May 6, 1947. R. F. DAVIS 2,419,988

ELECTRIC FURNACE CONTROL

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Fig. 1

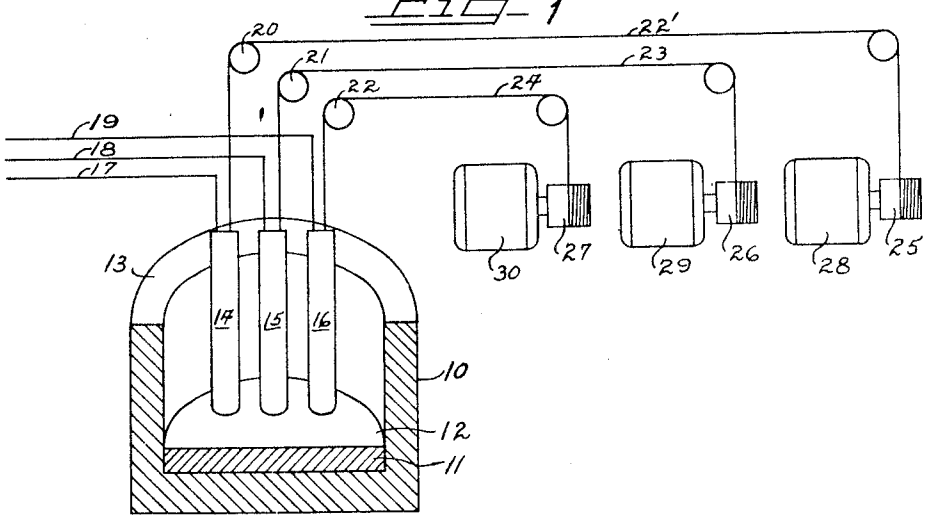


Fig. 2

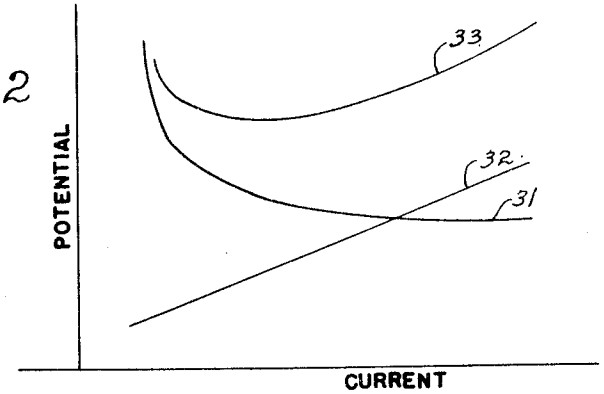
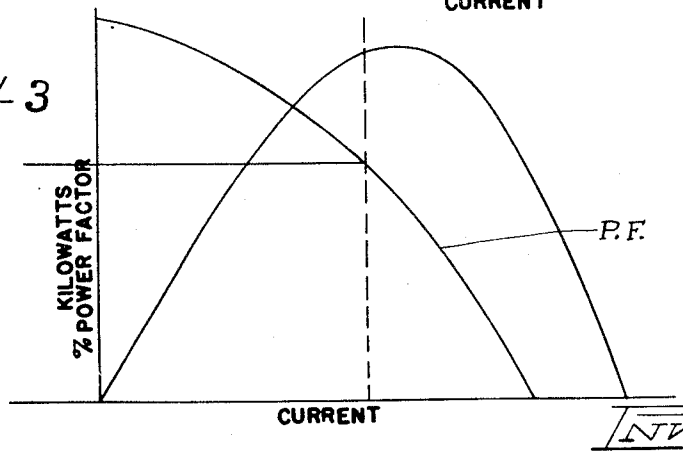


Fig. 3



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Fig. 4

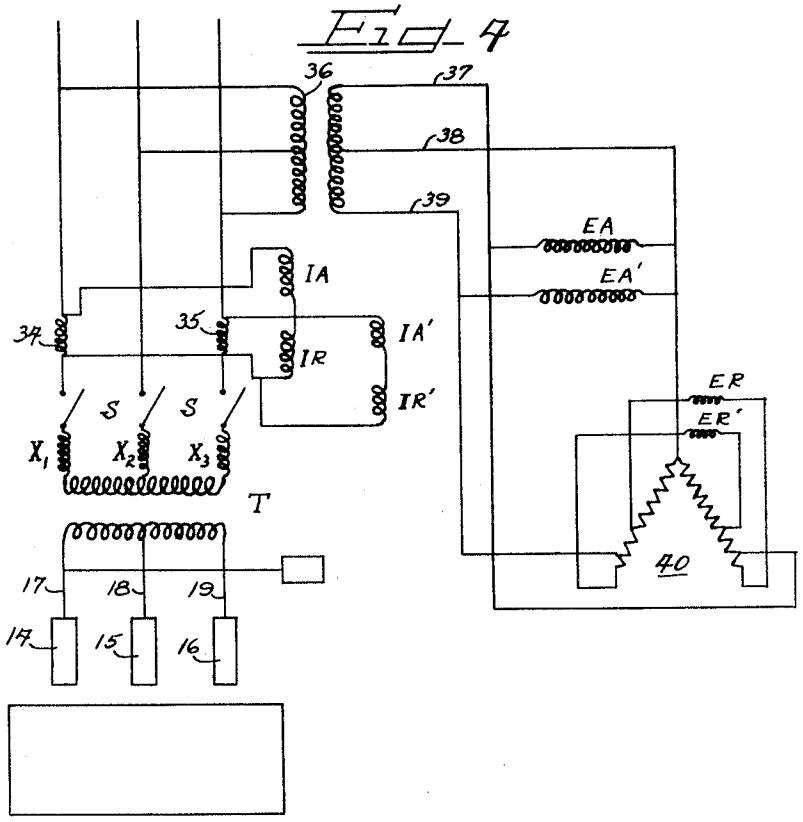
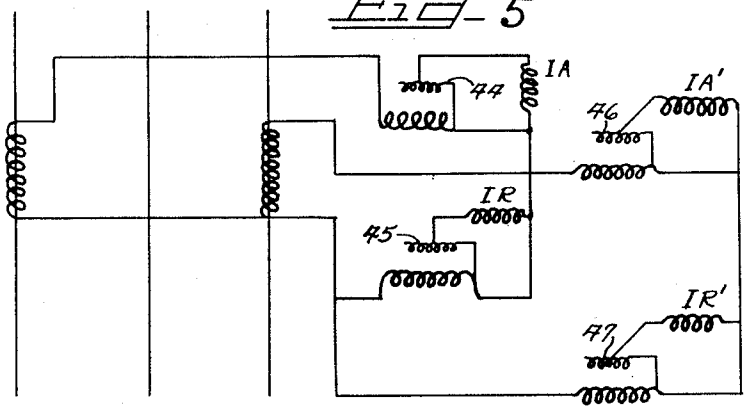


