Sept. 11, 1962 J. P. SEITZ 3,053,920

CONTROL FOR ELECTRIC FURNACE

Filed June 29, 1959 3 Sheets-Sheet 1

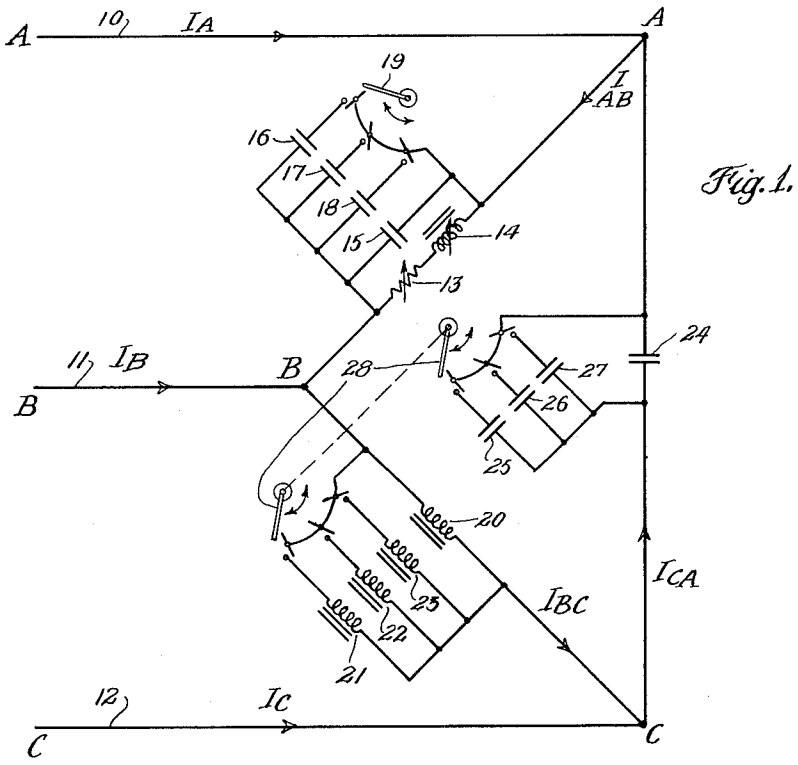


Fig. 1.

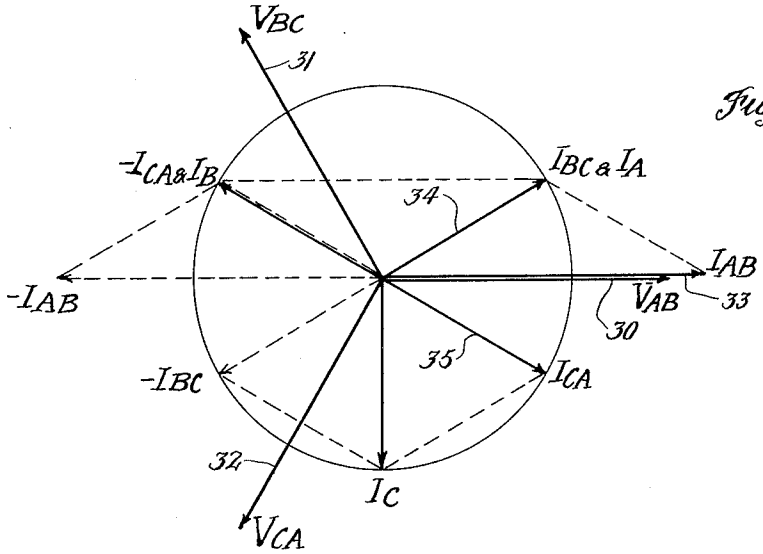


Fig. 2.

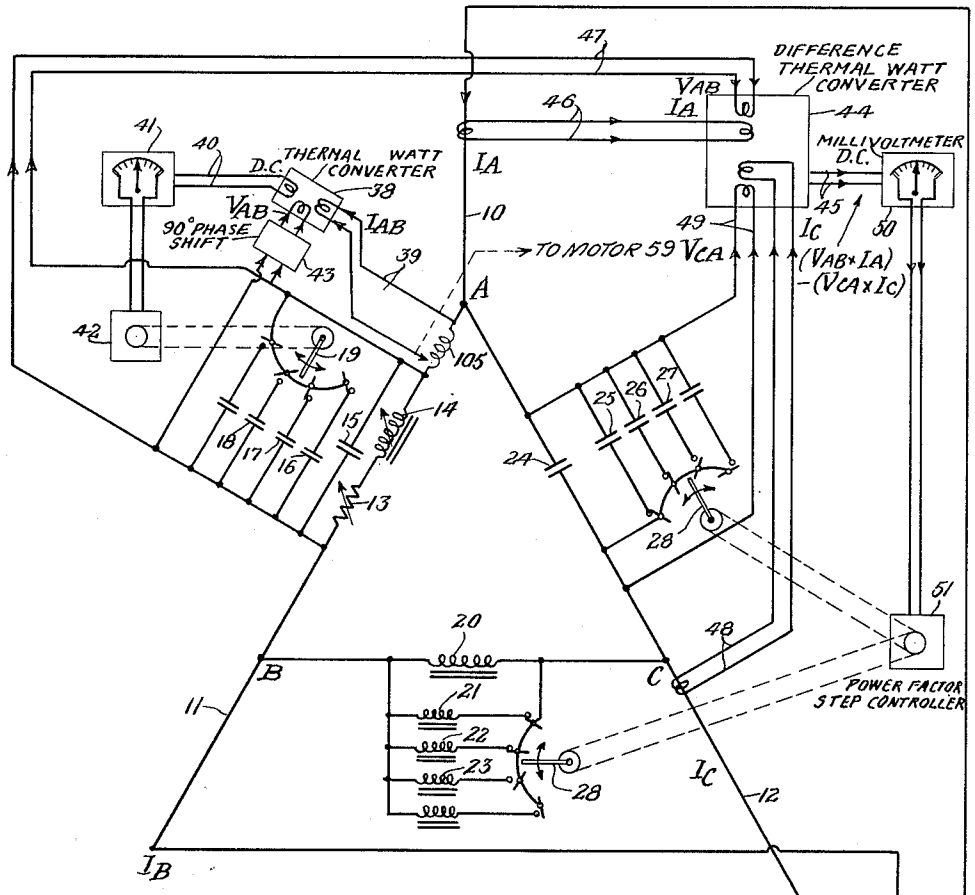
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Fig. 3.



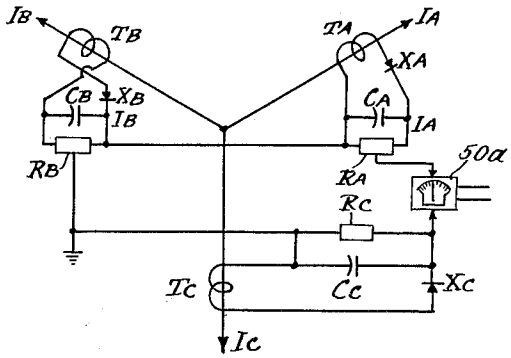


Fig. 3A.

