March 5, 1946. R. W. GILBERT 2,396,004

HIGH FREQUENCY DIELECTRIC HEATING APPARATUS

Filed Nov. 24, 1943

Fig. 1.

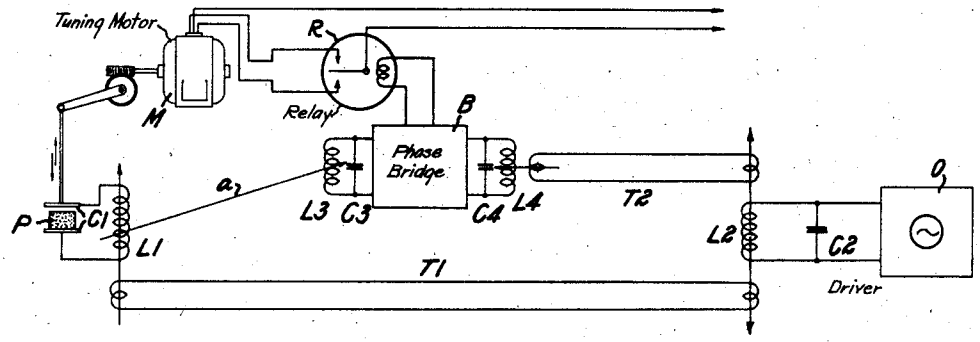


Fig. 2.

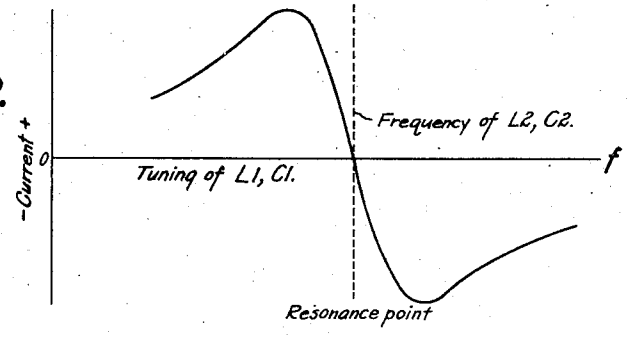


Fig. 3.

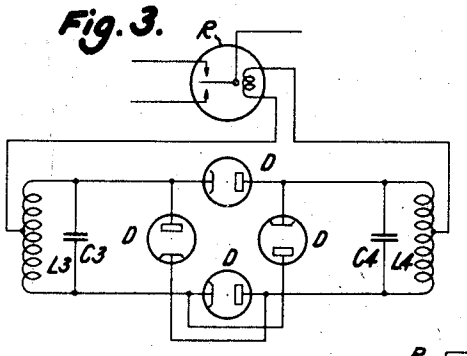


Fig. 4.

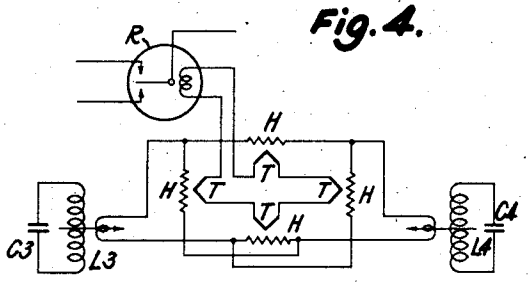
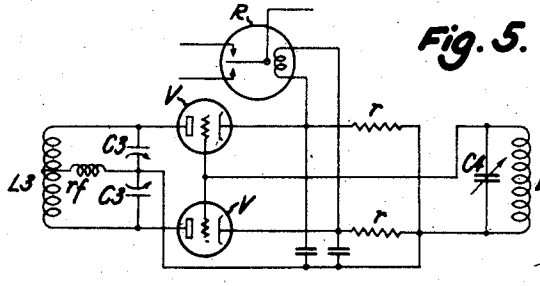


Fig. 5.