Fig. 5



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ELECTRIC FURNACE CONTROL

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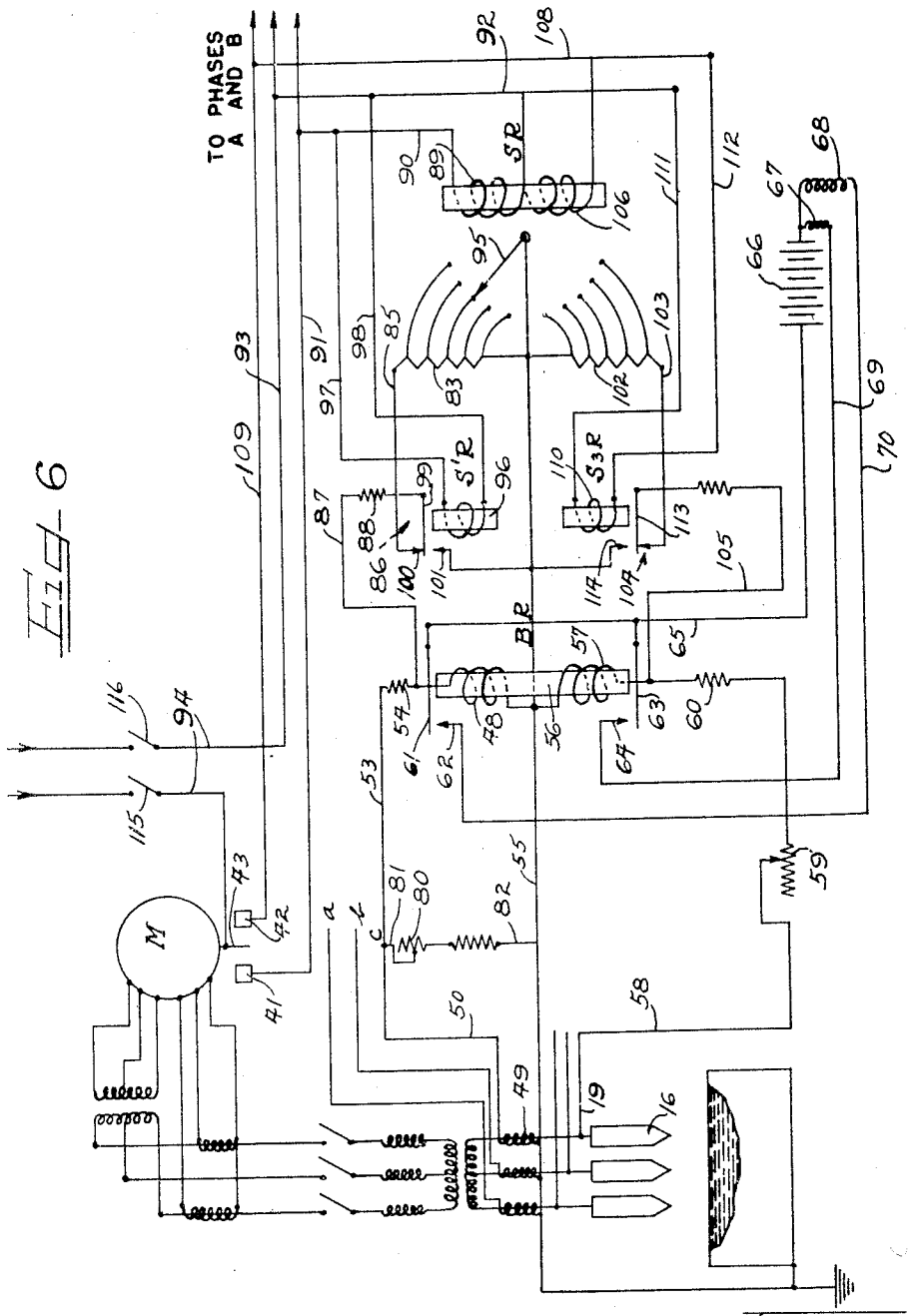


Fig. 6

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ELECTRIC FURNACE CONTROL

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Fig. 7

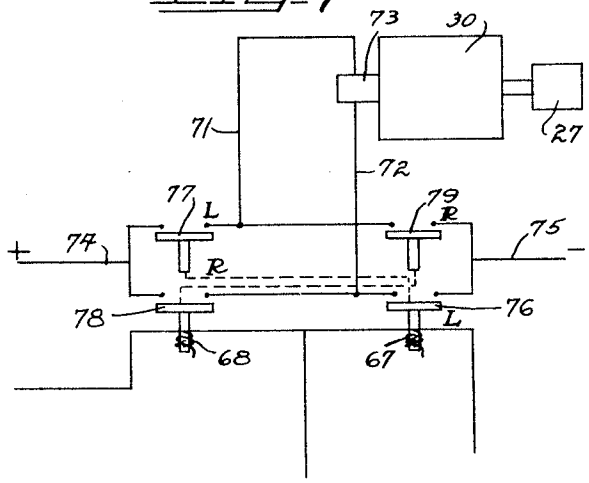
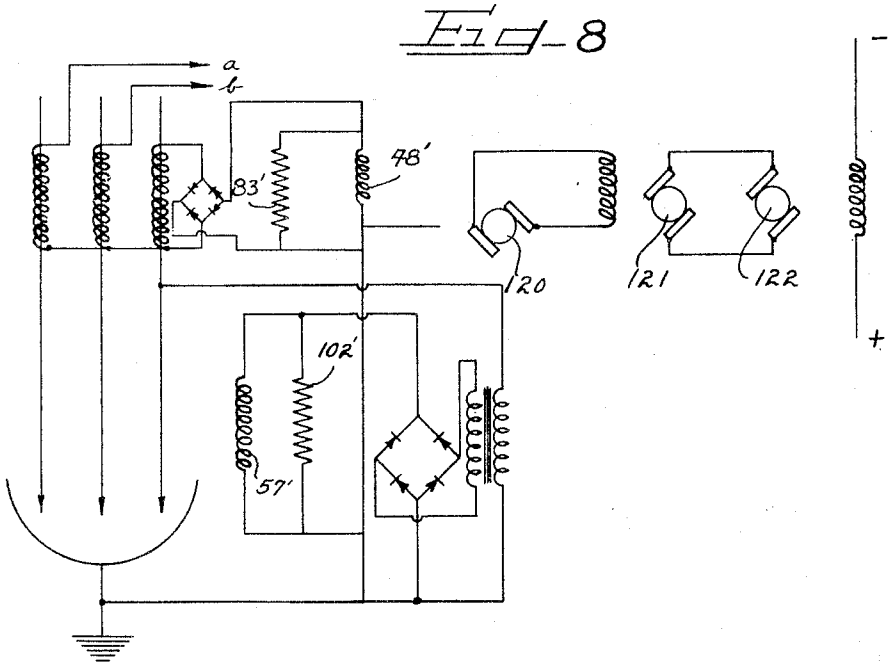


Fig. 8



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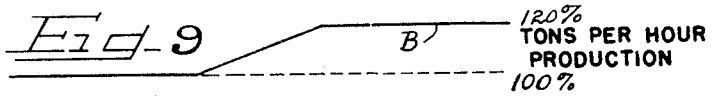
by The Firm of Charles Hobbs Attys

