

[54] **SOLID STATE INDUCTION COOKING SYSTEMS FOR RANGES AND SURFACE COOKING UNITS**

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[52] U.S. Cl. **219/10.49, 219/10.77, 321/14, 321/18, 321/45**

[51] Int. Cl. **H05b 5/04**

[58] Field of Search **219/10.49, 10.75, 219/10.77, 10.79; 321/10, 14, 18, 43, 45**

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Primary Examiner—Bruce A. Reynolds
Attorney—John F. Ahern et al.

[57] **ABSTRACT**

Solid state induction surface cooking units for domestic electric ranges and other cooking appliances are defined with respect to the operating parameters and functional components of complete induction heating systems suited for this use. The surface cooking units are designed for reliable, convenient, and safe operation, and for circuit packaging using hybrid and monolithic integrated circuits. Wide range power control of the inverter power circuits is needed for general cooking but is obtained within a limited ultrasonic operating range of the power semiconductors. The interdependent electrical and magnetic characteristics utilized in solid state induction cooking are related to the achievement of such desirable user features as the cool cooking surface, fast utensil warm-up, responsive heating, and unrestrained utensil mobility. In addition to cooking by changing the relative heating level, cooking is performed by setting the desired utensil temperature and by setting the desired utensil power level.

18 Claims, 24 Drawing Figures

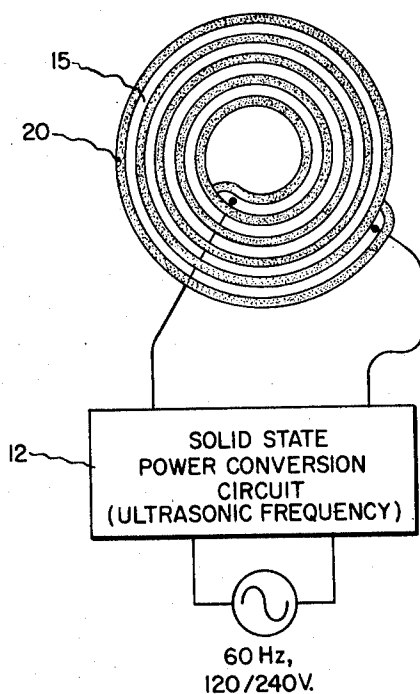


Fig. 1

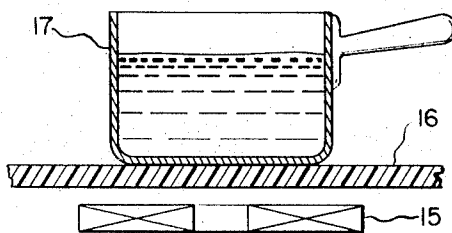
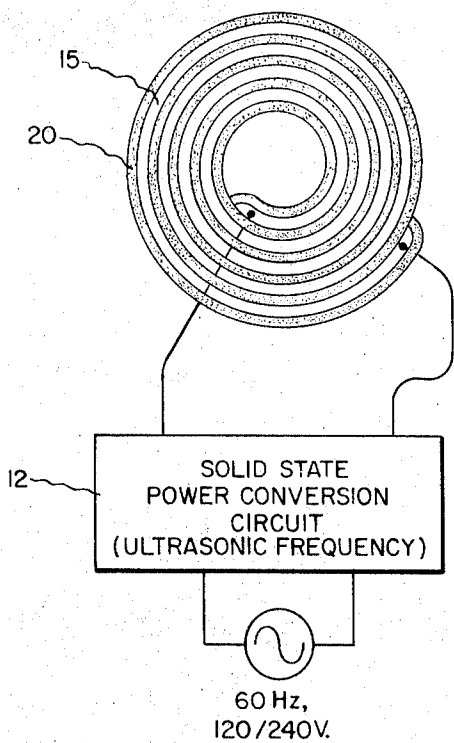


Fig. 2

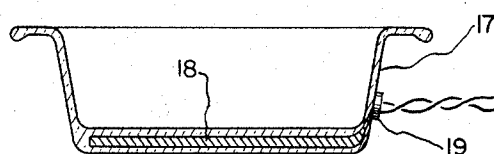


Fig. 3

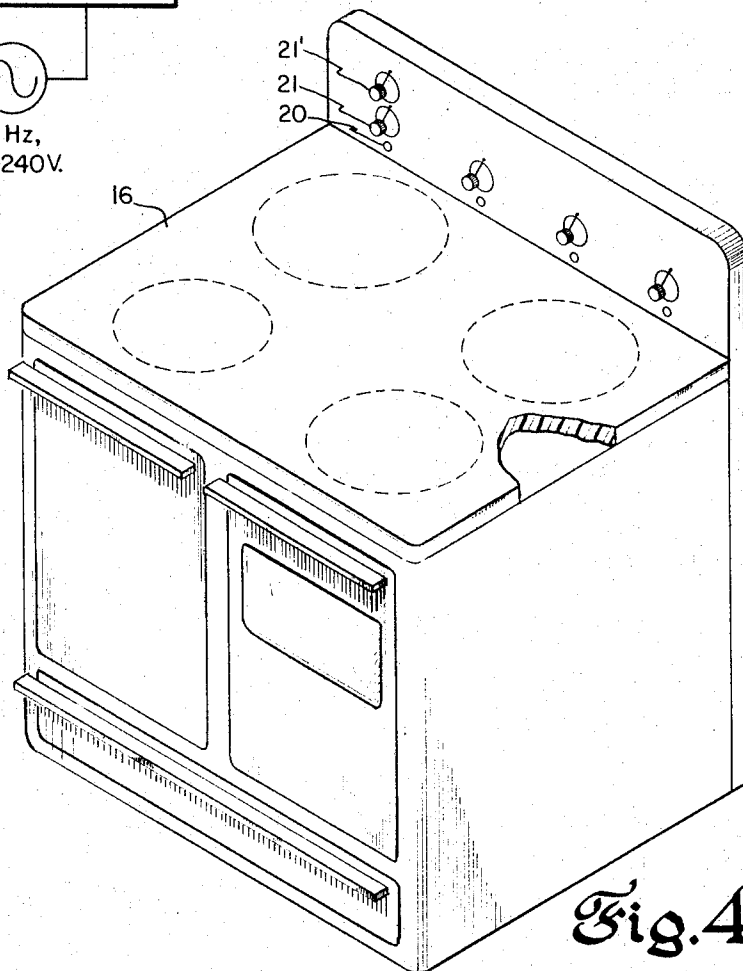


Fig. 4

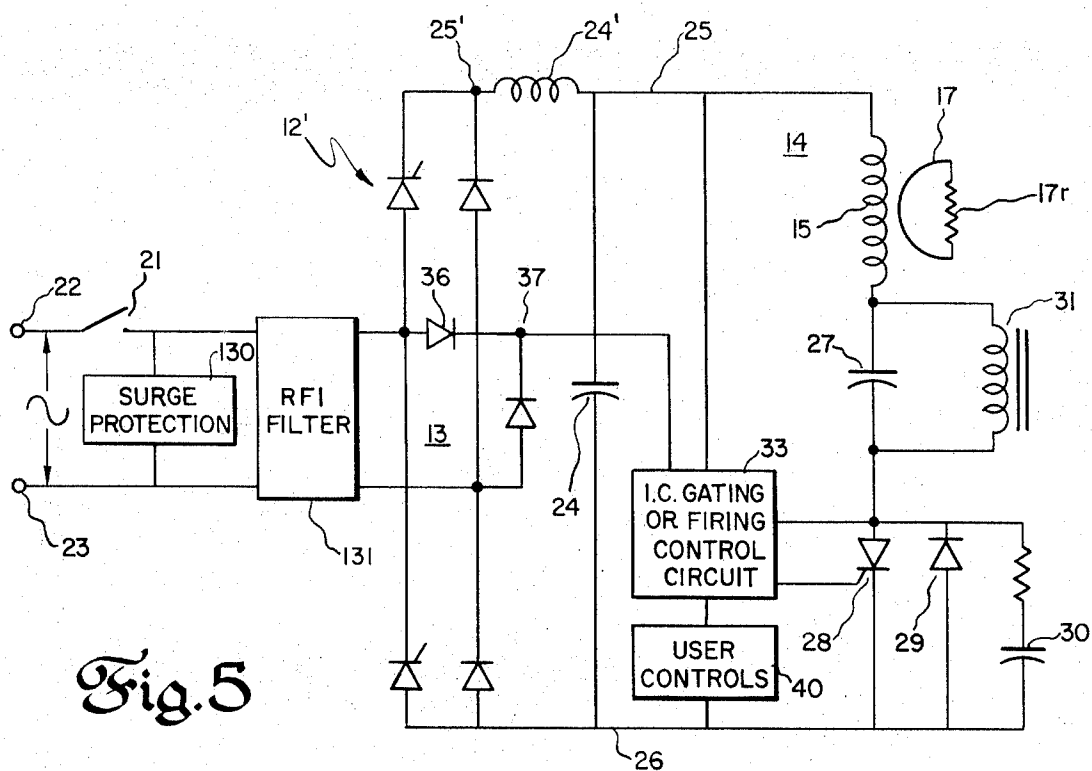
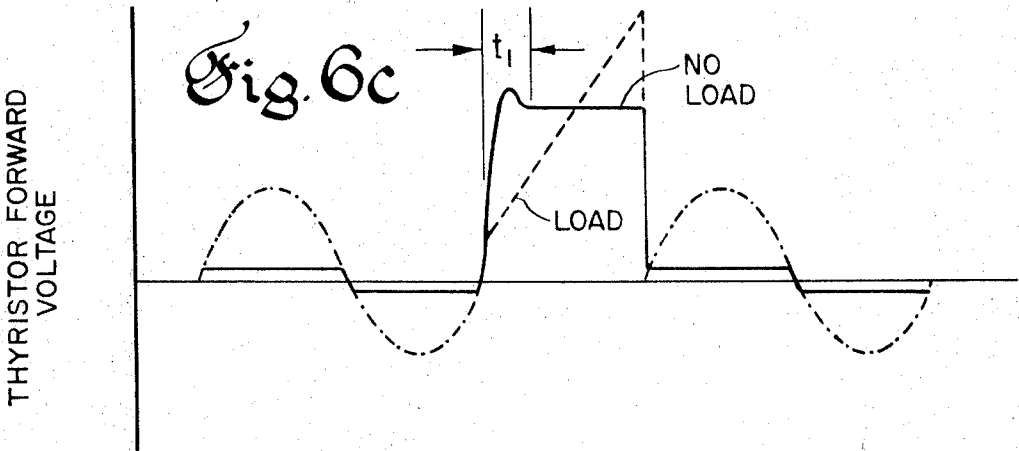
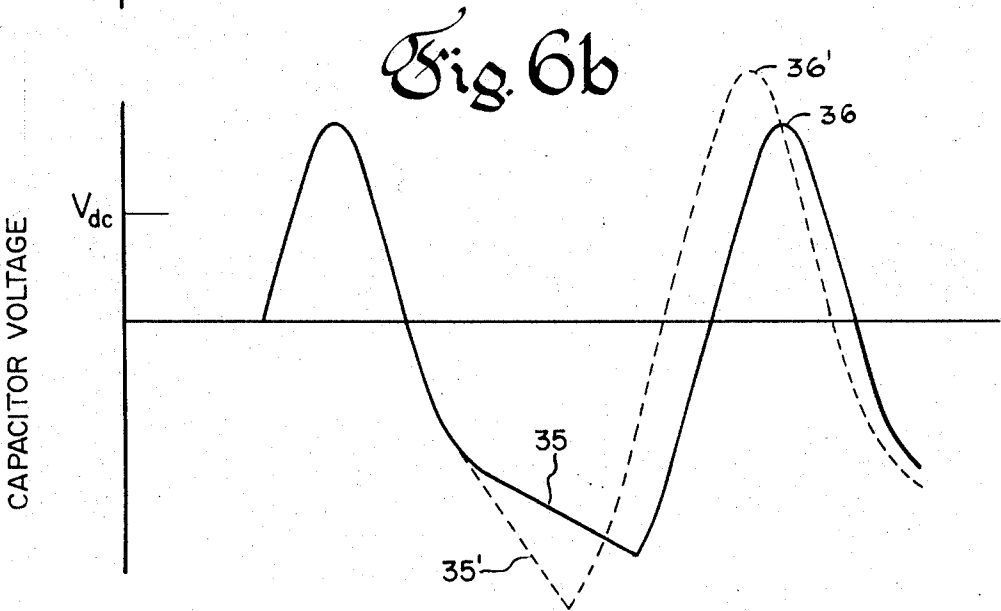
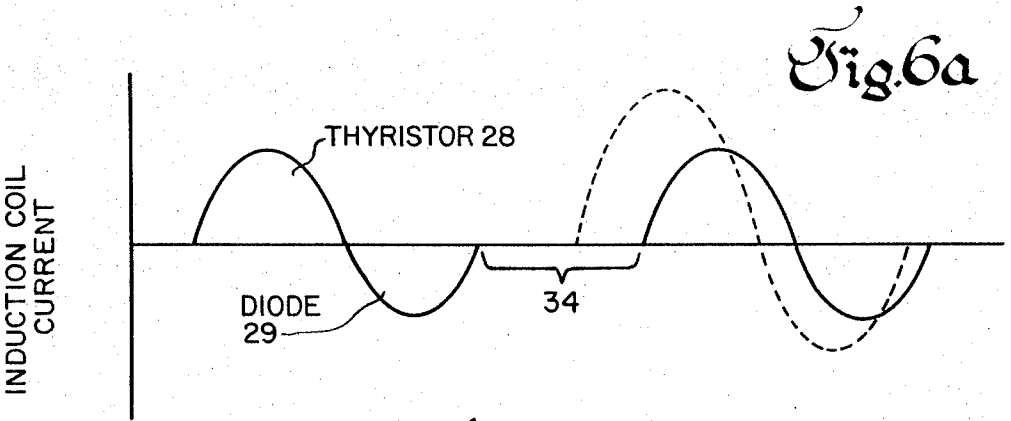


