

Dec. 27, 1960

E. MISHKIN

2,966,623

POLY-FIELD ALTERNATING-CURRENT INDUCTION MACHINES

Filed Dec. 28, 1955

3 Sheets-Sheet 1

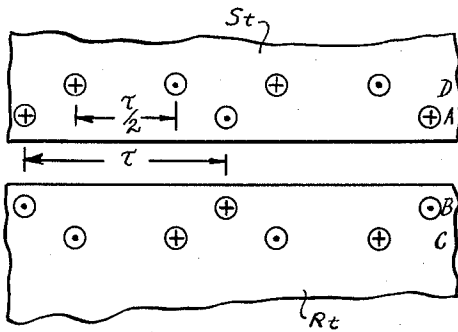


FIG. 1

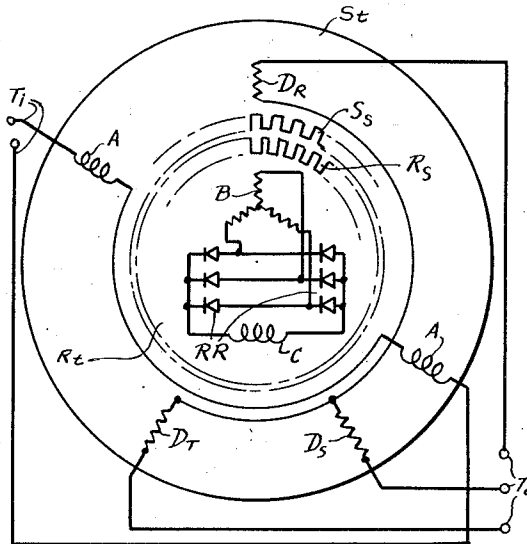


FIG. 2

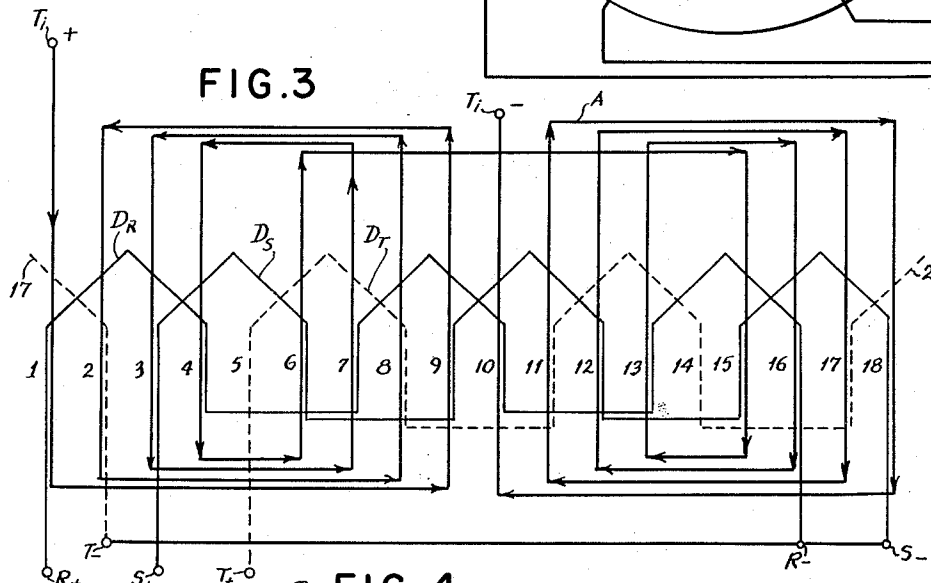


FIG. 3

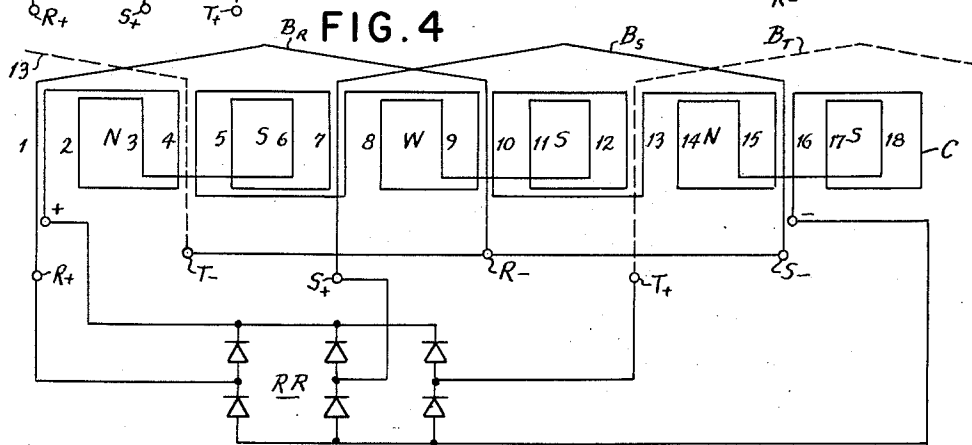


FIG. 4

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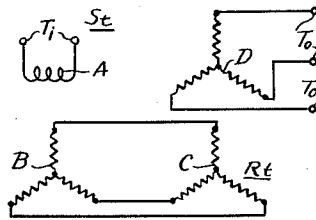
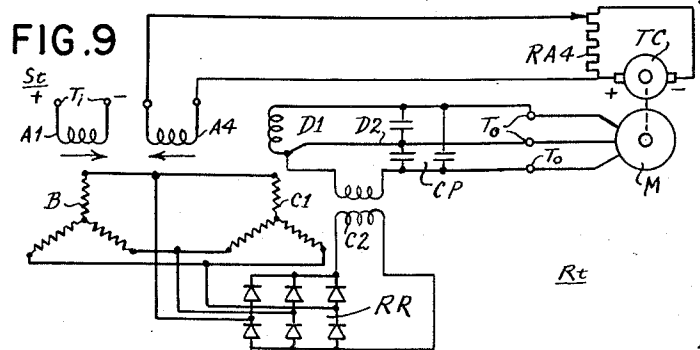
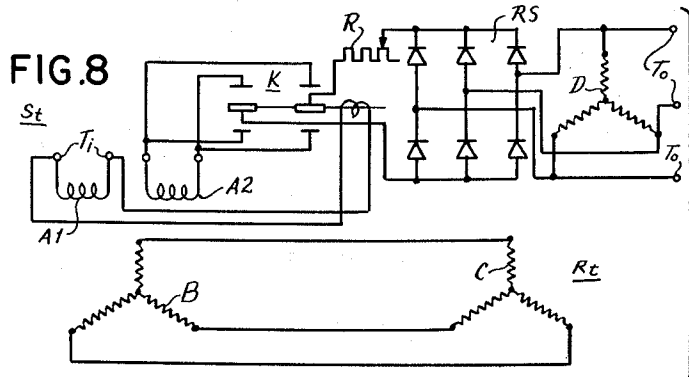
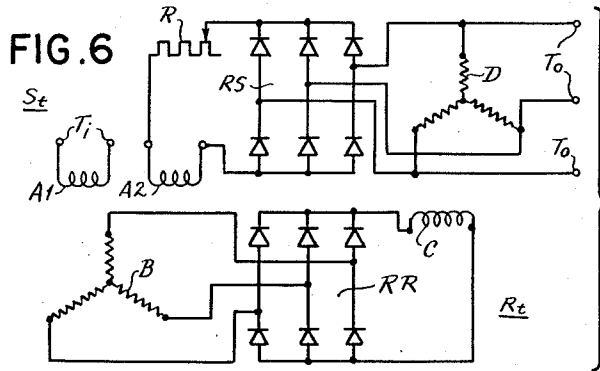
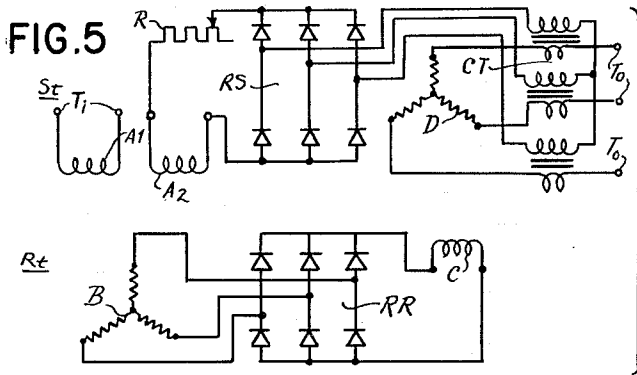