May 6, 1947. R. F. DAVIS 2,419,988

ELECTRIC FURNACE CONTROL

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Fig. 9



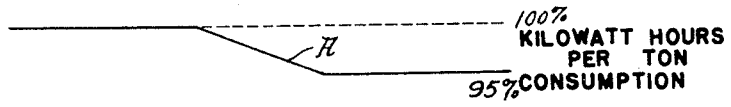


Fig. 10

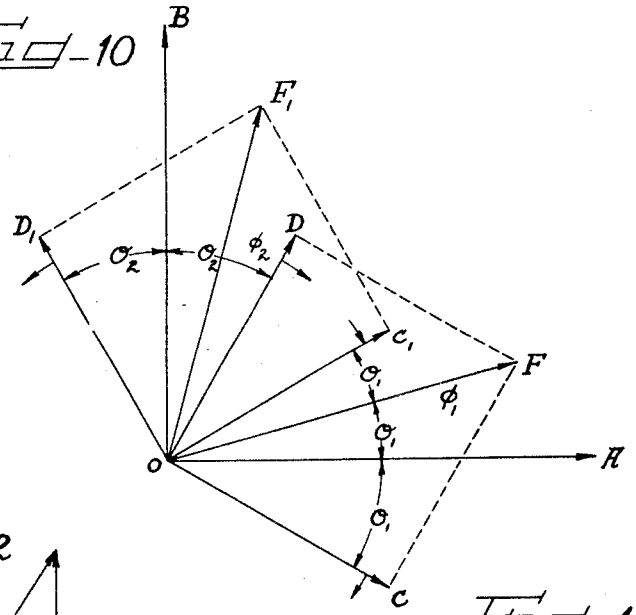


Fig. 12

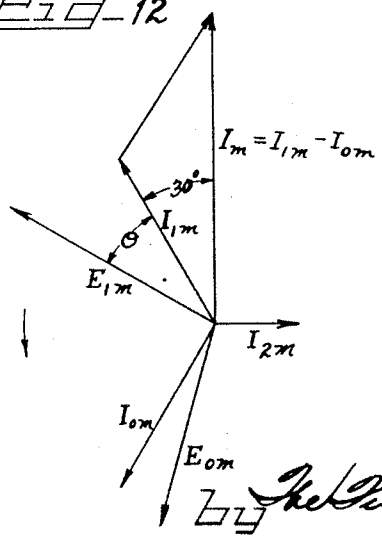
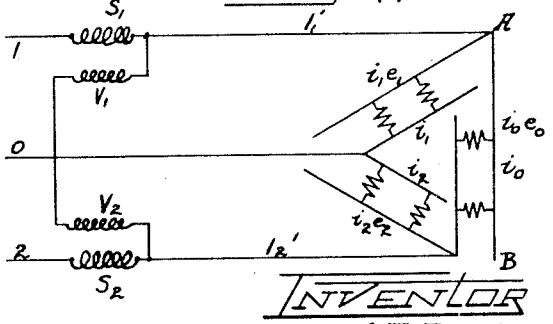


Fig. 11



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Patented May 6, 1947 2,419,988

UNITED STATES PATENT OFFICE

2,419,988

ELECTRIC FURNACE CONTROL

Ronald F. Davis, Sterling, Ill., assignor to Northwestern Steel and Wire Company, Sterling, Ill., a corporation of Illinois

Application January 8, 1945, Serial No. 571,900

16 Claims. (Cl. 13—13)

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My invention relates to an electric furnace control, and particularly to control arrangements for electric furnaces of the arc type, and it is a general object of my invention to provide an improved electric control system for an electric translating device having a power circuit including a load with a negative volt-ampere characteristic in order to obtain an optimum power flow condition during operation of the apparatus.

Heretofore, electric arc furnaces have been employed of the three-phase type and the single-phase type, the three-phase furnace being usually employed in the production of alloy steels and the single-phase furnace being usually employed in the production of non-ferrous alloys. The single-phase furnace includes one electrode which cooperates with the charge in the furnace and the three-phase furnace includes three electrodes, and it is customary to provide the electrodes for relative movement with respect to the remainder of the furnace. An arc furnace is usually connected to a source of power supply through tap changing transformers, a reactor and a circuit breaker arrangement and during the melting of a charge in the furnace, it is usually customary to employ different voltages during different cycles of the melting operation. With each value of applied voltage, there is a maximum amount of power input which it is desirable to impress on the furnace so as to obtain the most efficient operation and conventional arc furnace controls usually include a manual control circuit for balancing the arc current and arc voltage. For any particular voltage usually, the arc current may be changed by varying the relative distance between the relatively movable electrodes and the charge in the furnace and it is customary to provide the electrodes for relative movement through a motor which operates a winch which is connected to the electrodes through a cable. A control circuit for the motor including a contact making relay is usually provided which is responsive to current in the phases of the power circuit and if the current rises above a particular value, the control circuit of the motor may be energized to cause the winch to raise the electrode a certain amount, and if the current drops below a particular value, the motor may be energized to operate in the opposite direction so as to lower the electrode. Rheostats may also be provided in the control circuit for each phase for setting the operating current for each applied voltage and a manual control is also provided for each regulator so that the operator may raise and lower the electrodes. However,

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due to the complexity of the electrical circuits established in a three-phase arc furnace under various conditions encountered during the melting and refining of a heat of steel, it is sometimes difficult for the average operator to employ all the various parts of the operating equipment, so as to obtain even an approximation of the maximum efficiency which is attainable with a particular power installation.

It is therefore a general object of my invention to provide an improved automatic control arrangement for electric arc furnace operation which will maintain a predetermined balance between the arc current and the arc voltage in the various phases.

It is a further object of my invention to provide an improved automatic control arrangement for supplementing the conventional manual control usually employed in electric arc furnace operation.

It is a still further object of my invention to provide an improved control arrangement for controlling the relative values of current and voltage in a power circuit having a load with a negative voltage-current characteristic.

Further objects and advantages of my invention will become apparent from the following description referring to the accompanying drawings, and the features of novelty which characterize my invention will be pointed out with particularity in the claims annexed to and forming a part of this specification.

On the drawings:

Figure 1 illustrates somewhat diagrammatically an electric arc furnace of the three-phase type having motor operated winches for moving the electrodes;

Figures 2 and 3 illustrate electrical characteristics of an arc furnace which will be employed in describing the operation of an arc furnace;

Figure 4 illustrates diagrammatically a three-phase power circuit for an arc furnace with a meter which is employed in the operation of my control circuit;

Figure 5 illustrates the circuit of Figure 4 which is provided with tap changing transformers for varying the reference point of the meter;

Figure 6 is a circuit diagram of a control circuit for an electric arc furnace which is provided with an embodiment of my invention;

Figure 7 is a diagram of the control for the motor operated winch;

Figure 8 illustrates a modified form of the control circuit;

Figure 9 is a graph illustrating the operating

results of a furnace controlled according to my invention; and

Figures 10 through 12 are employed in the description of my improved reference meter.

