May 15, 1956 G. McPHERSON, JR 2,745,998

FREQUENCY CONTROL SYSTEM FOR VIBRATORY TRANSDUCER

Filed April 23, 1953 2 Sheets-Sheet 1

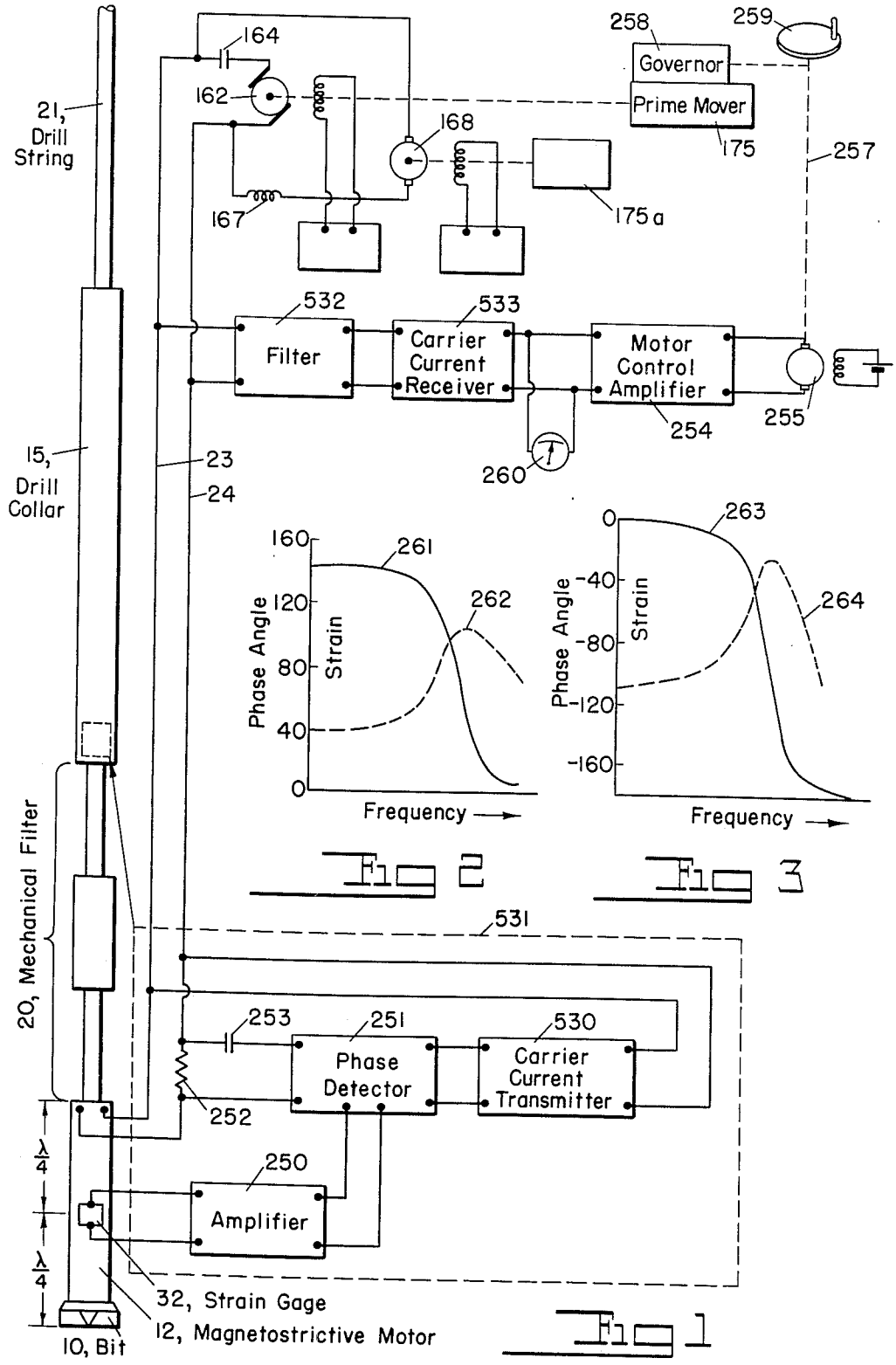


Fig 1

Fig 2

Fig 3

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FREQUENCY CONTROL SYSTEM FOR VIBRATORY TRANSDUCER

Filed April 23, 1953 2 Sheets-Sheet 2

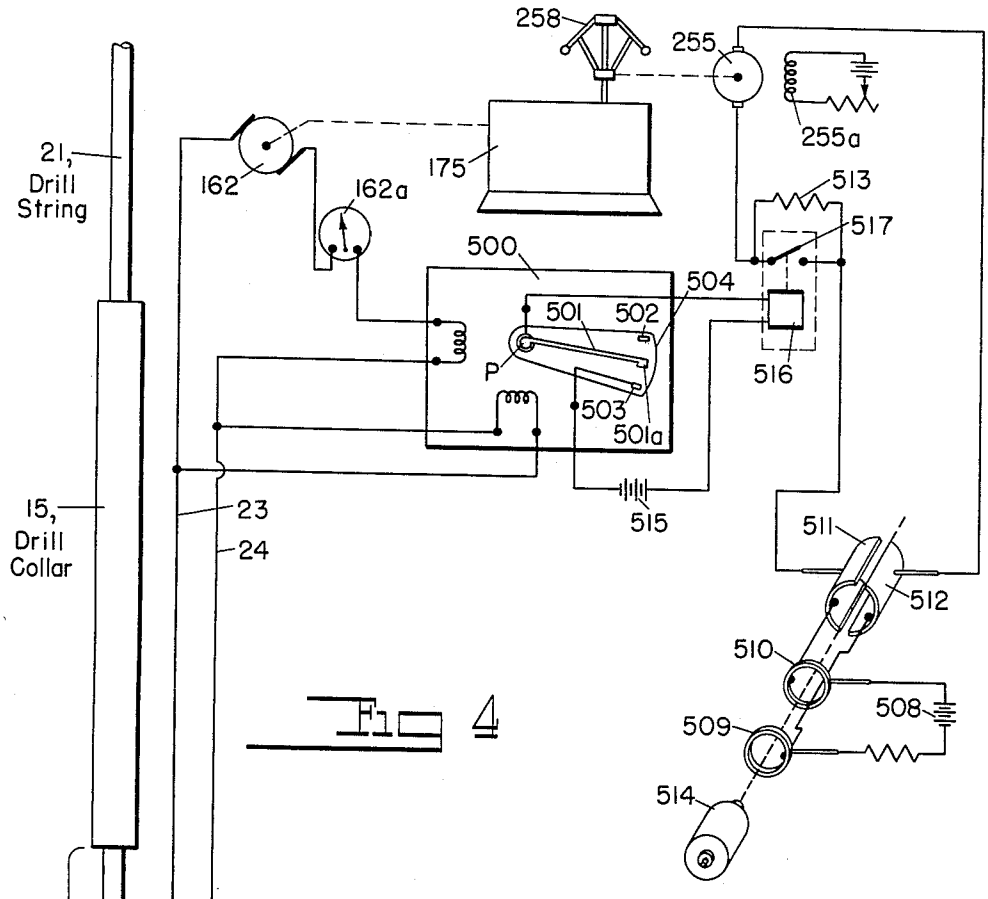
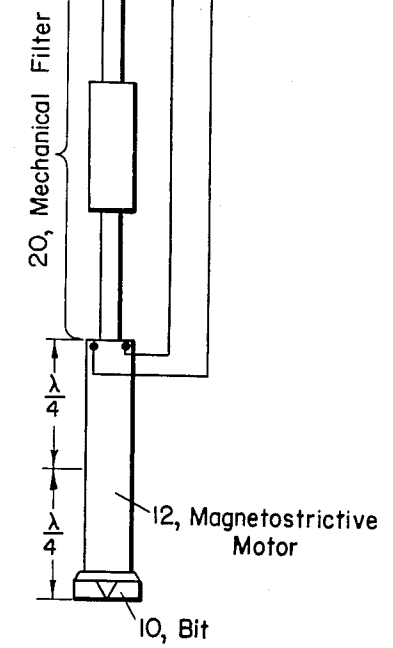


FIG 4



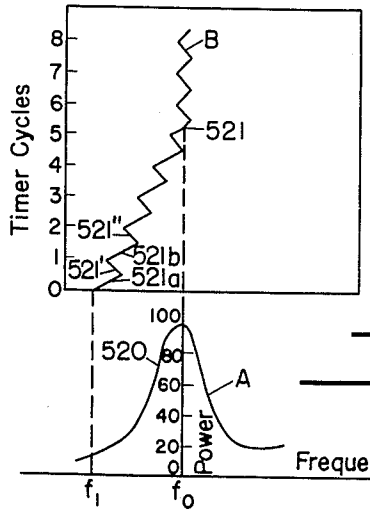


FIG 5

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FREQUENCY CONTROL SYSTEMS FOR VIBRATORY TRANSDUCER

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Application April 23, 1953, Serial No. 350,732

16 Claims. (Cl. 318—118)

This invention relates to frequency control systems, particularly to frequency control systems, preferably automatic, that are particularly adaptable and especially useful in vibratory well-drilling apparatus to maintain substantially optimum frequency of operation therein during varying conditions of drilling to enable the drilling equipment to attain the desired depth of the well at minimum cost and in minimum time.