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HIGH-FREQUENCY DIELECTRIC HEATING APPARATUS

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10 Claims. (Cl. 219—47)

This invention relates to high frequency dielectric heating apparatus, and particularly to heating apparatus of the type including a radio frequency driving unit or oscillator and one or more heating heads having resonant tank circuits coupled to the driving unit.

The size of the radio frequency driving equipment used in dielectric heating for plastic molding makes it impractical of location on the molder's bench and a remote connection to a relatively small heating head unit is desirable. Whether or not dimensional considerations impose this design requirement, it is not advisable to include the material to be heated directly in the main tank circuit of the driving equipment in view of the rather large temperature coefficient of dielectric constant of all thermo-setting molding materials. Government regulations require that high frequency heating equipment be maintained within allocated frequency channels because of possible stray radiations, but the oscillator frequency, particularly in the case of self-excited oscillators, drifts prohibitively when the molding material is located directly in the main oscillator circuit. Separate heating heads have been employed to avoid this frequency drift of the oscillator and to facilitate use at the molder's bench. The same detuning action takes place during heating of molding material located in the tank circuit of a heating head, and the detuning may be as much as fifteen percent in frequency. This detuning of the heater head circuit may not cause a prohibitive drift of the oscillator frequency but it does reduce the transfer of energy to the heating circuit.

An object of this invention is to provide a dielectric heating system including a high frequency oscillator, a heating circuit coupled to the oscillator, and electrical circuits for automatically maintaining the heating circuit in resonance with the oscillator during the heating of the thermo-setting or thermo-plastic material. An object is to provide a heating system of the type stated in which a phase sensitive bridge circuit develops a current for controlling a reversible tuning motor to maintain resonance of the heating circuit. Another object to to provide a high frequency dielectric heating system in which the heating circuit of a heating head is automatically tuned to resonance with the main tank circuit of a driving oscillator by a phase sensitive bridge, the bridge being coupled to the heating circuit and the tank circuit but affording substantially no cross-coupling between the same.

These and other objects and advantages of the invention will be apparent from the following specification when taken with the accompanying drawing in which:

Fig. 1 is a schematic diagram of an embodiment of the invention;

Fig. 2 is a curve showing the relation between the current output of the phase sensitive bridge and the tuning of the heating circuit; and

Figs. 3, 4 and 5 are circuit diagrams of different types of phase sensitive bridge networks that may be employed in the Fig. 1 circuit.

In Fig. 1 of the drawing, the resonant circuit L1, C1 contains the plastic material P to be heated as the dielectric of the condenser C1. This circuit is coupled to the high frequency output tank circuit L2, C2 of the driver oscillator O through an aperiodic transmission line T1, and the circuit L1, C1 must be kept in resonance with the driving frequency during the heating cycle for efficient energy transfer. The resonant frequency of the heating circuit is controlled by a reversible motor M having an appropriate mechanical coupling to an adjustable element of one of the circuit reactances, for example to a plate of the condenser C1.

In accordance with this invention, the motor M is controlled automatically to maintain the heating circuit L1, C1 in resonance with the driver output tank circuit L2, C2. A resonant circuit L3, C3 is adjustably and loosely coupled to the heating circuit, as indicated by the arrow *a*, and another resonant circuit L4, C4 is coupled to the driver output circuit L2, C2 by an aperiodic transmission line T2 that is similar to the transmission line T1 but more loosely coupled to equal, approximately, the coupling factor of the L1, C1 and L3, C3 circuits. A phase sensitive bridge network, indicated by the block B, is connected between the circuits L3, C3 and L4, C4 to develop a direct current that varies in direction and magnitude with the sense (capacitive or inductive) and the extent of the detuning of the heating circuit, and the direct current output of the bridge energizes a polarized relay R to control the reversible motor M to correct the tuning of the heating circuit by a progressive adjustment of a continuously variable reactance.