Fig. 5



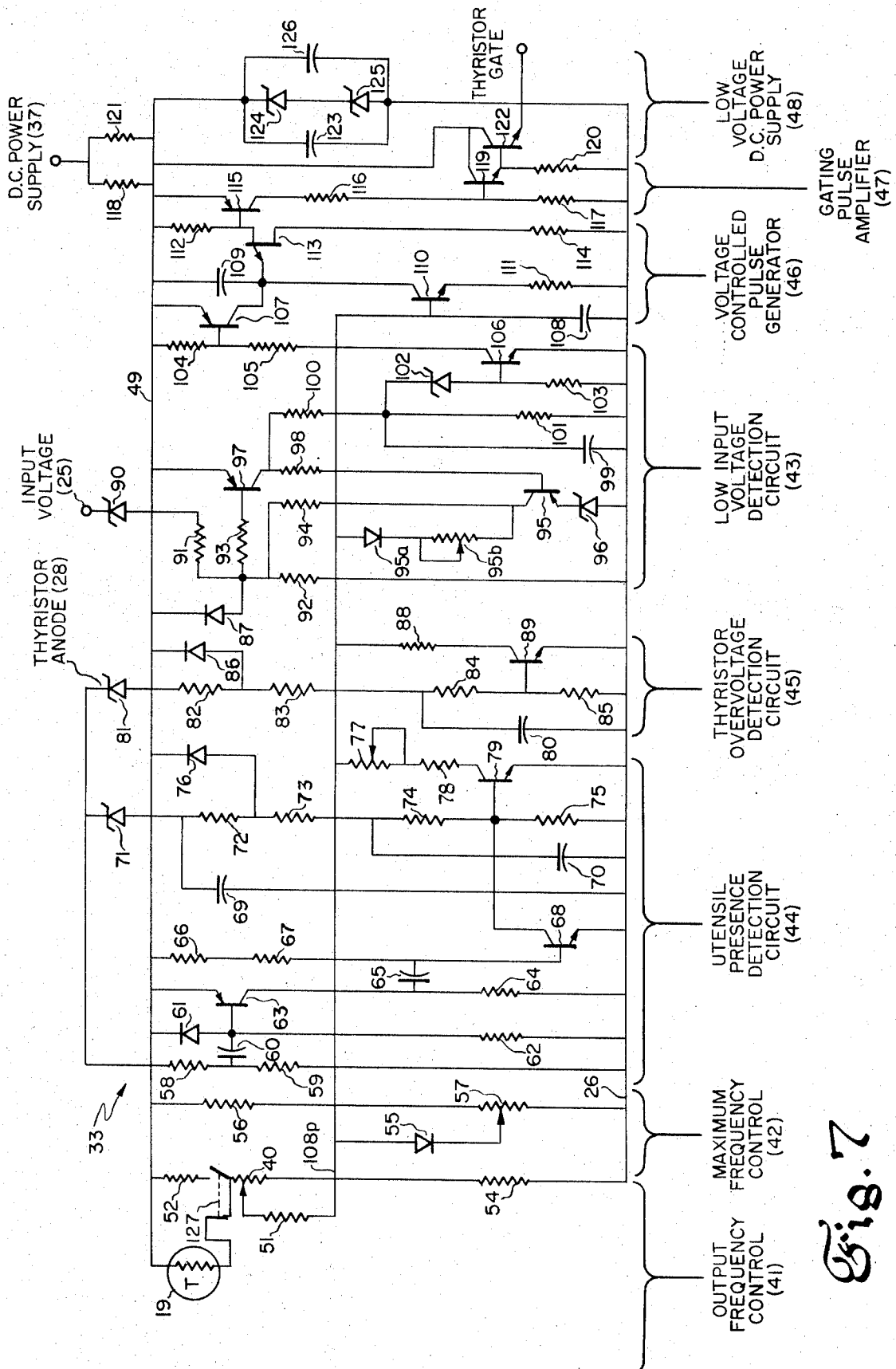


Fig. 7

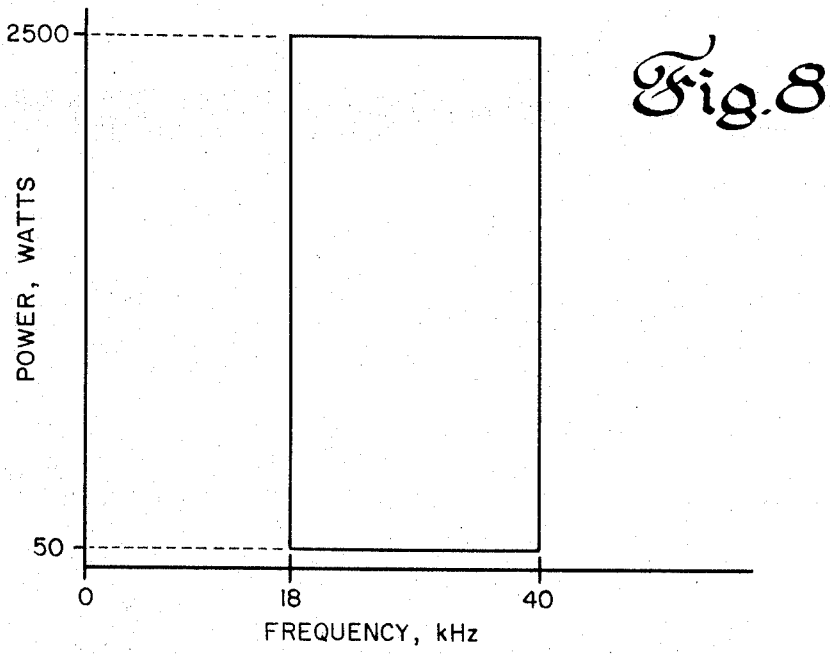


Fig. 9

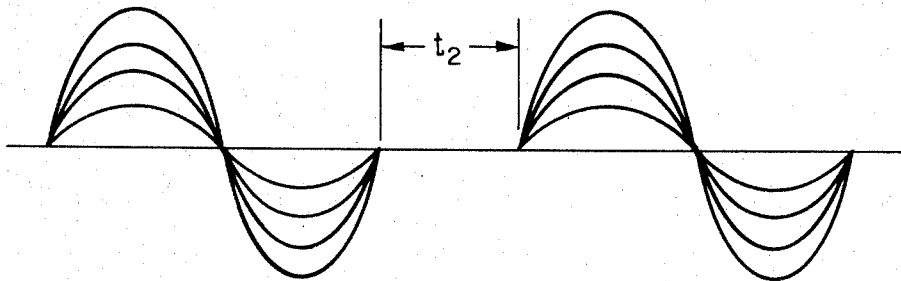
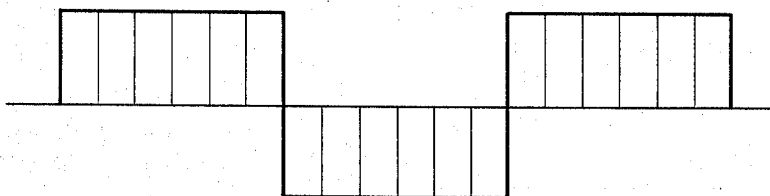