The frequency control systems of this invention are particularly useful in well-drilling systems of the type described and claimed in the copending application for U. S. Letters Patent of Boyd A. Wise et al., Serial No. 350,314. Such a drilling system includes a drill string having means for applying a static load to a drill bit secured to the lower end of a vibratory column at the lower end of a drill string, the column including an elongated magnetostrictive transducer. In the present invention, means are provided for supplying an alternating current to the transducer to produce a changing flux of high peak density therein and further means are provided responsive to measurable characteristics in the vibratory column, such as the strain at a suitable preselected location in the vibratory column and the resistive component of the impedance of the transducer, that may vary according to deviation from the resonant frequency, including means responsive to the alternating current supplied to the transducer, for controlling the frequency of excitation of the transducer to maintain the vibration of the column at substantially the resonant frequency of the column while in engagement with strata to be penetrated.

The objects and advantages of the present invention can be understood most fully in connection with an explanation of various problems and limitations involved in the drilling of deep wells. For economic reasons, deep wells, which may extend several miles underground, are necessarily of small diameter, the size of the casing ranging from about five inches to about 15 inches, the more usual size being from six to ten inches. The severe limitations of hole size require a motor type particularly suited to the application, if adequate forces and power are to be produced. Magnetostrictive motors of a specialized type, such as are shown in the copending application of Wise et al. mentioned above, meet the necessary limitations and requirements, and are especially well suited to the drilling of wells.

The severity of the limitations imposed by the small size of the bore hole is intensified as the drilling rate increases. As the bit penetrates more rapidly, the chips or fragments of the strata must be removed at higher rates, and it is necessary to increase the circulation of "mud," a term generally used to refer to the medium that carries away the drilling chips. The drill string and the drilling column must, of course, provide a flow passage for the circulation of mud at reasonable pumping pressures and in sufficient volume to remove the chips as fast as they are produced, and thus maintain the drill in contact with the strata to be penetrated and unimpeded in its progress by any substantial depth of chips or fragments.

To provide maximum rate of penetration with a given drilling system, it is necessary to operate the vibratory column substantially at resonance. For this reason, the vibratory column preferably has a length of approximately one-half wave length or an integral multiple thereof at a frequency near the middle of a band of operating frequencies available with a particular alternating current generator furnishing power to the transducer. Different conditions of drilling, as may arise from different types of rock formation to be penetrated, cause the natural resonant frequency of the vibrating column to vary, and it is necessary to be able to vary the operating frequency accordingly as changing conditions arise, in order to maintain operation substantially at resonance.

It is a primary object of the present invention, therefore, to provide frequency control systems, preferably automatic, for varying the operating frequency in vibratory drilling systems wherein the resonant frequency of a vibratory column may vary with changes in drilling conditions.

Because of the requirements that the drill string shall have an open, unobstructed passage for flow of drilling mud, available space for electrical conductors is at a premium. In accordance with the present invention, no extra conductors are required. Nevertheless, the control system responds to vary the frequency in direction and extent to maintain vibration of the transducer at or near maximum amplitude for high rates of drilling. In one modification, auxiliary conductors, if used, may be quite small or they may be eliminated by using carrier-current systems.

In a preferred form of the invention, advantage is taken of the fact that the resistive component of the impedance of the transducer changes with departure of operation of the transducer from its resonant frequency. By maintaining constant, or relatively so, the current supplied to the transducer winding, the frequency of maximum power will coincide with the frequency of maximum resistance. The frequency of the alternating-current power supply may be varied to maintain maximum power delivery to the transducer in response to changes in power as determined at the surface. In accordance with the invention, the speed of the generator is cyclically varied, first in one direction and then in the other direction to vary its frequency. The change in power with such cyclical changes in frequency is detected or observed. The cyclical variation is then modified so that a greater change in freqency occurs in the direction that increases the power output of the generator. With the greater change in the power-increasing direction, the generator frequency is varied so as to reach the frequency that provides maximum power output to the transducer.

In another form of the invention, the frequency of excitation of the transducer is controlled so as to maintain the vibration of the vibratory column in the drilling system at substantially the resonant frequency by means responsive to the phase relationship between the current supplied to the transducer and the strain at a suitable preselected location in the vibratory column. A preferred location from which to obtain a strain signal is at approximately the partial velocity node in the vibratory column. Another suitable location is at the bit. Using either of these locations, means are provided for detecting the phase relationship between the current and the strain and for varying the operating frequency in such manner as to maintain substantially a 90° phase relationship between the current and the strain, such phase relationship being a characteristic of substantially resonant operation.

It is a further object of this invention to provide frequency control systems having the features and advantages summarized in the foregoing paragraphs. Further

objects and advantages will be apparent from the following detailed description and the claims.

In the drawings:

Fig. 1 is a schematic view illustrating a frequency control system according to the present invention;

Fig. 2 is a graph explanatory of the theory of operation of the frequency control system of Fig. 1;

Fig. 3 is another graph similar to Fig. 2;

Fig. 4 is a schematic view diagrammatically illustrating another form of frequency control system according to the present invention; and

Fig. 5 is a graph explanatory of the operation of the system of Fig. 4.