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CONTROL FOR ELECTRIC FURNACE

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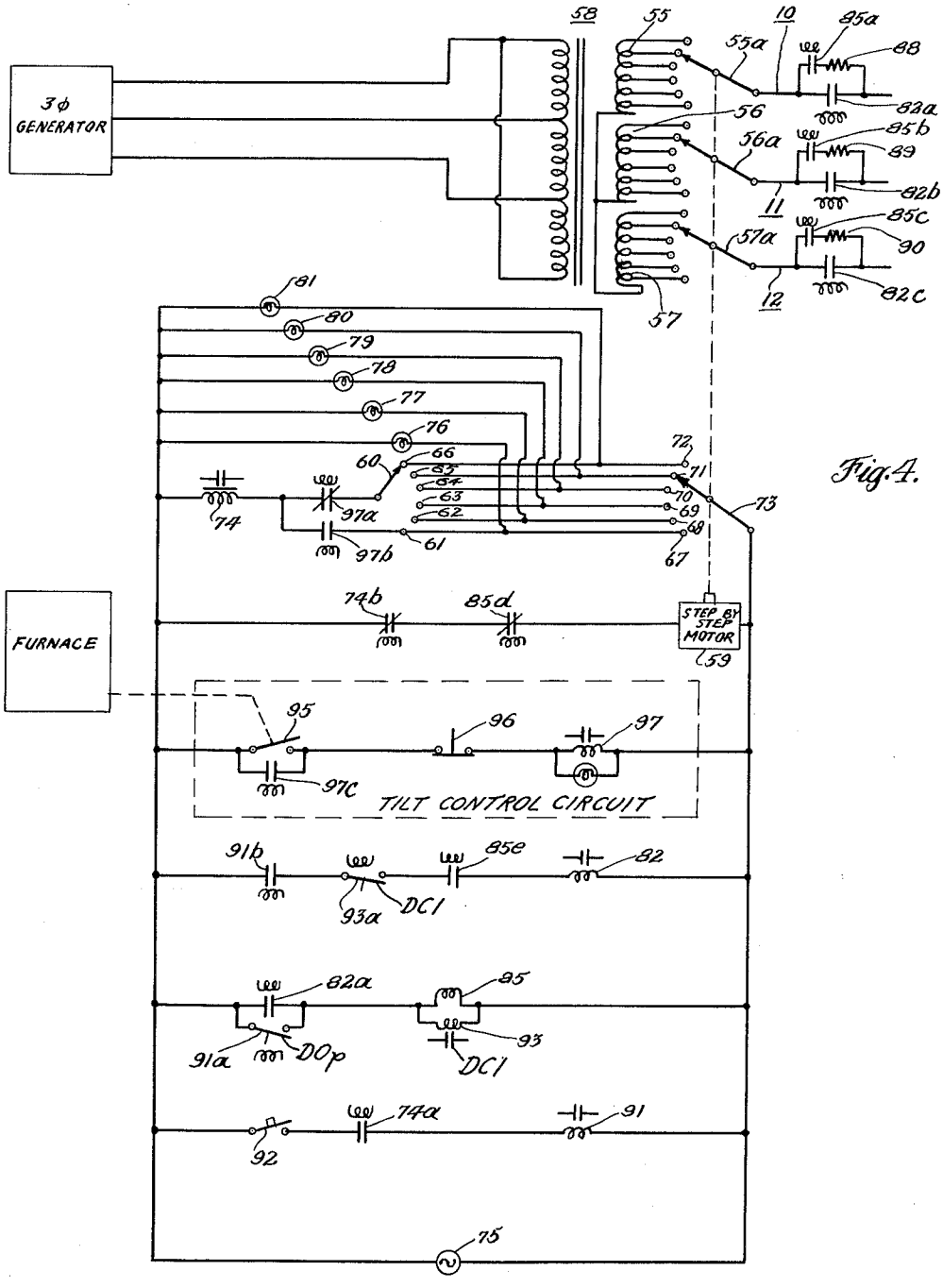


Fig. 4.

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3,053,920

CONTROL FOR ELECTRIC FURNACE

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Filed June 29, 1959, Ser. No. 823,587
19 Claims. (Cl. 13—26)

This invention generally relates to improvements in electric furnaces and is particularly concerned with an improved control system for a single phase induction furnace operative both to minimize the reactive power consumed and to present a balanced three phase load to three phase power source.

In electric furnaces of the type employing an inductive field generated by a coil to heat and melt a metal charge, it has been customary to add power factor correcting reactances in the coil circuit, as the level of metal in the furnace rises, to compensate for the increased inductive power required by the load and thereby minimize the power loss in the lines and generator. Since the large amounts of power required for furnace operation are usually distributed over the three lines of a three phase power supply system, it is desirable, when operating a single phase furnace, to distribute the furnace current equally over the three lines rather than draw all current from but two lines of the three line system. The former type of control is herein termed power factor control and the latter phase balance control.

According to the present invention there is provided an improved system for supplying both types of control, either automatically or manually, or in any combination thereof desired. More specifically, there are provided connections for coupling a single phase furnace winding across two lines of a three phase power system, together with an automatically or manually operating follow-up means arranged to compensate for the changing power factor of the load and thereby minimize the total reactive current drawn over the power lines. To equally distribute the furnace current over all three lines of the three phase system, there are additionally provided an adjustable current-lagging balancing reactance across the second two power lines and an adjustable current-leading balancing reactance across the third two power lines, the magnitudes of the balancing reactances being always equal to each other but being variable together in proportion to the useful power being drawn by the furnace. Either automatic or manually operated follow-up means may perform these functions, in such manner as to provide for both visual or other indication of their operation and for manual override of the controls at any time.

It is accordingly one object of this invention to provide combined power factor control and phase balance control, selectably operable by either automatically or manually controlled means.

A further object is to provide an improved regulator for economically operating a single phase load of varying characteristics from a three phase source of power.

A still further object is to provide these functions in an automatic manner.

Other objects and many attendant advantages will be more readily comprehended by those skilled in the art upon consideration of the following description, taken with the accompanying drawings wherein:

FIG. 1 is a simplified electrical schematic diagram illustrating the operation of one control system employing the present invention.

FIG. 2 is a three phase vector diagram showing the current and voltage relationship in the circuit of FIG. 1, when both the power factor of the furnace load has been corrected and the three phase power supply circuit is in balanced condition.

FIG. 3 is an electrical schematic illustration of an automatically operating system similar to FIG. 1.

FIG. 3*a* is a simplified electrical diagram showing a modification to the circuit of FIG. 3, and

FIG. 4 is a schematic illustration of a system for controlling energization of furnace circuits such as those of FIGS. 1 and 3.

