Nov. 9, 1948. E. MITTELMANN 2,453,529

METHOD OF HIGH-FREQUENCY HEATING

Filed July 19, 1943 2 Sheets-Sheet 1

Fig. 1.

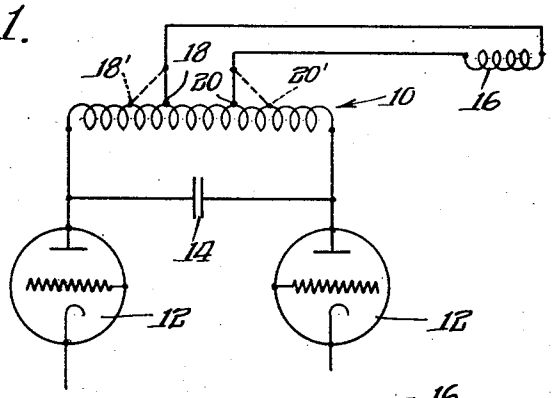


Fig. 2.

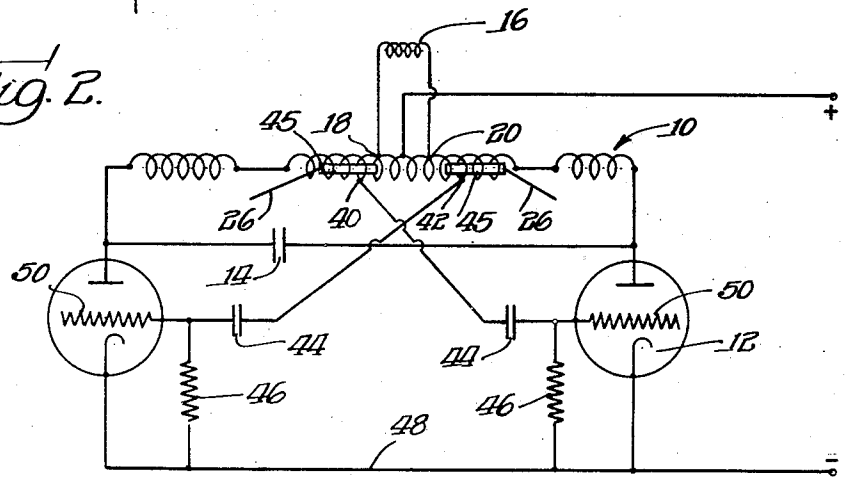
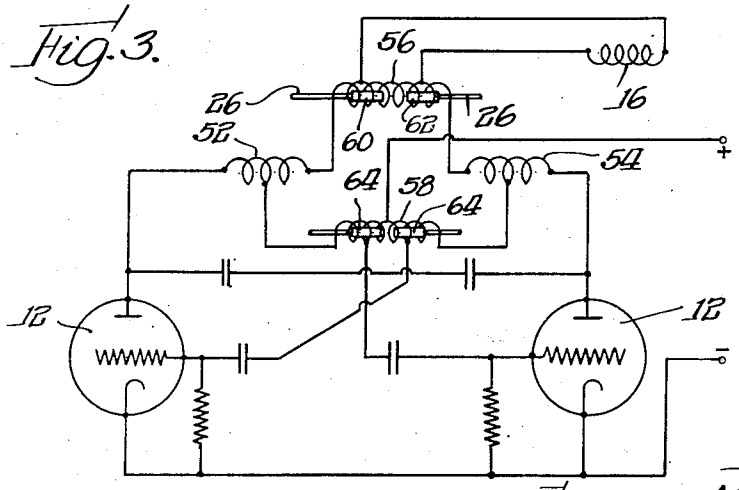


Fig. 3.



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Fig. 4.