FIG. 7

FIG. 10

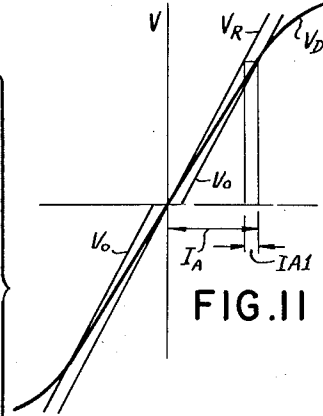
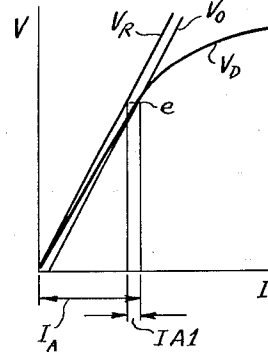


FIG. 11

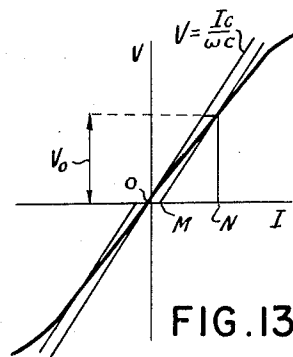


FIG. 13

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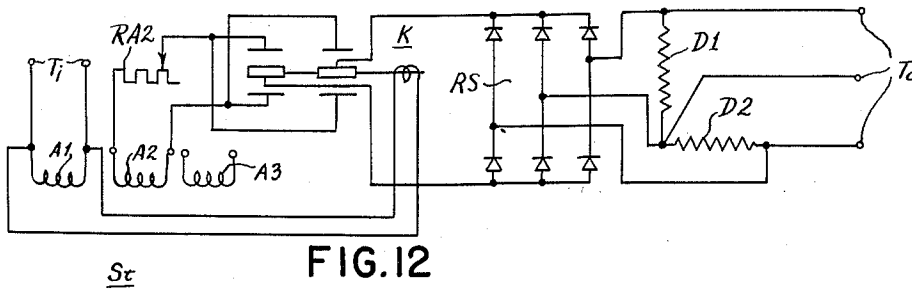
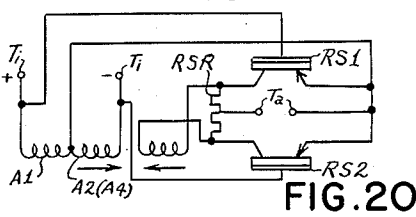
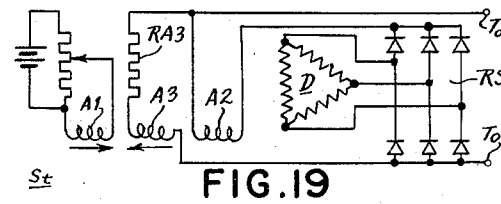
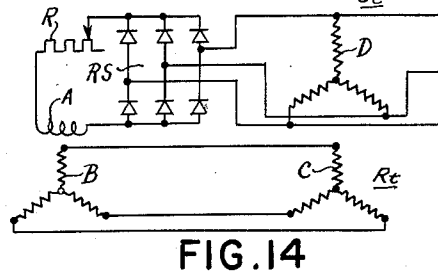
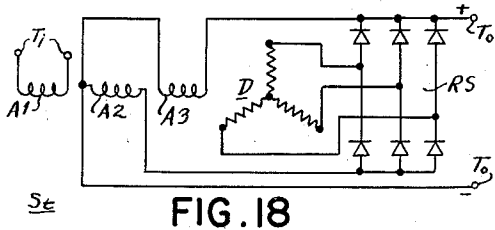
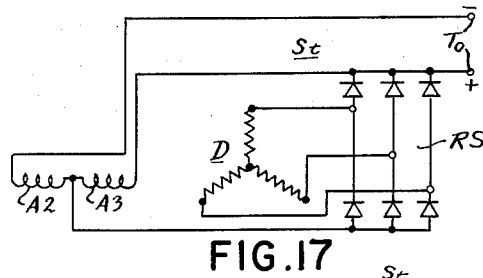
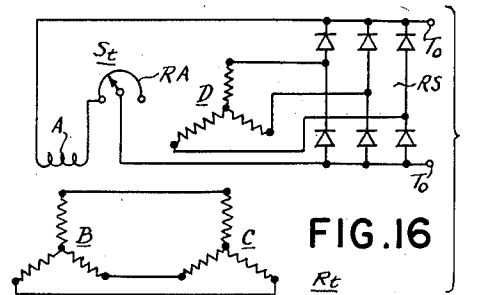
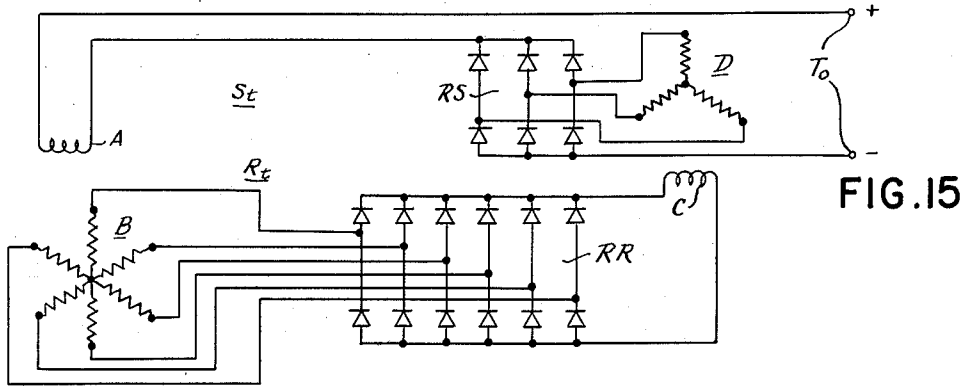
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POLY-FIELD ALTERNATING-CURRENT INDUCTION MACHINES

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20 Claims. (Cl. 318-148)

My invention relates to dynamo-electric machines generally of the alternating-current round-rotor type and, more particularly, to machines equipped with a plurality of cascade-connected field systems. In some of its specific, though not exclusive aspects the invention concerns rotary amplifying machines that may be looked upon as being A.-C. equivalents of two-stage D.-C. commutator machines of the type known under the trade names Amplidyne, Metadine, and Rototrol.