Referring now to FIG. 1 for a simplified illustration of one embodiment of the invention, there are shown three input power lines **10**, **11**, and **12** representing a three phase alternating current system in which the letters A, B, and C indicate the phase sequence. Lines **10** and **11** energize the induction coil of an electrical furnace, which in the drawing is depicted by its electrical equivalent circuit comprising a variable resistance **13** and a variable inductance **14**. Across coil **13**, **14** is provided a fixed compensating capacitor **15**, whose function is to draw a leading component of current from lines A, B and that is just equal to the lagging component introduced by the inductance **14** of the furnace coil and hence compensate for this inductance.

As a metal charge is introduced into the furnace and the molten metal level rises, inductance **14** increases, requiring progressively more compensating capacitance to be added, and for this purpose, additional capacitors **16**, **17**, and **18** are switchably connected in parallel arrangement with capacitor **15** and adapted to be successively added to or removed from, the circuit by means such as a step-by-step distributor switching arm, generally represented at **19**. If switch arm **19** is moved in a counterclockwise direction, for example, these additional capacitors are successively added to the circuit; whereas if the switch arm **19** is moved clockwise, they are successively removed, in reverse order, one-by-one. If desired, switch arm means **19** may be manually operated to add or remove capacitors as needed to compensate for changes in the inductance load and maintain a high power factor in the furnace coil circuit.

In addition to correcting for the power factor of the furnace coil circuit, as described above, it is also possible, according to the invention, to distribute the load current equally over the three input power lines **10**, **11**, and **12** and thus obtain maximum utilization of the three phase generator and power lines. To balance the three phase system under minimum load conditions, there is inserted in the second phase B, C (across power lines **11** and **12**) an inductive reactance **20**, and in the third phase C, A (across lines **12** and **10**), a capacitive reactance **24**, with the magnitude of reactances **20** and **24** being made equal. The magnitudes of these reactances are also so related to the magnitude of the resistive portion **13** of the furnace load to insure, when the power factor of the furnace load is corrected to a high value, that the three phase circuit is balanced and equal current flows over the three power lines **10**, **11**, and **12**.

However, as the metal level in the furnace rises during operation, the furnace draws more and more useful power and its effective load resistance **13** is reduced to permit a greater current to flow through the furnace coil. This changes the relationship between the furnace load and the balancing reactances **20** and **24** and unbalances the three line currents. To correct for this unbalance with changes in the load, there is preferably provided a bank of additional inductances **21** to **23**, inclusive, switchably connected in parallel with fixed inductance **20**; and a similar bank of capacitors **25** to **27**, inclusive, switchably connected in parallel arrangement with the fixed capacitor **24**. As shown, the switches in each bank may be cumulatively engaged in sequence or disengaged in the opposite sequence, one-by-one, by means of a distributor type switching arm **28**, and, in addition, both groups of switches are preferably actuated together by means of switch arm

28, as generally indicated by the dotted line. Thus, as switch arm 28 moves counterclockwise, for example, inductance 21 is connected in parallel with fixed inductance 20 in the second phase circuit and capacitor 25 is simultaneously connected in parallel with capacitor 24 in the third phase circuit.

The total inductive reactance in the second phase circuit is equal in magnitude to the total capacitive reactance provided in the third phase for all positions of the distributor switch arm 28. Consequently, as switch arm 28 is displaced in either direction, the reactance in each circuit is varied equally.

With this arrangement, adjustment of distributor switch 19 in the furnace coil circuit provides the necessary high power factor in the furnace load and subsequent adjustment of distributor switch 28, to add or remove equal values of reactances in the second and third phases, serves to balance the three phase system and distribute the load current equally over the three power lines 10, 11, and 12.

For a better understanding of this balancing operation, reference is made to FIG. 2 illustrating by vectors the magnitude and phase relation of the currents and voltages in FIG. 1 in the balanced condition. The three phase voltages are depicted as equal in length arrowed lines 30, 31 and 32, each displaced 120° apart; with the voltage across the first phase 30 or V_{AB} (across lines 10 and 11) being in the horizontal position and pointing to the right, the voltage across the second phase 31 or V_{BC} (across lines 11 and 12) being displaced 120° therefrom in the counter-clockwise direction, and that of the third phase 32 or V_{CA} (across lines 12 and 10) being displaced 120° counterclockwise from the second phase 31. Assuming that the furnace coil has been corrected for high power factor, the total current through the first phase or I_{AB} is in time phase with the voltage as indicated by the arrowed line 33 overlying the voltage line 30. However, the almost pure reactive current 34 or I_{BC} passing through the second phase lags its voltage V_{BC} by 90°, and the almost purely reactive current 35 or I_{CA} through the third phase leads the voltage across the third phase V_{CA} in the counterclockwise direction by 90°.

Referring again to FIG. 1, it is noted that the first line current I_A being drawn from the power source is equal to the difference of the currents flowing through the first and third phases or;

$$I_A = I_{AB} - I_{CA}$$

Similarly, the second line current I_B being drawn from the source over line 11, is equal to the difference in the currents flowing through the second and first phases or;

$$I_B = I_{BC} - I_{AB}$$

And the third line current I_C being drawn over line 12 is likewise equal to the difference in currents of the second and third phase or;

$$I_C = I_{CA} - I_{BC}$$

Performing these vector subtractions in FIG. 2, it is noted that all line currents I_A, I_B, and I_C may be made equal in magnitude and successively displaced 120 electrical degrees if the magnitude of currents I_{CA} and I_{BC} being directed through the third and second phases are adjusted in relation to I_{AB} as shown in the diagram and if the furnace current I_{AB} is in time phase with the furnace voltage V_{AB}. Since these currents I_{CA} and I_{BC} are proportional to the reactances of the balancing reactors and capacitors in these phases, which are always made equal by the joint switching device 28, and since these currents may be varied as desired by switching in or out additional balancing reactances, it is evident that the system may be continually balanced for equal currents over power lines 10, 11, and 12, despite changes in the furnace load, by operation of switching means 28.

Thus, by compensating for the power factor of the single phase furnace load and by adding equal inductive reactance in the second phase and capacitive reactance in the third phase, in the proper relationship to changes in the useful power consumed in the furnace load, a three phase source of power may energize the single phase furnace in a balanced manner, supplying equal value currents over the three power lines 10, 11, and 12. It is particularly important to note, however, that the order of connecting the balancing reactances is critical and that the lagging type balancing reactance should be placed in the second phase of the three phase system and the capacitive balancing reactances in the third phase for proper balancing operation.

FIG. 3 illustrates an embodiment of the invention similar to FIG. 1, but employing automatic follow-up controls for performing the power factor correction and phase balancing functions. In this embodiment, the components common to FIG. 1 bear the same numbers. Consequently it is noted that the furnace load 13, 14, is connected across phases A, B and is provided with a fixed compensating capacitor 15 and a group of additional capacitors 16, 17, and 18 adapted to be successively added in sequence to or removed from the circuit by actuation of the distributor switch 19 to correct the power factor. Similarly, a fixed inductance 20, together with a group of additional inductances 21, 22, and 23, is connected in the second phase B, C and a fixed capacitor 24, with a group of switchably connectable additional capacitors 25, 26, and 27, is connected in the third phase C, A, with the additional inductors and capacitors adapted to be added or removed sequentially by actuation of the ganged distributor switch 28 so as to always maintain equal valued reactances in both the second and third phases.