Referring to Figure 1 of the drawings, I have illustrated a conventional three-phase electric arc furnace including a body portion 10 formed of suitable material such as steel with a lining 11 of suitable refractory material upon which a charge 12 is placed which is composed of a suitable metallic material which it is desired to melt in the furnace. The furnace is closed by a cover 13 having three apertures through which extend electrodes 14, 15 and 16. Each of the electrodes has a lower end which is adapted to provide an arc between the lower end and the charge of metal so that three arcs are provided between the lower ends of the three electrodes and the charge of metal which acts as a common electrode for all the three electrodes. The upper ends of the electrodes 14, 15 and 16 are connected to a suitable source of potential through flexible conductors 17, 18 and 19, respectively. In order to be able to move the electrodes relative to the charge of metal so as to control the amount of arc current as well as to feed the electrodes as they wear out, the three electrodes are mounted from similar pulley mechanisms 20, 21 and 22 over which passes cables 22', 23 and 24, one end of each being attached to the upper end of the electrodes 14, 15 and 16. The other end of the cables are wound around winches 25, 26 and 27 and these three winches are in turn operated by three electric motors 28, 29 and 30.

The electric arc furnace works upon the principle of producing a relatively large amount of power in the arcs so as to melt the metal inside the furnace. One of the features of an arc is that it has a negative voltage-ampere characteristic as is illustrated by the curve 31 of Figure 2 in which current is plotted on the abscissa axis and potential on the ordinate axis. In order to provide a condition of stability in electric arc furnaces, it is customary to connect the electrodes across a relatively constant source of potential and connect them to the source through a suitable ballast which usually includes a reactance which, of course, has a positive potential-ampere characteristic as is indicated by the curve 32 in Figure 2. The combined characteristics of the arc furnace and the reactance result in a positive characteristic indicated by the curve 33 in Figure 2. It is to be understood that the amount of extra reactants that need be added to the circuit depends upon the electrical characteristics of the remaining part of the circuit as, of course, the lead lines to the electrodes also have a reactant value.

It is generally customary to provide about a fifty percent reactance drop in the circuit in order to stabilize it and in Figure 4, I have illustrated diagrammatically the power circuit of a three-phase arc furnace including the electrodes 14, 15 and 16 which are connected through the leads 17, 18 and 19 to a conventional tap changing transformer indicated by the letter T which are in turn connected to a source of potential through reactances marked X1, X2 and X3 and a circuit breaker indicated by the letter S in Figure 4. Although a reactance does not cause an energy loss in the circuit, the reactance lowers the power factor of the circuit and in Figure 3 I have illustrated the change in power factor with change in current in which current is plotted on the abscissa axis and power factor on the ordinate

axis. I have also plotted in Figure 3 a curve for kilowatts in the circuit and it will be seen that maximum power in the arc of this type is given when the power factor or percent reacting volts is equal to or greater than 70.7% depending upon the inherent reactance in the circuit It is not only desirable to operate the furnace at its maximum kilowatts in the arc as that is the place where the approximate maximum efficiency is obtained, but it is desirable to operate the circuit at as high a power factor as is possible since a lagging power factor increases the losses in the transformer and thus it is generally known that better power rates can be obtained in plants which can guarantee a relatively high power factor.

In order therefore to operate the electric arc furnace in the range of its maximum efficiency, I provide a control circuit for maintaining a ratio of the arc current and arc voltage within a predetermined range by a control circuit including a meter responsive to the power factor of the power circuit, such control circuit being illustrated in Figure 6. However, before proceeding with a description of my improved control circuit, I shall describe a power factor meter which is diagrammatically illustrated in Figure 4. The meter includes a four element arrangement having four coils, two being marked IA and two being marked IR which are connected to be responsive to a function of power current and reactive current respectively, and four elements, two being marked EA and two being marked ER which are connected to be responsive to a function of the power voltage and reactive voltage respectively. Thus conventional current transformers 34 and 35 are provided, two coils IA and IR being connected in series with the current transformer 34 and two coils IA and IR being connected in series with the current transformer 35. Also, the power factor meter is connected as is conventional to a potential transformer 36, the primary of which being connected to the three power lines. The secondary thereof is connected through three wires 37, 38 and 39 to three points on a conventional auto transformer 40. As is conventional, one of the voltage coils EA is connected between the lines 37 and 38 and the other coil EA' is connected across the lines 39 and 38 while the remaining two coils ER and ER' are connected to suitable points on the auto transformer 40, the purpose of which being to provide a suitable correction factor so that the meter will function as a suitable power factor meter. As will be described more completely hereinafter, the power factor meter indicated generally by the large letter M in Figure 6 includes stationary contacts 41 and 42 and a movable contact 43. Thus, when the meter M is set so as to have a neutral position for a predetermined power factor in the power circuit such as 70.7%, the movable contact 43 will be between the stationary contacts 41 and 42. Such a condition will be present when both components in the circuit are of the same magnitude and thus equal torque is produced in each pair of elements, but being in opposition, cancel, resulting in no movement of the movable contact. Any unbalance of the elements creates a directional torque proportional to the departure from equality and of the rate of response obtained by the damping magnet and the adjustable contact separation.

To provide means for calibrating for other desired values of power factors, tap ratio transformers 44 and 45 as illustrated in Figure 5 may be connected to one set of current coils IA and

IR and other transformers 46 and 47 may be connected to the other pair of current coils IA' and IR'. By varying the tap ratio transformers other selection of values above and below a 70.7 percent power factor may be obtained with the meter M.

In order to provide a control circuit which is responsive to a balanced or a predetermined ratio of the arc current to arc voltage as is illustrated in Figure 6, a balancing relay indicated by the letters BR is provided. This balancing relay has one coil 48 responsive to a function of the current in one of the phases and is connected to the phase which feeds the electrode 16 through a current transformer 49. It will be seen that one side of the current transformer 49 is connected to one side of the current coil 48 through a lead wire 50, and a conductor 53 in which is placed a suitable ballasting resistor 54. The opposite end of the current coil 48 is connected to the other side of the current transformer 49 through a conductor 55. It will be seen that the current coil 48 surrounds a core 56 of the balancing relay BR while the other end of the core 56 is surrounded by another coil 57 which is responsive to a function of the arc voltage. Thus, one end of the voltage coil 57 is connected to the conductor 55 while the other end is connected to the power lead 19 which connects with the electrode 16 through a conductor 58, an adjustable rheostat 59 and a ballasting resistor 60.

In order that operation of the balancing relay BR may initiate a control for varying the circuit characteristics of the phase such as the arc-current, the balancing relay is provided with a switch having a relatively movable contact 61 and a stationary contact 62 which are normally open but which are closed when the current coil 48 over-balances the voltage coil 57. Similarly, another switch is provided having a movable contact 63 and a stationary contact 64 which are also normally open but which will close when the voltage coil 57 over-balances the current coil 48. These switches in the balancing relay may be connected in any suitable manner for operating the motor 30 for either raising or lowering the electrode 16. Thus, it will be seen in Figure 6 that the relatively movable contacts 61 and 63 are connected through a conductor 65 and a source of potential 66 to operating coils 67 and 68 of a suitable forward and reversing control of the motor 30. The other side of the operating coil 67 is connected to the stationary contact 64 through a conductor 69 while the other side of the operating coil 68 is connected to the stationary contact 62 through a conductor 70.