Fig. 10



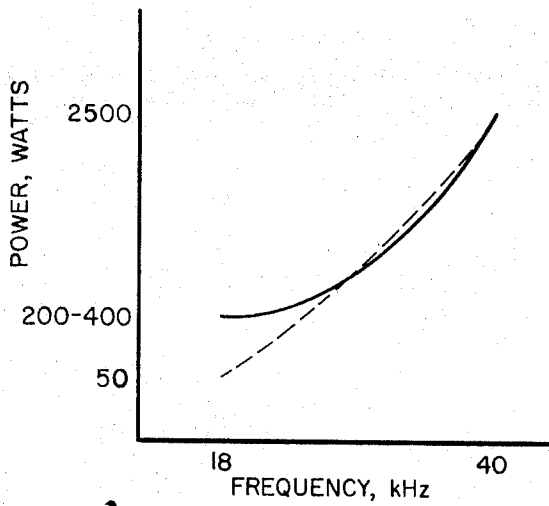


Fig. 11

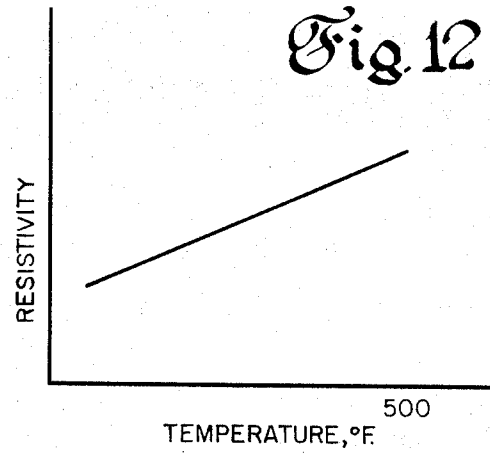


Fig. 12

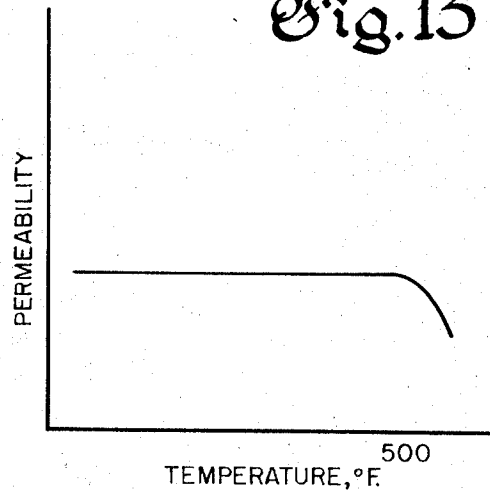


Fig. 13

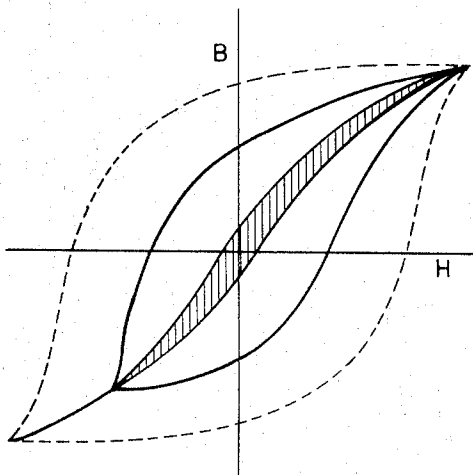


Fig. 14

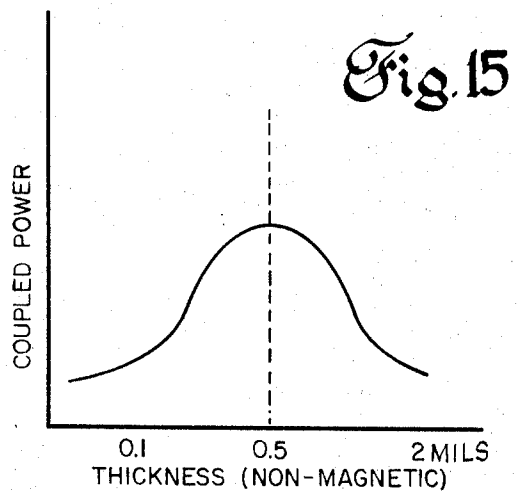


Fig. 15

Fig. 16

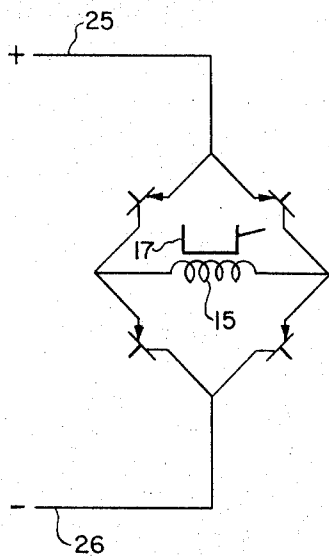


Fig. 17

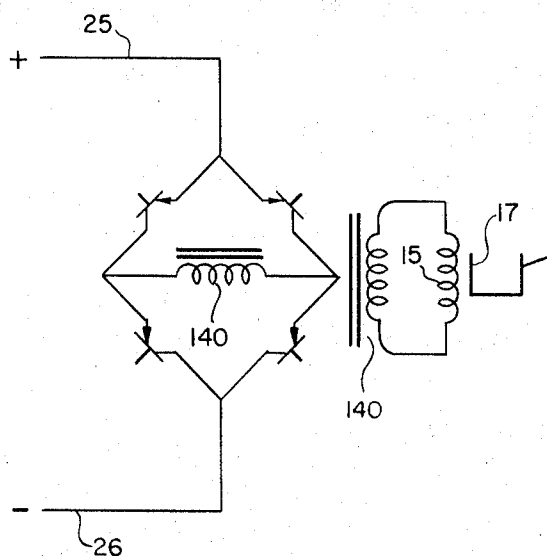


Fig. 18

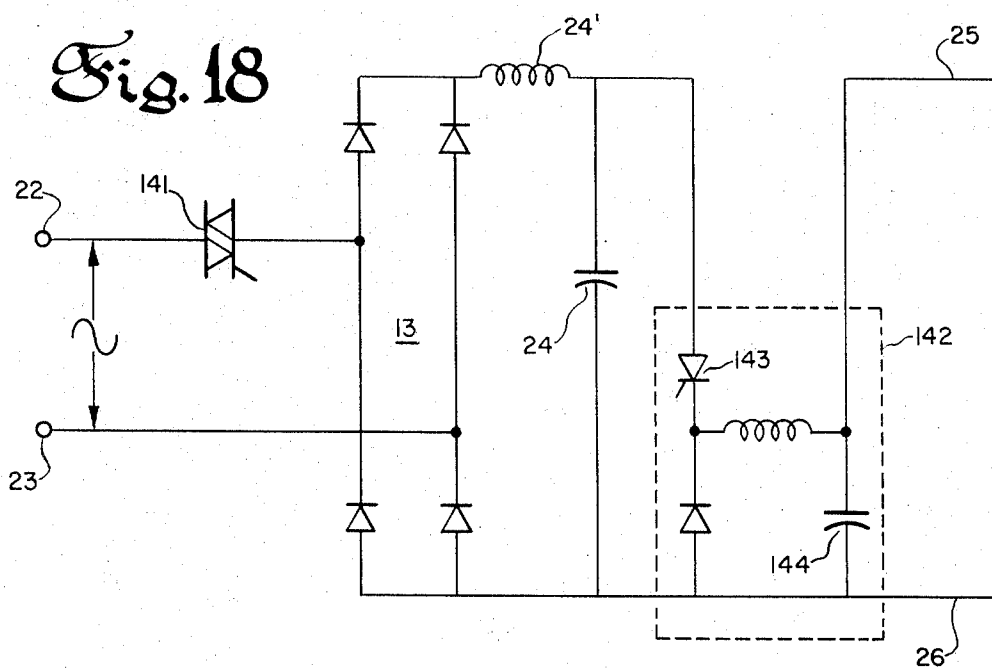


Fig. 19

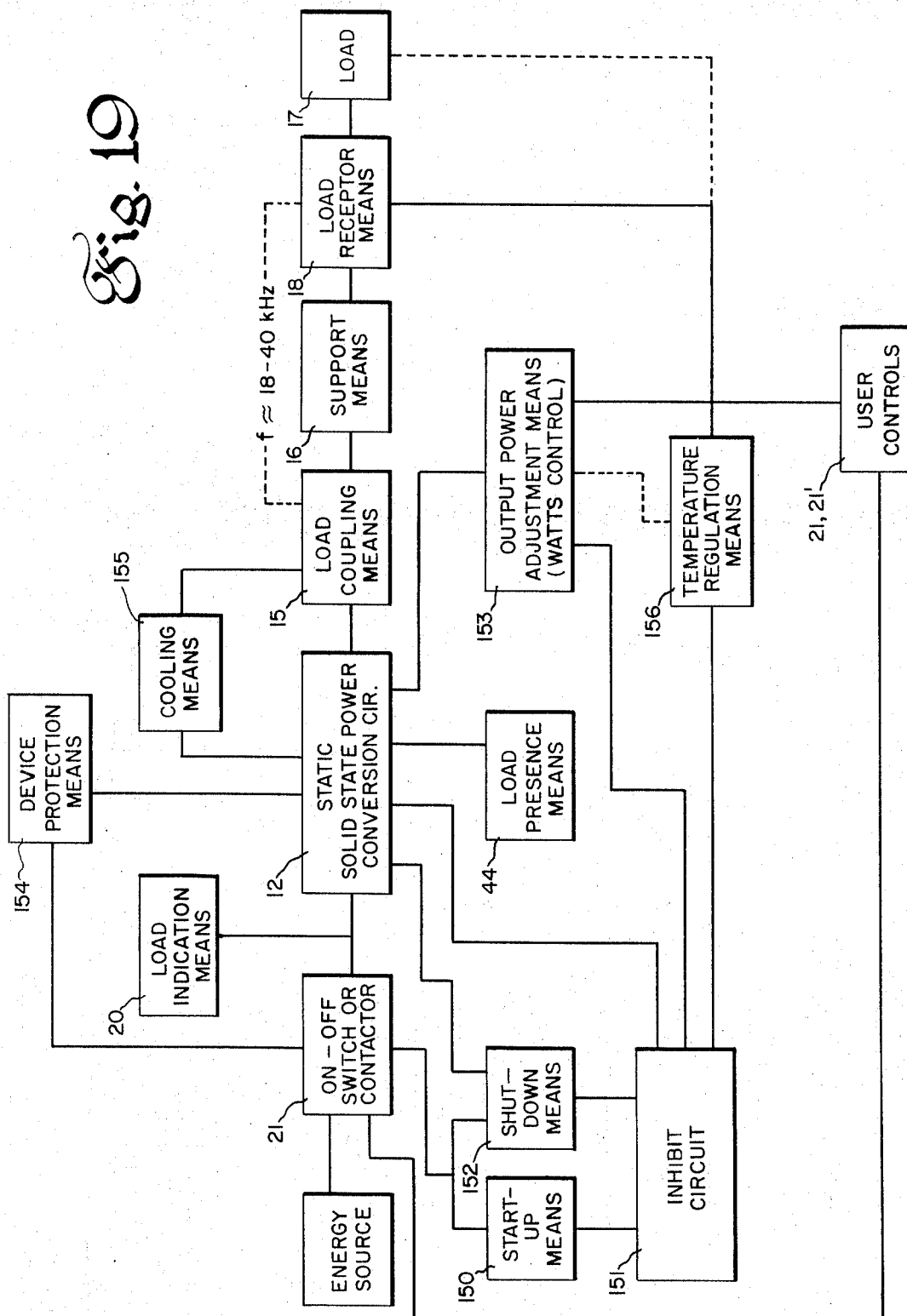


Fig. 20

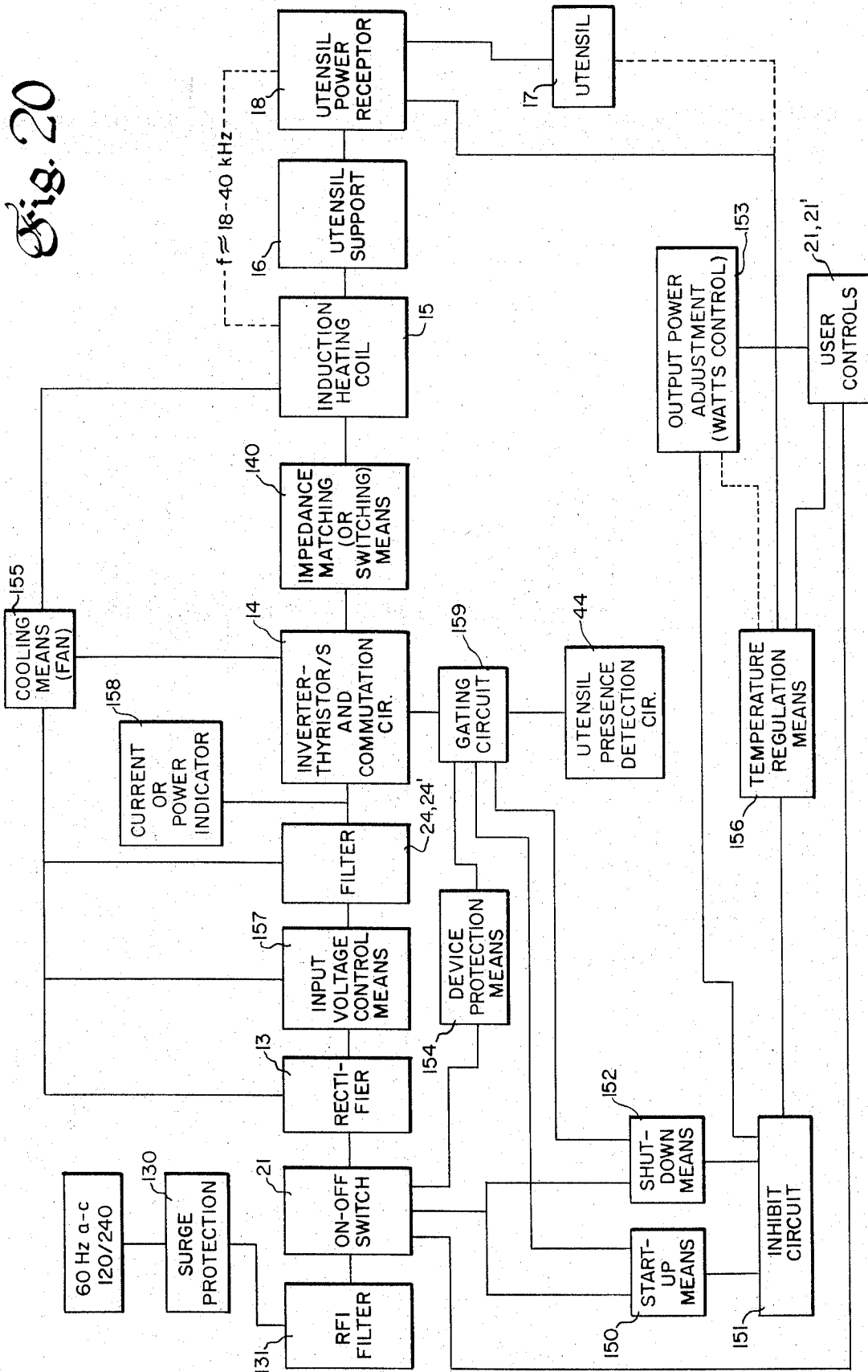


Fig. 21

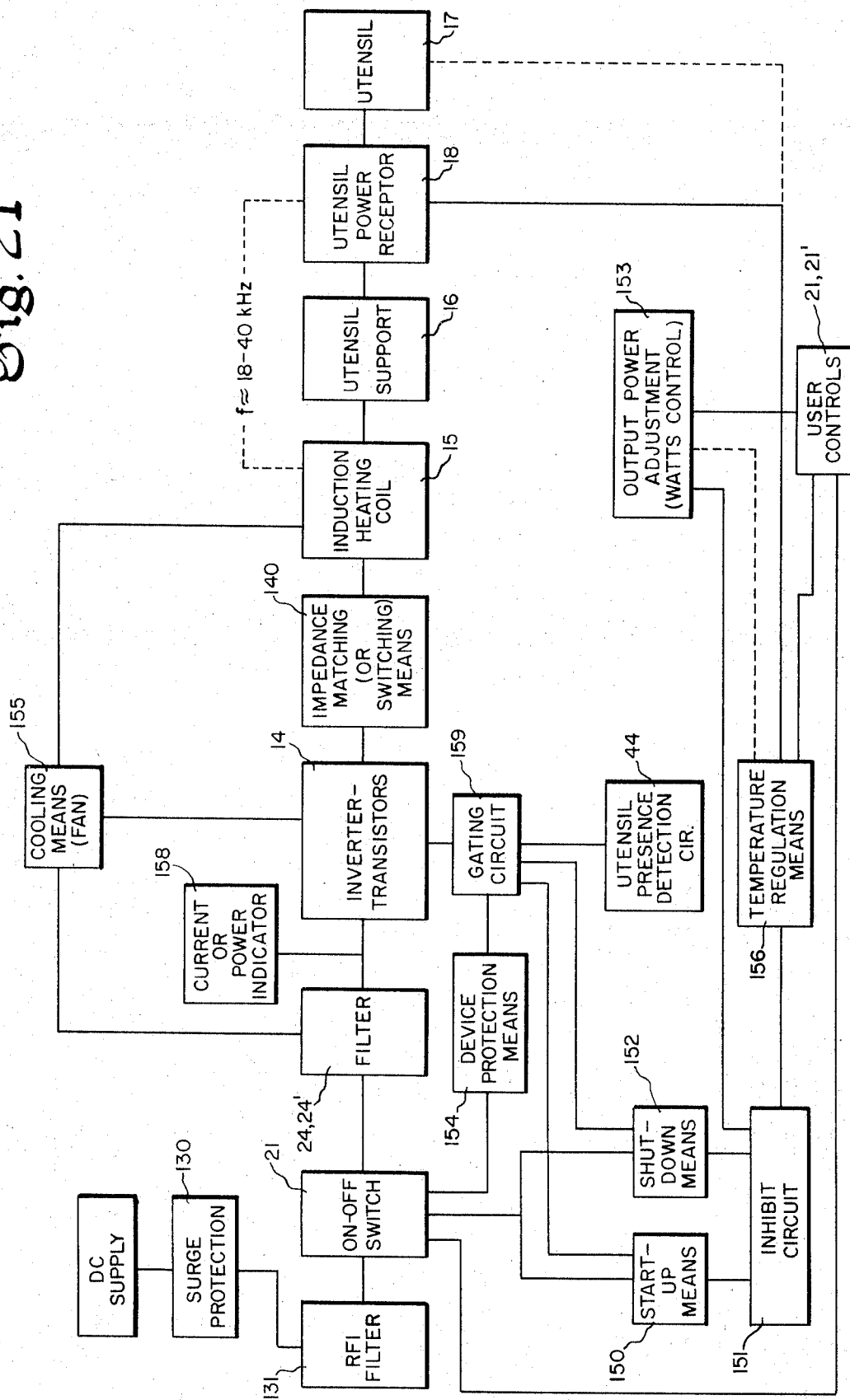
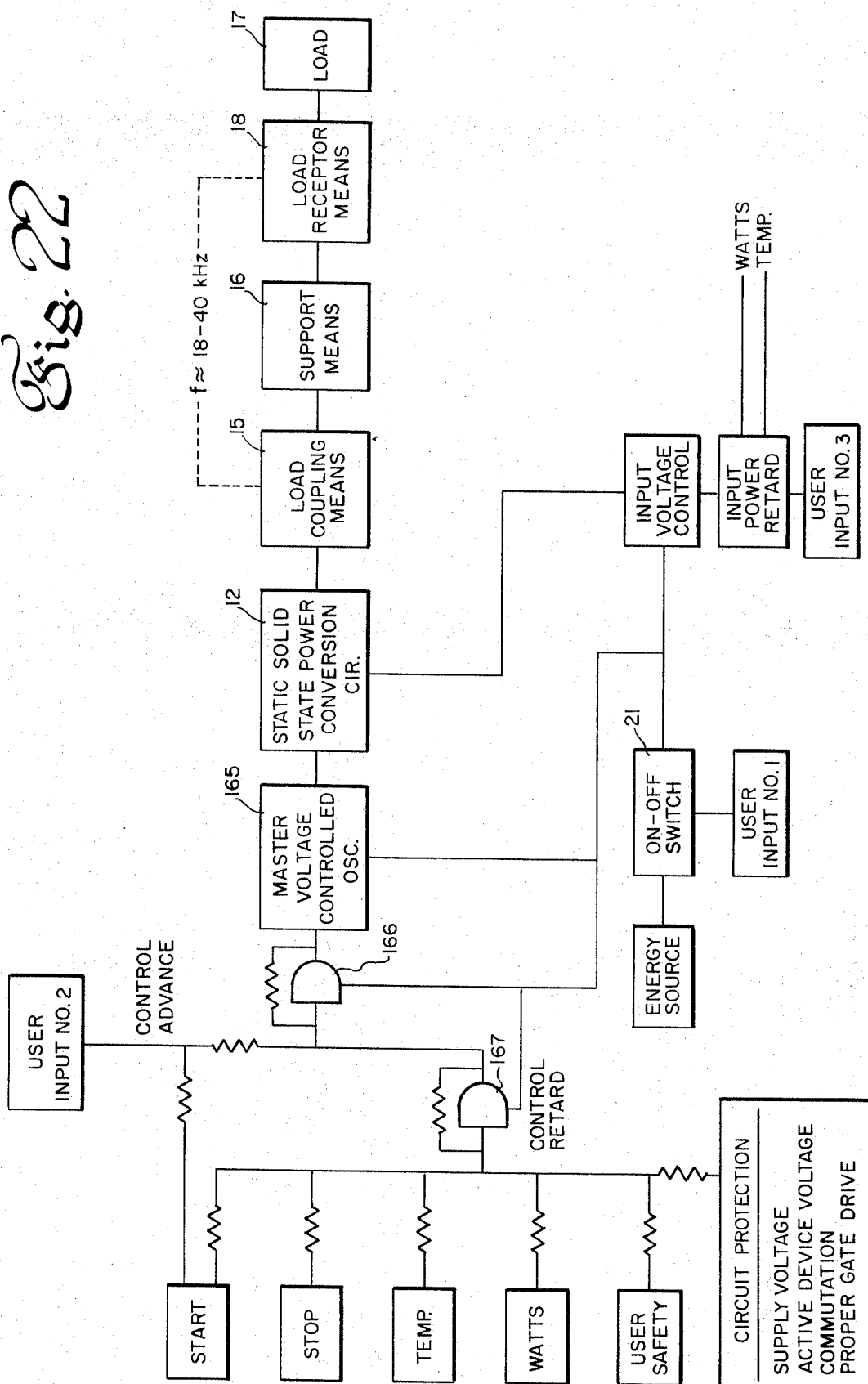