To automatically correct for the power factor of the furnace load circuit A, B there is provided a follow-up control responsive to the reactive power of the load to operate switching means 19 in such direction that capacitors 16, 17 and 18 are automatically added or removed from the circuit to reduce or minimize this reactive power. This follow-up control preferably includes a thermal watt converter 38 responsive to a current value proportional to I_{AB}, as measured over lines 39, and to a voltage value proportional to V_{AB} across the furnace coil to generate a reversible direct current output signal over lines 40 proportional to the reactive power or VAR. If the reactive power is inductive, a positive direct current voltage is generated; if the reactive power is capacitive, a negative direct current voltage is generated. The direct current output signal, through lines 40, energizes a millivoltmeter switching device 41, which both indicates (by means of a pointer or the like) the reactive power and its sign, and reversibly energizes a step-by-step controller switch 42 operating switching arm 19 in such direction as to add or remove the correcting capacitors from the circuit.

If desired, the function of the thermal watt converter 38 may be performed by any one of a number of known kilowatt measuring devices having a direct current output and being operable to indicate kilovars rather than kilowatts by employing a 90° phase shifting device 43 connected in the voltage measuring line, as shown. However, since this component as well as the millivoltmeter switch device 41 and step-by-step switch controller 42 are well known to those skilled in the art, further details of their construction are not believed necessary for an understanding of the present invention.

Thus by measuring a quantity proportional to the reactive power being consumed in the furnace load circuit and using this measurement to control a follow-up system, compensating capacitors may be automatically added or removed to minimize the reactive power being drawn from the generator and provide the necessary high power factor in the furnace load circuit.

It is believed evident, however, that in automatically correcting for the power factor of the furnace load, only the phase relationship existing between the voltage and current in the load circuit is important and it is not essen-

tial that the thermal watt converter unit 38 receive current and voltage signals identical with those existing in the load. On the other hand, it is desirable that the thermal watt converter 38 receive voltage and current signals of sufficient amplitude to operate with its intended accuracy and speed of response. For this reason the voltage energizing the thermal watt converter instead of being measured directly across the load 13, 14 but may be taken from a fixed amplitude voltage V of the three phase generator which is maintained in time phase relationship with the voltage across the load. Similarly the current signal across lines 39 energizing the thermal watt converter is obtained from a variable tap current transformer 105, as shown, whereby if the amplitude of the load current L falls below a desired value, the tap may be manually or automatically changed to increase the current signal supplied to watt converter unit 38. Since the voltage and current supplied to the load is varied with changes in the load, as will be more fully described hereafter, this manner of energizing the thermal watt converter 38 insures that the unit 38 always receives signals of sufficient amplitude to operate with the accuracy and speed of response intended.

To automatically control the phase balancing of the system according to the present invention and to provide for equal currents over the three power lines, 10, 11 and 12, as well as uniform phase displacement of these currents, there is provided a follow-up mechanism for comparing the useful power being consumed by the furnace with a power related to the values of the balancing reactances in the second and third phases of the system and utilizing the differences between these powers to automatically add or remove reactances from the balancing circuits. To obtain these power measurements, two thermal watt converter devices may be employed and combined in a single unit, generally designated 44 in FIG. 3, which is adapted to generate a reversible direct current error signal over its output lines 45 proportional to the difference of these powers.

In this circuit, the quantity proportional to the furnace power is obtained by detecting the current flowing through power line 10 or I_A by means of a current transformer connected in line 10 and generating a signal over lines 46; and this current may be multiplied in the thermal watt converter unit with a signal proportional to the voltage V_{AB} across the furnace coil 13, 14, obtained over lines 47, as shown. The product of these two signals is proportional to the useful power being consumed in the furnace, since power line current I_A includes the phase current I_{AB} as best shown by FIG. 1.

A quantity proportional to the power taken from the other power lines 11 or 12 may be similarly obtained by measuring the current I_C over power line 12 by a current transformer as shown and transmitting this signal to the thermal watt converter 44 over lines 48. This current is multiplied with voltage proportional to V_{CA} across the third phase. Since line current I_C over power line 12 also contains a component of current I_{CA} through the third phase, this latter product is related to the power taken from power line 12.

The direct current signal generated by thermal watt converter 44 is thus proportional to the difference of the powers taken over lines 10 and 12, and this direct current signal operates a millivoltmeter switching unit 50, that may be similar in construction to unit 41 in the power factor control, and serves to actuate a step-by-step switch controller unit 51. Energization of switch controller 51 reversibly positions the switch arms 28 to add or remove reactances from the second and third phases of the system B, C, and C, A respectively until a balance of all currents through the three power lines is obtained at which time the switch controller 51 is de-energized and the system remains in balance until variation of the furnace load again requires a change in the balancing reactances.

To insure that thermal watt converter unit 44 receives voltage signals of sufficient amplitude for proper operation despite changes in the voltage V with variation in the load requirements, the voltages energizing lines 47 and 49 of unit 44, instead of being taken directly from lines A, B and C, A across the second and third phases, may be supplied from constant amplitude voltage lines which are maintained in time phase with A, B, and C, A, respectively, and proportional thereto. The end result is the same, however, and this modification merely insures that the thermal watt converter unit 44 operates with its desired sensitivity and speed of response despite a reduction of the three phase power voltages as required by changing load requirements.

If desired, variable ratio current transformers (not shown) similar to transformer 105 in the power factor control circuit may be employed to energize the current signal lines 46 and 48 of thermal watt converter unit 44. The function of these transformers would be the same as that of transformer 105, namely to maintain the amplitude of these current signals in the same proportion to their line currents and at sufficient amplitudes to properly operate the thermal watt converter unit 44 with desired accuracy and speed of response despite variation in the power voltages.

A direct current signal may alternatively be obtained by means of the circuit illustrated in FIG. 3*a*, in which the power taken over the three lines is measured by deriving a voltage from each line proportional to the current passing therethrough by means of a transformer, rectifying the three voltages, and combining them in a manner to obtain an output D.-C. voltage which is linearly related to the phase unbalance in the system.

As illustrated in FIGURE 3*a* the voltages proportional to I_A and I_B are derived by transformers T_A and T_B. The secondary circuits include respectively, rectifiers X_A and X_B and resistors R_A and R_B shunted respectively by capacitors C_A and C_B. One-half of the sum of the rectified voltages appearing across R_A and R_B is compared with the similar voltage obtained in the circuit comprising T_C, rectifier X_C, resistor R_C and capacitor C_C. As will be seen from FIG. 3*a*, the circuit is arranged so that the D.-C. voltage delivered to D.-C. millivoltmeter switching unit 50*a* varies in magnitude and sign in accordance with the phase unbalance in the system. This arrangement produces an output voltage which varies linearly with variations in the power taken over the three lines. The output of switching unit 50*a* is fed to switch controller 51 and there utilized in a manner already discussed in connection with the arrangement of FIG. 3.