In order that operation at substantially the optimum or resonant frequency may be maintained in a vibratory drilling system despite the fact that the resonant frequency changes during drilling, a frequency control system should be provided to respond to the output of the transducer in such way as to regulate the frequency of the alternating current power in accordance with the changing resonant frequency of the transducer. Any one of several variables whose magnitudes change with departure of transducer operation from its resonant frequency, such as strain-gauge output, may be availed of in controlling frequency. One frequency control method of the present invention comprises regulating the frequency of the alternating-current power supply either manually or automatically in response to phase change as between the alternating current supplied to the transducer and the transducer strain in the vicinity of the bit, or preferably in the region of the partial node, where the waveform of the strain signal is more nearly sinusoidal. As a part of the present invention, it has been found that at resonance a phase difference of approximately ninety degrees exists between the alternating current and the transducer strain. Thus, as this phase angle changes from ninety degrees, the frequency of the alternating current generator or alternator should be changed in the direction to restore the ninety-degree relationship.

Fig. 1 schematically illustrates a preferred system for providing such control. The strain gauge **32** may be either at the bit **10** or at the partial node, as illustrated. The output from the strain gauge **32** is applied to an amplifier **250** whose output is fed to the input terminals of one input section of a phase-sensitive detector **251**. A current signal derived from a low resistance **252** inserted in the supply line **24** is applied, preferably through a high-capacitance blocking condenser **253**, to the input terminals of the other input section of the phase-sensitive detector **251**. The blocking condenser **253** is needed where, as in the circuit of Fig. 1, a direct-current component of power is supplied to the transducer as by the direct-current generator **168** driven by the prime mover **175***a* and connected through the inductance **167** to the transmission lines **23**, **24**, in addition to the alternating-current component of power supplied by the alternating-current generator **162** driven by the prime mover **175** and connected through the capacitor **164** to the transmission lines **23**, **24**.

The phase-sensitive detector **251**, preferably of the electronic type known in the art, provides at its output circuit **259** a direct-current potential approximately proportional to any variation from a ninety-degree phase relationship between the strain signal received from the strain gauge **32** and the current signal received from the low resistance **252** (which is unchanged in phase by the capacitor **253**). This output potential has one polarity when the phase relationship is greater than ninety degrees and has the opposite polarity when the phase relationship is less than ninety degrees. This output potential is applied to the input terminals of a motor control amplifier **254** which provides an output of sufficient amplitude to operate a motor **255**. The direction in which the motor **255** rotates is dependent upon the polarity of the voltage applied to it from the output of the motor-control amplifier **254**. It will be positive or negative in accordance with the polarity of the output of the phase-sensitive detector **251**.

When the phase relationship between the strain signal from the strain gauge **32** and the current signal from the low resistance **252** is ninety degrees, the output of the phase-sensitive detector **251** is zero, so the motor **255** receives zero voltage from the motor-control amplifier **254** and remains at a standstill. As the phase angle decreases, however, as by change in the phase of the strain or output of strain gauge **32**, the phase-sensitive detector **251** provides an output voltage of one polarity, which, as amplified by the motor-control amplifier **254** and applied to the motor **255**, causes the motor to rotate in one direction, a direction which through suitable gearing, as indicated by broken line **257** adjusts a governor **258** to change the speed of the prime mover **175** in the direction, and by an amount, which restores the ninety-degree relationship. A change in the phase of the strain in the opposite direction reverses the polarity of the output of the phase-sensitive detector **251**, thereby reversing the direction of rotation of the motor **255**, again to restore the ninety-degree relationship.

Considerable attenuation and phase shift may be present in transmitting the strain signal from the transducer to the top of a long drill string because of the characteristics of the line used to transmit this signal. The power transmission line may not be used for transmitting the unmodified strain signal since the strain signal is of the same frequency as that of the very much greater power-supply voltage.

To avoid this deterioration in the strain signal, and to avoid the effect of phase shift in the transmission line which may occur between the low resistance **252** and the transducer **12**, it is preferred that a sub-assembly including the resistor **252**, the strain signal amplifier **250**, the phase-sensitive detector **251** and a high-frequency carrier-current transmitter **530** be located in a container **531** inserted in the drill string **21** just above the mechanical filter **20**, as in the lower end of a heavy drill collar **15** forming a part of the static load to the bit **10**. The output signal from the phase-sensitive detector **251** is then used to modulate the carrier-current produced by its transmitter **530**. The modulated carrier signal, derived from the carrier-current transmitter **530**, is transmitted upward along the power transmission line **23**, **24**, and after passage through a filter **532** in the line is demodulated by a carrier-current receiver **533** for development of a direct-current potential that is proportional to the output of the phase-sensitive detector **251**, and whose polarity changes in the same manner as that of the output of said detector. This potential, applied to the input of the motor control amplifier **254**, controls the speed and direction of the motor **255** which in turn controls the speed of the alternator, and thus the frequency, to maintain the ninety-degree phase relationship between the current and the strain signal.

