

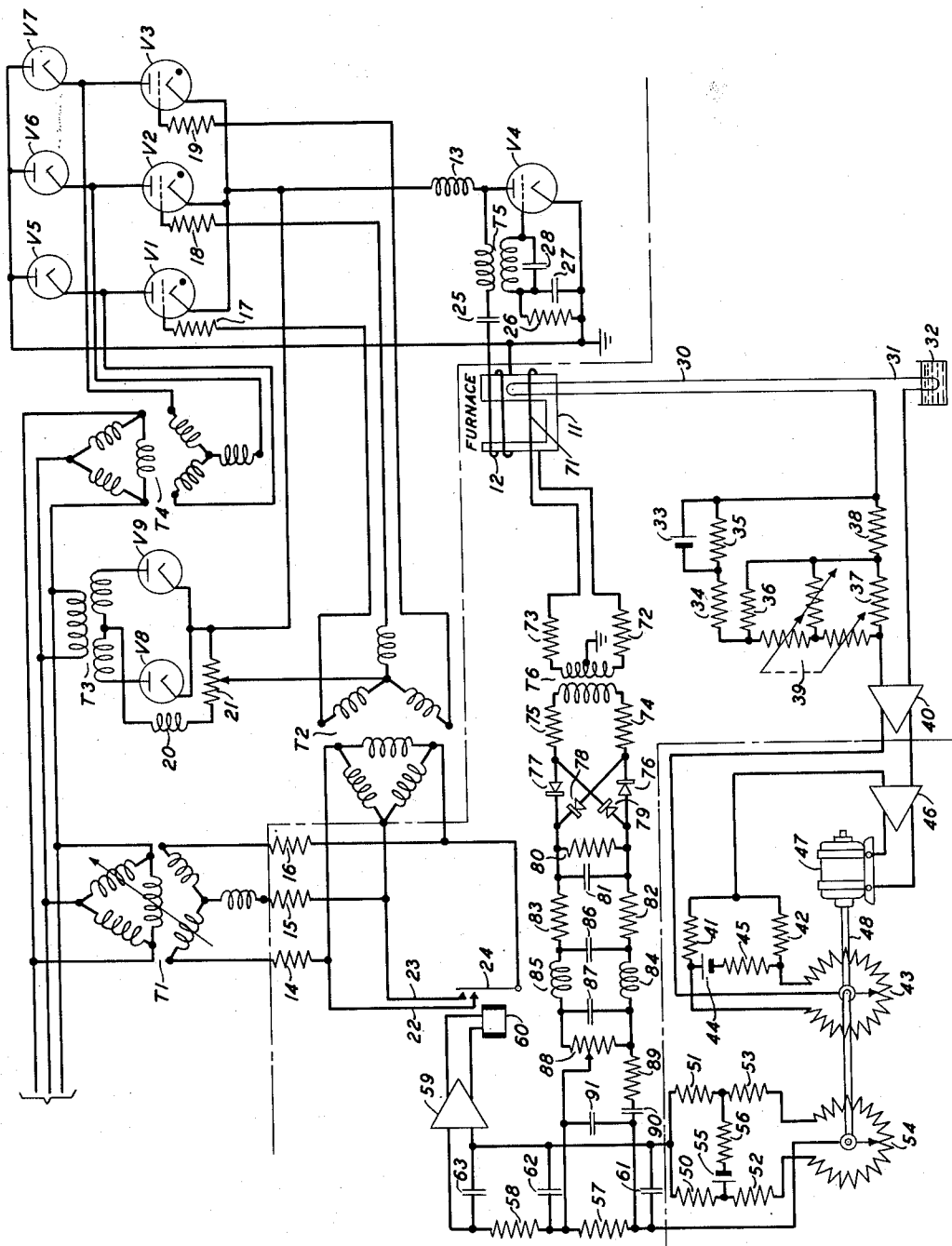
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TEMPERATURE-CONTROLLED INDUCTION FURNACE

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TEMPERATURE-CONTROLLED INDUCTION FURNACE

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4 Claims. (Cl. 13—24)

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This application relates to feedback control devices, and particularly to a system for controlling the temperature of an induction furnace.