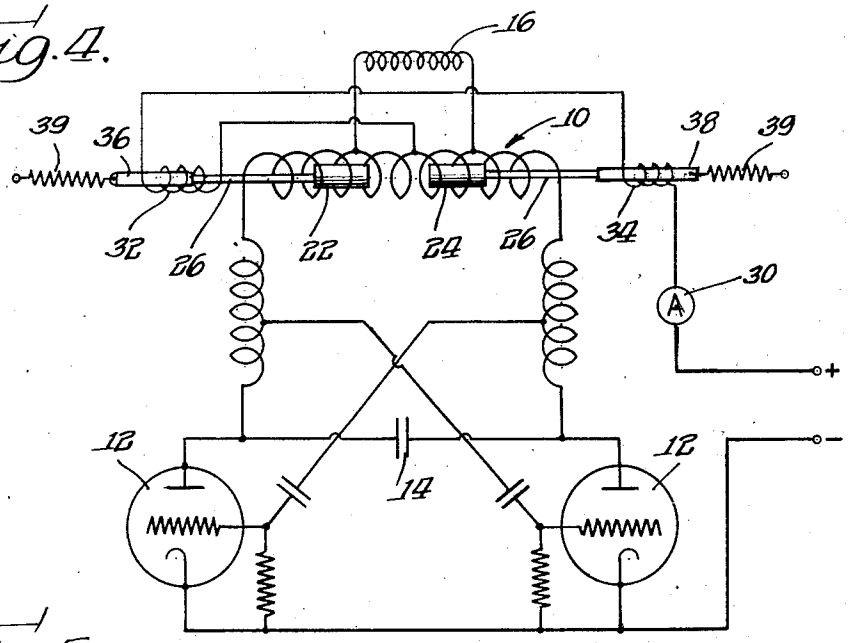


Fig. 5.

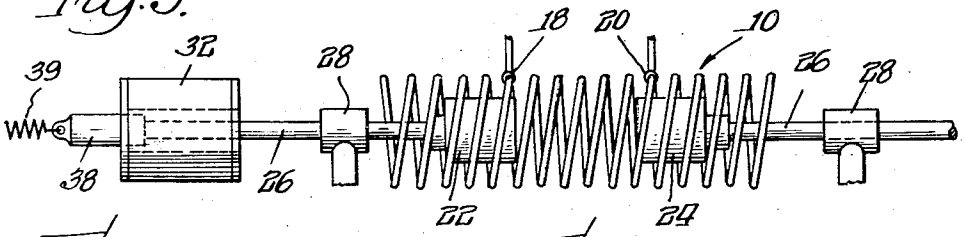


Fig. 6.

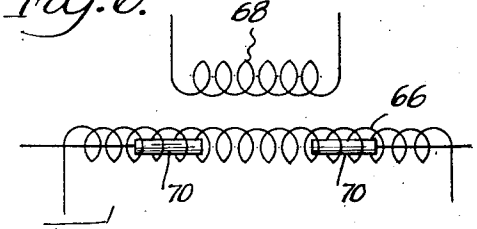


Fig. 7.

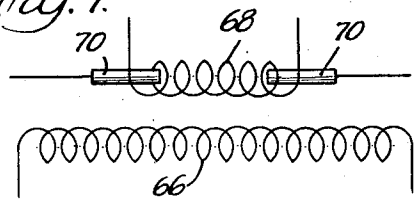


Fig. 8.

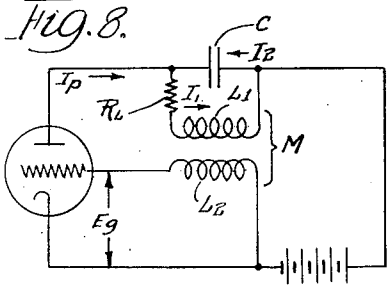
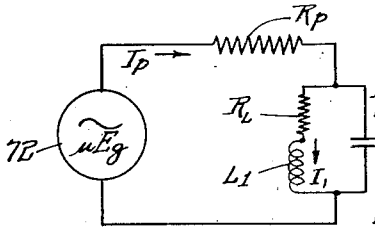


Fig. 9.