Of course, the governor **258** may be manually adjusted as by a wheel **259** in accordance with deflection from ninety degrees of the phase-angle meter **260**. In general, the meter **260** and provisions for manual control are provided even with a fully automatic system.

The soundness of the basis for the control system thus far described has been experimentally verified. In Fig. 2, the graph **261** illustrates the change in phase angle between the strain at the bit **10** and the alternating current supplied to the transducer. The graph **262** represents the strain at the bit. As the frequency increases, it will be seen that the phase angle decreases from about one hundred and forty degrees, passing through ninety degrees as the strain at the node approaches a maximum. The phase angle from about one hundred degrees to about forty degrees rapidly decreases and then more slowly decreases. The maximum strain occurs at a phase angle of about ninety degrees within the limits of accuracy of the measurements.

The graphs **263** and **264** of Fig. 3, respectively, correspond to those of Fig. 2 but the graph **263** represents phase angle between the alternating current supplied to winding **18** and the output of strain gauge **32** located at the nodal point or partial velocity node, as in Fig. 1. The angles have a minus sign since the strain at the partial velocity node is one hundred and eighty degrees out of phase with the strain at the bit **10**. The region of maximum strain occurs, graph **264**, in the region of ninety degrees.

The steepness of the change of phase angle of both Figs. 2 and 3 is a function of the "Q" of the transducer. It can be shown that Q equals the product of one-half the resonant frequency times the rate of change of phase with respect to the frequency at resonance. The higher the Q, the steeper will be the slope of graphs **261** and **263** in the region of ninety degrees. Thus, while band width at the resonant frequency is decreased corresponding to an increase in Q, the sensitivity of control is increased and the control system of Fig. 1 will function to maintain the transducer operating at its resonant frequency. For a decreased Q, the sensitivity of control is decreased but, for this case, the frequency of operation need not be controlled to within as close limits as for higher Q operation because of the increased band width. Thus, this automatic control system will function satisfactorly over a wide range of Q values.

Further in accordance with the invention, advantage has been taken of the fact that the resistive component of the transducer impedance has been found to be a maximum at a frequency not far removed from the resonant frequency of the vibratory column. By reason of that fact, and of a known relationship in electrical theory, a control system of a different type may be utilized, such as shown in Fig. 4. This second form of control system obviates the necessity of obtaining any signals from downhole sensing elements. The system functions in a manner to produce maximum power input to the transducer with a substantially constant current supplied thereto. With power output determined by the product of the circuit resistance and the square of the current, high transducer output will be maintained by adjusting the frequency in response to change in the resistive component of the transducer impedance. The control action is in a direction to raise or lower the frequency as needed to maintain the resistive component of the transducer impedance at a value approaching its maximum.

In its simplest form, and with the current held constant by any suitable means as by any well-known automatic constant current-control circuit operating on the exciter system, the alternator frequency is varied by changing the governor setting as by the adjusting wheel **259**, shown in Fig. 1, to maintain a maximum reading of a wattmeter **500** responsive to the power transmitted to the transducer through conductors **23** and **24**.

Attached to the shaft of the wattmeter **500** is a contact arm **501** movable between a mechanical bumper **502** and an electrical contact **503** for use in providing automatic frequency control. The bumper and electrical contact **503** are mounted on a light-weight vane **504** which is pivoted on, and rotatable relative to, the meter shaft which carries the pointer and the contact element **501**. Accordingly, when contact arm **501** is rotated in a clockwise direction during periods of increasing power, the contact **501***a* is moved against the contact **503**. Arm **501** then moves vane **504** in a clockwise direction maintaining closed a circuit through contacts **501***a* and **503**. During periods when the power output of alternator **162** is decreasing the contact arm **501** first opens said circuit and then engages the bumper **502** to move the vane **504** in a counterclockwise direction. The contact arm **501** may, if desired, serve also as the indicating needle of the wattmeter **500**.

The manner in which the relative movement between the contact arm **501** and the contact-carrying vane **504** automatically adjusts the governor **258** to maintain maximum power flow in lines **23** and **24** will now be explained. The armature of motor **255** which adjusts the setting of the governor **258** is energized from any suitable source of direct voltage **508** by way of slip rings **509** and **510** and direction-controlling commutator contact segments **511** and **512**. As shown, the motor **255** with its field winding **255***a*, energized from a suitable voltage source, will rotate at low speed in one direction. It is rotated at low speed by reason of the inclusion in the motor circuit of a speed-reducing resistor **513**. When the positions of contact **511** and **512** are reversed, the direction of rotation of motor **255** is, of course, reversed.

By driving the segments **511** and **512** at relatively low speed, as by a motor **514** of the type having a geared-down output shaft, the motor **255** adjusts the governor **258** first in a direction to increase the speed of the prime mover **175** and then in a direction to decrease its speed. The extent of the adjustment is small and is insufficient to make more than a slight change in frequency of the alternator **162**. Sufficient change, however, is made in the frequency for the response of the wattmeter **500** to indicate whether or not increased power results from an increase in frequency or whether decreased power results therefrom.

