **36** in the detonator assembly **31**. Insulating sleeves **54** and **55** are provided to protect the connections between leads **43** and **49** and **41** and **53** respectively. Movable contact member **50** is provided with a flat base **59** having an area substantially larger than the area of the open end of enlarged recess **46** in body member **44**. A screw **57** is threaded into a hole in base **59** to provide electrical contact between the movable contact member **50** and a second main electrical conductor **58** which is led into and through the next lower gun in the string (not shown) where it would be connected to a rectifier in a selective detonator assembly in the same manner as main conductor **40** is connected to rectifier **36** in detonator assembly **31** of gun **26**. The other end of electrical lead wire **53** is run through insulating body member **44** to a point where it emerges into the recess **46** and is then inserted into insulating and wire shearing plug **51** through which it runs to make electrical contact with movable contact member **50**.

The schematic diagram of a system of the present invention shown in FIG. 3 includes a source of D.-C. current **60**, a single pole single throw switch **61** and a double pole double throw reversing switch **62** for applying positive or negative voltage tc a main conductor **63** as desired. The voltage of the source **60** may, for example, be about 200 to 320 volts. The main conductor **63** in practice would be, for example, the central conductor of a reverse concentric cable, the insulating sheath of which is indicated at **64**. The system also includes a selective detonator assembly **65** adapted to be detonated by a positive voltage, an explosively actuated switch assembly **66**, a second selective detonator assembly **67** adapted to be initiated by a negative voltage, an explosively actuated switch assembly **68** and a terminal detonator assembly **69** adapted to be initiated by a positive voltage.

Selective detonator assembly **65** consists of a detonator **70** which may suitably be an electrical blasting cap, and a rectifier **71** or other suitable device designed to pass current in only one direction. The detonator assembly **31** of FIG. 2 shows a suitable mechanical arrangement which may be used in the construction of a typical detonator assembly such as **65** or **67** of FIG. 3. Explosively actuated switch assembly **66** includes a normally closed switch **72** and a normally open switch **73**. The explosively actuated switch assembly **33** of FIG. 2 shows a suitable mechanical arrangement which may be used in the construction of a typical explosively actuated switch assembly such as **66** or **68** of FIG. 3. The rectifier **71** in assembly **65** is connected in parallel with the main conductor **63** so as to offer a relatively low resistance to current flow when a positive voltage is applied to the system and the explosively actuated normally open switch **73** has been closed to connect the detonator **70** with the circuit ground.

Switch assembly **68** contains a normally open switch **76** and a normally closed switch **77**. The circuit branch including selective detonator assembly **67** contains a detonator **74** and a rectifier **75** or equivalent device poled to offer a relatively low resistance to current flow when a negative voltage is applied to the main conductor **63** and the explosively actuated normally open switch **76** is closed so as to connect the detonator **74** to circuit ground. The circuit branch including the terminal detonator assembly **69** contains a grounded detonator **78** and a rectifier **79** arranged to offer a relatively low resistance to current flow when a positive voltage is applied to the main conductor.

There is also provided a magnetic casing collar locator assembly **80**. This includes a high resistance col **81**, connected between the main conductor **63** and ground, and also includes a pair of back-to-back rectifiers, the pair of them being in parallel with each other and in series with the conductor **63**.

Operation

It may be assumed that initially the switch **62** is in the position where its arms are toward the left. The switch **61** is now closed. With the switch **62** in the left position, negative voltage is applied to the main conductor **63** and thereby to the rectifier **79**. The back-to-back parallel-connected rectifiers **82** and **83** permit the passage of voltage of either polarity (with the exception that for very small voltages of the magnitude generated by the magnetic casing collar locator they provide a high resistance, as will be explained later). Hence for voltages of the magnitude to be used for firing, and also for smaller voltages to be referred to later in connection with the testing of the circuit of FIG. 4, the rectifiers **82** and **83**, provide, in effect, a low-resistance connection between the upper part of the conductor **63** and that part of it below these rectifiers. From the previous description it will be understood that the rectifier **79** is arranged to offer high resistance when negative voltage is applied to it. For this reason not enough current can now flow through this rectifier to detonate blasting cap **78**. Also, none of the blasting caps in the string of guns can now be detonated for the reason that the switches such as **76** and **73** are open.

To fire the detonator of the bottom gun the switch **62** is now thrown to the right. This has the effect of applying positive voltage through the conductor **63** to the rectifier **79**, which now passes sufficient current to initiate the detonator **78** and thereby fire the bullets or shaped charges of the bottom gun.