Recapitulating the automatic operation of the power factor control and phase balancing control circuits, the power factor control measures a quantity proportional to the reactive power being consumed in the furnace coil circuit and continually adds or removes correcting capacitors 16, 17, and 18 by means of step-by-step controller 42 and arm 19 until the reactive power is minimized and the power factor of the circuit reaches a high value. This control insures that the current I_{AB} is maintained substantially in time phase with the voltage V_{AB} across the furnace coil 13, 14. The phase balance control, on the other hand, automatically adds or removes equal value inductors and capacitors from the second and third phases, respectively, until the current flow through each of the three power lines 10, 11, and 12 is made equal, thus balancing the three phase system by drawing equal currents over the three power lines to supply the single phase furnace load. This latter control is achieved by obtaining an error signal proportional to the difference between the useful powers being generated over power line 10 and power line 12 and using this error signal to vary the reactances in the second and third phase circuits until the signal error is minimized and equal power is generated over these two lines. It is only necessary to compare the powers being generated over two

lines of the three phase system rather than three, since, as discussed above, the magnitudes of the balancing reactances in the second and third phases are always made equal and the currents drawn through these phases are likewise equal at all times.

FIG. 4 shows additional features of the preferred embodiment of the invention including means for increasing or decreasing the voltage across the furnace power lines either in response to adjustments by an operator or automatically in response to certain changes in the furnace load. In addition, FIGURE 4 shows a preferred means for initially applying and removing power to, and from, the furnace in a manner to minimize the generation of undesirable current transients.

As shown in FIG. 4, the three power lines **10**, **11**, and **12** are each connected to movable taps **55***a*, **56***a*, and **57***a*, which engage contacts of the three phase secondary windings **55**, **56** and **57** of a main power transformer **58**, whose primary winding is energized by a three phase power generator. Since the power being transmitted by main transformer **58** to the furnace load is very great, these taps and contacts are large to possess the necessary current handling capacity and are consequently driven by a relatively slowly operating step-by-step motor **59**, which when energized, drives the taps one step at a time in only the direction of increasing voltage. Thus, if the voltage across power lines is to be increased by one unit, the taps **55***a*, **56***a*, and **57***a* are moved one step upward, whereas if the voltage is to be decreased by one unit, the taps will be driven upward step-by-step to the highest contact and thence to the lowest contact and again upwardly until the desired contact is reached. If only one unit increase in voltage is needed, the time involved may be only of the order of a few seconds, whereas if a decrease in voltage is needed, the time required may be of the order of about ten seconds.

To permit manually controlled adjustment of the position of these power taps, there is provided a follow-up system responsive to the position of an operator's control switch **60** to energize motor **59** and drive the power voltage taps **55***a*, **56***a*, and **57***a* to a corresponding position. As shown, the operator's switch **60** is provided with a number of contacts **61** to **66**, inclusive, which in turn are electrically connected to corresponding contactors **67** to **72**, inclusive, of a control switch **73** whose movable tap is connected to be driven by motor **59** together with power taps **55***a*, **56***a* and **57***a*.

Motor **59** is connected in series with normally closed contacts **74***b* of a relay **74** and the normally closed contacts **85***d* of a relay winding **85** across a power source **75** and hence is energized to continually drive control tap **73** as well as power taps **55***a*, **56***a*, and **57***a* until relay contacts **74***b* or **85***d* are opened to de-energize the motor. Relay winding **74** is placed in series circuit with the movable tap of the operator's switch **60** and is connected to one side of power source **75**, while the movable tap of control switch **73** is connected to the opposite side of power source **75**. Hence, when the operator's switch **60** and control switch **73** are in corresponding positions, engaging like positioned contacts, a completed circuit is formed from the power source **75** passing current through relay winding **74** and serving to open its contacts **74***b* in the circuit of motor **59** to de-energize the motor and complete the follow-up operation. Thus the movable tap of control switch **73** operates as a follower to operator's tap **60** and is continually positioned from contact-to-contact by means of motor **59** until it finds a contact position coincident with that established by the operator's setting of switch **60**, whereupon motor **59** is de-energized and the follow-up action is completed.

In addition to driving movable taps **55***a*, **56***a* and **57***a* of the transformer to vary the voltages V_{AB}, V_{BC} and V_{CA}, step-by-step motor **59** is also connected to vary the tap of current transformer **105** (see FIG. 3) in the reverse direction. It will be recalled that the function of current transformer **105** is to generate a current signal to thermal watt converter unit **38** that is proportional to the current being supplied to the load for the purpose of automatically correcting for the power factor of the load. However, as the voltage to the load is reduced by changing the power taps **55***a*, **55***b*, and **55***c* the current I_{AB} through the load circuit is also decreased. Consequently to insure that thermal watt converter **38** receives a current of sufficient amplitude for proper operation, the tap of current transformer **105** is positioned in the opposite direction to increase the amplitude of the signal being directed to unit **38** with decreases in load current I_{AB}, or the reverse, thereby to insure the proper functioning of the automatic power factor control circuit.

To enable the operator to determine the setting of the power taps, there is additionally provided a series of indicator lamps or the like **76** to **81**, inclusive, one for each contact of the control switch **73**, and each having one terminal thereof connected to its related contacts **67** to **72**, inclusive, of control switch **73**, and its other contact being connected in common with the other lamps to the opposite side of power source **75**. Thus for each position of control switch **73**, a completed electrical circuit is formed through a different one of said lamps to illuminate that lamp and indicate the existing position of control switch **73**, as well as that of power taps **55***a*, **56***a*, and **57***a*.

In initially applying power to the furnace over lines **10**, **11**, and **12**, it has been found desirable, as a means for eliminating electrical transients, to at first apply a reduced voltage, and shortly thereafter to apply the operating voltage desired. Similarly, in removing power from the furnace lines it has been found desirable to first reduce the voltage across the lines and thereafter totally disconnect this voltage. For this purpose, each of lines **10**, **11**, and **12** is provided with a series connected main relay contact **82***a*, **82***b*, and **82***c*, respectively, and a shunt relay contact with **85***a*, **85***b* and **85***c* respectively, in parallel therewith, with each shunt relay contact having a limiting resistor **88**, **89**, and **90** in series therewith. In initially energizing lines **10**, **11** and **12** by closing the shunt contactors **85***a*, **85***b*, and **85***c*, a reduced voltage is applied to these lines, due to the presence of limiting resistors **88**, **89**, and **90**. Thereafter, when the main relay contacts **82***a*, **82***b*, and **82***c* are closed, the full voltage is applied to these lines. Similarly, when it is desired to de-energize the furnace power lines, the main relay contacts **82***a*, **82***b* and **82***c* are first opened to establish the reduced power condition; then the shunt contacts are opened to totally de-energize the furnace power lines.