It is among the objects of my invention to devise a machine capable of plural-stage operation that requires neither a commutator nor slip rings and has a single stator and a single rotor both of the slot-wound or induction-rotor type of design customary with normal alternating-current induction machines, so as to combine facility of manufacture and small size with the advantage of eliminating the maintenance requirements, and hazards particular to contact-brush devices.

Another object of my invention concerns itself with plural-stage dynamo-electric amplifiers. The amplifying generators of this type now available are direct-current machines with salient poles and commutators requiring two sets of commutator brushes of proper angular displacement relative to each other. Satisfactory operation is predicated upon a critical design and critical brush adjustment, and the problems of armature-reaction compensation and balanced interpole excitation in such D.-C. machines are troublesome, aside from the fact that such machines are undesired in hazardous localities.

My invention, therefore, also aims at providing a plural-stage dynamo-electric amplifier which, while not exceeding the space requirements of the known amplifiers for given operating requirements, eliminates all hazard and minimizes or obviates the other difficulties associated with commutators or interpoles and is better suitable for operation at high altitude or in dust or lint containing atmospheres.

A further object of my invention, related to those mentioned above, is to provide a dynamo-electric plural-stage machine of high power gain that can readily be operated at higher speeds than the conventional dynamo-electric direct-current amplifiers and other direct-current generators so as to afford a higher output per unit weight of material used.

Still another object is to devise a direct-current generator for the purpose of power generation that, in comparison with the conventional direct-current commutator generators, can be given a narrower air gap and hence a smaller time constant and thus, in conjunction with high double-stage power gain, affords a simplified voltage regulation.

A further object of my invention is to provide a generator capable of producing a multi-phase alternating output voltage which varies in magnitude and phase sequence in dependence upon changes in magnitude and polarity of a direct-current input signal so as to permit controlling and reversing an alternating-current induction

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motor in analogy to direct-current drives of the Ward-Leonard type.

These and other objects and advantages of my invention, as well as its essential features, set forth with particularity in the claims annexed hereto, will be apparent from, and will be mentioned in, the following explanation and description with reference to the drawings in which:

Fig. 1 an explanatory diagram, Fig. 2 a schematic representation of a two-stage generator according to the invention, Fig. 3 a schematic wiring diagram of the stator, and Fig. 4 a schematic wiring diagram of the rotor of the same machine.

Figs. 5 and 6 are straight electric circuit diagrams of an amplifying machine similar to the one shown in Figs. 2 to 4 but equipped with different feedback circuits respectively.

Figs. 7 to 9 illustrate four respective other circuit diagrams of dynamo-electric amplifiers according to the invention.

Figs. 10 and 11 are explanatory voltage-current diagrams relating to machines similar to those of Figs. 6 and 8 respectively.

Figs. 12 and 13 are, respectively, a circuit diagram and an explanatory voltage-current diagram relating to still another amplifying generator.

Fig. 14 shows a circuit diagram for operation of a machine according to the invention as a motor.

Figs. 15 to 19 illustrate five different circuit diagrams of self-excited direct-current generators according to the invention.

Fig. 20 is a schematic circuit diagram of a feedback circuit applicable in machines according to the invention.

The same reference characters are used in all illustrations for functionally similar components.

The machines according to all illustrated embodiments have generally the design and appearance of a normal induction machine comprising a single laminated round stator and a single laminated round rotor which form an air gap between each other, the stator having a peripheral row of slots near the air gap and the rotor being preferably also provided with such a row of slots. The machine is provided with at least two inductively independent field systems each of which has windings on the stator and on the rotor so arranged as to form a number of pole-pairs different from the corresponding pole-pair number of the other system. One of the two field systems comprises a primary direct-current field winding in the stator slots and a poly-phase winding on the rotor. The other field system comprises a field winding on the rotor and a second alternating-current winding in the stator slots above or beside the turns of the direct-current field winding; and the field winding of the second system is electrically connected with the alternating-current winding of the first system to be energized therefrom.

The design and operation of such a machine will be understood from the following.

Two or more rotating or stationary electromagnetic fields can be accommodated in the air gap of a single rotating alternating-current machine. By suitably winding the field windings so that the respective fields have different numbers of pole pairs, these fields can be made non-interacting, so that no total electro-motive force is induced in the windings associated with one field by the magnetic field caused by the currents flowing in the windings of the other field.

Fig. 1 shows schematically an example of the windings in a machine with two non-interacting fields in the air gap. The machine, shown in developed form, comprises two stages. Windings A and B form one stage. Windings C and D form the other stage. Windings A and B are wound for the pole pitch τ . Windings C and

D have the pole pitch $\tau/2$. The magnetic induction associated with the current in winding C or D cannot induce voltage in winding A or B as any of the turns of winding A or B embraces a whole wave of the induction distribution or zero magnetic flux. By reciprocity, no voltage is induced in winding C or D by the magnetic field produced by the currents in windings A or B. It is obvious that no interaction will occur whenever windings A, B and C, D form different numbers of pole pairs respectively.

In the foregoing example the ratio of the pole-pair numbers of the two field systems is an even number. However, the pole-pair numbers may also have an odd ratio, for instance 3:1. This is the case with the machine illustrated in Figs. 2, 3 and 4 described presently.

As schematically shown in Fig. 2, the machine has a design similar to the usual wound-rotor induction machines but is not equipped with any slip rings. Both the stator S_t and the rotor R_t are to be made of good laminated magnetic steel sheets with as high a saturation point as possible. Stator and rotor are provided with respective rows of slots S_s , R_s adjacent to the air gap to accommodate the necessary windings. The various windings on the stator or rotor can be placed in separate slots or in the same slots, one above or beside the other.