The object of the invention is a system for controlling, within close limits, the temperature of an induction furnace.

A feature of the invention is a relay having contacts directly controlling the supply of power to the induction furnace.

Another feature of the invention is an auxiliary feedback loop energized by the power supplied to the furnace and supplying reverse feedback which serves to minimize the fluctuation of the power supply.

A further feature of the invention is the use of the auxiliary feedback loop to supply a carrier frequency used to transform the relay from an on-off device to a linear power amplifier, the gain of which can be controlled by adjusting the amplitude of the carrier.

The drawing shows a typical system embodying the invention.

The present system controls the temperature of an induction furnace, including a crucible 11, made of some infusible material, such as carbon, and an inductive winding 12, which heats the crucible 11 by inducing electrical currents therein. The furnace would also include any suitable mounting means, and heat insulation, etc. (not shown).

A suitable type of commercial power supply for energizing the furnace is shown in the upper portion of the drawing, but the invention is not limited to the use of this specific type of power supply, as many other known power supplies may be adapted for use in the system.

The primary windings of the power transformer T4 are connected to a suitable source (not shown) of three-phase alternating power. The secondary windings of transformer T4 are respectively connected to the anodes of the gas-filled triodes V1, V2, V3, and to the cathodes of the diodes V5, V6, V7. The cathodes of the triodes V1, V2, V3, are connected through choke coil 13 to the anode of the oscillator triode V4. The cathode of V4 is connected to the anodes of the diodes V5, V6, V7. When suitable potentials are supplied to the control grids of the triodes V1, V2, V3, currents will flow from one, or two, of the secondary windings of transformer T4, and the corresponding triodes through choke 13, triode V4, and two, or one, of the diodes back to the secondary windings.

The primary winding of transformer T3 is connected to some convenient source of power, such as one phase of the power supply; and the second-

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ary windings are connected to the anodes of the diodes V8, V9. The cathodes of the diodes V8, V9, are connected to one end of the winding of potentiometer 21, the other end of this winding being connected through choke 20 with the junction of the secondary windings of transformer T3. A pulsating unidirectional voltage will be developed across the winding of potentiometer 21.

The secondary windings of the isolation transformer T2 are respectively connected, through resistors 17, 18, 19, to the control grids of the triodes V1, V2, V3; the neutral point of these windings is connected to the brush of potentiometer 21; and the cathodes of diodes V8, V9, are connected to the cathodes of triodes V1, V2, V3. The brush of potentiometer 21 is adjusted so that, in the absence of other voltages, the bias voltage applied to the control grids of the triodes V1, V2, V3, is larger than the critical value, and the triodes V1, V2, V3, cannot conduct any anode currents.

The cathodes of tubes V1 to V9 are energized by the usual means (not shown).

The primary windings of the rotary, phase shifting, transformer T1 are connected in parallel with the primary windings of the power transformer T4; and the secondary windings of transformer T1 are respectively connected, through resistors 14, 15, 16 to the primary windings of the isolation transformer T2. The voltages induced in the secondary windings of transformer T2 overcome the bias voltage from potentiometer 21 and cause the triodes V1, V2, V3, to become conductive in regular order. By adjusting transformer T1, the portion of the cycle of the alternating voltage during which the triodes V1, V2, V3, are conducting may be adjusted, thus setting the average power delivered at a value which will approximately maintain the furnace at the desired temperature.

The relay contacts 22, 23, 24, are respectively connected to the primary windings of transformer T2, and, when these contacts are closed, the primary windings are short-circuited, cutting off the energization of transformer T2, so that the bias from potentiometer 21 will prevent the triodes V1, V2, V3 from conducting.

The control grid of triode V4 is connected through the primary winding of transformer T5, and the biasing resistor 26 and capacitor 27 to the cathode. Capacitor 28 tunes transformer T5 to some desired frequency, preferably in the supersonic range of frequencies. The anode of triode V4 is connected through the secondary winding of transformer T5, capacitor 25 and the

induction winding 12 to the cathode. When the triode V4 is supplied with anode current from the triodes V1, V2, V3, the system will oscillate and supply alternating power to the winding 12. The winding 12, and the cathode of triode V4 preferably are connected to ground.