When all circuits are in resonance, the L4, C4 circuit will be in phase with the heating circuit L1, C1 because both are coupled to the driving circuit L2, C2 in similar manner. The circuit L3, C3 is loosely coupled to circuit L1, C1 however, and will be in the quadrature phase that is characteristic of loosely coupled circuits. Thus, when circuit L1, C1 is in exact resonance with the driv-

er frequency, the two inputs to the phase sensitive bridge will be in quadrature. If circuit L1, C1 detunes from the driver frequency during a heating operation, it will shift in phase relative to the driver frequency and, in turn, will shift the circuit L3, C3 from its quadrature phase relationship with the circuit L4, C4, the direction of the shift being dependent upon whether the detuning of circuit L1, C1 is capacitive or inductive in direction.

The phase sensitive bridge can be of any of the so-called modulator bridges or ring modulators containing non-linear elements in a balanced circuit arrangement. Characteristically these devices deliver a modulation product output that is a function of the magnitude of the two input components times the cosine of their relative phase angles. If, as in this case, the two input components are of the same frequency the output will be direct current of a magnitude and direction dependent upon the phase and magnitude of the input components, and is zero when the phase is quadrature. Thus in the circuit of Figure 1 the phase sensitive bridge delivers a direct output current that is zero when L1, C1 is in exact resonance, of one polarity when detuned capacitively and of opposite polarity when detuned inductively. The characteristic bridge output in response to detuning is affected by the various magnitude changes accompanying detuning as well as phase, but the resonant point is unaffected by magnitude and this effect is unimportant. The curve of Fig. 2 illustrates a typical overall bridge output in response to heating head circuit detuning. The windings of the tuning motor M are so connected to the contacts of the relay R that the motor is energized to adjust the inductance L1 or the condenser C1, or both, in the proper sense to return the heating circuit to resonance with the driving circuit.

Any influence, such as the temperature-variant dielectric constant or the thermo-sensitive plastic material, that changes the capacity of the condenser C1 initiates a corrective action to restore optimum operating conditions. Various types of reversible motors may be employed in place of the rotary type that is shown schematically in Fig. 1, for example motors of the heated bimetallic strip or the solenoid-operated plunger types, and various types of phase sensitive bridges may be employed.

Different types of phase sensitive bridges that may be employed in the heating system are illustrated in Figs. 3 to 5. A simple ring modulator bridge of rectifier elements, specifically diodes D, is shown in Fig. 3. The resonant input circuits L3, C3 and L4, C4 form the conjugate arms of the bridge, and the relay R is connected to the midpoints of the inductances L3, L4. Other forms of non-linear elements suitable for operation at high frequency may be substituted for the diodes. As shown in Fig. 4, the phase sensitive bridge network may employ heater-thermocouple elements which, having square law input-output characteristic, function as non-linear elements. The heaters H are arranged in a closed circuit across which the input circuits L3, C3 and L4, C4 are connected, and the thermocouples T are connected in a series circuit including the relay R.

A preferred type of bridge circuit, as shown in Fig. 5, eliminates cross coupling of the resonant input circuits and thereby avoids loss of sensitivity and affords greater stability of operation. The ends of the inductance L3 are connected to the anodes of a pair of triode vacuum tubes V, and the center tap of L3 is connected through a radio frequency choke *rf* to the junction of the independently adjustable condensers C3, C3 and to the cathodes of the tubes through resistors *r*. The resonant circuit L4, C4 is connected between the cathodes and grids of the tubes V, and the relay R is connected across the cathodes of the tubes. The circuits L3, C3 and L4, C4 are substantially isolated from each other as the only cross coupling through the phase sensitive bridge network is that caused by interelectrode mutual capacitance which can be made negligible. The condensers C3 may be adjusted individually so that plate circuit excitation may be balanced for operational symmetry, and phase unbalance due to unequal mismatching of the transmission lines T1, T2 may be compensated by a slight detuning of either or both of the bridge input circuits.

The circuit of Figure 1 shows the high frequency driver remotely coupled to the other circuit components because in practice this is desirable. However, the transmission lines basically contribute nothing to circuit function, and the tank circuits shown so coupled may be directly coupled provided they are suitably disposed to minimize cross coupling, for example from the driver circuit L2, C2 directly to L3, C3. Other variations are also obvious. For example the heating head tank circuit L1, C1 may be tuned by motor control of an adjustable inductance L1 instead of C1.