Also as schematically indicated in Fig. 2, the machine is equipped with two field systems one being formed by windings A and B, and the other by windings C and D. The winding A is accommodated in the stator slots and consists of a single-phase direct-current winding which is connected to the input terminals T_i of the machine and is wound to form two poles. The appertaining secondary winding B is a three-phase winding and is wound into the slots of the rotor. It will be understood that in this case as well as in all other embodiments any other number of phases can be used in the poly-phase windings. The field winding C of the second system is a direct-current winding. It is connected with the secondary winding B of the first field system by a rectifier RR and is wound for six poles. The secondary winding of the second field system is a poly-phase winding, here exemplified by a three-phase winding, whose individual phases are denoted by D_R , D_S and D_T . These phase windings are shown star-connected to the output terminals T_o of the machine.

Fig. 3 shows the schematic wiring diagram for the stator of the same two-pole six-pole machine. In the illustrated example the stator, shown in developed form, has eighteen slots all traversed by winding turns which are denoted by numerals 1 to 18 respectively. As explained above, the direct-current field winding A of the stator, connected to the input terminals T_i , is wound for two poles. The secondary winding of the second field system has its individual phase windings D_R , D_S , D_T wound into the same row of stator slots. For simplicity, only one turn is shown for each phase winding. The phase windings are connected to terminals denoted by $R+$, $R-$, $S+$, $S-$, $T+$, $T-$. The terminals $R+$, $S+$, $T+$ are hereinafter simply called the output terminals and, in the circuit diagrams of Figs. 5 and following are designated collectively by T_o . The plus and minus signs used in Figs. 3, 4 denote the beginning and the end of the respective windings.

The corresponding wiring diagram of the rotor is illustrated in Fig. 4. The poly-phase field winding B is represented by one turn for each of its three phase windings B_R , B_S , B_T . This winding B is wound for two field poles to inductively cooperate with the two field poles of stator winding A. The three-phase current induced in winding B is rectified by the rectifier RR which is mounted on the rotor structure to rotate together therewith. The rectifier energizes the direct-current field winding C which is wound for six poles to induce poly-phase voltage in the six-pole winding D of the stator.

Windings B and C are wound into the same row of rotor slots, eighteen such slots being apparent from Fig. 4.

The principles of design and operation of a machine according to the invention may be incorporated in a large variety of circuit connections other than those shown in Figs. 2 to 4, depending upon the particular purpose or desired operating characteristic of the machine as will be explained below with reference to the examples shown in the subsequent illustrations. It will be understood that in all following embodiments the machine has a single laminated stator and a single laminated rotor both of the round type as explained above and both equipped with a plurality of windings wound into the same row of slots and forming a plurality of inductively independent field systems. For operation as an amplifier, the machine is rated to normally operate on the unsaturated and substantially linear portion of its magnetic characteristic, whereas for operation as a power generator a performance at a higher degree of saturation is usually preferred. The machines, normally, are driven at constant speed, for instance by a synchronous motor.

Referring first to rotary amplifiers, a number of embodiments and modifications will be described presently.

(1) *Phase-insensitive amplifier*.—With an internal circuit connection as shown in Figs. 2 to 4 and described above, the machine operates as a two-stage rotary A.-C. amplifier as follows. Direct current passes through the sinusoidally distributed A winding on the stator. E.M.F.'s are induced in the poly-phase B winding on the rotor due to its motion relative to the stator. The sinusoidally distributed C winding on the rotor is excited by the rectified B voltages. E.M.F.'s in stator winding D are induced by the rotating magnetic field associated with the currents in winding C. The two amplifier stages A—B and C—D are inductively independent as explained above. No voltages are induced in the windings of either stage by the magnetic field associated with the other stage.

Windings B and D may have any number of phases. The frequency of the output voltage induced in winding D depends on the number of poles of winding D and on the rotor speed. The rectifier RR on the rotor is shown as a bridge-type full-wave rectifier, but the rectifier components may be connected in any other suitable manner in accordance with any conventional circuit for poly-phase rectification.

Winding A may be composed of two or more separate winding units to permit controlling the amplified output by two or more input quantities. The separate winding units in such cases may aid or oppose each other's action.

Thus, Fig. 5 shows a separately excited input winding A1 and also an additional input winding A2 excited through a current transformer CT and a rectifier RS by direct current proportional to the generator output current. The armature reaction and the amplifier internal voltage drops can be fully or under- or over-compensated in this manner. The resistance R permits controlling the degree of compensation. While the effects of armature reaction are not by far as detrimental as in two-stage D.-C. commutator machines, such compensation tends to improve the amplification factor.

Fig. 6 shows an additional winding A2 energized by the rectified output voltage. In a similar way, and as shown in some of the following figures, a combination of output current and output voltage, or the difference between output current and/or voltage and some preset pattern value of current and voltage can be fed back to one or more component input windings. Various characteristics of the machine may thus be achieved, for instance constant output voltage, constant output current, or an output voltage rising or falling in a desired manner with the load.

The above-described two-stage amplifier can be further developed into a three and more stage amplifier with a resulting higher amplification and somewhat more complicated winding arrangements.

(2) *Phase-sensitive A.-C. amplifiers.*—Fig. 7 presents schematically the diagram of a two-stage phase-sensitive amplifier. It is similar to the machine described in the previous section except that the excitation winding C of the second stage is a three-phase or, generally, multi-phase A.-C. winding. The amplifier has two non-interacting stages A—B and C—D of different pole numbers as explained above. Direct current is fed into the sinusoidally distributed A winding on the stator. The rotor motion causes E.M.F.'s to be induced in poly-phase winding B, a three-phase winding being shown. The B voltages feed the C winding whose number of phases equals that of winding B, but the phase sequence is reversed. Consequently, the magnetic field produced by the C currents moves in the direction of rotor motion. The speed of this field relative to the stator is augmented by the mechanical speed of the rotor. E.M.F.'s are consequently induced in the D winding on the stator at a higher frequency and amplitude compared with those in C.

A reversal in polarity of the voltage applied to winding A will cause consecutively a 180° phase shift in the voltages of windings B—C and D.

Let n be the rotor speed in r.p.s., and let p and q be the number of pole pairs of the first stage A—B and the second stage C—D respectively. Then frequency of the currents in windings B and C is:

$$f_B = f_C = pn \text{ (c.p.s.)} \quad (1)$$

The output frequency f_D is:

$$f_D = q \left(n + \frac{f_C}{q} \right) = qn + f_C = n(p + q) \quad (2)$$

Neglecting losses, the ratio between the output power P_D and the power P_C fed into winding C is:

$$\frac{P_D}{P_C} = \frac{p + q}{p} = 1 + \frac{q}{p} \quad (3)$$

The power ratio in the first stage is similar to that existing in any synchronous machine.

As in the preceding embodiments, the winding A in Fig. 7 may consist of several component windings aiding or opposing each other to permit controlling the machine by several sources or signals simultaneously. Feedback loops may be added to compensate for the armature reaction and internal voltage drops or to provide the machine with some special characteristic.