Fig. 22



SOLID STATE INDUCTION COOKING SYSTEMS FOR RANGES AND SURFACE COOKING UNITS

CROSS-REFERENCE TO RELATED APPLICATIONS

The power converter circuit used in describing a specific example of the practice of the invention is disclosed and claimed in the concurrently filed application Ser. No. 211,926 by William P. Kornrumpf and John D. Harnden, Jr., entitled "Reliable Solid State Induction Cooking Appliance with Control Logic," and assigned to the same assignee as the present invention.

BACKGROUND OF THE INVENTION

This invention relates to solid state induction heating systems uniquely suitable for electric ranges and other cooking appliances for inductively heating cooking utensils.

The idea of applying induction heating to the cooking of food has been known generally for a number of years but has not resulted in a successful product that is competitive with the widely used gas range and the common electric range based on resistance heating. The basic mechanism of induction cooking is that an alternating magnetic field is coupled across a gap with the utensil bottom, which acts as a single turn secondary winding. Theoretically the process is efficient since heat is generated only in the metallic utensil where it is wanted. However, prior art proposals were bulky and expensive and otherwise not satisfactory for wide usage.

The development of solid state induction cooking appliances operating at ultrasonic frequencies of 18 kHz and above has made possible a significant reduction in cost and size and overcomes other deficiencies of the prior art equipment. Suitable solid state power circuits that can be used as ultrasonic frequency generators in an induction surface cooking unit for domestic electric ranges and other cooking appliances are described in the following two copending applications: Ser. No. 200,526 by David L. Bowers, Donald S. Heidtmann, and John D. Harnden, Jr.; and Ser. No. 200,424 by John D. Harnden, Jr. and William P. Kornrumpf, both filed Nov. 19, 1971, and assigned to the same assignee as this invention. Cool top appliances as therein described typically are comprised by a flat induction heating coil driven by a static power conversion circuit that includes a solid state inverter as an essential component. The power output of the inverter is modulated to change the heating level in the utensil and therefore the temperature at which the food is cooked.

The present invention is directed to other features of a complete induction heating system needed to build surface cooking units and ranges for performing a variety of cooking tasks more satisfactorily, and which is reliable and convenient for operation by technically unskilled persons such as housewives and chefs. Static power converters, especially those with semiconductor components, require protection to prevent malfunction and failure under abnormal circuit conditions such as overvoltages and overcurrents. Furthermore, the coupled utensil is the inverter load and the reflected impedance changes the inverter's electrical parameters. There are severe load requirements if the unit is to be operable with a variety of pots and pans of different sizes and materials, under both load and no-load condi-

tions, and even with loads the unit is not designed to heat since this is beyond the control of the manufacturer. The requirement for automatic and continuous operation means that the circuit design must anticipate circumstances that could cause failure or temporary shutdown. In an improved cooking unit it would further be desirable to have the option of heating the utensil to a specific temperature, as opposed to watts control of the inverter output, for the cooking of foods such as bacon that are best cooked within an acceptable temperature band.

SUMMARY OF THE INVENTION

Induction surface cooking units for typical domestic usage in electric ranges and built-in cooktop installations are characterized by a relatively cool, unobstructed cooking surface in the form of a substantially unbroken non-metallic utensil support plate beneath which the induction heating coil is mounted. The utensil support plate can be made of plastic as well as glass or ceramic material. A defining condition for successful induction cooking is the power-frequency relationship of the ultrasonic output power generated by the solid state power conversion circuit that drives the induction heating coil. All domestic cooking is performed with ultrasonic output power that has a power level between 50 and 2,500 watts and a frequency between 18 and 40 kilohertz. General purpose cooking requires wide range output power greater than a 10:1 ratio to the maximum 50:1 ratio, but this must be produced within the feasible operating range of solid state power devices without descending to audible frequencies. The 18-40 kHz frequency range is also desirable because the skin depth of current penetration is sufficiently thin that relatively light weight magnetic and non-magnetic cooking utensils can be used. The light weight utensils make possible fast warm-up and responsive heating. The cooking utensil is freely movable on the cooking surface since the utensil and support plate are not required to be optically flat and also because there are insignificant ponderomotive forces.

A complete induction surface cooking unit preferably employs a static power conversion circuit including filter means and an inverter for converting a filtered unidirectional voltage to ultrasonic power for driving the induction heating coil. Minimum components for reliable and convenient cooking in addition to the gating circuit for the inverter power devices include an inhibit circuit for selectively inhibiting operation of the inverter; start-up and shut-down means coupled to the inhibit and gating circuits for controlling transients and the application and removal of voltage from the inverter; device protection means; output power adjustment means; and user controls. A number of these functions can desirably be provided by an integrated circuit gating control circuit for controlling the inverter. Optional components depending on the model and circuitry are such things as surge protection means and an RFI filter connected across the input terminals, impedance matching or switching means, cooling means, a utensil presence detection circuit, a temperature regulating system, etc. The induction cooking system is described with respect to a specific surface cooking unit in an electric range or cooktop, and also with respect to a generalized system. Similar systems are given for the special cases using a thyristor inverter energized by an a-c source, and a transistor inverter ener-

gized by a d-c source. Another generalized system is described in terms of logic signal inputs and the other inputs for controlling the solid state power conversion circuit.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a plan view of a flat spiral induction heating coil and a block representation of a solid state power conversion circuit for supplying ultrasonic frequency power to the coil;

FIG. 2 is a schematic cross-sectional view showing the relation of the induction heating coil to the utensil support and cooking utensil;

FIG. 3 is a cross-sectional view of a different type of cooking utensil with an attached temperature sensor and an embedded receptor plate for coupling power to the utensil;

FIG. 4 is a fragmentary perspective view of an electric range with a smooth utensil support plate or cooking surface;

FIG. 5 is a schematic circuit diagram showing by way of illustration a solid state power converter suitable for the practice of the invention which comprises a phase controlled rectifier and a variable frequency series resonant inverter;

FIGS. 6a and 6b are waveform diagrams of the induction coil current and commutating capacitor voltage for the static power conversion circuit of FIG. 5, showing in each diagram the waveforms at two different output frequencies;

FIG. 6c is a waveform diagram of the thyristor forward voltage under load and no-load conditions (the sinusoidal induction coil current is illustrated for reference purposes);

FIG. 7 is a detailed schematic diagram of the gating control circuit shown in block diagram form in FIG. 5;

FIG. 8 illustrates the power-frequency operating "window" for domestic solid state induction surface cooking units;

FIGS. 9 and 10 show waveforms useful in explaining the principles of power modulation with circuits that generate sine wave and square wave shapes;

FIG. 11 shows in full lines the power-frequency characteristic for the converter of FIG. 5 obtained by solely varying the output frequency, while the desired characteristic with an extended low output power range is shown in dashed lines;

FIGS. 12 and 13 are respectively resistivity-temperature and permeability-temperature characteristics for suitable magnetic utensil materials;

FIG. 14 is a hysteresis loop for magnetic utensil materials illustrating minor loop operation for asymmetrical electrical circuits such as the FIG. 5 converter;

FIG. 15 is a power-thickness characteristic for non-magnetic utensil materials;

FIG. 16 is a schematic circuit diagram of a full bridge inverter implemented with transistors for producing the pulse width modulated square wave shapes given in FIG. 10;

FIG. 17 is similar to FIG. 16 but includes an impedance matching transformer;

FIG. 18 is a schematic circuit diagram of a d-c power supply with two other techniques for varying the input voltage, by phase controlling the alternating supply voltage in advance of the rectifier and by chopping the filtered d-c voltage;

FIG. 19 is a block diagram of the functional components of a generalized complete induction heating system for solid state induction surface cooking units, including some features that are optional;

FIG. 20 is a block diagram similar to FIG. 19 of a complete induction surface cooking appliance that is energized by a commercially available a-c source and incorporates an inverter with thyristor switches and commutation circuitry;

FIG. 21 is similar to FIG. 20 but shows by comparison the functional components of an induction surface cooking appliance energized from a d-c source that incorporates a transistor inverter; and

FIG. 22 is a logic type of block diagram of the required and optional function components and features of a complete induction cooking system for solid state surface cooking units.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Introduction

The induction cooking appliance shown in FIGS. 1-4 will be described with regard to an induction surface cooking unit in a domestic electric range but essentially the same mechanical structure and circuitry in higher and lower power versions is suitable for commercial cooking equipment and counter-top food cooking or warming appliances. The solid state power conversion circuit indicated generally at 12 is energized by either a source of alternating voltage or a source of direct voltage, and includes as an essential component a solid state inverter for generating an ultrasonic frequency wave that drives an induction heating coil 15. Induction heating coil 15 typically is a single layer, annular, flat spiral, air-core coil wound with braided ribbon or solid flat strip conductor with a rectangular cross section. To generate sufficient magnetic flux to heat the utensil to the desired heating level or specific utensil temperature, coil 15 is tightly wound with the short cross-sectional dimension of the conductor facing upwards and adjacent turns separated by a flat insulating strip 20. While coil 15 is ordinarily flat, it is within the scope of the invention to use a nominally flat coil such as one that is slightly dishd to improve the field distribution. Coils with ferrite return paths can also be used.

In the surface cooking unit (FIG. 2), induction heating coil 15 is appropriately mounted in a horizontal position immediately below a non-metallic utensil support 16 typically made of a thin sheet of glass or plastic. If required, support 16 can have some metallic content for shielding and decorative purposes, but this is necessarily limited to a small amount. Support plate 16 is commonly referred to as the cooking surface and supports the metallic cooking utensil 17 to be heated. Cooking utensil 17 is more particularly an ordinary cooking pot or pan, a frying pan, or some other available metallic utensil used in food preparation. The utensil can be made of a magnetic material such as magnetic stainless steel, enameled steel, or cast iron; a non-magnetic material such as aluminum and aluminum foil; or a laminated product such as copper-clad stainless steel or triple-clad (stainless-cast iron-stainless steel). Special cooking utensils are not required although the best and most efficient results are obtained by optimizing the size, shape, and material of the cooking utensil. High loss magnetic steel utensils couple well to coil 15 and are heated most efficiently, while cop-

per-clad utensils and thick aluminum utensils do not couple well to the coil, and the laminated and cast iron utensils are inbetween. Additionally, it is important to impedance match the utensil to the power circuit for best overall efficiency. FIG. 3 shows a non-metallic utensil 17', made for instance of plastic, with a metallic receptor plate 18 embedded in the utensil bottom to be heated inductively by coil 15. Any of these utensils may be used with an induction surface cooking unit when the coil 15, solid state power conversion circuit 12, and the gap between coil and utensil are properly designed. Ordinarily a gap of at least one-eighth inch is required between the top of coil 15 and the bottom of utensil 17 or receptor plate 18 to allow space for support 16, and the gap is no greater than about one-half inch in order to couple sufficient power into the utensil to produce adequate heating for cooking purposes.