This sequence of opening and closing the main and shunt relay contacts is obtained by placing a first control relay **91** across a power source **75** in series with an operator's on-off switch **92** and in series with contacts **74***a* of the above-mentioned voltage regulating relay **74**, which contacts for purposes of the present description, may be considered as being closed. Upon on-off switch **92** being closed by the operator, the first control relay **91** is energized to close its contacts **91***a* and **91***b*. Closure of contacts **91***a* permits current flow from power source **75** through a shunt relay winding **85**, which in turn closes the shunt contacts **85***a*, **85***b*, and **85***c* to apply reduced voltage to the furnace power lines **10**, **11**, and **12** through the limiting resistors **88**, **89**, and **90**. Energizing the shunt contactor relay winding **85** also opens its contact **85***d* which is in series with the tap changing motor **59** to prevent changing the power voltage taps **55***a*, **56***a*, and **57***a* at this time; and additionally closes its contacts **85***e* in the circuit immediately above the shunt relay winding **85**.

A short time after shunt winding **85** is energized, a second control relay winding **93** in parallel therewith is energized. Relay winding **93** is preferably of a conventional delayed closing type and hence operates when a given time has elapsed after initial energization. This second control relay **93** then closes its contacts **93***a* to

complete the circuit to the main contactor relay winding 82 which as shown is connected across source 75 in series with the contacts 91*b* of first control relay 91, shunt relay contacts 85*e*, and contacts 93*a* of the second control relay 93. Since all of these relays are now energized, the main contactor winding 82 is energized to close its main contacts 82*a*, 82*b*, and 82*c* in power lines 10, 11, and 12 and apply the full voltage on these lines.

Recapitulating the sequence of operation for initially energizing the furnace, the closing of on-off switch 92 energizes a first control relay winding 91 which in turn completes the circuit to energize the shunt relay winding 85 and apply reduced power to the furnace lines 10, 11, and 12. A short time later, a second control relay 93 is operated and this relay completes the circuit to the main power relay winding 82 which in turn closes its main contacts 82*a*, 82*b*, and 82*c* to apply full power to the furnace input lines 10, 11, and 12.

When it is desired to remove the voltage from the furnace power lines 10, 11, and 12, the on-off switch 92 is opened by the operator to de-energize the first control relay winding 91 which immediately opens its contacts 91*b* to deenergize main contactor relay winding 82 and open the main contactors 82*a*, 82*b* and 82*c* to power lines 10, 11, and 12. However, reduced power is still applied to these lines through the shunt contactors and resistors 85*a*, 88; 85*b*, 89; and 85*c*, 90 to eliminate undesirably large transients.

De-energization of the main relay 82 also opens contacts 82*d* in the winding circuit of shunt relay 85, but the shunt relay winding 85*a* still remains energized due to contacts 91*a* of the first control relay 91 being delayed in opening for a given time interval. Both delayed opening and delayed closing relays are well known to those skilled in the art and further details of these relays are believed to be unnecessary for purposes of describing the present invention.

After this given time delay has elapsed, relay contacts 91*a* open to de-energize the shunt relay winding 85 and thereby open the shunt contacts 85*a*, 85*b*, and 85*c* in the power lines 10, 11, and 12 to completely remove power from the furnace.

Recapitulating the sequence of operations for de-energizing the furnace winding, the operator first opens on-off switch 92 to de-energize the first control relay winding 91 whose contacts 91*b* in turn open to de-energize the main relay winding 82. The main relay contacts 82*a*, 82*b*, and 82*c* are consequently opened to remove the direct connection of power to the lines 10, 11, and 12 but the lines still receive a reduced voltage through the closed shunt contacts 85*a*, 85*b* and 85*c*. After a given interval has elapsed, the first control relay contacts 91*a* open to de-energize the shunt contactor relay winding 85, which in turn opens the shunt contactors 85*a*, 85*b*, and 85*c* to completely disconnect the furnace from the power source.

As is believed evident from the foregoing description, the power factor and phase balancing corrections are preferably performed in an incremental manner rather than in large step changes. For example, if only one balancing reactance is in circuit and rapid variation in the furnace load calls for a total of three reactances, the entire correction is not made immediately. Instead the second reactance is first added and then the third. Similarly, if all balancing reactances are in circuit and the furnace load changes rapidly, requiring the removal of the reactances, they are removed one-by-one until the circuit is again balanced. The reason for permitting only incremental changes is that electrical furnaces of this type consume large amounts of power, and the reactances are necessarily quite large. If several were added or removed from the circuit at one time, undesirably large transient effects would occur.

However, should the furnace load change rapidly, the relative slowness of operation of the step-by-step switching means would result in large unbalanced currents over the power lines. For example, when the molten metal is being poured from a full furnace the load changes rapidly from a condition requiring the maximum number of balancing reactances to one requiring the least number, and the step-by-step controller 28 is unable to remove reactances with sufficient speed to keep up with this rapid change of furnace load.

To correct for this condition, there is provided what may be termed a "tilt control" whose purpose is to reduce the power being supplied to the furnace during the pouring operation as well as to provide time for the power factor and phase balancing controls to correct for the changed load condition without excessive and undesirably large current unbalance.

Referring to FIG. 4 for an understanding of this operation, there is provided a tilt control circuit across power supply 75 including a tilt control switch 95 in series with a tilt reset switch 96 and a tilt control relay winding 97. The tilt control switch 96 is normally opened when the furnace is in upright position and the circuit is accordingly de-energized at this time but is adapted to be closed when the furnace is tipped over to pour the molten metal. Closing of switch 95 completes this series circuit and permits current to pass through tilt relay winding 97 operating this relay to close its two normally opened contacts 97*b* and 97*c* and open its normally closed contact 97*a*.

Closing of relay contacts 97*c* shunts the tilt control switch 95 and maintains the tilt relay winding 97 energized despite the later opening of tilt control switch 95 as the furnace is returned to upright position after being emptied. The opening of relay contacts 97*a* and the closing of contacts 97*b*, both being located in the operator's voltage selection switch circuit, serve to disconnect tap 60 of the operator's voltage selection switch from the right hand terminal of voltage control relay winding 74 and substitute instead the lowermost fixed contact 61 of this switch thereto. This has the same effect as if the operator had adjusted the position of his manual selector tap 60 to its lowermost position at contact 61 requiring a reduction in voltage to the furnace to its lowest value.

Assuming that the furnace was fully loaded and drawing maximum voltage prior to pouring, the main transformer power taps 55*a*, 56*a* and 57*a*, as well as the control follower tap 73 would be positioned at their uppermost contacts, and, therefore, the opening of relay contacts 97*a* and the closing of contacts 97*b* effectively result in a relative displacement of taps 60 and 73. In the manner discussed above, the relative displacement of these taps energizes step-by-step motor 59 to drive the follower tap 73 and the transformer power taps 55*a*, 56*a*, and 57*a* to the new setting or position of the tap 60, and thereby reduces the voltage being supplied to the furnace lines 10, 11, and 12. to the lowest value during and after the pouring operation. Thus during the pouring of the molten metal from the furnace, the voltage being supplied to the furnace is automatically reduced to its lowest value by operation of the tilt control circuit.