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2,453,529

UNITED STATES PATENT OFFICE

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METHOD OF HIGH-FREQUENCY HEATING

Eugene Mittelmann, Chicago, Ill.

Application July 19, 1943, Serial No. 495,273

3 Claims. (Cl. 219—13)

1

This invention relates to a method and means for heating objects and materials by high frequency current, and to an oscillator therefor.

A primary object of my invention is to provide means for maintaining oscillations in a self-excited oscillator notwithstanding variations in the load supplied by the oscillator, and for maintaining the load matched to the oscillator so that an optimum transfer of energy may be effected from the oscillator to the load as the load varies.

More specifically, it is an object of the invention to provide methods and means for so controlling a self-excited oscillation generator as to insure the maintenance of oscillations as the electrical characteristics of a heating load vary with the temperature to which it is heated, and to secure an optimum transfer of energy from the self-excited oscillation generator to the heating unit throughout the entire heating cycle.

A further object of the invention is to provide continuous impedance matching of the tank circuit of a self-excited high frequency oscillation generator to its load where the load impedance is variable.

My invention contemplates the provision of means for varying the inductance of desired portions of an inductance coil by selective variation of the permeability of localized parts of the magnetic field of the coil.

The invention may also be utilized to give smooth control of feed-back in a self-excited high frequency generator.

It is also an object of the invention to provide means to obtain selective variation in the impedance ratio of a tapped coil, or of coupled coils, without changing or switching tap connections to the coil, and preferably without substantial change of the total coil impedance.

Another object of the invention is to provide an impedance control of the character referred to, which can be made responsive to current or voltage variations in the circuits of the oscillator or in the circuits coupled to the oscillator, and which can be used to provide continuous and automatic impedance variation effective to maintain desired optimum conditions in the oscillator circuits and the circuits coupled thereto.

Thus the invention contemplates the matching of the tank circuit of a self-excited oscillation generator to a load or to the control of the feed-back in such oscillation generator, or to a combination of both matching and control of feed-back, in which latter case a constant impedance match at constant power level may be maintained.

2

It will be evident from the description that follows that the invention has utility in many other applications than the ones specifically mentioned and that it may be utilized to vary the impedance ratio of a high frequency transformer or autotransformer, and that such variation may be smoothly effected in response to the current or voltage conditions in any part of the oscillator circuits or of the circuits associated with the oscillator circuits.

Other objects and advantages of the invention will be apparent from the following description when taken in connection with the accompanying drawings, wherein:

Figure 1 is a schematic diagram of the tank circuit and oscillator with a load circuit conductively coupled to the tank coil.

Figure 2 is a schematic diagram illustrating the use of the invention for feed-back control.

Figure 3 is a schematic diagram of an oscillator circuit showing the invention used both for feed-back and coupling control to maintain the load matched to the generator and to maintain the oscillations of the generator, all as the load varies.

Figure 4 is a schematic diagram of an oscillator embodying the invention and showing automatic means for controlling the coupling and feed-back in response to plate current variations.

Figure 5 is a fragmentary enlarged view of the automatic control means diagrammatically shown in Figure 4.

Figures 6 and 7 are schematic diagrams illustrating other manners of using the invention to control the impedance ratios of transformers which may be used to couple an oscillator to a load.

Figure 8 is a schematic diagram of the fundamental circuit of an oscillator illustrating certain principles of the invention.

Figure 9 is a schematic diagram of the equivalent circuit of an oscillator, for illustrating certain principles of the invention.

The present application is a continuation-in-part of my application Serial No. 384,662, filed March 22, 1941, now Patent No. 2,324,525, dated July 20, 1943, and a continuation-in-part of my application Serial No. 452,101, filed July 23, 1942, now abandoned.