As has been stated above, any suitable type of control may be employed for operating the motor 30 and in Figure 7 I have diagrammatically illustrated a control circuit for the motor including a pair of lines 71 and 72 which are connected to opposite sides of the armature 53 of the motor 30. It will be understood that when current from a source of supply 74 and 75 passes through the armature in one direction, the motor will be rotated in one direction and when the current passes through the motor in the opposite direction, the motor will be operated in the other direction. As will be seen from the diagrammatic representation in Figure 6, the operating coil 67 will operate switches 76 and 77 to rotate the motor in one direction such as to lower the electrode 16 while the operating coil 68 will operate switches 78 and 79 to cause the motor to rotate in the opposite direction such as to raise the electrode 16.

In order to provide an arrangement for adjusting the balance of the current coil 48 and the voltage coil 57 of the balancing relay BR, a current adjusting rheostat 80 is provided which is connected in shunt with the current coil 48 by the conductors 81 and 82. The current adjusting rheostat 80 may be operated in any suitable manner such as manually and by turning the rheostat in one direction the operator may cause the electrode control to raise the electrode while adjusting the rheostat in the opposite direction the operator may cause the electrode to be lowered.

In case the current adjusting rheostat 80 is manually operated, it will be appreciated that the operator may not be able to maintain merely by inspection of the circuit a predetermined balance between the arc-current and arc-voltage. Also, in order to provide a supplementary control or second control for counteracting any wrong adjustments or any incorrect adjustments of the current adjusting rheostat 80, I have provided a second control which is responsive to operation of the power factor meter M. This may be accomplished in any suitable manner and in Figure 6 it will be seen that I have provided a control circuit including a stepping relay indicated by the letters SR. The stepping relay SR includes a shunting resistance 83 which has one side thereof connected to the conductor 55 and the other side thereof connected to the other side of the current coil 48 through a conductor 85, a normally closed contact 86 of a shunting relay indicated by the letters S'R and a conductor 87 in which is placed a ballasting resistor 88. In order to operate the stepping relay SR, a coil 89 is provided which is connected for operation by the meter M. Thus one side of the operating coil 89 is connected through a conductor 90 and a conductor 91 to the stationary contact 41 while the other side of the coil 89 is connected through conductors 92 and 93 to one side of a source of control supply indicated by the numeral 94. The other side of the control supply 94 is connected to the movable contact 43 so that when the contacts 41 and 43 are closed, the coil 89 of the stepping relay will be operated to move the movable member 95 of the potentiometer of the stepping relay so as to cut in or out a part of the shunting resistor 83 or 102.

In order to operate the shunting relay S'R, the relay is provided with an operating coil 96 which is connected to the conductors 90 and 92 through conductors 97 and 98, and therefore each time the operating coil 89 of the stepping relay SR is operated, the coil 96 of the shunting relay S'R will also be operated. It will be noted that the shunting relay has a movable contact 99 of the switch 86 which is normally in contact with the stationary contact 100. However, when the shunting relay operates, the movable contact 99 will contact the stationary contact 101, thus opening the circuit of the stepping relay SR and preventing any arcing of the movable potentiometer member 95 when the stepping relay is operated. Also, closing of the contacts 99 and 101 will provide a shunting circuit for the current coil 48, thus insuring operation thereof with respect to the voltage coil whenever the meter M operates.

The stepping relay SR is provided with a resistor 102 which is connected in shunt with the voltage coil 57. Thus, the resistor 102 is connected at one side to the conductor 55 and at the opposite side to a conductor 103 through a switch 104 of a second shunting relay S3R to the other

side of the voltage coil through a conductor 105. Operation of the stepping relay SR is provided through an operating coil 106, operation of which moves a potentiometer arm 95 on the various taps of the resistors 83 or 102 in the opposite direction from that caused by operation of the operating coil 89. The operating coil 106 has one side thereof connected to the conductor 92 and the opposite side connected through conductors 108 and 109 to the other stationary contact 42 of the meter M. Thus, movement of the meter M in the opposite direction to contact the movable contact 43 and the stationary contact 42 will operate the stepping relay SR so as to change the shunting effect of the resistor 102 or 83 which shunts the voltage coil 57. The shunting relay S3R has an operating coil 110 which is similarly connected to the lines 92 and 108 through the conductors 111 and 112. Thus, when the coil 106 is energized, the coil 110 will also be energized, thus moving the movable contact 113 of the shunting relay S3R to contact the stationary contact 114 and disconnecting the resistor 102 from the circuit while the stepping relay SR is being operated and providing a shunting path for the voltage coil 53 so as to provide a definite unbalance when the coil is being operated by the meter M.

Control Operation

Let us first assume that the furnace has been started on its primary melt-down and has progressed to a point of stability wherein the furnace is capable of full heat absorption. The operator then closes the coil supply circuits by closing switches 115 and 116 which initiate operation of the supplementary control. Sequence of operation will then follow one of three patterns, depending upon the setting of the current adjusting rheostat 80 by the operator.

Case No. 1

Let us consider the first case when the arbitrary adjustment is less than that necessary for ultimate power input. With this condition prevailing, insufficient current is shunted through the current adjusting rheostat from the current coil 48 of the balancing relay BR. Thus, the correcting control must further weaken the coil 48 by removing additional resistance from the resistor 83 sufficient to create a balance between the arc-current and arc-voltage, in which case the power flow is at its predetermined quantity. As will be seen from an inspection of Figure 3, the power factor is a function of current and thus when the current is not sufficiently high, the power factor will be greater than that necessary for optimum operation, and it will therefore cause the meter M to operate so that the movable contact 43 will contact with the stationary contact 41 or R. This energizes the shunting relay S'R which shunts the current coil 48 and removes the rheostat resistor 83 from the circuit. This will cause the stepping relay SR to operate which will remove a portion of the resistor 83 from the shunting circuit. The value of the shunting resistance controlled by the relay S'R is made such that over-correction results, and the electrodes are lowered in the furnace to a point where slightly more than optimum input is drawn. The movable contact 43 will then be moved from the stationary contact 41 which will thereby deenergize the shunting relay S'R and the stepping relay SR. The shunting relay 83 will therefore have less resistance in it or the shunting circuit including the resistor 83 will draw more current from the current coil 48 than heretofore. If this small increment of shunting effect was insufficient to maintain proper flow of power then the contact 43 will again contact the stationary contact 41 sending additional impulses through the shunting relay S'R and the stepping relay SR. This continues until conditions imposed upon the circuit by the reference meter M are met.

Case No. 2

When the selected value by the operator is higher than that required for efficient operation, the control relay M will respond closing the contacts 43 and 42 which will operate the shunting relay S3R and the stepping relay SR thus weakening the voltage coil or strengthening the current coil of the balance relay and progressively raising the electrodes until optimum power results. It will be understood that these circuits including the stepping relay SR and the shunting relay S3R will operate similarly to that described above.