Fig. 8 presents a machine similar to that shown in Fig. 6 but equipped with a polarized two-pole relay K which changes the polarity of the voltage fed back into the compensating winding A2. This change is dependent upon the polarity of the control current in winding A1. The coil actuating the polarized relay K is connected in series or in parallel (as shown) with the control winding A1. Similarly, a current transformer may be arranged in the output line and feed back a voltage proportional to the output current (see Fig. 5). A fully, under- or over-compensated amplifier will result. In analogy to the amplifiers previously described, various combinations of voltage and current, or their differences from some preset values, can be fed back to the input in order to obtain special machine characteristics.

It will be understood that the polarized relay K is only one of the available means for reversing the feedback polarity in dependence upon the polarity of a D.-C. voltage. For instance, the relay K may be replaced by a magnetic amplifier whose A.-C. power is supplied from the output winding D and whose D.-C. output, proportional to the A.-C. voltage, is applied to winding A2, the polarity of the D.-C. output being controlled by the polarity of the input voltage of winding A1. Magnetic amplifiers of the push-pull type are suitable for this purpose. If the rectifier device RS has a polarity-controllable output a separate reversing device is not needed (see Fig. 20).

(3) *Two-phase generator of variable phase sequence.*—

Fig. 9 shows a two-phase generator which, combined with a two-phase induction motor M, may be considered as an A.-C. equivalent of the known Ward-Leonard drive.

Disregarding at first the added components CP, A4, RA4 and TC, the machine operates as follows. A change in polarity of the input signal applied to winding A reverses the phase sequence of the output at terminals To, thereby reversing the sense of rotation of the two-phase motor M fed from this generator. No input at A1 will cause zero voltages of both output phases D₁ and D₂. This will bring the motor to standstill, the motor drawing no current.

The two-phase generator with a variable phase sequence combines the features of both amplifiers described in the previous two sections. It comprises three pairs of windings A₁—B, C₁—D₁ and C₂—D₂ wound for three different numbers of pole pairs so as to be mutually non-interacting. Windings A₁, B, C₁ and D₁ form a phase-sensitive A.-C. rotary amplifier described in section 2. Windings A₁, B, C₂ and D₂ constitute a phase-insensitive amplifier explained in section 1.

A change in polarity of the input voltage (V_A), applied to winding A₁, causes a phase shift of 180° of the voltage (V_{D1}) of the output phase winding D₁ and no shift in the voltage (V_{D2}) of the other output phase D₂.

Let p , q and r be the number of pole pairs of windings A₁ and B, C₁ and D₁, C₂ and D₂ respectively. Then the frequency f_B , f_{C1} of the currents in windings B and C₁ is

$$f_B = f_{C1} = pn \text{ (c.p.s.)} \quad (4)$$

Seen from the stator, the magnetic field produced by the currents in C₁ moves at a speed

$$n \pm \frac{pn}{q} = n(1 \pm q) \quad (5)$$

(+ when the phase sequence of C₁ differs from that of B; — when the phase sequence is the same). The frequency f_{D1} of the D₁ voltages consequently is:

$$f_{D1} = qn \left(1 \pm \frac{p}{q} \right) = n(q \pm p) \quad (6)$$

The frequency f_{D2} of the D₂ voltages is

$$f_{D2} = rn \quad (7)$$

These two frequencies ought to be equal. Hence

$$r = q \pm p \quad (8)$$

A simple combination is to give windings A₁ to B two poles, windings C₁ and D₁ four poles, windings C₂ and D₂ six poles.

The number of turns of windings C₁, C₂, D₁ and D₂ and their distribution is to be chosen so as to obtain equal voltages V_{D1} and V_{D2} of the D₁ and D₂ windings. The relative position of windings C₂, D₂ with respect to C₁ and D₁ is such as to produce a phase shift of 90° between the voltages V_{D1} and V_{D2} . The generator shown in Fig. 9 can be provided with feedback loops similar to those described with reference to Figs. 5, 6 and 8, an example being described presently.

One of the advantageous uses of a Ward-Leonard A.-C. equivalent system of the type shown in Fig. 9 is for positional servo systems whose frequent reversal of the motor M is required and relative long periods of motor standstill are involved. For such use, reversible A.-C. drive according to the invention affords minimum losses during standstill periods as no current is then drawn by the motor. However, an A.-C. drive system of this type is also suitable for motor speed control especially in cases where the motor is to be regulated for operation at a given speed. The components A4, RA4 and TC added in Fig. 9 and not yet considered in the foregoing description serve to exemplify such a speed regulation.

The winding A4 is a stator D.-C. field winding wound for the same pole number and the same poles as the winding A₁ so that both conjointly provide the input

field. Winding A4, during normal operation, is differentially related to winding A1 and is energized by voltage proportional to the motor speed and of a polarity dependent upon the running direction of motor M. In the present example, the speed-responsive voltage is supplied from a tachometer generator TC through a voltage-adjusting potentiometer rheostat RA4.

When the signal input applied to winding A1 has the indicated polarity and the motor M runs at the proper speed, the tachometer polarities are also as indicated in Fig. 9, and the differential action of windings A1 and A4 is balanced to just the extent required to maintain the motor speed. Any departure of the actual speed from the correct value will cause a corresponding position or negative change in the resultant field of the two windings with the effect of restoring the correct speed value. If the polarity of the signal in winding A1 reverses while the motor M is running, the two windings A1 and A4 at first have cumulative effects with the result of braking and decelerating the motor until it reverses its running direction. Thereafter the two windings A1 and A4 are again differentially effective to regulate the motor speed. It will be understood that, while a D.-C. tachometer TC is shown in Fig. 9, a brushless A.-C. tachometer with a rectifier device may be used, the rectifier device having either an output polarity reversible under control by the input polarity of winding A1 or having an additional pole reversing device generally of the performance described above with reference to device K in Fig. 8. However, the speed-responsive feedback signal for winding A4 may also be electrically derived from the current and stator voltage of the motor M in a manner generally known for speed-controlling an induction motor by varying the amplitude of its stator voltage.

(4) *Regenerative A.-C. amplifier.*—In a generator as shown in Fig. 6, the feedback control resistor R can be rated and adjusted so as to tune the no-load resistance characteristic to the unsaturated and substantially linear portion of the magnetic characteristic. Relating to such tuning, Fig. 10 shows the output voltage V_D as a function of the total input current I_A (in ampere-turns).

The hysteresis effect of the iron path is neglected. The relationship between the voltage V_R across adjustable resistance R and winding A2, on the one hand, and the current in winding A2 (ampere-turns) is given by the straight line V_R . The slope of this line depends upon the value of resistance R and the speed at which the amplifier is driven. The resistance R is preferably adjusted so that the rise of the straight line V_R is somewhat steeper than that of the straight portion of the V_D curve. When no current flows in winding A1, no V_D voltage is induced and the V_R line cuts the V_D curve at the origin. When a slight current I_{A1} is fed into winding A1, the V_R line is moved to the right to the V_0 line which cuts the V_D curve at the point e defining the output voltage V_D corresponding to the control current in A1. Fig. 10 shows the total input current or total ampere-turns I_A cumulatively provided by both windings A1 and A2. The actual control current or controlling ampere-turns I_{A1} provided by winding A1 alone and necessary for producing the output voltage defined by point e , is only a fraction of the total I_A required. Thus the power amplification factor of the machine is increased appreciably.