It is to be understood that other variations that may occur to those familiar with the design and operation of high frequency circuits fall within the spirit of my invention as set forth in the following claims.

I claim:

1. A high frequency dielectric heating apparatus comprising a radio frequency power source having a tank circuit, a heating circuit coupled to said tank circuit, the reactive elements of said heating circuit being an inductance and a condenser having plates between which the material to be heated will be placed, a reversible motor for adjusting one of said condenser plates, thereby to tune said heating circuit, and means for automatically controlling said motor to maintain said heating circuit in resonance with said tank circuit; said means including a phase sensitive bridge network having resonant input circuits coupled respectively to said tank circuit and said heating circuit.

2. A high frequency dielectric heating apparatus as recited in claim 1, wherein one of the resonant input circuits of the bridge network is coupled to its associated circuit through an aperiodic transmission line.

3. A high frequency dielectric heating apparatus as recited in claim 1, wherein said resonant input circuits are coupled to their associated circuits by aperiodic transmission lines.

4. A high frequency dielectric heating apparatus as recited in claim 1, wherein the tank circuit is coupled to said heating circuit and to its associated bridge input circuit by approximately equal coupling factors.

5. A high frequency dielectric heating apparatus comprising a radio frequency power source having a tank circuit, a heating circuit coupled to said tank circuit, the reactive elements of said heating circuit being an inductance and a condenser having plates between which the material to be heated will be placed, one of said reac-

tive elements being continuously variable for tuning the heating circuit, a reversible motor for adjusting said continuously variable reactive element to tune the heating circuit, and means for automatically controlling said motor to maintain said heating circuit in resonance with said tank circuit; said means including a phase sensitive bridge network having resonant input circuits coupled respectively to said tank circuit and said heating circuit, a direct current output circuit for said bridge network, and a relay in said output circuit, said relay having contacts in the reversing control circuits of said motor.

6. In a high frequency dielectric heating apparatus, a radio frequency power source having a tank circuit, a heating circuit coupled to said tank circuit, said heating circuit comprising an inductance connected across condenser plates between which dielectric material to be heated will be placed, a reversible motor for adjusting one of said condenser plates, thereby to tune the heating circuit, a polarized relay for controlling the energization of said motor, and means responsive to the sense and the magnitude of the detuning of the heating circuit from resonance with the tank circuit for supplying a current to said relay; said means comprising a modulator bridge with non-linear side arms connected between conjugate input circuits coupled respectively to said tank circuit and said heating circuit, and a direct current output circuit connected to said polarized relay.

7. In a high frequency dielectric heating apparatus, the invention as recited in claim 6, wherein said non-linear elements are rectifiers.

8. In a high frequency dielectric heating apparatus, the invention as recited in claim 6, wherein said non-linear elements are diode rectifiers.

9. In a high frequency dielectric heating apparatus, the invention as recited in claim 6, wherein said non-linear elements are heater-thermocouple elements.

10. In a high frequency dielectric heating apparatus, a radio frequency power source having a tank circuit, a heating circuit coupled to said tank circuit, said heating circuit comprising an inductance connected across condenser plates between which dielectric material to be heated will be placed, a reversible motor for adjusting one of said condenser plates to tune said heating circuit, a polarized relay for controlling the energization of said motor, and means responsive to the sense and the magnitude of the detuning of the heating circuit from resonance with the tank circuit for supplying a current to said relay; said means comprising a phase sensitive network comprising a pair of tubes each having a grid and plate cooperating with a cathode, a pair of resonant input circuits coupled respectively to said tank circuit and to said heating circuit, one input circuit being connected across the plates of said tubes, a connection from the mid-point of that input circuit to the cathodes of said tubes through resistors individual to the tubes, the second input circuit being connected between the grids of the tubes and the cathodes through said individual resistors, and means connecting said polarized relay across the tube cathodes.

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