In the drawings the reference numeral 10 is used to designate generally an inductance coil. The numeral 12 is used to indicate electron tubes, schematically indicated as the conventional triodes. In Figure 1 only the tank circuit of the oscillator is shown, with its connections to the plates of the oscillator tubes 12. The tank circuit

consists of the inductance 10 shunted by the tank condenser 14. A coil 16 is used to transfer the high frequency energy from the oscillator tank circuit to a load, the coil 16 being connected to the tank coil 10 at taps 18 and 20.

When the oscillator is used as a generator, as in heat treating or drying apparatuses, the load consists of some conductive object in the field of the heating coil 16. The coil 16, with an object or material positioned in the field thereof, has an effective impedance which varies with the temperature of the object. This effective load impedance also varies with the objects or materials as successive objects are placed in the field of the coil to be heated thereby.

It is well known that maximum power transfer is obtained between coupled units when the impedance of the load circuit matches that of the supply unit. The connection of the load circuit to the taps 18 and 20 makes the coil 10 an impedance matching device since it functions simply as a step-down autotransformer which by the proper selection of taps may be utilized to match the impedance of the oscillation generator to that of the load in order to secure maximum power transfer from the generator to the load. For example, as the effective impedance of the load increases, the step-down ratio of the transformer may be adjusted by changing the connections of the heater coil from the taps 18 and 20 to the taps 18' and 20', as suggested by the dotted lines in Figure 1, so that the portion of the tank coil included between the taps is thus of greater inductance and the impedance matching condition between the load and the generator restored.

The making of such changes with sufficient rapidity and most conveniently, requires in practice some sort of switching or relay arrangement to effect the tap changeover and to protect the oscillator during the changeover period. Obviously this is a step by step method which precludes the smooth variation of the impedance or coupling ratio to maintain inductance matching of the load to the generator throughout the heating cycle and the required switching or relay arrangements represent some expense and complications in manufacture.

According to my invention, I support within the coil 10 movable pieces, rods, or plugs 22 and 24, as shown in Figure 5. These core pieces are preferably formed from a powdered iron compound, well known in the art for its qualities of high permeability and relatively small losses at high frequency. These core members are mounted on rods 26 of ceramic or other insulating material, the rods being slidably guided in suitable supports 28, and the core pieces are thus movable in an axial direction within the coil. It will be evident from Figure 5 that when these core pieces are moved to positions such that they are almost wholly within the turns of the coil between the taps 18 and 20, the inductance of the coil between those taps may be increased, and conversely it will be evident that if the core pieces are withdrawn from the center of the coil toward its ends, the inductance of the portion between the taps will be decreased. The result is just the same as if the tap connections were changed, but the adjustment can be effected smoothly and continuously, instead of by fixed, finite steps, and no switching operation being required to effect the adjustments, no switching or relay arrangements are required for the protection of the oscillator. With fixed connections of the heater coil to a suitably chosen fractional portion of the tank circuit, the value of the inductance between the taps can be made continuously and instantaneously variable in the same way as if those connections were made to slide along the turns of the tank circuit.

Preferably the coil 10 and the core pieces 22 and 24 are so related to each other that the axial length of the coil is much greater than the axial length of the core pieces, so that those pieces can be withdrawn from the portion of the coil between the taps without approaching too closely the end turns of the coil. When this relation obtains, the overall inductance of the coil will be substantially unaffected by the position of the core pieces within their working range of adjustment. The advantage of such a constant overall inductance is that the operating frequency of the oscillator will not be disturbed.