When the bottom gun is fired, the explosive waves set up by the detonation open the switch **77** and close the switch **76**. The way in which this is accomplished may be understood by referring to the typical construction of an explosively actuated switch shown at **33** in FIG. 2. The explosive waves force the movable contact member **50** into recess **46**. As the movable contact member **50** moves into recess **46**, insulating and shearing plug **51** shears the electrical lead **53**. This has the effect of opening the normally closed switch **77** in the schematic representation of this portion of the apparatus, as seen in FIG. 3. As a second effect, the upward movement of the movable contact member **50** causes the spring wire electrical contact **52** to engage the stationary metal electrical contact member **48**. This completes a circuit from the main conductor through the rectifier and detonator of the next-to-bottom gun to ground. As shown in FIG. 2, a path may be traced through a portion **40** of the main conductor, rectifier **36**, the lead **42**, detonator **35**, the leads **43** and **49**, the stationary contact member **48**, spring wire contact **52**, the movable contact member **50**, and thence to its flat base portion **59** which comes into contact with the body of metallic coupling **23**, when it has been forced upwardly as now assumed. As seen in the schematic diagram, FIG. 3, this same path may be traced from the main conductor **63** through one or the other of the rectifiers of the magnetic casing collar locator, and downwardly through the lower part of the main conductor **63** and through the rectifier **75**, the detonator **74** and through switch **76**, to the ground. Thus, in summary when the member **50** is forced upwardly, it has two effects. It brings the spring wire contact **52** into engagement with the stationary contact **48**, and this, as seen in FIG. 3, is represented by the closing of the switch **76**. The other effect of the upward movement of the member **50** is to shear off the lead **53**, and this is represented in FIG. 3 corresponding to the opening of the switch **77**. The closing of the switch **76** and opening of the switch **77** has the effect of arming the detonator assembly of the next-to-bottom gun. So long as the switch **62** remains in the right-hand position, however, the detonator of this assembly will not be initiated. This is true because the rectifier **75** is arranged to provide high resistance to the passage of current, so long as it receives positive voltage from the main conductor **63**. It may again be noted at this point that no detonator assembly above **67** can be fired at this time regardless of the polarity of the voltage in the conductor **63** because all other energizing current paths are open, so long as the switches corresponding to the switch **73** are open.

To fire the next-to-bottom gun, the switch **62** is next thrown to the left. This applies negative voltage to the main conductor **63**, and thence to the rectifier **75**. This rectifier now allows sufficient current to pass through the detonator **74** to cause it to be initiated, thereby firing the charges in the next-to-bottom gun. This has the effect of closing the switch **73** and opening the switch **72**, thereby arming the next higher gun. The switch **62** is next thrown to the right, thereby applying positive voltage to the main conductor **63** and the rectifier **71** and thus initiating detonator **70**.

The action of the magnetic casing collar locator assembly **80** will now be described. It is often important to locate a perforating gun at an exactly measured depth in a cased oil well, for example, in order to perforate only the particular section of casing encompassed by the oil-producing earth formation to be treated or drained. Measurement of the length of cable payed out is an indication of the depth to which the gun has been lowered. The depth may be checked by detecting and identifying a well casing collar located at a known depth and using that collar as a reference point for accurately positioning the gun. To detect such collars, as the apparatus passes them, the magnetic casing collar locator includes a magnetic circuit, including permanent magnets, arranged so that when they pass a collar, there is a change in the magnetic flux in the magnetic circuit, and the coil **81** is arranged in this path so that when this flux changes a very small voltage is induced in the coil. This voltage appears in the upper part of the lead **63**, and is detected by suitable voltage responsive means connected to the lead, but not illustrated in the drawing. Such means may, for example, include an amplifier and a recording or indicating voltmeter.

A characteristic of the rectifiers **82** and **83**, assumed here to be of the silicon type, is that even when a voltage is applied to such a rectifier in the forward direction, if this voltage is small enough the rectifier provides a relatively high resistance. The voltage generated by the magnetic casing collar locator is small enough to result in this type action. It may thus be seen that these rectifiers **82** and **83** tend to isolate the lower part of the circuit from the effects of the coil **81**.

It is desirable that magnetic casing collar assemblies be capable of use, interchangeably with circuits of the type shown in FIGS. 3 and 4, on the one hand, or with other firing circuits, for example circuits which themselves omit the rectifiers such as **71**, **75** and **79**. The latter type circuit would fire a plurality of charges at once. The rectifiers **82** and **83** are useful in such circuits for making sure that the voltage generated by the coil **81** does not accidentally fire the charges.