The armature reaction and the internal voltage drop of the machine due to the resistance and leakage inductances of the particular windings B, C and D can be fully compensated, over-compensated or under-compensated by an additional feedback loop connected to a third additional A-winding, substantially as explained above in section 1.

The regenerative amplifier is to be driven by a constant-speed motor, such as a synchronous motor, as the value of the adjustable resistance R depends upon the speed.

(5) *Phase-sensitive regenerative A.-C. amplifier.*—In

an amplifier as shown in Fig. 8, the resistor R can be rated for tuning the no-load resistance characteristic to the unsaturated portion of the magnetic characteristic as explained in the previous section. Then the output voltage V_D has a phase shift of 180° whenever the polarity of the voltage V_{A1} feeding the input winding A1 is changed; and the rectified voltage applied to resistor R and winding A2 is then likewise reversed in polarity due to the action of the reversing device K.

The relationship between the rectified voltage V_D , the total input current $I_A = I_{A1} + I_{A2}$, and the actual control current I_{A1} in winding A1 is represented in Fig. 11 which is essentially a generalization based upon Fig. 10.

If an additional A3 winding (see Fig. 12) is provided in the input stage of the machine and is energized from a current transformer in the output line of the amplifier (see Fig. 5), the machine can be given full, over- or under-compensation of armature reaction and of internal voltage drops due to resistances and leakage reactances associated with the individual windings. Additional A windings (such as winding A4 in Fig. 9) for multiple control or regulating purposes or multiple feedbacks may also be used.

(6) *Regenerative two-phase generator.*—Fig. 12 shows a phase-reversible generator similar to that of Fig. 9 but equipped with a regenerative feedback loop energized from the two-phase output voltage and supplying the winding A2 of the input stage. A reversing device K changes the polarity of the rectified voltage V_D in accordance with the polarity of the voltage applied to input winding A1. Only the stator S_t is shown in Fig. 12, the rotor R_t being in accordance with Fig. 9.

The addition of the regenerative loop appreciably increases the amplification factor of the generator. An additional feedback loop energized from a current transformer in the output line and feeding an additional winding A3 through a rectifier device can be provided (see Fig. 5) to compensate for armature reaction and voltage drops due to resistance and leakage reactance of the individual windings. Such a current feedback circuit, for a machine as shown in Fig. 12, requires a polarity reversing device of the type exemplified by relay K, a single relay K being suitable for reversing the polarity relative to both windings A2 and A3.

(7) *Regenerative capacitive feedback.*—The feedback loops described in sections 4, 5 and 6 provide the greater part of the required input current from the output voltage, thus reducing the input power and correspondingly increasing the amplification factor. A similar effect can be achieved, in all above-described cases, by connecting capacitors of proper magnitude across the output of the first or second stage. Such capacitors are shown at CP in Fig. 9. The capacitive current leads the output voltage by 90° and is consequently in phase with the magnetizing current which induces this voltage. Fig. 13 shows the relation of output voltage V to magnetizing current I (ampere-turns). The magnitude of the capacitor CP is to be chosen so as to make the straight line

$$V = \frac{I_c}{WC}$$

I_c being the capacitive current referred to the input, somewhat steeper than the linear part of the output voltage-current characteristic. An input magnetizing current of the magnitude OM shifts the straight line to the right. The developed voltage V_0 normally requires a magnetizing current ON of which only the portion OM is to be supplied by the input to the machine.

This method of regenerative feedback is superior to the one shown in previous sections as it requires no special A-winding and no additional polarity reversing device. It is especially convenient in case of loads of very poor power factors. Its drawbacks are the need for capacitors and lack of compensation for active loads.

(8) *Poly-field synchronous motor.*—The phase-sensi-

tive A.-C. rotary amplifier discussed in section 2 can be operated as a synchronous motor. Fig. 14 shows the connection diagram of this motor. The A-winding is excited from the A.-C. supply source through a rectifier Rs or from any outside D.-C. source. The motor starts as wound-rotor induction machine (windings D and C). Alternating current at a frequency f is being applied to winding D on the stator and causes a rotating magnetic field of the speed n_s (r.p.s.):

$$n_s = \frac{f}{q} \quad (9)$$

wherein q is the number of pole pairs of windings D and C. The rotor moves at the speed n (r.p.s.) in the same direction as this field. Currents are consequently induced in windings C and B at the frequency.

$$f_c = f_B = (n_s - n)q = f - nq \quad (10)$$

The magnetic field associated with the currents in winding B moves in the direction opposed to the rotor motion. The rotor gains speed until it is "pulled in" by the synchronous torque. This occurs when both fields associated with the currents in windings A and B respectively are synchronized, i.e. when

$$f_B = f - nq = pn \quad (11)$$

The final speed therefore is:

$$n = \frac{f}{p+q} \quad (12)$$

This motor has all the advantages of the usual synchronous machine, such as constant speed and good power factor, but it has no slip rings and needs no synchronizing equipment.

(9) *D.-C. and A.-C. generators.*—In principle, the A.-C. amplifiers described above with reference to Figs. 1 to 12, are also applicable as D.-C. amplifiers if the A.-C. output circuit of stator winding D is connected to the load circuit or to the generator output terminals through a rectifier. Such a machine then furnishes amplified direct current in response to a direct-current signal. Similar machines, properly dimensioned for operation on the desired range of their magnetic characteristic, are also suitable as A.-C. or D.-C. power generators. Examples of such D.-C. generators are shown in Figs. 15 to 19 and described presently.

Fig. 15 shows the basic circuit diagram of a series D.-C. generator. Winding B is shown as a six-phase winding, winding D as a three-phase winding. Excitation current for winding A is supplied by the machine itself. The rectified output current from winding D passes through winding A before leaving the machine. Fig. 16 shows a shunt generator. Winding A is connected across the output terminals To of the rectified D voltage. The variable resistor Ra in series with winding A serves to regulate the excitation current which in turn controls the output voltage.

The excitation current for such D.-C. generators may also be provided by feeding back the rectified output voltage, as well as the load current, thus obtaining a compound D.-C. generator combining characteristics of the series and the shunt generators. Fig. 17 presents such an arrangement. The excitation winding consists of two parts A2, A3. Winding A3 is connected parallel to the rectified D output voltage. Winding A2 is connected in the load circuit in series with winding A3. Fig. 18 shows a modified circuit of a compound D.-C. polyfield generator. Winding A3 is connected in the load circuit, and both windings A2, A3 are serially connected across the rectifier Rs.