There is a certain definite relationship between the variations in the load impedance and the constants of the oscillator circuit, as will later be described, and therefore the position of the core pieces can be controlled by suitable means, as shown in Figure 4, so that the maintenance of proper impedance match is automatic. In a circuit arrangement such as shown in Figure 4, a plate current, indicated by the ammeter 30, will vary in proportion to the power transferred to the load circuit. Other factors in the oscillator circuit remaining unchanged, the plate current will be a maximum when the optimum amount of energy is transferred to the load, i. e., when the impedance of the load equals the impedance of the generator. Hence by passing the plate current through the coils of solenoids 32 and 34 of which the cores 36 and 38 are secured to the rods 26, the change in the impedance between the load taps may be proportionate to the change in plate current. As shown in Figure 4, the solenoid coils 32 and 34 are preferably connected in series between the positive side of the plate supply source and the center power supply tap of the tank. Springs 39 attached to the outer ends of the solenoid cores and secured to suitable fixed points may be employed to constantly urge the core pieces outwardly of the coil. By proper adjustment of these springs, the forces exerted by them tending to pull the core pieces outwardly can be made to balance the opposing forces exerted by the solenoids when the plate current is a maximum, so that the cores will find positions of rest where the coupling or impedance ratio of the coil 10 is such that the plate current is a maximum, and hence as the impedance of the load changes, the impedance or coupling ratio of the tapped coil is correspondingly altered to maintain maximum power transfer at every instant throughout the heating cycle.

In order to ensure maintenance of oscillations in the self-excited oscillation generator, it is desirable, and in some cases necessary, to vary the feed-back, i. e., the value of the voltage fed back from the tank circuit to the grid circuit of the oscillator. There is a certain definite relation, as will be described hereinafter, between the variations of the load impedance and the changes required in the feed-back voltage to maintain oscillations in the generator. As shown in Figure 2, the feed-back voltage may be controlled by varying the permeability of certain portions of the coil 10. As shown in this figure, a portion of the high frequency voltage across the inductance of the tank circuit, is taken off at taps 40 and 42 of coil 10 and is applied by coupling condensers 44 and grid resistors 46, each con-

denser 44 being connected by the tap of the coil 10 and the grid 50, and each resistor being connected between the grid and the cathode bus 48. The voltage drop across the resistor is applied to the grids and maintains the system in oscillation. The intensity or amplitude of the oscillation varies according to the proportion of the total tank voltage which is taken off at the taps 40 and 42. This proportion is varied by moving core pieces 45, similar to the core pieces 22 and 24, axially within the coil 10 in the manner previously described with reference to the core pieces 22 and 24. Smooth and continuous instantaneous feed-back control is obtained by movement of the core pieces 45. Automatic control may be provided by making the movement of the core pieces dependent upon the variation of some suitably chosen voltage or current, for example, the plate current of the oscillator.

Figure 3 illustrates an arrangement in which means are provided for controlling both the impedance matching of the load to the generator and the control of feed-back to maintain oscillations. For convenience, the inductance of the tank circuit is illustrated as comprising coils 52 and 54 which may be referred to as the end portions of the tank circuit coil, and the coils 56 and 58 which may be referred to as the center portion of the tank circuit coil. The coil 56 is connected in series with the end portions 52 and 54, while the coil 58 is connected to taps on the end portions 52 and 54. The load supplying coil 16 is connected to taps on coil 56 while the power supply plate voltage source is connected to the center tap of the coil 58 and the feed-back voltage is taken from other taps on the coil 58. Movable core pieces 60 and 62, similar to the core pieces 22 and 24, are supported within coil 56 for adjustment of the coupling or impedance ratio to maintain the equivalent load impedance matched to the generator impedance, and movable core pieces 64, similar to the core pieces 45, are supported in the coil 58 for adjustment of the feed-back voltage. The core pieces may be manually adjusted in each instance as determined by meter readings in the oscillator and/or load circuits, or they may be provided with automatic control means, such as previously described.