Operation of solid state power conversion circuit 12 to impress an ultrasonic frequency wave on induction heating coil 15 results in the generation of an alternating magnetic field, and the magnetic flux which is produced is coupled across the air gap through non-metallic support 16 to utensil 17 or receptor plate 18. An ultrasonic frequency above 18 kHz or so is considered to be the upper limit of human hearing and is selected to make the cooking appliance inaudible to most people. The other end of the band of feasible ultrasonic frequencies is 40 kHz and is determined primarily by economic considerations in conjunction with the high frequency limitations of available power devices. An essential feature of the invention is the non-metallic support plate 16 which, as shown in FIG. 4, has a relatively smooth and substantially unbroken utensil supporting surface. This is not to preclude the existence of small apertures in the cooking surface for sensors or indicators. At ultrasonic frequencies, there are insignificant reaction forces of attraction or repulsion which at lower frequencies would cause utensil 17 to move horizontally when placed on the cooking surface approximately centered with respect to one of the induction surface cooking unit positions illustrated in dashed lines. FIG. 4 shows the induction surface cooking unit incorporated in an electric range, with a control knob 21 for each unit on the upstanding control panel for turning the individual unit on and off and setting the desired heating level or power level. In the model illustrated, one cooking unit has an additional control knob 21' for setting a specific utensil temperature to which the utensil is to be heated. Indicator light 20 turns on when power is applied to indicate an energized unit. Built-in counter-top induction surface cooking units, often referred to as cooktops, have the same configuration.

The transfer of energy to utensil 17 to heat it is relatively efficient since heat is generated only in the utensil and none is lost because of mismatch in size between the heating element (coil) and utensil. Hence, less electrical power is used as compared to conventional electric ranges and the operating costs are lower, and is consistent throughout the life of the appliance. Another feature of induction cooking is that the surface of support plate 16 is relatively cool since in addition to not being heated directly by the induction heating mechanism, the highest temperatures involved are about 450°-500°F, the approximate maximum temperature to which the bottom of utensil 17 is heated to cook food. Because of the cool cooking surface, spilled

foods do not burn and char and therefore both support plate 16 and utensil 17 are easy to clean. A cool, smooth cooking surface also makes it possible to use the surface before cooking, or even immediately after cooking, for other functions relating to food preparation such as opening cans, trimming and cutting vegetables, transferring cooked foods from a cooking utensil to a serving dish, etc. The utensil is heated more uniformly than is the case with the conventional gas range or electric range based on resistance heating, and in particular there is an absence of localized hot spots at high heating levels. Moreover, the inductive heating of cooking utensils results in a low thermal mass system. Heating begins promptly because of the fast warm-up period. Since there is a relatively low storage of heat in utensil 17, the temperature to which the utensil is heated can be changed rapidly, as from boiling to simmering to warming temperatures.

Complete induction heating systems uniquely suited for solid state induction surface cooking units for domestic usage are illustrated in block diagram form in FIGS. 19 to 22. The details of these heating systems are tailored for domestic ranges and cooktop units, whether built-in or portable, with a complete range of available heating levels for a variety of cooking tasks from rapid boiling to warming easily burned foods. It will be appreciated, however, that to some extent the principles discussed are applicable to commercial cooking equipment, on one hand, and portable food warming appliances with a power output of 50-400 watts, on the other hand. The desirable characteristics of the electrical and magnetic systems for these induction surface cooking units are discussed with regard to FIGS. 8 to 18. This discussion touches on some of the alternative electrical circuits that are not mentioned elsewhere in this application or in the cross-referenced applications. The same comment can be made that some of these characteristics are specifically for domestic ranges and cooktops, but many are of general applicability in higher and lower power cooking and warming units. To facilitate the understanding of these block diagrams, characteristics, and circuits, it is advantageous to review in some detail the structure and operation of one form of induction surface cooking unit that is illustrative of the practice of the invention. The description is largely by way of summary of the operation of the circuit, and for further details the reader is referred to the aforementioned concurrently filed application, Ser. No. 211,926. Identical components are designated by the same reference numerals and operate in the same manner.

Detailed Circuits of a Specific Induction Surface Cooking Unit

Solid state power conversion circuit 12 in FIG. 5 is energized by a commercially available source of alternating voltage and includes as major components a phase controlled rectifier 13 and a variable frequency one-thyristor series resonant inverter 14 in which induction heating coil 15 is used in a dual function to couple power to the utensil as well as to provide commutating inductance in the thyristor commutation circuit. The inverter is therefore relatively simple and inexpensive and requires only one gating or firing circuit. The input terminals 22 and 23 of power converter 12 are energized by a 120 volt, 60 Hz single phase source of a-c supply voltage. Where the energy source is the

utility power supply, the solid state equipment usually requires the connection of a surge protection device or circuit 130 and an RFI filter 131 between input terminals 22 and 23. The first protects the surface cooking unit from voltage surges in the power distribution system, while the second prevents ultrasonic or radio frequency energy generated by the cooking unit from creating a disturbance in the utility power system. Conventional devices and networks can be used. The d-c power supply, provided by full wave phase controlled bridge rectifier 13 and a filter network including series filter inductor 24' and a shunt filter capacitor 24, produces a varying d-c input voltage for inverter 14. This is one technique for controlling the power output of the inverter and therefore the heating level or specific utensil temperature. Another power control mechanism is to change the inverter output frequency and therefore the rate of supplying current pulses to the induction heating coil. Suitable phase control circuits for the SCR's in rectifier 13 are given in the SCR Manual, 4th edition, published by the General Electric Company, Semiconductor Products Department, Syracuse, N.Y. copyright 1967. Rectifier 13 can be a full wave diode rectifier when it is desired to control the power output of inverter 14 solely by varying the inverter output frequency in the manner to be explained.

The power circuit connected between d-c input terminals 25 and 26 comprises induction heating coil 15 connected in series with a commutating capacitor 27 and the inverse-parallel combination of a unidirectional conducting thyristor 28 and a power diode 29. A series RC snubber circuit 30 is also coupled across the load terminals of thyristor 28 for dv/dt protection to limit the rate of rise of reapplied forward voltage to the device. A reset inductor 31 connected directly across commutating capacitor 27 functions to recharge capacitor 27 between cycles of operation when both thyristor 28 and diode 29 are non-conducting. The load for the inverter is the electrical loss in the utensil. As the physical equivalent for utensil 17 in FIG. 5 suggests, utensil 17 functions as a single turn secondary winding with a series resistance 17r representing the resistive part of the I²R or eddy current losses, and hysteresis losses where applicable. Induction heating coil 15 functions as the primary winding of the air-core transformer, and the current and voltages induced in utensil 17 when the induction surface cooking unit is in operation are determined essentially by the transformer laws. In an equivalent electrical circuit (not here illustrated) for coil 15 and utensil 17, coil 15 is represented by a series connected inductance 15i and resistance 15r and these are in turn in series with the parallel combination of a resistance 17r and an inductance 17i representing the utensil.

With the utensil load in place, the commutating inductance for the series resonant circuit comprising coil 15 and commutating capacitor 17 is composed of both the coil inductance 15i and the reflected utensil inductance 17i. Under no-load conditions when the utensil is removed from the induction surface unit, the amount of commutating inductance increases. This causes a change in the resonant frequency of the series resonant circuit and there is a decrease in the inverter output frequency. With an average or selected utensil load in place, this series resonant circuit is tuned to resonance at a resonant frequency higher than the highest desired output frequency. In explaining the operation of the

power circuit, it is assumed that the surface cooking unit is operated in the watts control mode by setting the desired utensil heating level by the use of control knob 21. Gating control circuit 33 supplies gating or firing signals at a variable repetition rate to the gate of thyristor 28, to operate the inverter with a corresponding repetition rate or output frequency according to the power output in watts that is desired. Under steady state operating conditions, it is assumed that commutating capacitor 27 is reset negatively by the operation of reset inductor 31 in the interval following the previous conduction cycle. The application of a gating pulse to thyristor 28 causes it to turn on, energizing the damped series R-L-C oscillatory circuit comprising coil 15, commutating capacitor 27, and the reflected inductance and losses in utensil 17. A positive polarity half-sinusoidal current pulse flows through induction heating coil 15 and charges commutating capacitor 27 to a value exceeding the supply voltage V_{dc} . At the end of the half cycle, the voltage on commutating capacitor 27 reaches a peak and the current drops to zero and then reverses as commutating capacitor 27 discharges negatively through diode 29. Commutating capacitor 27 applies a reverse bias to thyristor 28, and turn-off of the thyristor is assured by the reverse voltage applied by conducting diode 29. At the end of the negative polarity half cycle, the current through induction heating coil 15 remains zero since the next gating pulse is not applied to thyristor 28 at this time. While devices 28 and 29 were conducting, the current in reset inductor 31 was increasing due to the net positive d-c voltage on commutating capacitor 27 during the conduction cycle. During the power circuit off-time, reset inductor 31 discharges thereby leaving commutating capacitor 27 with a net negative charge at the end of the circuit off-time. The supplying of a gating pulse to thyristor 28 begins the next complete cycle of operation. FIG. 6a shows in full lines the sinusoidal induction current coil for two complete cycles of operation separated by a time delay interval 34 corresponding to the circuit off-time. The corresponding commutating capacitor voltage under steady state conditions with the utensil load in place is shown in full lines in FIG. 6b. At the end of the conduction cycle the magnitude of the negative voltage on capacitor 27 is lower than the peak positive voltage, and the action of reset inductor 31 during the interval 34 is to change the capacitor voltage almost linearly as indicated at 35, leaving the capacitor with a net negative charge at the end of interval 34. Due to this extra charge on commutating capacitor 27, the peak capacitor voltage 36 during the next cycle of operation is higher, as compared to a power circuit without reset inductor 31, since the system energy is replenished. The effect of shortening the off-time interval 34 by increasing the repetition rate of the gating pulses is to increase the inverter output frequency and therefore the current and power supplied to utensil 17. Increasing the inverter output frequency also has the beneficial result of increasing the amplitude of the sinusoidal current pulses as well as their frequency. This is illustrated in FIG. 6a by the second cycle dashed line current waveform. By advancing the thyristor gating pulse, the ratio of conduction time to capacitor recharge time increases, thereby on a steady state basis increasing the average current in reset inductor 31. The result is that, referring to the dashed line capacitor voltage characteristic of FIG. 6b, commutating capacitor

27 is charged negatively to a higher negative voltage during the circuit off-time as indicated at 35' so that the peak capacitor voltage 36' during the next conduction cycle is higher than the peak voltage 36 for the lower inverter frequency case. A limit on inverter frequency is reached when the value of the current in reset inductor 31 becomes significant in comparison to the high frequency reverse current pulse in coil 15 and commutating capacitor 27, since this in effect reduces the commutation time available to the thyristor. In summary, there are two effects that increase the power in watts applied to utensil 17 when the inverter output frequency is increased. There are larger and more frequently applied current pulses in induction heating coil 15. In addition, watts control of the amount of heat generated in utensil 17 can be obtained by varying the input d-c voltage by using the phase controlled rectifier 13.

The function of gating or firing control circuit 33 in FIG. 5 is not only to generate a train of variable repetition rate gating pulses for thyristor 28, but also to incorporate control logic which ensures reliable, automatic, and satisfactory operation of the induction surface cooking unit. This is done in this control circuit by modifying the normal operation of the control circuit and in particular the operation of the turn-on circuitry for producing the gating or firing signals that initiate turn-on of thyristor 28. The gating pulse repetition rate is changed to a lower, more satisfactory value, and the generation of gating pulses is inhibited completely when certain predetermined abnormal circuit conditions are sensed that tend to lead to malfunction or failure of the power device or other power circuit components. In addition to these protective circuit features the control circuit is used during startup and shutdown of the unit, and to adapt the unit for operation in the no-load condition by sensing the absence of the utensil coupled to the induction heating coil and modifying the operation of the control circuit.

Gating control circuit 33 is preferably fabricated as a monolithic or hybrid integrated circuit. In order to avoid the addition of power consuming components to the inverter power circuit, the trade off is made of retaining a relatively simple and inexpensive power circuit at the expense of increasing the complexity of the control circuit. Hence the desirability of manufacturing it in integrated circuit form. It is also desirable to fabricate the thyristor-diode combination 28, 29 and power rectifier 13 as hybrid or monolithic integrated circuits.

These low cost approaches are needed especially in consumer oriented appliances to reduce the cost, save space, and improve reliability and serviceability. I.C. gating control circuit 33 includes a low voltage power supply which, for proper operation of the gating circuit, is energized when power is applied to inverter 14. Accordingly, the low voltage power supply can be connected to power rectifier terminal 25'. An alternative arrangement here shown is to supply gating control circuit 33 with continuous direct voltage independent of the power circuit by using an additional pair of half wave rectifiers 36 connected to the input terminals of main rectifier 13. The low voltage power supply is then connected to output terminal 37 of the auxiliary rectifier. Another important feature of gating control circuit 33 in terms of use in consumer appliances is that it is adjusted to the desired setting by appropriate user controls 40 that are accessible to the user, such as an

adjustable resistor or potentiometer that is adjusted by turning control knob 21.

The components illustrated in the detailed circuit diagram of gating control circuit 33 in FIG. 7 are numbered consecutively from left to right for the convenience of the reader. Control circuit 33 is energized by a low voltage d-c power supply 48 which establishes a positive low voltage terminal 49 and the common negative terminal 26 between which most of the components of the control circuit are connected. Low voltage d-c power supply 48 comprises a pair of voltage dropping resistors 118 and 121 connected in parallel between the auxiliary d-c supply terminal 37 and low voltage terminal 49, and also a pair of Zener diodes 124 and 125 and two filter capacitors 123 and 126 all connected between low voltage terminals 49 and 26. Filter capacitor 123 is an energy storage electrolytic capacitor while filter capacitor 126 is a high frequency ceramic capacitor to provide a low source impedance so that there is sufficient current to generate a gating pulse of the required magnitude. The Zener regulated supply provided at the low voltage terminals is typically 15 volts.