It will now be assumed that the motor **255** is rotating in a direction to increase the frequency of alternator **162** and that the power through lines **23** and **24** to the transducer is increasing. Accordingly, a circuit will be completed from one side of a voltage source **515** through an operating coil **516** for a relay contact **517** and through the contacts **501***a* and **503** to the other side of the voltage source **515**. The relay contact **517** closes to remove the resistor **513** from the motor control circuit as by placing a short circuit around it. The effect of short-circuiting the resistor **513** is to increase the speed of the motor **255**. Thus, when increasing frequency results in an increase in power, the motor **255** runs faster in the direction to increase the frequency of the alternator **162**. As soon as the positions of the commutator contact segments **511** and **512** are interchanged from their positions as illustrated, however, the motor **255** is energized for reverse rotation. The resultant reduction in frequency of the alternator **162** reduces the power in lines **23** and **24** and the wattmeter **500** immediately responds to move contact arm **501** to open the circuit of relay coil **516**. Accordingly, the resistor **513** is effectively inserted in the motor circuit to slow down the motor and to produce a slower speed of operation in reducing the frequency than occurred in its operation to increase the frequency.

The system responds to develop maximum power output. The power is increased by the rising frequency and the vane **504** is moved in a clockwise direction by contact **501***a* but is not moved in the counterclockwise direction until after the opening of the circuit and not until contact member **501** engages the bumper **502**.

The graphs **520** and **521** of Fig. 45, plotted with frequency as abscissae and respectively with power and timer cycles as ordinates, are helpful in understanding the operation of the control system. The graph **520** is exemplary of the relationship between power to the transducer **12** and frequency.

Plotted in arbitrary units with f_0 corresponding to the frequency at which maximum power is obtained, graph **521** illustrates the variations in frequency produced by the control system as it adjusts the frequency of the alternator for generation of maximum power. It has been assumed that the frequency f_1 is about 7½ per cent below the frequency f_0 for maximum power. The graph **521** illustrates operation with resistor **513** having a value such that the motor speed will be doubled when it is removed from the motor circuit.

It is seen from graph **521** that about six timer cycles are required for the system to adjust the alternator **162** for the development of maximum power. More par-

ticularly, it is observed that the motor **255**, when operating to adjust the frequency as indicated by the segments **521***a*, **521***b*, etc., increases the frequency to a greater extent than opposite rotation of the motor decreases the frequency. The latter is illustrated by the segments **521'** and **521''**, etc. For the case where the frequency is too high, the system functions to reduce it. The graph would be a mirror-image of graph **521** located to the right of the broken line drawn at f_0.

The contact **503** and the bumper **502** may be adjusted on the vane **504** to vary their separation distances. Ordinarily such adjustment is made only when the system is first placed into operation, to provide the sensitivity needed for stable control of a particular installation. The graph **521** is to be considered only as exemplary of the operation of one system, since with different contact positions the adjustments of generator frequency in increasing and decreasing directions may vary substantially from those shown. The number of timer cycles required for the system to reach equilibrium may in some cases be less than the six which have been illustrated and in other cases may be more.

It will be understood, of course, that, while the forms of the invention herein shown and described constitute preferred embodiments of the invention, it is not intended herein to illustrate all of the possible equivalent forms or ramifications of the invention. It will also be understood that the words used are words of description rather than of limitation, and that various changes, such as changes in shape, relative size, and arrangement of parts, may be substituted without departing from the spirit or scope of the invention herein disclosed.

What is claimed is:

1. In a well-drilling system comprising a drill string having means for applying a static load to a drill bit secured to the lower end of a vibratory column at the lower end of said drill string, said column including an elongated magnetostrictive transducer: means for supplying an alternating current to said transducer to produce a changing flux of high peak density therein, and means responsive to measurable characteristics in said vibratory column that may vary according to deviation from the resonant frequency, including means responsive to the alternating current supplied to said transducer, for controlling the frequency of excitation of said transducer to maintain the vibration of said column at substantially the resonant frequency of said column while in engagement with strata to be penetrated.

2. In a well-drilling system comprising a drill string having means for applying a static load to a drill bit secured to the lower end of a vibratory column at the lower end of said drill string, said column including an elongated magnetostrictive transducer: means for supplying an alternating current to said transducer to produce a changing flux of high peak density therein and means responsive to the phase relationship between the current supplied to said transducer and the strain at a suitable preselected location in said vibratory column for controlling the frequency of excitation of said transducer to maintain the vibration of said column at substantially the resonant frequency of said column while in engagement with strata to be penetrated.