Figures 3 to 5 illustrate embodiments of the invention in which means is employed for varying the impedance ratio of tapped coils. However, similar results can be obtained with inductively coupled coils as diagrammatically indicated in Figures 6 and 7. As shown in Figure 6, the load energy is transferred from the tank coil 66 by a secondary coil 68 inductively coupled to it. For convenience, the coils are shown side by side, but, as is well known, they may be made coaxial, commonly with the coil of fewer turns on the outside. Movable core pieces 70 may be adjusted along the axis of the tank coil 66 which forms the primary of the transformer, of which the coil 68 is the secondary. Because of the relatively large leakage flux in the air core coils, changes in the location of the core pieces will vary the impedance ratio of the transformer. When the transformer is of such structure that the coils are placed side by side in space, instead of coaxial, the desired adjustment of the impedance ratio can be obtained by placing the movable core pieces in the secondary or pick-up coil 68, as illustrated in Figure 7. In order to maintain maximum transfer of energy as the load varies and to insure the maintenance of oscillations, i. e., operation of the oscillator, the adjustments effected must be such as to maintain certain definite relationships.

Any vacuum tube oscillator circuit may be simplified to, and represented by, the diagram of Figure 8, in which I_p represents the alternating component of the plate current delivered to the tank circuit, including the inductance L_1 shunted by the condenser C and with the resistance R_L in series with the inductance L_1, the resistance R_L being equivalent to the total loss resistance of the load and the tank circuit. The inductance L_1 is equivalent to the inductance of the tank circuit, and all inductance components reflected by the load. The capacitance C_1 represents the tank circuit capacitance and all capacity components reflected from the load. Inductance L_1 is related inductively to a feed back coil L_2 connected between the grid and cathode of the tube and applying a grid voltage E_g to the grid. A certain mutual inductance M exists between the tank coil L_1 and the feed back coil L_2, as indicated in Figure 8. The existing grid voltage is related to the current I_1 in the tank coil according to the following equation:

$$E_g = M\frac{dI_1}{dt} \tag{1}$$

The circuit of Figure 8 may be further simplified to eliminate the tube and is represented by the equivalent circuit of Figure 9, in which a current I_p, equivalent to the alternating component of the plate current, is supplied by a generator 72, the voltage of which is μE_g. The current I_p passes through a resistance R_p, which is the equivalent loss impedance or resistance of the tube and to the tank circuit comprising condenser C shunted by an inductance L_1 in series with the resistance R_L, C, L_1, and R_L representing or being equivalent to the capacitive, inductive, and resistive components of the load and the tank circuit.

Applying Kirchhoff's laws to the equivalent circuit of Figure 9, it will be seen that

$$\mu Eg = R_p I_p + R_L I_1 + L_1\frac{dI_1}{dt} \tag{2}$$

and

$$I_p = I_1 + I_2 \tag{3}$$

Since the voltage across the two branches of the tank circuit must be equal, then

$$\frac{1}{C}\int I_2 dt = R_L I_1 + L_1\frac{dI_1}{dt} \tag{4}$$

On differentiating this last equation, an expression is obtained for the current I_2 thus—

$$I_2 = R_L C\frac{dI_1}{dt} + L_1 C\frac{d^2I_1}{dt^2} \tag{5}$$

By combining Equations 1, 2, and 3,

$$\mu M\frac{dI_1}{dt} = R_p(I_1 + I_2) + R_L I_1 + L_1\frac{dI_1}{dt} \tag{6}$$

which, by substitution of I_2, according to Equation 5, reduces to the following form:

$$\frac{d^2I_1}{dt^2} + \left[\frac{R_L}{L_1} + \frac{1}{R_p C} - \frac{\mu M}{R_p L_1 C}\right]\frac{dI_1}{dt} + \frac{(R_p + R_L).I_1}{R_p L_1 C} = 0 \tag{7}$$

The well known, general form of equation for the occurrence of oscillation in a circuit is

$$L\frac{d^2I}{dt^2} + R\frac{dI}{dt} + \frac{I}{C} = 0 \tag{8}$$

which reduces to

$$\frac{d^2I}{dt^2} + \frac{R}{L}\times\frac{dI}{dt} + \frac{I}{LC} = 0 \tag{9}$$

A comparison of Equations 7 and 9 reveal in-

stantly that they are of the same general form and the conditions for occurrence of oscillations in the circuit represented by Equation 7 may be obtained simply by comparing the coefficients of the respective terms of the equations.