Voltage controlled pulse generator 46 produces a train of gating pulses at a variable repetition rate which are amplified by gating pulse amplifier 47 before being applied to the gate electrode of power thyristor 28. Output frequency control circuit 41 determines the basic input voltage level to voltage controlled pulse generator 46 and thus the gating pulse repetition rate and consequently the inverter output frequency. These functional units in combination are the turn-on circuitry for initiating a complete cycle of conduction of thyristor 28 and diode 29.

Voltage controlled pulse generator 46 comprises essentially a complementary unijunction transistor relaxation oscillator. The emitter of complementary unijunction transistor 113 is connected to the junction of a main timing capacitor 109 and a transistor 110 which functions as a variable impedance in the charging circuit by virtue of the fact that the collector current is a function of the base voltage. The d-c voltage level on a control capacitor 108 connected between the base of transistor 110 and terminal 26 determines the rate of charging of capacitor 109 and hence the pulse generation rate. In operation, main timing capacitor 109 charges negatively through transistor 110 and emitter resistor 111 and causes complementary unijunction 113 to break over and conduct in each charging cycle when the emitter peak point voltage is reached. Capacitor 109 then discharges through base resistor 112 and generates a current pulse that is amplified by gating or firing pulse amplifier 47. Because control capacitor 108 is relatively large the repetition rate ramps from one setting to another as the power level is adjusted or as the protection circuits and other circuits operate automatically in the manner to be explained. Gating pulse amplifier 47 comprises a small transistor amplifier 115 having its base connected to the base 1 of complementary unijunction 113. The voltage level between emitter resistors 116 and 117 produced when transistor 115 is turned on is the input voltage to a Darlington amplifier comprising transistors 119 and 122. A relatively high current gating pulse is assured by the low source impedance provided by filter capacitor 126 as previously mentioned. Emitter resistor 120 assures a rapid turn-off of transistor 112 when the pulse is

completed. Output frequency control 41 is basically a variable resistance divider network for adjusting the d-c voltage level on control capacitor 108. User adjustment potentiometer 40 is connected through isolating resistor 51 to the positive terminal 108p of control capacitor 108, and places a variable amount of resistance in series with the control capacitor. The value of resistor 52 determines to a first order the maximum output frequency that is possible, while the value of resistor 54 determines the minimum output frequency. The pointer of potentiometer 40 is connected for movement with control knob 21 (FIG. 4), which is referred to as the watts control since it adjusts the power output of inverter 14.

As is well known, failure of thyristor 28 can occur if the anode voltage exceeds the peak forward voltage of the device or if there is insufficient turn-off time to switch the device from the conducting to the forward blocking condition. In gating control circuit 33, maximum frequency control 42 and thyristor overvoltage detection circuit 45 provide device protection by overriding output frequency control 41 upon the detection of certain abnormal circuit conditions. In addition, snubber circuit 30 in the power circuit (FIG. 5) provides additional device protection by preventing dv/dt firing. Maximum frequency control circuit 42 sets the output frequency limit by operating as a clamp on the voltage across control capacitor 108. A maximum frequency limit is needed to prevent the inverter from entering the unstable short commutation time mode of operation for the reasons given in the discussion of FIG. 6a. Diode 55 is normally reverse biased, but when the potential of terminal 108p rises above a critical voltage as determined by the setting of potentiometer 57, the diode becomes forward biased and conducts. Diode 55 and the portion of potentiometer 57 between its pointer and negative terminal 26 is in parallel with control capacitor 108 so that the voltage across the capacitor is limited to 0.6 volts above the value set by potentiometer 57.

Thyristor overvoltage detection circuit 45 monitors the thyristor forward blocking voltage at the anode of the device and adjusts the repetition rate of voltage controlled pulse generator 46 to keep the thyristor in a safe operating mode. Due to the fact that the amplitude of the sinusoidal current pulses in the inverter and the commutating capacitor voltage increases with an increase in inverter output frequency, circuit 45 lowers the output frequency when the forward blocking voltage exceeds a predetermined critical value lower than the peak forward voltage rating of the thyristor. This reduces the forward blocking voltage applied to the thyristor. A string of Zener diodes 81 (only one is illustrated) or other suitable voltage responsive sensors such as metal oxide varistors sense the voltage at the anode of thyristor 28. Zener diode 81 is normally non-conductive, but supplies current to resistor string 82-85 when the overvoltage threshold level is reached. The resulting voltage drop across resistor 85 turns on a transistor 89 with the result that control capacitor 108 is discharged through resistor 88 and the collector-emitter path of transistor 89. Resistors 84 and 85 set the level of overvoltage detection and provide a positive turn-off bias for transistor 89. Resistor 83 and capacitor 80 form a low pass filter which is used to eliminate any transient component of rising thyristor anode voltage passed by the Zener string. Until capaci-

tor 80 charges to a predetermined voltage, there is insufficient voltage across resistors 84 and 85 to supply the required base drive current for transistor 89. Diode 86 becomes conductive under appropriate conditions to prevent the application of an overvoltage to transistor 89.

Low input voltage detection circuit 43 monitors the input voltage to inverter 14 at positive input d-c supply terminal 25 and is operative to initially reduce the repetition rate of gating pulse generator 46 and, after a predetermined time delay, to lock out or inhibit the pulse generator. This circuit operates during start-up when the unit is initially energized but before filter capacitor 24 is fully charged, and is effective to control starting transients caused by the interaction of the series resonant power circuit and the parallel resonant circuit formed by reset inductor 31 and capacitor 27.

These transients could under certain conditions cause a commutation failure. During shut-down when the induction cooking unit is turned off this circuit operates to remove power from the power circuit in a satisfactory, controlled manner since the pulse generator continues to operate for a short time after sensing a low power circuit voltage. Furthermore, when the input voltage is too low to yield sufficient commutation energy in commutating capacitor 27, as during a temporary voltage reduction or a brown-out, there may be a commutation failure. A low input d-c voltage below a predetermined level is sensed by a Zener diode 90 or other voltage responsive sensor. Under normal conditions, Zener diode 90 is conductive and supplies current to the remainder of the detection circuit, and it is the absence of this current that triggers the operation of the circuit. A transistor 97 is normally biased to the non-conducting state by the current flow through Zener diode 90 and resistors 91 and 92 which establishes a reverse biasing potential at the base of the transistor. The sensing of a low input voltage establishes base drive current for transistor 97 by the connection of the base to negative terminal 26 through resistors 93 and 92. Another transistor 95 also turns on in snap-action fashion by means of the feedback connection established with transistor 97 by resistors 98 and 94. The clamping circuit comprising diode 95a, adjustable resistor 95b, the collector-emitter of transistor 95, and Zener diode 96 is connected directly across the terminals of control capacitor 108. Upon the turn-on of transistor 95, the voltage across control capacitor 108 is clamped by the forward biased diode 95a and conducting transistor 95 to the voltage of Zener diode 96. This voltage level sets the basic inverter output frequency to the lower frequency limit, typically 18 kHz. At this frequency, it would be safe to start firing thyristor 28 at any voltage above the lower limits set by Zener diode 90.

A continuation of the low input voltage condition requires that the firing of thyristor 28 be halted completely. This is accomplished by clamping the voltage across main timing capacitor 109 which is effected by rendering conductive a clamping transistor 107 connected directly across its terminals. The change of state of transistor 97 from non-conducting to conducting also initiates current flow through the low pass filter comprising a resistor 100 and time delay capacitor 99. After a predetermined time delay dependent upon their time constant, capacitor 99 is charged to a voltage level sufficient to cause Zener diode 102 to break-

over and conduct. The voltage drop across a resistor 103 in series with Zener diode 102 biases a transistor 106 to the conducting state, and the resulting current flow through series connected resistors 104 and 105 supplies base drive current to clamping transistor 107. Since main timing capacitor 109 cannot charge up, voltage controlled pulse generator 46 is inhibited and prevents the subsequent generation of firing pulses. Upon the return of sufficient input d-c voltage to enable satisfactory operation of the power circuit, Zener diode 90 conducts causing transistors 97 and 95 to turn off initially. Upon the discharge of capacitor 99 through discharge resistor 101, transistors 106 and 107 also turn off. Control circuit 33 then starts generating gating pulses at a safe minimum repetition rate and increases the repetition rate to obtain the desired inverter output frequency at a rate determined by the time constant of control capacitor 108 and the control impedance of output frequency control circuit 41. During shutdown of the induction cooking unit, when power is removed, the main power supply filter capacitor 24 of course requires a few 60 Hz cycles to discharge. As soon as the input voltage sensed by Zener diode 90 drops to a low enough value, transistors 97 and 95 turn on to clamp control capacitor 108 to a voltage resulting in a low repetition rate. At the end of the time delay, a clamping transistor 107 conducts and inhibits further generation of gating pulses. This controlled de-energization of the power circuit controls the stopping transients, which could cause a commutation failure.

Utensil presence detection circuit 44 lowers the repetition rate of the gating pulses generated by voltage controlled pulse generator 46 to an audible level when the induction surface cooking unit has no load. This is one way to annunciate to the user an operating unit. In the event the audible annunciation is not desired an alternate procedure is to reduce the output frequency to the lower limit (18 kHz). This circuit is rendered operative by the sensing of a power circuit parameter indicative of the absence of a utensil coupled with the induction heating coil, in particular the high initial re-applied forward voltage at the anode of thyristor 28. The principle of operation of utensil presence detection circuit 44 is that with no utensil load coupled to induction heating coil 15, the inverter power circuit is essentially an undamped oscillatory L-C circuit with little loss in the high frequency resonant circuit. This means that commutating capacitor 27 (before the additional charge supplied by reset inductor 31) charges negatively almost as far as it does positively. By comparison, in the loaded case (see FIG. 6b) the peak negative capacitor voltage at the end of the conduction cycle is considerably less than the peak positive capacitor voltage. Conversely, looking at the thyristor forward voltage at the anode of the device as shown in FIG. 6c, the initial re-applied forward voltage for the no-load situation illustrated in full lines during the interval t_1 is characteristically higher than for the load situation shown in dashed lines. The induction coil current is drawn in dot-dash lines for reference purposes. Utensil presence detection circuit 44 recognizes the initial value only of the re-applied thyristor anode voltage, and is operative in response to the sensing of a predetermined voltage level indicative of the absence of a coupled utensil to reduce the inverter output frequency to a safe, low frequency.

Portions of utensil presence detection circuit 44 are identical or similar to the thyristor overvoltage detection circuit 45 previously described. These are Zener diode string 71 (only one is illustrated), resistors 72-75, protective diode 76, low pass filter capacitor 70, and resistor 78 and transistor 79. The overriding discharge circuit for control capacitor 108 includes a variable resistor 77 in addition to resistor 78 and transistor 79. A predetermined relatively high thyristor anode voltage, less than needed to actuate Zener diode string 81, causes Zener diode string 71 to breakover and conduct to thereby turn on transistor 79 and tend to discharge control capacitor 108. A monostable multivibrator arrangement is used to inhibit transistor 79 so that it can become conductive only during the relatively short time interval t_1 (such as 4 microseconds) after the appearance of an initial high re-applied forward voltage at the anode of the thyristor. The monostable timing circuit (components 58-68) has a connection to the anode of thyristor 28 and includes two normally conducting transistors 63 and 68. Transistor 63 is ordinarily biased to the conducting condition by the voltage across resistor 62, while transistor 68 is biased by resistors 66 and 67. Capacitor 65 is thus charged to approximately 15 volts, positive at the left-hand plate. The collector of transistor 68 is near ground potential and is connected directly to the base of transistor 79, thereby clamping transistor 79 off.

When the thyristor anode voltage goes positive in each conduction cycle due to the re-applied forward voltage, a reverse bias is applied through resistor 58 and capacitor 60 to the base of transistor 63, which turns off. Capacitor 65 is still charged, however, and due to the fact that the positive plate is not coupled to negative terminal 26 through resistor 64, the base of transistor 68 is driven sharply negative and turns off.

During the ensuing interval t_1 before transistor 68 turns back on, the overvoltage detection circuit comprising components 70 to 79 is free to operate. As soon as transistor 68 turns off, capacitor 65 discharges through resistors 64, 66, and 67, and at the end of the interval t_1 transistor 68 is no longer reverse biased and again turns on. The inhibiting of transistor 79 by the monostable timing circuit with the exception of the time interval t_1 occurs in each conduction cycle. During those cycles when the utensil is not coupled with the induction heating coil, the initial high re-applied forward voltage is sensed by Zener diode string 71, as a result of which transistor 79 turns on during the interval t_1 in each conduction cycle and partially discharges control capacitor 108. This arrangement overrides output frequency control 41 and reduces the inverter output frequency to the audible range, where it can be heard by the user. The power output at the reduced frequency is sufficiently low that there is little danger involved in heating other metallic objects that may be inadvertently placed on the cooking surface. A small metallic object such as a spatula, which has considerable area but is relatively thin, is a small load for the inverter and does not prevent turning down the power by operation of the utensil presence detection circuit.