In addition to reducing the line voltage as the load requirement is rapidly diminished during the pouring, the automatic tilt control performs still another important function in aiding the operation of the power factor correcting and phase balancing controls. In the power factor control, for example, a full load requires all of the correcting capacitors 16, 17, and 18 to be inserted (see FIG. 1) whereas to maintain a high power factor for an empty or almost empty furnace requires that all of these capacitors be disconnected from the circuit and only fixed capacitor 15 be connected.

Since the power factor capacitors and the step-by-step switching means for adding or removing them from the circuit are necessarily large and slow moving to handle the large current capacity, it may not be possible during the pouring operation to maintain the power factor of

the furnace load at a high value. Similarly the rapid reduction of furnace load during the pouring operation requires that most if not all of the balancing inductors and capacitors across the second and third phases of the system be rapidly removed to maintain a balanced three phase load. Consequently, the automatic reduction of line voltage to a low value by means of the tilt control minimizes the power loss that would normally result from low power factor of the load, and the three phase unbalance of the system that would be occasioned by a rapid change in the character of the load during the pouring of the molten metal.

The voltages impressed across the power lines **10**, **11**, and **12** after the pouring operation is completed remain at their lowest value until an operator actuates the tilt reset switch **96**, whereupon the tilt relay **97** is de-energized and its contacts **97***b* and **97***c* are opened and contacts **97***a* are closed to disengage the tilt control. By waiting for a few moments until the power factor and balancing controls have made the necessary changes for no load conditions, the operator may then actuate tilt reset switch **96** and thereby ready the system for the introduction of a new load.

It is to be particularly noted that, during any operation of the voltage regulating follow-up means, the power energizing the furnace is always turned off automatically to prevent the generation of transient currents. This is accomplished by the operation of relay winding **74** which is de-energized whenever the operator's voltage selecting tap **60** has a different position than that of the follower control tap **73**. When relay winding **74** is de-energized, its contact **74***a* (located in series circuit with the first control relay winding **91**) opens, thus de-energizing relay winding **91**, which serves to turn off the power in the same manner as if the operator's on-off power switch **92** were opened.

From the above description it is believed evident that either automatic or manual means, or any combination thereof may be employed to correct for the power factor of the load and to achieve phase balancing control in accordance with the present invention. For example, by disengaging the step switch controller **42** in the furnace load circuit, an operator need only read the indicator of the millivoltmeter **41**, and noting the presence of reactive power, manually operate the switches to add or remove capacitors **16**, **17**, and **18** from the circuit until the reactive component is eliminated or minimized. Similarly to achieve manually controlled phase balancing of the system, an operator need only actuate ganged switch **28** until ammeters (not shown) in the three lines **10**, **11**, and **12** indicate equal current flow over the three lines; or, alternatively, by observing the reading of millivoltmeter **50**, adjust switch **28** until the reading is zero, indicating that the power being taken over line **10** equals that over line **12**, and that the system is in balance. Furthermore, the time delayed reduction in voltage when the furnace is turned on, and the similar time delayed reduction in voltage when the furnace is turned off, may likewise be performed manually by substituting manually operated switches for the relays described above, as may be the control brought about during tilting of the furnace at a time when the load is rapidly changing from a full furnace to an empty or near empty furnace.

I claim:

1. In a three phase system having a variable resistive and reactive induction furnace load across one phase thereof, means for balancing said system to distribute the load current equally over the three phases, said means including means for adding and removing reactances in said load circuit to balance the reactive portion of said load, a balancing inductance circuit connected in the second phase of said three phase system and a balancing capacitance circuit connected in the third phase, the reactance of said inductance balancing circuit being always equal in magnitude to the reactance of said capacitive balancing circuit and being related to the magnitude of the resistive portion of the load, and means for varying together the magnitude of said inductive and capacitive balancing circuit with changes in the resistive load, whereby to provide equal current over the three phases.

2. In a three phase system having a variable resistive and reactive induction furnace load across one phase thereof, means for automatically balancing said system to distribute the load current equally over the three phases, said means including follow-up means responsive to the reactive power of said load to add and remove correcting reactances in said load circuit and minimize the reactive power in said first phase, a balancing inductance circuit connected in the second phase of said three phase circuit and a balancing capacitive circuit connected in the third phase, the magnitude of reactance in said inductance balancing circuit being equal to the magnitude of reactance in said capacitive balancing circuit, and follow-up means responsive to variation of said resistive load for jointly varying the capacitive circuit and inductive circuit in proportion to change of said resistive load.

3. In a control system for an electrical induction furnace for coupling a three phase power generator to a single phase furnace load winding, means for minimizing the reactive power taken from the generator and distributing the furnace load equally over the three phases of the generator, said means including a plurality of power factor correcting capacitors sequentially connectable and disconnectable in circuit with said load winding, means responsive to the power factor of said load to switch in and out said power factor correcting capacitors in response to variation in the power factor of said load, a plurality of first balancing reactive devices sequentially connectable and disconnectable in circuit with the second phase of said generator and constructed and arranged to draw a lagging current therethrough, a plurality of second balancing reactive devices sequentially connectable and disconnectable in circuit with the third phase of said generator and constructed and arranged to draw a leading current therethrough, and means responsive to the unbalance in said three phase generator lines for switching in and out said first and second balancing reactances in unison in their respective phases to restore the balance.

4. In a control system for an electrical furnace for coupling a three phase generator to a single phase furnace load, means for connecting the load across one phase thereof, means responsive to variation in the power factor of said load for maintaining the power factor at a high value, a variable reactance circuit connectable across the second phase of said generator and constructed and arranged to draw a lagging current therethrough, a second variable reactive circuit connectable across the third phase of said generator and constructed and arranged to draw a leading current therethrough that is equal in magnitude to that of the lagging current of the second phase, and means responsive to variation in the useful power consumed by said load for changing the magnitudes of the reactive circuits across said second and third phases together in proportion to changes in said useful power of the load whereby to substantially equally distribute said load current over the three phases of said generator.

5. In a control system for an electrical furnace for coupling a three phase generator to a single phase load, means for connecting the load across one phase thereof, means responsive to variation in the power factor of said load for maintaining the power factor at a high value, a variable reactance circuit connectable across the second phase of said generator and constructed and arranged to draw a lagging current therethrough, a second variable reactive circuit connectable across the third phase of said generator and constructed and arranged to draw a leading current therethrough that is equal in magnitude to that of the lagging current of the second phase, means responsive to the difference between the useful power of the furnace load and the in phase product of

one of the other line currents and the voltage between that other line and the next succeeding line for equally varying the values of the leading and lagging reactances to minimize said difference, whereby to balance the current drawn over the three lines of the generator.