For the maintenance of a steady state of oscillations, the coefficient

$$\frac{R}{L}$$

of the first order term of the general Equation 9 must disappear or become equal to 0. Hence, the corresponding coefficient of the first order term of the circuit represented by Equation 7 must become equal to 0 or

$$\frac{R_L}{L_1}+\frac{1}{R_pC}-\frac{\mu M}{R_pL_1C}=0 \tag{10}$$

Upon multiplication of all terms of Equation 10 by the reciprocal value of the angular frequency

$$\frac{1}{\omega}$$

the following equation is obtained:

$$\frac{R_L}{\omega L_1}+\frac{1}{\omega}\cdot\frac{1}{R_pC}=\frac{\mu M}{\omega L_1R_pC} \tag{11}$$

Since the Q of the equivalent tank circuit of Figure 9 is equal to

$$\frac{\omega L_1}{R_1},\ \frac{1}{Q}$$

may be substituted for the first term of Equation 11,

$$\frac{1}{Q}=\frac{\mu M}{\omega L_1R_pC}-\frac{1}{\omega CR_p} \tag{12}$$

which may be simplified to

$$\frac{1}{Q}=\frac{1}{\omega CR_p}\cdot\left[\frac{\mu M}{L_1}-1\right] \tag{13}$$

and since the tank circuit (Figure 9) is at resonance

$$\omega L_1=\frac{1}{\omega C}$$

and Equation 13 may be written

$$\frac{1}{Q}=\frac{\omega L_1}{R_p}\cdot\left[\frac{\mu M}{L_1}-1\right] \tag{14}$$

To solve the above equation to obtain the value of R_P, representing the internal impedance of the oscillation generator, said equation may, by transposition, be written as follows:

$$R_p=Q\omega L_1\left[\mu\frac{M}{L_1}-1\right] \tag{15}$$

The Q of the tank circuit shown in Figure 9 in terms of a resistance R_H parallel to the condenser C and which resistance is equivalent to the resistance R_L, and hence may replace the resistance R_L, is

$$Q=\frac{R_H}{\omega L_1} \tag{16}$$

Hence, by substituting the Q of Equation 16 for the Q of Equation 15, an equation can be obtained representing the relationship between the internal impedance R_P of the oscillation generator and the equivalent parallel resistance R_H representing all the power losses in the heating load and the tank circuit. This equation is as follows:

$$R_p=R_H\cdot\left[\mu\frac{M}{L_1}-1\right] \tag{17}$$

Equation 17 may be transformed to

$$R_H=\frac{R_p}{\mu\frac{M}{L_1}-} \tag{18}$$

This Equation 18 signifies that, so long as the equivalent parallel loss resistance R_H is equal to the ratio of the internal impedance of the oscillation generator to the factor

$$\mu\frac{M}{L}-1$$

oscillations may be maintained in the steady or stable state. In other words, for any particular feed-back voltage, which is dependent upon the ratio of M/L, the oscillator will continue to operate if the equivalent parallel loss resistance R_H is of a certain value or ratio to the internal impedance R_P of the oscillator itself. Although oscillations will be maintained if the ratios of the quantities comply with the conditions of Equation 18, the power transferred will not necessarily be at its optimum value. Optimum transfer of power from the oscillation generator to the load can only be obtained when

$$R_H=R_p \tag{19}$$

The conditions of Equations 18 and 19 can be met simultaneously only when the denominator of Equation 18 is equal to unity, i. e.,