In the foregoing discussion, the induction surface cooking unit is in the watts control mode of operation in which control knob 21 on the upstanding control panel of the range (FIG. 4) is adjusted to obtain the desired heating level in the utensil. The watts output is

adjustable continuously, but control knob 21 can of course have a scale with a series of spaced indications to which the user sets the control knob to effectively achieve stepped control of the watts output much as in the modern push-button range. To obtain power outputs lower than that corresponding to the lower limit of the ultrasonic frequency range (18 kHz), phase controlled rectifier 13 is operated to reduce the d-c input voltage to inverter 14. The gating circuit for the phase controlled thyristors in rectifier 13 preferably has an adjustable resistor to select the phase control angle, and this adjustable resistor is arranged with user potentiometer 40 such that there is continuous control of the output power. Alternatively, the induction surface cooking unit can be used in the temperature control mode of operation in which the other control knob 21' on the range control panel is associated with a scale graduated in degrees representing a specific temperature to which the utensil is to be heated. As was previously mentioned, by way of illustration the temperature is measured by means of a thermistor 19 (FIG. 3) removably attached to utensil 17 or 17' with a pair of wires that extend beneath utensil support 16 and have connection with gating control circuit 33. Specifically, thermistor 19 is assumed to have a positive temperature coefficient and is effectively connected in parallel with resistor 52 in output frequency control 41 with an interlocking switch 127 to insert one resistive element in the circuit and remove the other and vice versa. A negative temperature coefficient thermistor is in similar manner connected in parallel with resistor 54.

As is well known, thermistor 19 has a variable resistance depending upon the sensed utensil temperature. For a positive temperature coefficient thermistor, the resistance increases with increasing temperature. The result is that the total amount of resistance in the resistive voltage divider formed by thermistor 19, potentiometer 40, and resistor 54 is now variable, rather than being fixed as before. Assuming that the surface cooking unit and thermistor 19 are properly calibrated, setting control knob 21' to the desired temperature adjusts the position of the pointer along potentiometer 40. When thermistor 19 senses a utensil temperature lower than the set value, its resistance is also low. In the voltage divider, the ratio of the resistance below the pointer to that above the pointer is relatively high, so that control capacitor 108 charges to a higher voltage thereby increasing the repetition rate of the generation of gating pulses. Consequently more power is coupled to the utensil and it heats up to a higher temperature. Conversely, when thermistor 19 senses a higher utensil temperature than is desired, its resistance is also relatively high, and consequently the voltage on control capacitor 108 decreases. A reduced amount of power is coupled to the utensil and its temperature decreases until an equilibrium is established between the repetition rate of voltage controlled pulse generator 46 and the sensed temperature.

Conventional recipes for cooking food are expressed in relative heating or cooking terms, or give a temperature to be set. Many recipes call for high, medium, or low heat, or use widely known cooking terms such as warm, simmer, and low boil. Other recipes call for cooking at a particular specified temperature. It is recognized that the watts control and temperature control modes of operation of the induction surface cooking

unit are used with recipes that give instructions in this manner. Induction cooking makes possible a new type of food cooking recipe in which the instructions are given in terms of power levels to which the cooking equipment is set, for example, heat at 500 watts for ten minutes. The underlying principle of the new cooking technique is that for the first time it is possible to measure the approximate power actually coupled to the utensil and used by the utensil for cooking the food, and is consistent and repeatable to use. Due to the transformer relation between the utensil and the electronic circuit in the cooking equipment, the power actually delivered to the utensil is approximated by measuring the primary side power. This requires the addition of a wattmeter or other power measuring instrumentation to the surface cooking unit. To follow cooking instructions specifying the watts setting, the user simply adjusts the power level by turning control knob 21 to set the pointer of the wattmeter at the watts level given by the recipe. The direct setting of watts is also possible with the adjustment to that setting being made automatically by the circuit. Further information on this new method of cooking food and appropriate instrumentation is given in the concurrently filed application, Serial No. 212,058 by the same inventors, assigned to the same assignee, entitled "Method and Equipment for Cooking Electronically by Specifying Watts Setting."

30 Electrical and Magnetic Characteristics of Solid State Cooking Systems

The solid state induction cooking units herein described have a set of interlocking or matching electrical and magnetic characteristics that combine to produce cooking appliances with new and improved features as compared to prior cooking equipment whether based on induction heating or some other principle. The new cooking appliances are unique in that the cooking surface is cool to the human touch even immediately after removing a heated utensil from the surface. The magnetic flux of course does not directly generate heat in the non-metallic or non-conducting utensil support plate 16, and as was previously mentioned the utensil temperature at no time rises above 450°-500°F. Consequently, it is possible for the first time to use plastic counter-top cooking surfaces. The magnetic field distribution of the flat or nominally flat induction heating coil 15 is such that the utensil is heated relatively uniformly without excessive temperature gradients in the utensil bottom or localized hot spots corresponding to the burner or coil positions in conventional gas and electric ranges. An important feature to the user is the complete, unrestrained freedom to move the utensil on the cooking surface, as when stirring. The ponderomotive forces at ultrasonic frequencies are insignificant, and there are further no attraction forces of a mechanical nature between the utensil and support plate since it is not necessary that there be optically flat surfaces to promote the transfer of heat as in some of the glass-ceramic resistance heated tops. When using a 60 Hz a-c voltage source, it is necessary to provide a well-filtered d-c input voltage to the inverter to prevent vibration of the utensil due to a 120 Hz modulation of the power coupled to the utensil. The ultrasonic operating range is selected primarily to make the cooking unit inaudible to the user, but an added advantage of this frequency range is that the skin depth of induction

heating at these frequencies makes possible the use of relatively thin, light weight utensils. By comparison, at 60 Hz the skin depth is much thicker and requires the use of relatively heavy, thick utensils in order to take advantage of the full heating capacity of the alternating magnetic field. The use of relatively thin, efficiently heated utensils provides for fast warm-up and quick response to changes in heating levels.

There are several important physical and electrical constraints to be observed in the construction of a practical solid state induction surface cooking unit. An obvious constraint is the outside diameter of induction heating coil 15, which must transfer the required power to the utensil yet have a maximum diameter suitable for use with ordinary sized pots and pans, and yet not interact with adjacent coils or other pans. A diameter of 6-12 inches is appropriate for a variety of different sizes of utensils. A similar type of constraint is the range of impedances of ordinary utensils. Efficiency of power transfer to the load is promoted by source-to-load impedance matching, but the situation here is that the input circuit impedance is fixed if minimum cost is to result. This is because the utensil bottom functions as a single turn secondary winding, and the primary side supply voltage is fixed at 120 or 240 volts, 60 Hz, from which it follows that the primary side impedance is also fixed. This dictates certain impedance matching characteristics in the power conditioning equipment. It is possible for the primary side power converter to include an impedance matching transformer, however none is used in the converter shown in FIG. 5 in order to reduce the number of components and the cost of the circuit.

A critical constraint in the construction of solid state induction surface cooking units are the limits of the feasible ultrasonic high frequency range, namely, 18 kHz at one end and 40 kHz at the other. As has been mentioned, the upper limit of 40 kHz is determined by economic considerations in conjunction with the high frequency limitations of available power semiconductors with sufficient current carrying capacity to deliver the required power for a full range of cooking tasks. At higher frequencies, moreover, the rfi filtering problems are increasingly difficult and costly, making compliance with government communication agencies more difficult. In domestic appliances, this power output range is from 2500 watts to 50 watts for the full spectrum of cooking tasks from extremely rapid heating and boiling, on one hand, and warming easily burned foods such as rice, on the other hand. In FIG. 8 the feasible ultrasonic frequency range, 18-40 kHz, is plotted against the required power range for successful cooking, 50-2,500 watts. The area or "window" that is created is in a pictorial manner the defining condition for successful solid state induction cooking. A power range of 2,500-50 watts is a 50:1 control range and this must be obtained within the limitations that the operating frequency can only be between 18 and 40 kHz. Some ranges and cooktop units, of course, use only a portion of this frequency range above 18 kHz, for example, 18-30 kHz, and do reasonably good cooking with a power range of 12:1 or 15:1, for example, 1,200-100 watts. Food warming appliances require a much more limited power and frequency range. Some induction cooking inverter circuits such as a parallel resonant inverter may operate at a single operating frequency and vary the output power over a limited

range in some other manner. The "window" concept of FIG. 8 is intended to encompass all of these and to convey the interpretation that domestic solid state induction cooking is carried out within these power limits and frequency limits. For general cooking, a power range of at least 10:1 up to 50:1 is needed.

Among the characteristics of a solid state inverter for induction cooking appliances, in addition to being operable within at least a portion of this frequency range, are that it be capable of being inhibited, started and stopped without issuing audio information. The inverter must be controlled by a control element that is easily operated by a non-technical user, and the inverter must not fail when the control element such as user potentiometer 40 is slewed, that is changed rapidly from one setting to another. In considering the requirement for a wide range of output power, such as 10:1 to 50:1, the two general types of idealized wave shapes which can be utilized are illustrated in FIGS. 9 and 10. FIG. 9 is recognized as the non-symmetrical sinusoidal wave shape produced by the single-thyristor series resonant inverter such as that shown in FIG. 5, but inverters that produce symmetrical sinusoidal current pulses are also suitable. The time delay interval t_2 between discrete sinusoidal pulses is made as small as possible but cannot be reduced to zero to assure reliability of the thyristor commutation, especially in view of the variety of loads to be heated. The output power is modulated by widening the interval t_2 until limited by the threshold of audio frequencies, and by supplying a variable d-c input voltage which lowers the peak amplitudes of the waves. In a perfectly linear system in which the power is controlled only by changing the operating frequency, a 2:1 power range is achieved with the upper limit at 36 kHz, a 10:1 power range with the upper limit at 180 kHz, and a 30:1 range with the upper limit at 540 kHz. The latter two situations are clearly impractical. The desirable one-thyristor series resonant inverter of FIG. 5, which generates a amplitude current pulse as the operating frequency is increased, produces a power-frequency characteristic such as is shown by the solid line curve in FIG. 11. A power range in the order of 5:1 to 7:1 is obtained, and to obtain a power output below about 400 watts, it is necessary to use some other power control technique such as varying the d-c input voltage, changing the commutation circuit parameters, making use of pulse width modulation techniques, etc. The full range power-frequency characteristic shown in dashed lines in FIG. 11 is the one ideally sought after. It will be noted that solely changing the d-c input voltage usually does not obtain the wide range power control. In FIG. 7, by way of example, low input voltage detection circuit 43 is operable at 90 volts for a normal d-c input voltage of 150 volts.

Another suitable system for obtaining wide range power control is to use an inverter that produces square or rectangular wave shapes such as is shown in FIG. 10. The power is controlled by the pulse width modulation technique, by decreasing the width of each pulse to produce lower power outputs. The narrower pulses have increased harmonic content, but this occurs at decreased power levels, and therefore the ability of the system to deal with increased harmonic content is favorable. Pulse width modulation can be combined with the frequency deviation technique for wide range power control.

Some of the magnetic characteristics of induction cooking systems will be discussed with regard to FIGS. 12-15. Referring to FIG. 12, the resistivity of metals increases with increasing temperature, thus producing greater power losses in the utensil. This is a favorable situation from the standpoint of power control and impedance matching. The utensil or power receptor magnetic material must be one that has a Curie temperature in excess of about 500°F, which has been established as being the maximum pan bottom temperature in induction cooking. At the Curie temperature there is a change in permeability with a resulting poorer, less efficient coupling to the induction heating coil. The condition of a substantially constant permeability at least until 500°F is shown in FIG. 13. The induction cooking system may or may not make use of the full B-H hysteresis loop of the magnetic material depending on the nature of the ultrasonic generator and the extent to which it may produce a non-symmetrical wave shape. Minor loop operation results from the use of a converter such as that in FIG. 5 with an asymmetrical current pulse output. This is illustrated in FIG. 14. The dashed line hysteresis loop is a completely symmetrical minor loop, while the full line asymmetrical loop within it is produced by an asymmetrical cooking system such as FIG. 5. The d-c loop is shaded.

The skin depth of inductively heated magnetic materials at operating frequencies of 18 to 40 kHz is such that full advantage can be taken of the induction heating phenomenon while still using relatively thin utensils. The proper choice of material is governed by an understanding of the process of heating in utensil 17 or receptor plate 18. The depth of penetration is generally given as being proportional to the square root of resistivity divided by the relative permeability times the frequency. Thus, the depth of penetration varies with the square root of frequency and is dependent both on resistivity and the magnetic property characteristics of the material. Some typical metal thicknesses may be of help in understanding the numbers involved. For 52S aluminum the depth of penetration at 25 kHz is approximately 0.030 inches while for copper it is approximately 0.016 inches. Since the magnetic properties do not enter into the choice of these materials, the only thing that has to be considered then is the resistance coefficient as a function of temperature which is positive and essentially linear for the materials. By contrast, the depth of penetration for iron and steel is in the order of 5.7 mils at 25 kHz. Skin depth should be less than the utensil or power receptor thickness for most efficient heating. The utensils at these operating frequencies can be relatively thin, but are efficiently heated so that there is fast warm-up and fast response to changes in the power level. In general, the thickness of the magnetic material is no less than the skin depth, but can be up to several times greater. As here used, lightweight magnetic utensils are considered to have a thickness of about 25-50 mils. Referring to FIG. 15, the amount of power coupled to non-magnetic utensils and receptors such as aluminum or copper is a function of thickness and has an optimum value. For the frequency range of interest, the power is most efficiently coupled to the utensil when it has a thickness of about 0.5 mils, the thickness of aluminum foil, and there is very poor coupling at thicknesses of less than 0.1 mil and greater than 2 mils.