3. In a well-drilling system comprising a drill string having means for applying a static load to a drill bit secured to the lower end of a vibratory column at the lower end of said drill string, said column including an elongated magnetostrictive transducer: means for supplying an alternating current to said transducer to produce a changing flux of high peak density therein and means responsive to the phase relationship between the current supplied to said transducer and the strain at approximately the partial velocity node in said vibratory column for controlling the frequency of excitation of said transducer to maintain the vibration of said column at substantially the resonant frequency of said column while in engagement with strata to be penetrated.

4. In a well-drilling system comprising a drill string having means for applying a static load to a drill bit secured to the lower end of a vibratory column at the lower end of said drill string, said column including an elongated magnetostrictive transducer: means for supplying an alternating current to said transducer to produce a changing flux of high peak density therein and means responsive to the phase relationship between the current supplied to said tranducer and the strain at said bit for controlling the frequency of excitation of said transducer to maintain the vibration of said column at substantially the resonant frequency of said column while in engagement with strata to be penetrated.

5. In a vibratory drilling system including an alternating current source connected to energize a vibratory column including a magnetostrictive transducer, the resonant frequency of said vibratory column being variable with changes in drilling conditions, an automatic frequency control system comprising means for measuring the current supplied by said alternating current source to said transducer, means for measuring the strain at approximately a partial node in said vibratory column, means for detecting the phase relationship between said current and said strain and for providing a direct-current output of one polarity when said phase relationship is greater than 90 degrees, a direct-current output of opposite polarity when said phase relationship is less than 90 degrees, and zero output when said phase relationship is 90 degrees, and means responsive to said output for controlling the frequency of the current supplied by said alternating-current source to maintain said current and said strain in substantially 90-degree phase relationship.

6. In a vibratory drilling system including an alternating-current source connected to energize a vibratory column including a magnetrostrictive transducer, the resonant frequency of said vibratory column being variable with changes in drilling conditions: an automatic frequency control system comprising means responsive to the current supplied by said alternating-current source to said transducer for providing a current signal to an input section of a phase-sensitive detector, strain-gauge means located at approximately a partial node in said vibratory column for providing a strain signal to an input section of said phase-sensitive detector, means forming a portion of said phase-sensitive detector for providing a direct-current output of one polarity when the phase relationship between said current signal and said strain signal is greater than 90 degrees, a direct-current output of opposite polarity when said phase relationship is less than 90 degrees and zero output when said phase relationship is 90 degrees, and means responsive to said output for regulating a speed-control governor of a prime mover driving said alternating-current source to control the frequency of the current supplied by said alternating-current source in such manner as to maintain said current signal and said strain signal in substantially 90-degree phase relationship.

7. In a well-drilling system comprising a drill string having means for applying a static load to a drill bit secured to the lower end of a vibratory column at the lower end of said drill string, said column including an elongated magnetostrictive transducer: means for supplying an alternating current to said transducer to produce a changing flux of high peak density therein and means responsive to the resistive component of the impedance of said transducer for controlling the frequency of excitation of said transducer to maintain the vibration of said column at substantially the resonant frequency of said column while in engagement with strata to be penetrated.

8. In a well-drilling system comprising a drill string having means for applying a static load to a drill bit se-

cured to the lower end of a vibratory column at the lower end of said drill string, said column including an elongated magnetostrictive transducer: means for supplying an alternating current to said transducer to produce a changing flux of high peak density therein and means responsive to the resistive component of the impedance of said transducer for controlling the frequency of excitation of said transducer to maintain the vibration of said column at substantially the resonant frequency of said column while in engagement with strata to be penetrated, including means for maintaining constant alternating current amplitude supplied to said transducer and means for varying the frequency of said current to provide maximum power input to said transducer.

9. In a well-drilling system comprising a drill string having means for applying a static load to a drill bit secured to the lower end of a vibratory column at the lower end of said drill string, said column including an elongated magnetostrictive transducer: a power generating system for supplying power to said transducer including an alternating current generator for supplying alternating current of constant amplitude to said transducer, driving means for said generator, and means responsive to change in the power output of said generator for varying the speed of said driving means until said generator delivers power to said transducer at maximum value.

10. In a vibratory drilling system, including an alternating-current generator connected to energize a vibratory column including a magnetostrictive transducer, the resonant frequency of said vibratory column being variable with changes in drilling conditions: an automatic frequency control system comprising means including said alternating-current generator for supplying alternating current at substantially constant amplitude to said transducer, driving means for said generator, speed-control governor means for said driving means, means for cyclically regulating said governor means to vary the speed of said driving means, and thereby to regulate the frequency of the alternating current supplied by said generator to said transducer, first in one direction then in the opposite direction, wattmeter-type means responsive to any increase or decrease in the power output of said generator including electrical switching means to control said cyclic operation of said driving means in such manner as to increase the variation of said frequency in the direction that increases said power output so as to exceed the variation in frequency in the opposite direction, when at the midfrequency about which said variations are produced the power output of said generator is measurably below the output of said generator at the frequency of maximum output.