It may be understood that the circuit of the present invention is highly useful irrespective of whether a magnetic casing collar locator is used or not. If it is to be omitted, it would be replaced by a continuous connection of the upper part of the conductor **63** with the part of that conductor which in the drawings appears immediately below the assembly **80**.

Also, with circuits of the types shown in FIGS. 3 and 4, the rectifiers in series with the detonators, such as **71**, **75** and **79**, although they readily permit the passage of large voltages in the forward direction, tend to isolate the detonators from voltages of the small magnitude generated by the magnetic casing collar locator coil **81**, and for that reason, even if a magnetic casing collar locator is to be used, the rectifiers **82** and **83** can, in some embodiments, be omitted and replaced by a continuous portion of the main conductor **63**.

It will be understood that the individual detonators which have been referred to, such as **78**, **74** and **70** may each fire a single charge, or, in other arrangements, each detonator may be arranged to fire a group of charges.

Thus the apparatus is applicable to firing a plurality of charges, one by one, or in groups, in a single gun, and it is also applicable to firing respective guns, one by one, each gun including a plurality of charges.

Although three detonator assemblies are shown in FIG. 3, two, three, four or more may be actuated by the present system. There have been described in these various assemblies, devices, here illustrated as rectifiers, selectively responsive to voltage of one polarity, at least one of these devices being arranged to be responsive to voltage of one polarity and at least another of these devices being arranged to be responsive to voltage of the opposite polarity. In an illustrative arrangement, the apparatus may be regarded as including two sets of rectifiers, one set being responsive to positive voltage and one set to negative voltage, the rectifiers being spaced along the length of the well with the first set alternating with the second set. By a switching arrangement, the polarity of the voltage applied to the rectifiers is reversed in a step by step manner so as to initiate the corresponding detonators controlled by the rectifiers in a corresponding step by step manner.

In FIG. 4 there is diagrammatically shown another circuit which is in many respects similar to that of FIG. 3, but includes additional features. Certain elements in FIG. 4 which correspond to those of FIG. 3 are designated in FIG. 4 by reference numerals higher by 100 than the corresponding numeral in FIG. 3. Thus, element **171** in FIG. 4 corresponds to element **71** in FIG. 3, etc.

The selective detonator assemblies **165**, **167** and **169** in FIG. 4 include, respectively, in addition to the rectifiers **171**, **175** and **179**, other rectifiers **193**, **187** and **189**, connected in parallel branch paths, as shown. These other rectifiers like the ones mentioned previously, are preferably of the silicon type. Resistor **188** is connected in series with the rectifier **179** and its detonator **178**. Resistors **186** and **192** are similarly connected with respect to their rectifiers **175** and **171**, and to the associated detonators, respectively.

The rectifier **189** is in a branch path connected in parallel with the rectifier **179**, its detonator **178** and its resistor **188**. The rectifier **189** is turned in a direction opposite to that of the rectifier **179**. The rectifiers **187** and **193** are respectively similarly connected.

Thus the rectifiers which are, at some time in the operation of the system, conductive in response to positive voltage applied to the conductor **163** are **179** and **171**, and **187** and **182**. Those responsive to negative voltage are **175**, **189** and **193**, and **183**.

Whenever the voltage applied to any of the rectifiers **187**, **189** and **193** is in its forward direction, it provides in effect a low-resistance shunt path around whatever circuit elements are in parallel with it, including the associated detonator. This shunt path being of much lower resistance than the path including the detonator, is the preferred one for current flow.

An advantage of the additional rectifiers **193**, **187** and **189** is to limit the inverse voltage applied to their associated rectifiers **171**, **175** and **179**. Thus, before the bottom gun is fired, when a negative voltage is applied through the conductor **163** to the detonator assembly **169**, the rectifier **179** does not conduct, but the rectifier **189** does. The voltage across the branch circuit including rectifier **179**, detonator **178** and resistor **188** is limited to the forward voltage across the rectifier **189** which is of the order of a volt or two under typical operating conditions. In a similar manner, after the bottom gun has been fired and the switch **176** has been closed, and the switch **177** has been opened, the rectifier **187** protects the rectifier **175**, when positive voltage is applied through the main conductor.

With the protection described above, the system eliminates any tendency for inverse voltages to burn out the rectifiers **171**, **175** and **179**, and to cause misfiring.