A thermocouple 30 is associated with the furnace 11 in any suitable manner, to measure the temperature of some desired region. The cold junction 31 is maintained at constant temperature by some suitable means, such as the ice bath 32.

If the furnace temperature is to be maintained within a narrow range of temperature, a large part of the thermocouple voltage may be neutralized to increase the percentage variation in the control voltage. A suitable source of voltage 33, such as a stable dry cell, is associated with resistors 34, 35, 36, 37, 38, so that the voltage drops across resistors 37, 38, will oppose and neutralize a large part of the voltage from the thermocouple 30, 31. The network 39 may be adjusted to compensate for any slight change in the voltage of the source 33. The residual voltage is amplified in a suitable amplifier 40.

The apparatus shown in the lower left portion of the drawing schematically illustrates a known form of recorder. Resistors 41, 42, with the winding of potentiometer 43 form a bridge circuit, energized by current from the source 44 through resistor 45. The brush of potentiometer 43 is driven by shaft 48, but is insulated therefrom, and is connected to the output circuit of amplifier 40 to oppose the amplified residual thermocouple voltage. The junction of resistors 41, 42, is connected to one side of the input circuit of amplifier 46, and the other side of the input circuit of amplifier 46 is connected to the output circuit of amplifier 40. The output circuit of amplifier 46 is connected to servomotor 47, driving shaft 48. If the potential selected by the brush of potentiometer 43 is not equal to the output voltage of amplifier 40, motor 47 is energized, driving shaft 48 until the voltage supplied to the input circuit of amplifier 46 is reduced to a small value.

Resistors 50, 51, 52, 53, with the winding of potentiometer 54, form a bridge energized by current from the source 55, through resistor 56. The brush of potentiometer 54 is connected through resistors 57, 58 to one side of the input circuit of amplifier 59, while the other side of the input circuit is connected to the junction of resistors 50, 51. The output circuit of amplifier 59 is connected to the relay winding 60, controlling contacts 22, 23, 24.

The brush of potentiometer 54 is driven by shaft 48, but is insulated therefrom, thus, if the furnace temperature is too high, an unbalanced voltage will be supplied to the input circuit of amplifier 46 which drives motor 47, moving the brush of potentiometer 54 to supply a voltage to the input circuit of amplifier 59 which energizes winding 60 to close contacts 22, 23, 24, cutting off the supply of alternating power to the furnace. When the temperature of the furnace falls, the motor 47 moves the brush of potentiometer 54 to reduce the voltage supply to amplifier 59, deenergizing the winding 60 to release the contacts 22, 23, 24. The system, as described, will operate as an on-off servo control loop. The relay 60 preferably is a known type of relay having mercury wetted contacts.

A pick-up coil 71 is disposed in inductive relationship with the induction winding 12, and

is connected through resistors 72, 73 to the primary winding of transformer T6. The secondary winding of transformer T6 is connected through resistors 74, 75, to the full-wave rectifier formed of elements 76, 77, 78, 79, which is terminated by resistor 80. Resistors 82, 83, inductors 84, 85 and capacitors 81, 86, 87 form a filter, which is terminated by the winding of potentiometer 88. One end of the winding of potentiometer 88 is connected through resistor 89 and capacitor 90 to one end of resistor 57, while the brush of potentiometer 88 is connected to the junction of resistors 57, 58. Capacitor 91 is connected across resistor 57, while capacitors 61, 62, 63, are connected across the input circuit of amplifier 59, to form with resistors 57, 58, a low-pass filter.

The main control loop, including servomotor 47, is energized by the thermocouple voltage, and, thus, responds rather slowly to a change in the alternating power supplied to the furnace; whereas, the auxiliary loop, including the pick-up coil 71 is energized directly by the alternating power supplied to the furnace and will rapidly respond to any variations in the alternating power supplied to the furnace, thus stabilizing the operation of the system.