Case No. 3

When the balance of the reference meter is disturbed by some other changes in the furnace condition, faster correct input is accomplished. The closure of the reference meter M in the direction of the deviation is accomplished by operation of the control relays which again adjust the balance values in sufficient amount to return the furnace to normal.

While only short intervals are required for correction, no periodic shunting or surging occurs in the circuit as the system is made deadbeat by the fact that the variations in the circuit are made by small increments until proper compensation is established. Changes made by the operator of his adjusting rheostat while under supervision of the supplementary control have no permanent effect on the circuit as flow is automatically returned to normal by the reference meter control M.

In the control circuits described above, only one individual phase control has been described, but it is understood that the other two phases are similarly controlled. Thus in Figure 6 I have shown my improved control as applied to phase *c* and similar control circuits are employed for controlling phases *a* and *b* which circuits are in turn controlled by the reference meter M.

It will be understood that any other suitable means may be employed which is responsive to arc-current and arc-voltage instead of the balancing relay BR and I have shown in Figure 8 a control circuit including a dynamo electric machine having current responsive and voltage responsive field coils 48' and 57' which are connected in opposition, providing excitation for exciting armature 120 which in turn provides field excitation for generator armature 121. The latter controls the winch motor 122. It is, of course, to be understood that the fields 48' and 57' may be controlled according to my invention by the potentiometer resistors 83' and 102' which are similar to the stepping relay SR. It is also to be understood that shunting relays similar to S'R and S3R may be employed.

In order to indicate the results obtained over a period of time of a three-phase arc furnace which was controlled according to my above mentioned invention as compared with the results in a furnace controlled according to past practice, I have illustrated in Figure 9 a graph in which time is plotted on the abscissa axis and

kilowatt hours percent ton consumption on the ordinate axis for a curve marked A, and tons per hour per production on the vertical axis for the curve marked B. It will be seen that for the first four months with a furnace operated according to past practice which includes operation of a balancing relay by a manual rheostat to balance the arc-current and arc-voltage 100% in tons per hour are obtained with an input of 100% kilowatt hours per ton, while during the four months in which the same furnace was operated according to my improved control about 120% in tons per hour are obtained with an input in kilowatt hours per ton of about 95%.

I shall now describe below by mathematical analysis the operation of my improved reference meter:

The choice of a modified watthour meter as a basically sound instrument for the determination of power factor in a three phase arc furnace load with its attendant unbalanced and fluctuating nature, may be demonstrated by the following mathematical analysis of the principia of operation characteristically fundamental to induction watthour meters. Also simple external changes in connecting the various elements may alter their mode of interaction when their resultant torques are integrated to a common mechanical system.

As the production of a rotating field is necessary in this instrument and must be derived from an alternating current represented by

$$i=I_m \cos wt$$

we may represent the instantaneous value of field strength by

$$h=H_m \cos wt$$

When two coils with a common center and with their planes at right angles to each other are connected to different phases of a quarter phase circuit, the currents will produce alternating fields, the intensities of which will differ by one quarter of a period. Then the instantaneous values of the two fields can be represented by

$$h_1=H_{1m} \cos wt$$

$$h_2=H_{2m} \sin wt$$

The resulting field will be the vector sum of h_1 and h_2

$$h=\sqrt{\frac{h_1^2}{6}+h_2^2}$$

$$h=\sqrt{H_{1m}^2 \cos^2 wt+H_{2m}^2 \sin^2 wt}$$

When $H_{1m}=H_{2m}$

$$h=\sqrt{H_{1m}^2(\cos^2 wt+\sin^2 wt)}$$

$$h=H_{1m}$$

When $H_{1m}=H_{2m}=H_m$

$$h_1=H_m \cos wt$$

$$h_2=H_m \sin wt$$

$$h_1^2+h_2^2=H_m^2=\text{equation of a circle}$$

and the resultant field will rotate at constant angular speed, determined by the frequency.

When the two component fields have unequal maximum values, the two harmonically alternating fluxes at right angles to each other in space may be replaced by two rotating fluxes of different magnitudes rotating in opposite directions but having the same angular speeds.

In Fig. 10, let $OA=2H_{1m}$ and $OB=2H_{2m}$ represent two harmonic fluxes, produced by two circular coils having a common center but having planes at right angles to each other. OA and OB are fixed in direction but vary in magnitude according to the sine law. The flux OA may be considered as being the projection of two equal vectors, each equal to ½ OA, rotating in opposite directions at a uniform speed so as to make one complete revolution while the values of OA pass through one cycle.

Let OC and OC_1 represent the two component vectors at the instant they make an angle θ_1 with OA. At this instant the intensity of the field along OA is given by $2OC \cos \theta_1=2OC \cos wt$, where

$$w=2\pi f$$

Similarly OB may be considered as the resultant of two vectors OD and OD_1 each equal to ½ OB.

Combining the two components that rotate in the same direction, we get the two components OF and OF_1 which differ in magnitude, rotate in opposite directions, but have the same angular speeds.

The numerical value of OF and OF_1 in terms of OC and OD, and thus in terms of OA and OB, can be obtained analytically as follows:

$$OF^2=OC^2+OD^2-2OC \times OD \cos ODF$$

and

$$OF_1^2=OC_1^2+OD_1^2-2OC_1 \times OD_1 \cos OD_1F_1$$

but

$$OC=OC_1=H_{1m} \text{ and } OD=OD_1=H_{2m}$$

Then

$$OF^2=H_{1m}^2+H_{2m}^2-2H_{1m}H_{2m} \cos ODF$$

and

$$OF_1^2=H_{1m}^2+H_{2m}^2-2H_{1m}H_{2m} \cos OD_1F_1$$

$\angle ODF$ is the supplement of $\angle COD$

but

$$\angle COD=\angle AOD+\angle COA=\frac{\pi}{2}-\theta_2+\theta_1$$

hence

$$\angle ODF=\pi-\left(\frac{\pi}{2}-\theta_2+\theta_1\right)=\frac{\pi}{2}+(\theta_2-\theta_1)$$

Similarly

$\angle OD_1F_1$ can be shown equal to $\frac{\pi}{2}-(\theta_2-\theta_1)$

Now

$$\frac{\pi}{2}$$

is the physical angle between the fluxes OA and OB, but $\theta_2-\theta_1$ is the time-phase difference expressed as an angle between the alternating fluxes of which OA and OB represent the maximum values. Representing this phase difference by O_0, we arrive at:

$$OF^2=H_{1m}^2+H_{2m}^2+2H_{1m}H_{2m} \sin \theta_0$$

$$OF_1^2=H_{1m}^2+H_{2m}^2-2H_{1m}H_{2m} \sin \theta_0$$

That is, in place of one resultant field, rotating with a uniform speed in one direction, there are two fields with different amplitudes, rotating in opposite directions. The angular shifting of the magnetic field induces currents in the disk, and the reaction between these currents and the magnetic field causes the disk to rotate.