Figs. 17 to 19 illustrate only the stator St of the machine, it being understood that the rotor may correspond either to the one shown in Fig. 15 or to the one shown in Fig. 16. That is, in the respective embodiments of Figs. 15 to 19, the field winding C of the second field

system may either be excited from winding B by direct-current or by alternating-current, depending upon the particular requirements, a direct-current winding C being preferable for maximum power amplification.

(10) *A.-C. generators.*—The machines described in section 9 may also serve as polyfield A.-C. generators. It is merely necessary to take the output directly from winding D; and the rectifier in the stator circuit is required only for supplying the shunt winding A in Fig. 16 or A3 in Fig. 17. In an alternating-current series generator of this type, the current-feedback winding (A in Fig. 15, A2 in Figs. 17, 18) may then be excited from a current transformer excited by the alternating output current of winding D and connected through a rectifier to the A-winding in a manner similar to the current-feedback connections CT—RS—A2 shown in Fig. 5.

It is obvious that the above-described machines can be designed for simultaneous or selective operation as D.-C. and as A.-C. generators supplying a mixed D.-C. and A.-C. load.

The machine shown in Fig. 19 has three component direct-current field windings A1, A2, A3 on the stator. The poly-phase winding D on the stator is here shown delta-connected. The output circuit of the machine is energized from a full-wave rectifier RS and extends through the field winding A2 so that the machine operates fundamentally as a series generator. The field winding A3 is connected across the output circuit to be excited by direct current proportional to the generator output voltage. A resistor RA3 is preferably connected in series with winding A3 for adjusting purposes. The field winding A1 is separately excited from a suitable direct-current source of constant voltage through a potentiometer rheostat RA1. The two windings A1 and A3 are poled to operate in differential relation to each other. This system operates to regulate its output voltage in accordance with a desired magnitude corresponding to the selected setting of rheostat RA1. When the output voltage increases beyond the desired value the resultant direct current field acting upon the rotor winding B is weakened so that the machine tends to reestablish the correct output voltage. When the output voltage drops below the correct value the resultant direct-current field of the stator is increased with the effect of increasing the output voltage to the correct value.

It will be recognized that a direct-current generator in accordance with the principles described with reference to Figs. 15 to 19 may also be designed and used as a direct-current amplifier. For instance in Fig. 19 the field winding A1 may be excited by a variable signal current in order to provide at the output terminals To an amplified direct current. The same effect can be obtained, for instance, with a machine according to Fig. 18 if a separately excited input winding A1 is added as shown. Similarly, and as mentioned, the alternating-current amplifiers described above with reference to Figs. 2 to 12, as far as the circuit diagrams and fundamental principle of operation are concerned, can likewise be used for the purpose of generating alternating power current. As mentioned, however, amplifying machines according to the invention, as a rule, are rated to normally operate on the unsaturated and substantially linear portion of their magnetic saturation characteristic, whereas for application of the invention for power generators, either D.-C. or A.-C., it is generally desirable to rate the machines for operation within a higher range of saturation.

It has been mentioned that machines according to the invention may be provided with D.-C. feedback circuits of reversible output polarity (sections 2, 3, 6) and that a reversing contact device such as shown at K in Figs. 8, 9, 12 is not needed if polarity-reversible rectifier means are used. An example of such rectifier means is schematically illustrated in Fig. 20.

Fig. 20 shows two stator windings A1 and A2(A4) which are differentially related to each other. The input

signal is applied to the terminals T_i of winding A1. The winding A2(A4), which may correspond to winding A2 in Figs. 8, 9 or to winding A4 in Fig. 12, is energized from a supply of alternating current represented by terminals T_a . The source of alternating current may be a current transformer connected to the output circuit of the stator winding D (not shown in Fig. 20), or it may consist of an alternating-current tachometer generator as described with reference to Fig. 9, or of some other alternating-current or voltage supply. The alternating current from source T_a is rectified by a rectifier arrangement which is represented only by its essentials, comprising two transistor rectifiers RS1 and RS2 in bridge-connection with a mid-tapped resistor RSR and with the winding A2(A4). The base electrodes of the two transistors RS1 and RS2 are connected to the respective input terminals T_i . Consequently, for any given polarity of the D.C. input signal at terminals T_i , only one of the two transistors RS1, RS2 is operative to conduct one-half wave of the alternating current from source T_a . When the polarity of the input signal at terminals T_i is reversed, the other transistor becomes conductive so that the rectified current in winding A2(A4) is reversed. It will be understood that smoothing devices may be added and that it is generally preferable to use a multi-phase full-wave rectifier network instead of the single-phase half-wave network shown in Fig. 20.

It will be obvious to those skilled in the art, upon a study of this disclosure, that my invention permits of a great diversity of uses and modifications and hence may be embodied in dynamo-electric machines and drive systems other than specifically illustrated and described herein, without departing from the essential features of the invention and within the scope of the claims annexed hereto.

I claim:

1. A dynamo-electric machine, comprising a single laminated round stator and a single laminated round rotor forming an air gap between each other, said stator having a peripheral row of slots near said gap, two inductively independent field systems having respectively different numbers of pole pairs, one of said systems comprising a primary direct-current field winding in said row of stator slots and a polyphase winding on said rotor, said other system comprising another field winding on said rotor and a second alternating-current winding located in said same row of stator slots, each of said two windings on said rotor consisting throughout of conductors separate and insulated from those of the other rotor winding, and said two rotor windings being electrically connected with each other so that said rotor-polyphase winding forms exclusively a current source and said field winding on said rotor forms exclusively a load energized from said source, said rotor having a single peripheral row of slots, and said conductors of said respective two rotor windings being disposed in said single row of rotor slots.

2. A dynamo-electric machine, comprising a single laminated round stator and a single laminated round rotor forming an air gap between each other and having respective peripheral rows of slots near said gap, two inductively independent field systems having respectively different pole-pair numbers of an odd ratio, one of said systems comprising a direct-current field winding on said stator and a first polyphase winding on said rotor, said other system having a field winding on said rotor and a second alternating-current winding on said stator, said direct-current field winding and said second alternating-current winding being both located in juxtaposition to each other within said row of stator slots, said first alternating-current winding and said other field winding being located in juxtaposition to each other within said row of rotor slots but being individually complete and separate from each other, and circuit means electrically interconnecting said latter two windings on said rotor.

3. A dynamo-electric machine, comprising a single

laminated round stator and a single laminated round rotor forming an air gap between each other and having respective peripheral rows of slots near said gap, two inductively independent field systems having respectively different numbers of pole pairs, one of said systems comprising a first direct-current field winding in said row of stator slots and a first polyphase alternating-current winding in said row of rotor slots, said other system comprising a second direct-current field winding in said same row of rotor slots and a second alternating-current winding in said same row of stator slots, and rectifier means mounted on said rotor and connecting said second direct-current field winding with said first polyphase winding.