In a particular application of the system, any deviation from the specified temperature must be corrected and averaged out within 6 seconds, thus requiring the system to function as a controller for error frequencies as high as 0.167 cycle per second. From the theory of servomechanisms, it may be shown that, if a servo system is permitted to oscillate, the oscillating frequency is twice the highest error frequency at which it will function, thus, the oscillating frequency of the present system should be, at least, 0.334 cycle per second. A larger frequency of self-oscillation will increase the accuracy and speed of the control action.

Without the auxiliary control loop the main control loop will function as a simple on-off temperature control system. Since the relay operates very rapidly, and has no neutral position, the alternating power is either on, or off, and the temperature of the furnace will oscillate about the desired temperature. If the heating effect of the alternating power, and the cooling tendency of the furnace are well matched, the power will be turned on for about one-half of the time. In this case, the highest frequency of oscillation of the system is obtained when the power generator is adjusted to deliver maximum power during the power-on periods and the rate at which the furnace cools is adjusted to be equal to the rate at which this power causes it to heat. The period of self-oscillation of the main control loop under these conditions is approximately $1\frac{3}{4}$ seconds, equivalent to 0.57 cycle per second, which is considerably larger than the required minimum value of 0.35 cycle per second.

The auxiliary control loop provides local reverse feedback around amplifier 59, relay 60, and the alternating power generator. In addition to directly controlling the alternating power supplied to the furnace, the auxiliary control loop acts to improve the transmission versus frequency characteristic of the system, so that the period of self-oscillation of the main control loop is reduced from $1\frac{3}{4}$ seconds to $1\frac{1}{2}$ seconds, increasing the frequency to 0.67 cycle per second.

While satisfactory results may be obtained from an off-on system, better results will be obtained

in certain applications if the magnitude of the corrective effort of the system is proportional to the error. Proportional operation may be secured by designing the complete auxiliary loop so that this loop will oscillate at a frequency which is at least five times the highest frequency of the error, and may conveniently be say 10 cycles per second. Due to the transformations of power in the auxiliary loop, the oscillatory current will not be sinusoidal, but will appear as a rectangular wave at the relay contacts, and the duty cycle of this wave will be varied by the error signal from the main control loop.

These 10 cycles per second oscillations serve as a carrier current to linearize the operation of the relay 60; and may provide a gain adjustment of the transmission around the main control loop. By adjusting the amplitude of the 10-cycle carrier at potentiometer 88, the control loop can be transformed from a simple oscillating control system to one in which the transient response is under-damped, critically damped, or overdamped.

The low-pass filter, formed of elements 81 to 87 may have a 16 cycles per second cut-off, to discriminate against undesired currents, yet to determine the auxiliary loop oscillating frequency at 10 cycles per second.

What is claimed is:

1. In combination with a furnace energized by an inductive winding, temperature sensitive means mounted in said furnace, a main control circuit connected to said sensitive means to produce an error voltage representing the difference between the temperature indicated by said sensitive means and a desired temperature, an amplifier connected to said control circuit and energized by said error voltage, a relay having a winding connected to said amplifier and a set of con-

tacts, a source of alternating power connected to said inductive winding and controlled by said relay contacts, a pick-up coil inductively associated with said inductive winding, and a circuit connecting said pick-up coil to said amplifier.

2. The combination in claim 1 in which said coil, amplifier, relay and source are designed to produce a low frequency oscillation.

3. The combination in claim 1 in which said coil, circuit, amplifier, relay and source function as a local feedback loop which corrects extraneous fluctuations in the power supplied by said source and does so at a speed several times that at which the main control loop is capable of function.

4. In a power control system a source of electrical power, a power consuming load connected to said source, pick-up means associated with said load, a low-pass filter connected to said pick-up means, a level control connected to said filter, an amplifier connected to said level control and a relay having an operating winding connected to said amplifier and a set of contacts controlling the power supplied to said load, said pick-up means, filter, level control, amplifier, relay and source being designed to produce a low frequency oscillation of said contacts.

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