The resistors **192**, **186** and **188** are advantageous in providing a readable difference in the resistance of the branch circuits in which they are located and the branch circuits in parallel with them. This may be better explained as follows: In the preferred method of operating the system, before any gun is fired, the system is tested to determine that the desired gun is properly armed. For this purpose the effective input resistance of the system, as seen through the upper end of the main conductor **163**, is measured, making use of a very low applied D.-C. voltage, this resistance being measured when the voltage is positive and also when it is negative. Thus, for this testing operation there is provided a source of known low D.-C. voltage, a reversing switch for applying positive or negative voltage from that source to the main conductor **163**, and a meter responsive to the current flowing from that source into the main conductor **163**. Except for that meter and the size of the voltage source, this circuit for the testing operation has the same arrangement as that shown in FIG. 4. The meter may conveniently be calibrated to read the resistance in ohms.

The voltage source used for this testing operation is small enough in magnitude that there is no danger, under any conditions, of its actuating any of the detonators. It is, on the other hand, large enough to pass in the forward direction through one of the rectifiers in the magnetic casing collar locator **180**.

When the bottom gun is properly armed, application of this low voltage to the system in a positive direction should produce an indication of relatively high resistance, because now conduction of the rectifier **179** and nonconduction of the rectifier **189** will cause the measurement to be influenced materially by resistor **188**. This resistor like the resistors **186** and **192** may, for example, be about 100 ohms.

On the other hand when the low voltage is applied to the conductor **163** with negative polarity, the conduction will be through the rectifier **189**, and a low resistance will be measured.

Such measurements indicate that the bottom gun is properly armed.

The bottom gun is next fired, by applying a high positive voltage to the conductor **163**, as previously described.

Next the system is checked to determine whether the next-to-bottom gun is properly armed. Now the application of a low negative voltage will result in a measurement of high resistance (through the rectifier **175**), and the application of a low positive voltage will result in the measurement of a low resistance (through the rectifier **187**), provided the system is properly armed. Other types of indications show that something is wrong with the system. If, for example, the switch **176** did not close after the detonation of the bottom gun, as above, an extremely high resistance or open circuit condition will be measured for both positive and negative applied voltage. This is an indication that the system is not properly armed.

After the next-to-bottom gun is fired, the system is again checked, and if a low positive voltage gives an indication of relatively high resistance and the low negative voltage gives an indication of low resistance, this indicates that the top gun is properly armed. It is then fired with the use of the high positive voltage.

The optimum value of the resistors **188**, **186** and **192** is the value which gives the maximum measurable difference in resistance during the above testing steps, for small positive and negative applied voltages, while still allowing enough current flow through the detonator to permit reliable detonation when the high voltage is applied.

It is apparent from the foregoing description that the present invention provides extremely useful methods, systems and apparatus for the selective firing of a plurality of remote explosive charges under a wide variety of conditions and that the invention is especially suitable for use in the perforation of cased wells since it provides a safe and reliable means for selectively firing any number of perforating guns in a well on a single run without subjecting the casing to prohibitive stresses.

The terms and expressions which have been employed are used as terms of description and not of limitation, and there is no intention, in the use of such terms and expressions, of excluding any equivalents of the features shown and described or portions thereof, but it is recognized that various modifications are possible within the scope of the invention claimed.

I claim:

1. In apparatus for selectively firing charges in a well, in combination, a plurality of branch circuits, a first device connected in one of said branch circuits and selectively responsive to voltage of only one polarity for firing one of said charges, a second device connected in another of said branch circuits and selectively responsive to voltage of only the opposite polarity for firing another of said charges, means connected to each of said branch circuits for applying voltage to said devices of the polarity to which said first polarity-selective device is selectively responsive, to actuate said first device to fire a first of said charges, and means for later reversing the polarity of said applied voltage, to actuate said second polarity-selective device to fire another of said charges, said apparatus including circuit means in interconnected relationship

with said one branch circuit and responsive to the firing of the first said charge for thereafter preventing current flow in said one branch circuit.

2. In combination, a plurality of branch circuits, each of said circuits including a rectifier and a current responsive detonator in series; means including a D.-C. voltage source, a switch and a conductor in interconnecting relationship with each other, said conductor being connected to each of said branch circuits, for applying D.-C. voltage to said rectifiers and for reversing its polarity, at least one of said rectifiers being oriented to pass current readily in response to positive voltage received from said conductor and the remainder being oriented to pass current readily in response to negative voltage received from said conductor, and pressure sensitive means operatively associated with the rectifier and the detonator in each of said branch circuits for preventing the actuation at any given moment of all but one of said detonators, whereby operation of said switch to alternate positions in steps actuates said detonators in corresponding steps.