6. In a control system for energizing a single phase furnace winding connectable across lines 1 and 2 of a three phase power supply, a lagging current reactive means connectable across lines 2 and 3 of the power supply, a leading current reactive means connectable across lines 3 and 1 of the supply, the magnitude of said leading and lagging reactive means being equal, means connecting the furnace load winding across lines 1 and 2 of the power supply, correcting means responsive to the power factor of said furnace load for maintaining said power factor at a high value, means responsive to the difference between the in phase product of the furnace winding voltage and current through line 1 and the in phase product of one of the other line currents and the related voltage between that other line and its next succeeding line for equally varying together the values of the leading and lagging reactance means to reduce said difference; whereby to balance the current drawn over each of the three lines of the power supply.

7. In a three phase power system for energizing a single phase winding of an electrical induction furnace containing a load, means responsive to the reactive power consumed by the said furnace for minimizing the reactive power drawn through said phase, means responsive to the useful power consumed by said furnace for maintaining the current drawn from the three phase system equally over the three lines, and means responsive to pouring of the furnace load for temporarily reducing the power to the furnace to a minimum value to provide sufficient time for said reactive power minimizing means and equal current maintaining means to effect their control functions without excessive disturbance.

8. In a three phase power system for energizing a single phase winding of an electrical induction furnace having a load, means responsive to the reactive power consumed by said furnace for minimizing the reactive power drawn through said phase, means responsive to the useful power consumed by said furnace for maintaining the current drawn from the three phase system equal over the three lines, and means for selecting a desired voltage for energizing the furnace and provided with follow-up means responsive to said selecting means for adjusting the voltage supplied to the furnace.

9. In a three phase power system for energizing a single phase induction furnace load connectable across one phase thereof, means responsive to the reactive power supplied to said load to minimize said power, a current lagging balancing variable reactance device across the second phase, an equal value current leading variable reactance device across the third phase, and means responsive to unbalance of the three phase system for varying said reactance devices together to restore balance, said means including a product difference means responsive to the product of load voltage and first line current and the product of voltage across one of the balancing reactances and third line current for transmitting an error signal proportional to the difference thereof, and an actuator responsive to said error signal for varying said balancing reactances.

10. In a three phase power system for energizing a single phase induction furnace load connectable across one phase thereof, means responsive to the reactive power supplied to said load to minimize said power, a current lagging balancing variable reactance device across the second phase, an equal value current leading variable reactance device across the third phase, and means responsive to unbalance of the three phase system for varying said reactance devices together to restore balance, said means including means measuring the product of furnace load voltage and the sum of currents through the load and current leading reactance, means measuring the product of voltage across said current leading reactance and the sum of currents through said leading and lagging reactances, and means responsive to the difference between said products for varying said reactance devices.

11. In a three phase power system for energizing a single phase winding of an electrical induction furnace, means responsive to the reactive power consumed by said furnace for minimizing the reactive power drawn through said phase, and means responsive to the useful power consumed by said furnace for maintaining the current drawn from the three phase system equal over the three lines.

12. In a three phase power system having a variable resistive and reactive load connectable across one phase thereof, means for balancing said system to obtain equal current over the three power lines and minimize the reactive component of current therethrough, said means including means responsive to the power factor of said load for maintaining the power factor at high value, a current lagging variable reactance device connected across the second phase thereof, a current leading variable reactance device connected across the third phase thereof with said lagging and leading devices drawing equal magnitude reactive currents therethrough, and control means responsive to unbalance of the three phase system for varying said lagging and leading devices together to restore current balance.

13. In a three phase power system for energizing a single phase winding of an electrical induction furnace, means responsive to the reactive power consumed by said furnace for minimizing the reactive power drawn through said phase, means responsive to the useful power consumed by said furnace for maintaining the current drawn from the three phase system equal over the three lines, means responsive to rapid reduction of the furnace load during pouring of the furnace for reducing the power to a minimum value whereby to provide sufficient time for said reactive power minimizing means and equal current maintaining means to effect their respective corrections without excessive disturbance.

14. In a three phase power system for energizing a single phase winding of an electrical induction furnace, means responsive to the reactive power consumed by said furnace for minimizing the reactive power drawn through said phase, means responsive to the useful power consumed by said furnace for maintaining equal the current drawn from the three phase system over the three lines, an on-off control and time delay means responsive to on-operation of said on-off control to at first apply a reduced voltage to the furnace and a given time interval thereafter apply the full operating voltage thereto.

15. In a three phase power system for energizing a single phase winding of an electrical induction furnace, means responsive to the reactive power consumed by said furnace for minimizing the reactive power drawn through said phase, means responsive to the useful power consumed by said furnace for maintaining the current drawn from the three phase system equal over the three lines, means for selecting a desired voltage for energizing the furnace, follow-up means responsive to said selecting means for adjusting the furnace voltage accordingly, and time delay means responsive to said selecting means for at first applying a reduced voltage to the furnace and a given time interval thereafter applying the selected voltage thereto.

16. In a three phase power system for energizing a single phase winding of an electrical induction furnace, means responsive to the reactive power consumed by said furnace for minimizing the reactive power drawn through said phase, means responsive to the useful power consumed by said furnace for maintaining the current drawn from the three phase system equal over the three lines, means for selecting a desired voltage for energizing the

furnace, follow-up means responsive to said selecting means for adjusting the furnace voltage accordingly, means responsive to tilting of the furnace for reducing the voltage to a minimum value, and time delay means responsive to said follow-up means for at first applying a reduced voltage to the furnace and a given time interval thereafter applying the selected voltage thereto.

17. In a three phase system having a variable resistive and reactive induction furnace load across one phase thereof, means for balancing said system to distribute the load current equally over the three phases, said means including means for adding and removing reactances in said load circuit to balance the reactive portion of said load, a balancing inductance circuit connected in the second phase of said three phase system and a balancing capacitance circuit connected in the third phase, the reactance of said inductance balancing circuit being always equal in magnitude to the reactance of said capacitive balancing circuit and being related to the magnitude of the resistive portion of the load, means for varying together the magnitude of said inductive and capacitive balancing circuit with changes in the resistive load whereby to provide equal current over the three phases, and means responsive to rapid variation of the furnace load from a substantially full load condition to a substantially no load condition during pouring of the furnace for reducing the furnace voltage to a minimum value.

18. In the system of claim 17, means for selecting a desired voltage for energizing the furnace, and means responsive to said selecting means for adjusting the furnace voltage accordingly.

19. In the system of claim 18, a time delay means selectively responsive to said selecting means, and said reducing voltage means, for at first applying a reduced voltage to the furnace and a given time interval thereafter applying the voltage determined by said selecting means and said voltage reducing means.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,053,920 September 11, 1962

James P. Seitz

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 10, line 20, for "96" read -- 95 --.

Signed and sealed this 8th day of January 1963.

(SEAL)
Attest:

ERNEST W. SWIDER
Attesting Officer

DAVID L. LADD
Commissioner of Patents

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