Accordingly an expression may be derived for the driving torque. If we represent the mean of

the induced or eddy currents by I, and the average flux by ϕ, the driving force is given by

$$T=k\phi I$$

But the eddy currents are proportional to the product of flux and relative speed of the magnetic field and the disk, or

$$T=k''\phi^2 wr$$

where wr is the relative speed. It was shown that ϕ is the equivalent of two magnetic fields, rotating in opposite directions at the same angular speed. If in Fig. 1, OF_1 and OF represent ϕ_1 and ϕ_2, the opposite torques due to these two rotating fields are

$$T_1=k_1\phi_1^2(w_1+w)$$
$$T_2=k_1\phi_2^2(w_1-w)$$

Where w_1 is the angular speed of the rotating fluxes and is equal to $2\pi f$, w is the angular speed of the disk.

The retarding torque, due to the permanent magnets when at a fixed distance from the shaft, is given by

$$T_3=k_2\phi_3^2 w$$

where ϕ_3 represents the flux of the permanent magnets.

The retarding torque, due to the permanent magnets, is in the same direction as T_1, hence T_1+T_3 retard the disk, while T_2 drives it. When constant speed has been reached, the algebraic sum of these torques equals zero, or

$$T_2=T_1+T_3$$

thus

$$k_1\phi_2^2(w_1-w)=k_1\phi_1^2(w_1+w)+k_3\phi_3^2 w$$
$$k_1(\phi_2^2-\phi_1^2)=k_1(\phi_2^2+\phi_1^2)w+k_3\phi_3^2 w$$

but

$$\phi_2^2=H_1^2+H_2^2+2H_1H_2\sin\theta_0$$

and

$$\phi_1^2=H_1^2+H_2^2-2H_1H_2\sin\theta_0$$

Hence

$$\phi_2^2-\phi_1^2=4H_1H_2\sin\theta_0$$

and

$$\phi_2^2+\phi_1^2=2(H_1^2+H_2^2)$$

Therefore

$$4k_1H_1H_2w_1\sin\theta_0=2k_1(H_1^2+H_2^2)w+k_3\phi_3^2 w$$

w_1 equals $2\pi f$, and replacing $8\pi k_1$ by K_1, we have

$$K_1fH_1H_2\sin\theta_0=2k_1w(H_1^2+H_2^2)+k_3\phi_3^2 w$$

where the term $K_1fH_1H_2\sin\theta_0$ equals the driving torque, and $2k_1w(H_1^2+H_2^2)$ equals the retarding effect due to the rotating fields, and $k_3\phi_3^2 w$ equals the retarding effect due to the permanent magnets.

When w is low, the effect of $2k_1f(H_1^2+H_2^2)\,w$ is negligible and the retarding effect is due to $k_3\phi_3^2 w$.

Thus for all practical purposes

$$K_1fH_1H_2\sin\theta_0=k_3\phi_3^2 w$$

Now H_1 is proportional to the voltage, and H_2 is proportional to the series current in a watthour meter element. Then if

$$H_1=K'E$$
$$H_2=k''I$$

Then

$$K_1k'k''EIf\sin\theta_0=k_3\phi_3^2 w$$
$$EI\sin\theta_0=K_0\phi_3^2 w$$

Where

$$K_0=\frac{k_3}{K_1k'k''f}$$

That is, the product of current, pressure, and the sine of the phase difference between the magnetic field due to series and voltage currents respectively, is proportional to the speed of the disk. The actual power is, however equal to $EI\cos\theta$, hence,

$$\sin\theta_0=\cos\theta$$
$$\theta_0=\frac{\pi}{2}\pm\theta$$

It follows that when two elements are connected to a three phase delta load as in Fig. 2.

$$w=e_0i_0+e_1i_1+e_2i_2$$

and the torque equals

$$t=e_1i'_1+e_2i'$$

but

$$i'_1=i_1+i_0$$

and

$$i'_2=i_2-i_0$$

hence

$$w-t=e_0i_0+e_1i_1+e_2i_2-(e_1i_1+e_1i_0+e_2i_2-e_2i_0)$$
$$w-t=e_0i_0-e_1i_0+e_2i_0=i_0(e_0-e_1+e_2)$$

but

$$e_0-e_1+e_2=0$$

therefore

$$w-t=0$$

As the instantaneous torque is equal to the power, the average torque must equal the average power in the system regardless of balanced or unbalanced loads. The instantaneous torque on each element is

$$t_1=e_1i_1$$

and

$$t_2=e_2i_2$$

where e_1, e_2, i_1, and i_2 are the instantaneous line voltages and currents respectively. In a delta connected system e_1 and e_2 are the instantaneous voltages at load terminals, and i_1 and i_2 are the differences between currents in mains 1 and 0 and mains 2 and 0, Fig. 11.

Thus in Fig. 3, I_{1m}, I_{2m}, and I_{0m} are the maximum values of currents in branches AO, BO, and AB of Fig. 2. I_{1m} is shown as lagging θ degrees behind E_{1m}. The vector difference between I_{1m} and I_{0m} is I_m which lags 30° behind I_{1m} and $(\theta+30°)$ degrees behind E_{1m}. The average torque on one element is then $T_1=EI\cos(\theta+30°)$ degrees, and by similar process of reasoning it can be shown that the average torque on the other element is $T_2=EI\cos(\theta-30°)$ degrees, where E is the effective pressure between mains and I is the effective value of current in the mains.

When $\theta=0°$

$$T_1=T_2=EI\cos 30°$$

When $\theta=30°$

$$T_1=EI\cos 60°$$

$$T_2=EI \text{ or } 2T_1$$

When $\theta=45°$

$$T_1=EI\cos 75°$$

$$T_2=EI\cos 15°$$

When $\theta=60°$

$$T_1=EI\cos 90°=0$$

$$T_2=EI\cos 30°=\tfrac{1}{2}\sqrt{3}EI$$

When $\theta=90°$

$$T_1 = EI \cos 120 = -\frac{EI}{2}$$

$$T_2 = EI \cos 60 = +\frac{EI}{2}$$

In this case the two torques are equal and opposite.

Now it follows that if two more elements T_3 equivalent to T_1, and T_4 equivalent to T_2, respectively, but having their current elements reversed and their potential elements displaced by 90°, are connected mechanically together:

When $\theta=0°$

$T_1=T_2$ maximum positive direction of rotation

$$T_3 = -\frac{EI}{2} T_4 = +\frac{EI}{2} = \text{zero torque}$$

When $\theta=90°$

$$T_1 = -\frac{EI}{2} T_2 = +\frac{EI}{2} = \text{zero torque}$$

$T_3=T_4$ maximum negative direction of rotation

When $\theta=45°$

$T_1=EI \cos 75°$, and $T_2=EI \cos 15°=$
½ maximum positive direction of rotation
$T_3=EI \cos 75°$, and $T_4=EI \cos 15°=$
½ maximum negative direction of rotation

$$(+T_1)+(+T_2)=(-T_3)+(-T_4)$$

Thus no movement in either direction results and the contacts are in their normal or open position. Under these conditions the instrument indicates that a power factor of 70.7% exists regardless of the magnitude of the load or its degree of unbalance. At load power factors higher then 70.7% rotation will tend to be in a positive direction with its attendant closure of contacts, and at power factors under this value the opposite effect is obtained.