11. In a vibratory drilling system, including an alternating-current generator connected to energize a vibratory column including a magnetostrictive transducer, the resonant frequency of said vibratory column being variable with changes in drilling conditions: an automatic frequency control system combining means including said alternating-current generator for supplying alternating current at substantially constant amplitude to said transducer, driving means for said generator, speed-control governor means for said driving means, means for cyclically regulating said governor means to vary the speed of said driving means, and thereby to regulate the frequency of the alternating current supplied by said generator to said transducer, first in one direction then in the opposite direction, wattmeter-type means including a movable contact arm associated with a movable vane having affixed thereto a bumper member and an electrical contact oppositely disposed about said movable contact arm and responsive to any increase or decrease in the power output of said generator in such manner as to close an electrical circuit energizing a relay for actuating electrical switching means for shorting across said resistance upon the occurrence of a measurable increase in power during a portion of a governor-regulating cycle, to control said cyclic operation of said driving means in such manner as to increase the rate, and thereby the magnitude, of variation of said frequency in the direction that increases said power output so as to exceed the variation in frequency in the opposite direction, when at the midfrequency about which said variations are produced the power output of said generator is measurably below the output of said generator at the frequency of maximum output.

12. In a vibratory drilling system, including an alternating-current generator connected to energize a vibratory column including a magnetostrictive transducer, the resonant frequency of said vibratory column being variable with changes in drilling conditions: an automatic frequency control system comprising means including said alternating-current generator for supplying alternating current at substantially constant amplitude to said transducer, driving means for said generator, speed-control governor means for said driving means, means including a source of direct voltage connected through rotating commutator means for cyclically reversing the polarity of the voltage received from said source and connected through a resistance to the armature winding of a direct-current motor connected to control the setting of said governor for cyclically regulating said governor means to vary the speed of said driving means, and thereby to regulate the frequency of the alternating current supplied by said generator to said transducer, first in one direction then in the opposite direction, wattmeter-type means including a movable contact arm associated with a movable vane having affixed thereto a bumper member and an electrical contact oppositely disposed about said movable contact arm and responsive to any increase or decrease in the power output of said generator in such manner as to close an electrical circuit energizing a relay for actuating electrical switching means for shorting across said resistance upon the occurrence of a measurable increase in power during a portion of a governor-regulating cycle, to control said cyclic operation of said driving means in such manner as to increase the rate, and thereby the magnitude, of variation of said frequency in the direction that increases said power output so as to exceed the variation in frequency in the opposite direction, when at the midfrequency about which said variations are produced the power output of said generator is measurably below the output of said generator at the frequency of maximum output.

13. In combination, an electromechanical transducer whose resistance component of electrical impedance is a maximum at a frequency approximating the mechanical resonant frequency of the transducer, means including an alternating-current generator for supplying alternating current of constant amplitude to said transducer, driving means for said generator, and means responsive to change in the power output of said generator for varying the speed of said driving means until said generator delivers power to said transducer at maximum value.

14. In combination, an electromechanical transducer whose resistance component of electrical impedance is a maximum at a frequency approximating the mechanical resonant frequency of the transducer, means including an alternating-current generator for supplying alternating current at substantially constant amplitude to said transducer, driving means for said generator, means for cyclically adjusting said driving means to vary the frequency of said generator first in one direction and then in the opposite direction, means responsive to change in the power output of said generator for modifying said cyclic operation of said driving means to increase the change of said frequency in one direction more than in the other direction until the frequency of the said generator has been changed to produce maximum output of said generator.

15. In an electrical power generating system in which the power output of a generator has a maximum value

at a given frequency and is less as its frequency varies from that value, the method which comprises cyclically varying the speed of said generator first in one direction and then in the other direction to vary its frequency, detecting the changes in power with said changes in frequency, and in response to the relative changes in power with said changes of frequency, modifying said cyclical variation of speed of said generator to produce a greater change in the direction that increases its power output than in the direction that decreases its power output until maximum power output from the generator is attained.

16. In a well-drilling system in which the resonant frequency of a vibratory transducer changes during penetration of subsurface strata, resulting in a deviation between the frequency of the driving current and the resonant frequency with a resultant decrease of the vibratory forces, the method of compensating for changes in said resonant frequency by varying the speed of the supply

generator in manner comprising cyclically varying the speed of said generator first in one direction and then in the other direction to vary its frequency, detecting any increase or decrease in power with said changes in frequency, and in response to the relative changes in power with said changes of frequency, modifying said cyclical variation of speed of said generator to produce a greater change in the direction that increases its power output than in the direction that decreases its power output until maximum power output from the generator is attained.

References Cited in the file of this patent

UNITED STATES PATENTS

1,621,280	Roucka	Mar. 15, 1927
1,843,299	Pierce	Feb. 2, 1932
1,966,446	Hayes	July 17, 1934
2,068,577	Stratton	Jan. 19, 1937
2,095,120	Belfils et al.	Oct. 5, 1937