4. In a machine according to claim 1, said field winding in said rotor slots being a polyphase winding of the same phase number as said first polyphase winding and having its respective phase connected with those of said said first polyphase winding to be energized by alternating current.

5. A dynamo-electric machine, comprising a single laminated round stator and a single laminated round rotor forming an air gap between each other and having respective peripheral rows of slots near said gap, two inductively independent field systems having respectively different numbers of pole pairs, one of said systems comprising primary direct-current field winding means in said row of stator slots and a first polyphase alternating-current winding in said row of rotor slots, said other system comprising a field winding in said same row of rotor slots and a second alternating-current winding in said same row of stator slots, said rotor field winding being electrically connected with said first alternating-current winding to be energized therefrom, and rectifier means connecting said stator polyphase winding with said direct-current field winding means on said stator.

6. A dynamo-electric amplifier machine, comprising a single laminated round stator and a single laminated round rotor forming an air gap between each other and having respective peripheral rows of slots near said gap, two inductively independent field systems having respectively different numbers of pole pairs, one of said systems comprising primary direct-current field winding means in said stator slots and a first polyphase alternating-current winding in said rotor slots, said other system comprising a field winding in said rotor slots and a second alternating-current winding in said stator slots, each of said two windings on said rotor consisting throughout of conductors separate and insulated from those of the other rotor winding, means electrically connecting said two rotor windings with each other, whereby said first polyphase winding forms exclusively a current source and said field winding on said rotor forms exclusively a load energized from said source, said direct-current field winding means on said stator comprising a separate-excitation winding having input terminals for applying an input signal, and said second alternating-current winding on said stator having output terminals for delivering amplified output current under control by said signal.

7. A dynamo-electric amplifier machine, comprising a single laminated round stator and a single laminated round rotor forming an air gap between each other and having respective peripheral rows of slots near said gap, two inductively independent field systems having respectively different numbers of pole pairs, one of said systems comprising primary field winding means in said stator slots and a first polyphase alternating-current winding in said rotor slots, said other system comprising a field winding in said rotor slots and a second alternating-current winding in said stator slots, said rotor field winding being electrically connected with said first alternating-current winding to be energized therefrom, said stator primary field winding means comprising a separately excitable input winding and a feedback winding, an output circuit connected to said stator alternating-current winding, and a feedback circuit connecting said out-

put circuit with said feedback winding for exciting said feedback winding in response to an operating magnitude of said output circuit.

8. A dynamo-electric machine according to claim 6, comprising a circuit connecting said stator direct-current winding means with stator alternating-current winding and including rectifier means for componently exciting said winding means by variable direct current dependent upon an electric operating magnitude to said stator alternating-current winding.

9. In a dynamo-electric machine according to claim 6, said stator direct-current winding means comprising a second winding inductively cumulative with respect to said separate excitation winding, and a feedback circuit including rectifier means and connecting said second winding for exciting it by direct current derived from said stator alternating-current winding.

10. In a dynamo-electric machine according to claim 6, comprising a feedback circuit connecting said stator direct-current winding means with said stator alternating-current winding and including rectifier means for componently exciting said winding means by variable direct current dependent upon an electric operating magnitude of said stator alternating-current winding, said feedback circuit comprising a polarity reversing device between said rectifier means and said winding means, said device being connected with said input terminals and responsive to the signal polarity for reversing the component feedback excitation in dependence upon change of said signal polarity.

11. A dynamo-electric machine according to claim 6, comprising a third field system having a pole-pair number different from those of said other two field systems, said third field system comprising a field winding in said rotor slots and a third alternating-current winding in said stator slots, one of said two rotor field windings having an alternating-current circuit connected with said first alternating-current winding, rectifier means mounted on said rotor and connecting said other rotor field winding with said first alternating-current winding, and a multiphase output circuit containing said second and third alternating-current windings in respectively different phases, whereby polarity reversal of said input signal causes phase-sequence reversal in said output circuit.

12. A dynamo-electric machine according to claim 6, comprising electric circuit means connecting said stator polyphase winding with said direct-current field winding means on said stator structure and comprising rectifier means for supplying direct current from said stator alternating-current winding to said field winding means, said circuit means having resistance means and having its resistance characteristic tuned to the unsaturated and substantially linear portion of the magnetic characteristic of the machine.

13. A dynamo-electric machine, comprising a single laminated round stator and a single laminated round rotor forming an air gap between each other and having respective peripheral rows of slots near said gap, two inductively independent field systems having respectively different numbers of pole pairs, one of said systems comprising primary direct-current field winding means in said row of stator slots and a first polyphase alternating-current winding in said row of rotor slots, said other system comprising a field winding in said same row of rotor slots and a second alternating-current winding in said same row of stator slots, said rotor field winding being electrically connected with said first alternating-current wind-

ing to be energized therefrom, an output circuit, rectifier means connecting said output circuit with said second alternating-current winding on said stator, and said primary direct-current field winding means being connected with said rectifier means for direct-current self-excitation of the machine.

14. In a dynamo-electric machine according to claim 13, said primary direct-current field winding means being connected in series with said rectifier means.

15. In a dynamo-electric machine according to claim 13, said primary direct-current field winding means being shunt connected to said rectifier means.

16. In a dynamo-electric machine according to claim 1, said primary direct-current field winding means on said stator comprising a plurality of component field windings, one of said component field windings having input terminals for separate excitation, an output circuit, rectifier means connecting said output circuit with said second alternating-current winding on said stator, and a second one of said component field windings being connected with said output circuit to provide the machine with component self-excitation.

17. In a dynamo-electric machine according to claim 16, said second component field winding being connected in series with said rectifier means to provide current-responsive self-excitation, and said primary direct-current field winding means on said stator comprising a third component field winding connected in shunt relation to said rectifier means to be energized in proportion to the direct-current output voltage.

18. In a dynamo-electric machine according to claim 1, said field winding of said other field system being a polyphase winding located in said stator slots, a polyphase input circuit connected with said latter polyphase winding, and rectifier means connecting said primary direct-current field winding of said stator with said input circuit for energizing said latter field winding by rectified current.

19. A variable voltage drive comprising a generator according to claim 11 and a plural-phase induction motor connected with said output circuit to be reversibly driven under control by said input signal.

20. A dynamo-electric machine, comprising a single laminated round stator member and a single laminated round rotor member forming an air gap between each other and having respective peripheral rows of slots near said gap, two inductively independent field systems having respectively different numbers of pole pairs, one of said systems comprising a direct-current field winding in said row of stator slots and a first polyphase alternating-current winding in said row of rotor slots, said other system comprising a field winding in said same row of rotor slots and a second alternating-current winding in said same row of stator slots, said rotor field winding being electrically connected with said first alternating-current winding to be energized therefrom, and rectifier means interposed between the field winding on one of said stator and rotor members and the alternating-current winding on the same member, whereby the field winding of one field system receives rectified current from the alternating-current winding of the other field system.

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