The angular speed of the moving contact is proportional to the degree of divergency from the normal zero torque condition existing at 70.7% power factor and the retarding force exerted by the permanent magnets. The other factor introduced in the time interval of contact closure is governed by the physical separation of the stationary contacts.

It will, of course, be understood that various details of construction may be varied through a wide range without departing from the principles of this invention and it is, therefore, not the purpose to limit the patent granted hereon otherwise than necessitated by the scope of the appended claims.

I claim as my invention:

1. In an electric arc furnace control having a charge portion in which the material to be melted is placed and a power circuit including a relatively movable electrode, control means responsive to the deviation of the power factor in the power circuit from a predetermined value, and means responsive to said control means for moving the electrode so as to change the power factor of the power circuit in a direction toward said predetermined value.

2. In an electric translating apparatus having a power circuit including a pair of electrodes across which current flows to produce an arc, means responsive to departure of arc current and arc voltage from a predetermined balance of arc current and arc voltage for changing the electrical characteristics of said power circuit, and

means responsive to the power factor of said power circuit for modifying said predetermined balance of arc current and arc voltage.

3. In an electric arc furnace, a power circuit including a pair of electrodes across which current flows to produce an arc during operation of the furnace, a first control circuit means responsive to the relative values of arc current and arc voltage, means responsive to said first circuit control means for varying the circuit characteristics of said power circuit, and second control circuit means responsive to the power factor of the power circuit for varying the response characteristics of said first control circuit means.

4. In an electric arc furnace, a power circuit including a pair of electrodes across which current flows to produce an arc during operation of the furnace, a first control circuit means responsive to the relative values of arc-current and arc-voltage, means responsive to said first circuit control means for varying the circuit characteristics of said power circuit, and second control circuit means including reference means responsive to an electrical condition of said power circuit for varying the response characteristics of said first control circuit means.

5. In a control circuit for a power circuit having a pair of electrodes across which an arc is drawn, balancing relay means responsive to the relative values of arc-current and arc-voltage, means responsive to operation of said balancing relay means for changing the electrical characteristics of the arc across said electrodes, and power factor responsive means responsive to the power factor in said power circuit for effecting a change in the response characteristics of said balancing relay means.

6. In an electric arc furnace having a relatively movable electrode from which an arc is drawn to a charge in the furnace, a first control circuit including a balancing relay having a first coil responsive to arc current and a second coil responsive to arc voltage, means responsive to operation of said balancing relay upon variation from a predetermined value of the effect of said first and second coils for effecting movement of said electrode, rheostat means for changing the relative effects of said first and said second coils to effect operation of said balancing relay, and means responsive to the power factor in said power circuit for correcting the effect of said rheostat means on said first and said second coils.

7. In an electric arc furnace having a relatively movable electrode from which an arc is drawn to a charge in the furnace, means including relay means having coils responsive to functions of the arc current and arc voltage for effecting movement of said electrode to maintain a predetermined balance between the arc current and arc voltage, and means responsive to a function of the phase angle between the arc current and arc voltage for modifying operation of said relay means to maintain a different balance between the arc current and voltage.

8. In an electric arc furnace, having a power circuit including a pair of electrodes across which a power arc is drawn, means for varying the relative values of arc current and arc voltage, and means responsive to the differences of functions of arc current and arc voltages and to the phase angle in the power circuit for controlling operation of said arc current and arc voltage varying means.

9. In an electric arc furnace having an electrode from which an arc is drawn to a charge

in the furnace when the electrode is connected to a source of potential, a first control circuit including a balancing relay having a first coil responsive to a function of arc current and a second coil responsive to a function of arc voltage, means responsive to an unbalance of said first and second coils for effecting raising or lowering of said electrode, rheostat means connected in shunt with one of said balancing relay coils for effecting operation of said balancing relay, and second rheostat means connected in shunt with said one of said balancing relay coils for effecting operation of said balancing relay, and means responsive to the phase angle between said power current and power voltage for effecting operation of said second rheostat means.

10. In an electric arc furnace having an electrode from which an arc is drawn to a charge in the furnace when the electrode is connected to a source of potential, a first control circuit including a balancing relay having a first coil responsive to a function of arc current and a second coil responsive to a function of arc voltage, means responsive to an unbalance of said first and second coils for effecting raising or lowering of said electrode, rheostat means connected in circuit with one of said balancing relay coils for effecting operation of said balancing relay, and a second rheostat means connected in circuit with one of said coils of said balancing relay, means for effecting operation of said balancing relay, and means responsive to the phase angle between said current and voltage flowing through said power circuit for effecting operation of said second rheostat means.

11. In an electric arc furnace having a pair of electrodes across which an arc is drawn during operation thereof, a power circuit for energizing said electrodes, and means responsive to the change in power factor of the power circuit for maintaining a predetermined power input into said furnace for a predetermined voltage impressed on said furnace.

12. In an electric arc furnace having an electrode across which an arc passes during operation thereof, a first control circuit including a balancing relay having a first coil responsive to a function of the arc current and a second coil responsive to a function of the arc voltage, operating means responsive to a predetermined unbalancing of said first and second coils for moving said electrode to vary the power current, manually operable rheostat means connected to one of said coils for unbalancing said coils for effecting operation of said balancing relay, and a second rheostat means connected to one of said coils and automatically operable in response to a function of said power circuit for unbalancing said balancing relay for effecting operation of said relay means.

13. In an electric arc furnace having an electrode across which an arc passes during operation thereof, a first control circuit including a

balancing relay having a first coil responsive to a function of the arc current and a second coil responsive to a function of the arc voltage, operating means responsive to a predetermined unbalancing of said first and second coils for moving said electrode to vary the power current, manually operable rheostat means connected to one of said coils for unbalancing said coils for effecting operation of said balancing relay, and a second rheostat means connected to one of said coils and automatically operable in response to a variation of the power factor of said power circuit from a predetermined value for unbalancing said balancing relay for effecting operation of said operating means.

14. In an electric arc furnace having an electrode across which an arc passes during operation thereof, a first control circuit including a balancing relay having a first coil responsive to a function of the arc current and a second coil responsive to a function of the arc voltage, operating means responsive to a predetermined unbalancing of said first and second coils for moving said electrode to vary the power circuit, manually operable rheostat means connected across one of said coils for unbalancing said coils for effecting operation of said balancing means, and a second rheostat means connected across said one of said coils and automatically operable in response to a variation of the power factor of said power circuit for unbalancing said balancing relay for effecting operation of said operating means.

15. The method of control of an electric arc furnace having relatively movable electrodes and a power circuit supplying current to said electrodes which includes the step of moving said electrodes relative to each other as a function of the power factor of the furnace current to maintain a predetermined power factor.

16. The method of control of an electric arc furnace having relatively movable electrodes and a power circuit supplying current to said electrodes which includes the step of moving said electrodes relative to each other as a function of the departure of the power factor of the furnace current from a predetermined value to maintain such predetermined power factor.

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