3. In combination, a plurality of branch circuits, each of said circuits including a rectifier and a current responsive detonator in series; means including a D.-C. voltage source, a switch and a conductor in interconnecting relationship with each other, said conductor being connected to each of said branch circuits, for applying D.-C. voltage to said rectifiers and for reversing its polarity, at least one of said rectifiers being oriented to pass current readily in response to positive voltage received from said conductor and the remainder being oriented to pass current readily in response to negative voltage received from said conductor, pressure sensitive means respectively connected to the said individual branch circuits for preventing the actuation at any given moment of all but one of said detonators, whereby operation of said switch to alternate positions in steps actuates said detonators in corresponding steps, and, connected in parallel with each of said branch circuits, another rectifier oriented in a direction opposite to the one in its parallel branch circuit, for limiting the inverse voltage appearing across said first-mentioned rectifiers.

4. Apparatus according to claim 3 including a resistance in each of said branch circuits, in series with the said rectifier and detonator therein.

5. In apparatus for selectively firing a plurality of charges in a well, in combination, a plurality of detonators, a source of unidirectional voltage, control means connected to said source, said control means being switchable to a first condition and to a second condition, for producing alternatively an output voltage having a first polarity or a second polarity, a first set of devices selectively responsive only to said output voltage having said first polarity for actuating individual ones of said detonators respectively, at least one other device selectively responsive only to said output voltage having said second polarity for actuating another of said detonators, said devices being spaced in said well with said last-mentioned device being interposed between the devices of said first set, means for normally preventing the actuation of more than one of said detonators at a time, and means for applying said output voltage to said devices, whereby actuation of said control means repeatedly to its said first and second conditions actuates said devices one at a time to cause said detonators one by one to fire said charges selectively.

6. Apparatus according to claim 5 in which said devices comprise rectifiers.

7. In apparatus for selectively firing a plurality of charges in a well, in combination, a plurality of voltage-controlled actuating circuits spaced along said well, one for each of said charges, each of said actuating circuits including a device having a preferential direction of current flow, said devices being poled in opposite directions, alternately, in successive ones of said actuating circuits, means including a main conductor for applying D.-C.

voltage to said actuating circuits, a control for shifting the polarity of said applied D.-C. voltage, at least some of said actuating circuits including a pressure responsive switch connected thereto for normally maintaining its said actuating circuit in a disarmed condition to prevent the firing of its said charge until an adjacent charge has been fired, whereby the firing of said charges may be controlled by operation of said control to repeatedly reverse the polarity of said voltage applied to said actuating circuits.

8. Apparatus according to claim 7 including a magnetic casing collar locator comprising a coil connected to said main conductor for generating a voltage when said collar locator passes a casing collar, and a pair of parallel reversely connected rectifiers connected in series with said conductor at a point below the junction of said coil with the same.

9. In apparatus for selectively firing a plurality of charges spaced along the length of a well, in combination, a plurality of devices selectively responsive to voltage of one polarity, said devices comprising a first group and a second group, each of said groups comprising at least one said device, said first group being selectively responsive to voltage of only a first polarity for firing individual ones of said charges respectively, and said second group being selectively responsive to voltage of only the opposite polarity for firing other individual ones of said charges respectively, said devices being spaced along the length of said well, with the devices of said first and second groups alternating, means for normally preventing the firing of all of said charges except the lowermost unfired one, means for applying voltage to said devices of the polarity to which said first group is selectively responsive, to actuate the lowermost one of said devices in said first group to fire its said charge, and means for repeatedly reversing the polarity of said applied voltage to actuate successively higher ones of said polarity-selective devices, to fire successive ones of said charges.

10. A voltage selective detonator assembly comprising, in combination, a rectifier and an electrical blasting cap connected in a series circuit whereby said series circuit offers a high resistance to the passage of direct current in response to voltage of one polarity, and offers a substantially lower resistance to the passage of direct current in response to voltage of the opposite polarity, so that said blasting cap may be actuated selectively by voltage of controlled polarity, and another rectifier connected in parallel with said series circuit and poled in a direction opposite to that of said first mentioned rectifier, said other rectifier serving to prevent inverse voltages from causing misfiring of said blasting cap.

11. Apparatus according to claim 2 in which said pressure sensitive means includes a plurality of explosively actuated switch assemblies, respectively interposed between successive junctions of said branch circuits and said conductor, each comprising a pair of contacts in series with said conductor, a pair of contacts in series with an adjacent one of said branch circuits and an explosively actuated movable member for opening said first pair of contacts and closing said second pair of contacts.

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