$$\mu\frac{M}{L_1}-1=1 \tag{20}$$

or

$$\frac{M}{L_1}=\frac{2}{\mu} \tag{21}$$

The significance of Equation 21 is that, so long as the ratio M/L_1 is equal to, or greater than, twice the reciprocal value of the amplification factor, which is substantially a constant, the equivalent impedance of the load may be matched to the impedance of the oscillation generator while the oscillator is maintained in a steady state of oscillation. Thus by suitably calibrating the movement of the core pieces to maintain the feed-back ratio M/L_1 equal to, or greater than, twice the reciprocal value of the amplification factor of the oscillator, the oscillator may, by manual or automatic adjustment, be maintained in a steady state of oscillation while permitting the impedance coupling ratio between the tank circuit of the oscillator and the load to be so adjusted as to maintain the equivalent impedance of the load equal to the internal impedance of the oscillation generator. The calibration of the movement of the core pieces may, of course, be related to any measurable factor of the oscillator circuit which is indicative of the variations in the load coupled to the oscillator. Thus, for example, the movement of the adjustor for the core pieces may be calibrated in terms of the plate current, as revealed by the plate current meter 30 (Figure 4), so that as the load varies the feed-back is correspondingly varied by varying M/L_1 to comply with the limit conditions of Equation 21.

It will be evident further that where the feed-back alone is varied to maintain the oscillator in a stable condition of oscillation without regard to the obtaining of a maximum transfer of energy, the feed-back adjustor may be calibrated to meet the limiting conditions of Equation 18. When the feed-back is adjusted with the load to meet the limiting conditions of Equation 21, then the impedance ratio or the coupling of the load to the transformer may be manually or automatically adjusted by adjustment means calibrated to meet the conditions of Equation 19, i. e., that the equivalent parallel loss resistance

of the load equal the internal impedance of the generator.

While the invention has been illustrated in connection with an oscillator employing an inductive feed-back from the plate circuit to the grid circuit, similar arrangements can be employed in accordance with the invention where the feed-back from the plate-to-grid circuit is obtained through a variable condenser arrangement.

Changes may be made in the form, construction, and arrangement of the parts without departing from the spirit of the invention or sacrificing any of its advantages, and the right is hereby reserved to make all such changes as fairly fall within the scope of the following claims:

What I claim is:

1. The method of heat treating an object the electrical characteristics of which vary with the absorption of energy by the object, which method comprises coupling the object to be heated with reactive heating means to which high frequency energy is supplied from an electronic high frequency generator having coupled plate and grid circuits between which energy is transferred to maintain oscillations, so that the equivalent impedance of the load across the points of coupling to the generator is substantially equal to the internal impedance of the generator between the same terminals, varying the coupling of the heating means to the generator in definite relation to variations in the electrical characteristics of the object, and varying the feed-back between the plate and grid circuits of the generator in definite relation to the variation in the electrical characteristics of the object to maintain the generator in a steady state of oscillation.

2. The method of heat treating an object the electrical characteristics of which vary with the absorption of energy by the object, which method comprises coupling the object to be heated with heating means to which high frequency energy is supplied from an electronic high frequency generator, so that the equivalent impedance of the load across the points of coupling to the generator is substantially equal to the internal impedance of the generator between the same terminals, varying the coupling of the heating means to the generator in definite relation to

variations in an electrical quantity which varies with variation in the electrical characteristics of the object to match the load to the internal impedance of the generator, and varying the feed-back between the plate and grid circuits of the generator in definite relation to said electrical quantity when the feed-back voltage is changed by adjustment of the coupling ratio to maintain the intensity of oscillations of the generator.

3. The method of controlling the supply of high frequency energy to a varying load from an electronic high frequency generator, which method comprises simultaneously varying the coupling ratio between the plate circuit of the oscillator and the load and the feed-back ratio between the plate circuit and the grid circuit of the generator in such a manner as to maintain R_H equal to R_p and M/L at least as great as $2/\mu$ where R_H represents the equivalent parallel loss resistance of the load and the frequency determining circuits of the generator across the points of coupling, R_p represents the internal impedance of the generator, M/L represents the feed-back ratio between the plate and grid circuits, and μ represents the ratio of the alternating component of the plate voltage to the alternating component of the grid voltage.

EUGENE MITTELMANN.

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