Some of the other types of inverters and d-c power supplies that can be used are illustrated in FIGS. 16-18. In addition to the one-thyristor series resonant circuit in FIG. 5, other one-transistor, two-thyristor, and two-transistor series and parallel resonant inverters and multicylinder inverters can be used in constructing induction surface cooking units. FIG. 16 shows a four-transistor full bridge inverter suitable for generating the pulse width modulated square wave shapes shown in FIG. 10. Each pair of opposite transistors is turned on and off for a variable amount of time to modulate the output power. In this inverter the transistors directly supply power to induction heating coil 15 which is connected across opposite junctures of the bridge, the other two opposite junctures being connected to d-c input terminals 25 and 26. FIG. 17 shows the same circuit with the addition of an impedance matching transformer 140 between the transistor bridge and induction heating coil 15. The preferred arrangement shown in FIG. 5 does not use an impedance matching transformer but it may be required in some circuits where the primary side impedance cannot in some other manner be matched to the fixed secondary side with the single turn secondary winding and fixed load presented by utensil 17. FIG. 18 shows two additional ways, other than using a phase controlled rectifier, for reducing the input voltage to achieve wide range power control. The first involves phase controlling the a-c input voltage by connecting a solid state triac device 141 between input terminal 22 and one of the inputs to full wave diode bridge rectifier 13. Triac device 141 is a bidirectional conducting thyristor that can be phase controlled for each polarity of the supply voltage in the same manner as a silicon controlled rectifier. The other technique (only one is used in a given circuit) is to use a chopper or time ratio control circuit 142 to reduce the magnitude of the filtered d-c voltage produced by the full wave diode rectifier 13 and filter network 24', 24. In this known d-c to d-c conversion circuit, the ratio of on-time to off-time of a thyristor 143 varies the voltage across an auxiliary d-c supply capacitor 144, across which the d-c input terminals 25 and 26 for the inverter are taken.

Block Diagrams of Complete Solid State Induction Cooking Systems

FIG. 19 shows the block diagram of a generalized solid state induction cooking system including some features that are optional depending upon the particular model of the electric range or cooktop unit. In view of the extensive foregoing discussion, it is believed only a minimum number of remarks need be made by way of further explanation. As important point, however, is that the foregoing circuits are illustrative of the practice of the invention, and other circuit approaches can be used to obtain the same function. Moreover the functional components can be interrelated in a different manner that has been specifically shown. In these block diagrams the functional components that are readily identifiable and have the same functional relationship to the other components as they do in FIGS. 1-7 are identified by the numerals. Additional components and functional units not previously designated by a separate numeral are identified by new numerals. In FIG. 19 the energy source is a generalized alternating or direct voltage source. The application of power to static solid state power conversion circuit 12 by the

closing of switch or contactor 21 is displayed to the user by a load indication means such as the indicator light 20 in FIG. 4. Switch or contactor 21 also energizes the start-up circuit means 150 which acts through an inhibit 151 to control static solid state power conversion circuit 12. In gating control circuit 33, FIG. 7, the start-up circuit is provided by the operation of low input voltage detection circuit 43, and the inhibit circuit function is provided by clamping transistor 107 and its operating circuitry. Start-up circuit means 150 controls the starting transients and assures the safe and controlled application of power to the load coupling means or induction heating coil 15. Load receptor means 18 can be provided by the bottom of utensil 17, which is the load, or by a separate plate 18 embedded in the utensil as shown in FIG. 3. Output power adjustment means 153 is the watts control that adjusts the power level or heating level, and this component also acts through inhibit circuit 151 to control or shut down static solid state power conversion circuit 12 under certain conditions, as when a maximum output frequency is exceeded. It is essential in solid state equipment to provide a device protection means 154 to assure proper functioning of the circuit.

A fan or other cooling means 155 for static power converter 12 and load coupling means 15 may or may not be needed depending upon the amount of heat generated by the solid state circuit and the coil, as well as such considerations as packaging. The load presence means 44, which need not be identical to the utensil presence circuit 44 disclosed in FIG. 7, is clearly an optional feature that is desirable from the standpoint of ease of operation in reducing power consumption and user safety, but is not essential to a low cost model. The temperature regulating means or temperature control 156 is also an optional feature that is provided only on deluxe models. As is indicated by the dashed lines, the type of temperature control here disclosed senses the temperature by means of thermistor 19 (FIG. 3) and operates to change the heating level by means of output power adjustment means 153 to obtain the temperature set by control knob 21'. The temperature control function is also obtained by operating through inhibit circuit 151 to selectively and temporarily inhibit operation of static power conversion circuit 12. Either an on-off temperature control system can be used or a proportional mode system that permits current flow for a variable number of cycles while inhibiting power generation for the remainder of a base interval. An on-off temperature control system using a thermostat to control the static power converter is disclosed in aforementioned application Ser. No. 200,526.

FIG. 20 is a block diagram of a solid state induction cooking system in which the energy source is the utility power supply and which uses an inverter 14 constructed with thyristor devices. The energy source is a 60 Hz, 120 or 240 volt source of a-c voltage. Although not heretofore mentioned, the same cooking system can be used with 50 Hz supply common in Europe in view of the ability of rectifier 13 to rectify any input supply voltage regardless as to the frequency. Similarly polyphase or single phase power can be utilized. Surge protection circuit 130 and RFI filter 131 function, as was mentioned in the discussion of FIG. 5, to respectively protect the cooking system from power supply surges, and to prevent high frequency disturbances in the utility power supply caused by the operation of the

cooking unit. Input voltage control means 157 is obtained, for instance, by using a phase controlled rectifier or by using one of the alternative circuits shown in FIG. 18 for phase controlling the input voltage by means of a triac or chopping the filtered d-c voltage by means of a time ratio control circuit. An optional feature is a current or power indicator 158, in the form of an ammeter or wattmeter on the upstanding range control panel (FIG. 4) to display the state of the circuit to the user. The power indicating instrument is required if the range or surface cooking unit is to be equipped with the ability to cook using recipes that specify the watts setting, as previously explained.

An impedance matching means 140 such as impedance matching transformer 140 (FIG. 17) may be required to some circuits to match the primary side impedance to the fixed secondary side impedance for the reasons given previously. It may also be desired to have an impedance switching scheme to obtain efficient power coupling over a greater load range. Gating circuit 159 is here shown as a separate functional unit. Components 150-154 and 44 have the functional relationship to gating circuit 159 as is used in implementing gating control circuit 33, FIG. 7. The temperature regulating means 156 is again an optional feature.

FIG. 21 is a similar block diagram of a solid state induction cooking system that operates from a battery or other direct voltage supply and uses an inverter implemented with power transistors. Transistor devices, of course, do not require a commutation circuit. In view of the similarity to FIG. 20, it is believed that no further comments are needed. It is noted, however, that a filter network 24, 24' is still needed to assure a well-regulated source of d-c input voltage for inverter 14.

FIG. 22 is a logic type of block diagram for a generalized solid state induction cooking system. It is another way of presenting much of the material given in FIGS. 19-21. As in gating control circuit 33, FIG. 7, the output frequency of static solid state conversion circuit 12 is determined by a master voltage controlled oscillator 165. The various logic inputs that determine the repetition rate of master voltage control oscillator 165 are combined in a summing circuit 166. Summing circuit 166 is in the form of an operational amplifier equipped for addition by means of a resistor between the amplifier output and input, and another resistor connected between this same amplifier input and the source of logic signals. The two types of logic signals are the control advance signals that normally operate to increase the repetition rate of master oscillator 165, and the control retard logic signals that ordinarily operate to decrease the repetition rate. The system is energized by means of user input No. 1 which operates on-off switch 21. The start logic signals are controlled by user input No. 2, and this is the only type of control advance logic applied to summing circuit 166.

The various control retard logic signals are combined in a second summing circuit 167 and applied to the first summing circuit 166. The control retard logic includes start logic, stop logic, temperature control logic, watts control logic, user safety logic, and circuit protection logic. The start logic can also operate to retard master oscillator 165 if the proper starting conditions are not present, such as insufficient input voltage to assure enough commutation energy in the commutating capacitor for proper operation of the inverter. The user safety logic can be provided, for instance, by utensil

presence detection circuit 44, since this circuit automatically turns down the power output of static power converter 12 when there is no utensil coupled with the load coupling means (coil 15). Consequently, miscellaneous metallic objects that are inadvertently placed on the cooking surface, such as jewelry, spatulas, or other small food preparation implements, are not heated to high temperature that could be dangerous to the user. Specific types of circuit protection logic were explained in detail with regard to FIG. 7, and include protection against a low supply voltage, a high active device voltage, insufficient commutation energy, and lack of proper gate drive. These different types of control retard logic signals are combined in summing circuit 167 such that any one of them, or their combined effect, causes a reduction in the repetition rate of master oscillator 165.

The output power of static power converter 12 is also reduced independently by the input voltage control technique. User input No. 3 operates the input power retard logic, which in turn directly controls the input voltage control, the watts control logic, and temperature control logic.

In summary, solid state induction surface cooking units for domestic ranges and other cooking appliances incorporate unique induction heating systems that have been described with emphasis on the operating parameters and functional features that enhance their acceptability for mass usage by assuring reliable and convenient operation. These new cooking appliances are based on inter-related electrical and magnetic characteristics that achieve improved appliances with a good looking, easy to clean, cool cooking surface which for the first time can be made of plastics as well as other non-metallic materials. Other desirable user features are consistent performance, fast warm-up of lightweight utensils, responsive heating without temperature gradients, and complete freedom to move the utensil without restraint. In addition to cooking by adjusting the relative heating level, induction ranges and surface cooking units when properly equipped perform cooking by setting the utensil temperature and for the first time by setting the utensil power level.

While the invention has been particularly shown and described with reference to several preferred embodiments thereof, it will be understood by those skilled in the art that the foregoing and other changes in form and detail may be made therein without departing from the spirit and scope of the invention.

What we claim as new and desire to secure by Letters Patent of the United States is:

1. A domestic induction surface cooking unit comprising

a nominally flat induction heating coil mounted adjacent a substantially unbroken non-metallic utensil support to thereby provide a relatively cool cooking surface,

a solid state power conversion circuit for converting a supply voltage to ultrasonic output power that drives said induction heating coil and generates an alternating magnetic field for coupling the power to a cooking utensil, wherein

the ultrasonic output power is between 50 and 2,500 watts and has a frequency between 18 and 40 kilohertz, and the solid state power conversion circuit produces wide range ultrasonic output power for

general cooking purposes with a ratio of maximum to minimum output power of 10:1 to 50:1.

2. A cooking unit according to claim 1 in which the maximum output power is about 1,500 watts and the minimum output power is about 50 watts.

3. A cooking unit according to claim 1 in which said solid state power conversion circuit includes a full bridge inverter constructed with power semiconductors that produce rectangular voltage pulses, and

means for controlling said power semiconductors to pulse width modulate said rectangular voltage pulses to adjust the power coupled to the cooking utensil.

4. A cooking unit according to claim 3 in which said bridge inverter is additionally operated at a variable ultrasonic frequency to achieve wide range power control.

5. A domestic induction surface cooking unit comprising

a nominally flat induction heating coil mounted adjacent a substantially unbroken non-metallic utensil support to thereby provide a relatively cool cooking surface,

a solid state power conversion circuit for converting a supply voltage to ultrasonic output power that drives said induction heating coil and generates an alternating magnetic field for coupling the power to a cooking utensil, wherein

the output power is between 50 and 2,500 watts and has a frequency between 18 and 40 kilohertz, and said solid state power conversion circuit produces a unidirectional voltage and includes filter means for filtering the unidirectional voltage, and further includes an inverter energized by the filtered unidirectional voltage that produces wide range ultrasonic output power for general cooking purposes with a ratio of maximum to minimum output power of 10:1 to 50:1.

6. A cooking unit according to claim 5 in which the maximum output power is about 1,500 watts and the minimum output power is about 50 watts.

7. A cooking unit according to claim 5 in which said solid state power conversion circuit includes a time ratio control circuit coupled between said filter means and inverter for changing the magnitude of the filtered uni-directional voltage energizing the inverter for wide range power control.

8. A domestic induction surface cooking unit comprising

a nominally flat induction heating coil mounted adjacent a substantially unbroken non-metallic utensil support plate to thereby provide a relatively cool cooking surface,

a static power conversion circuit including filter means and an inverter controlled by solid state power device means for converting a filtered unidirectional voltage to an ultrasonic frequency wave that drives said induction heating coil for coupling output power to a cooking utensil,

a gating circuit for selecting the intervals of conduction of said power device means,

an inhibit circuit coupled to said gating circuit for selectively inhibiting operation of said inverter,

start-up and shut-down circuit means coupled to said inhibit circuit and gating circuit for controlling starting and stopping transients and the application to and removal of voltage from said inverter,

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device protection means for protecting said power device means from undesired voltages and currents,

output power adjustment means coupled to said gating circuit and inhibit circuit for varying the output power of said inverter and therefore the heating level of the utensil, and

user control means for energizing and de-energizing said static power conversion circuit and setting a selected utensil heating level.

9. A cooking unit according to claim 8 further including surge protection means and a radio frequency interference filter connected across the input terminals of said static power conversion circuit.

10. A cooking unit according to claim 8 wherein said static power conversion circuit further includes a full wave rectifier and means for controlling the magnitude of the filtered unidirectional voltage to obtain wide range control of the output power and therefore of the utensil heating level.

11. A cooling unit according to claim 8 further including cooling means for said induction heating coil and static power conversion circuit.

12. A cooking unit according to claim 8 further including a current meter located between said filter means and inverter for displaying the state of the circuit to the user.

13. A cooking unit according to claim 8 further including utensil presence detection circuit means coupled to said gating circuit for sensing the absence of a cooking utensil coupled to said induction heating coil and modifying the operation of said gating circuit.

14. A cooking unit according to claim 8 wherein said device protection means comprises means for monitoring the filtered unidirectional voltage supplied to said inverter and actuating said inhibit circuit in response to the sensing of a predetermined low voltage level.

15. A cooking unit according to claim 8 wherein said device protection means comprises means for monitoring the voltage at a terminal of said solid state power

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device means and reducing the power output of said inverter in response to the sensing of a predetermined high voltage level.

16. A solid state induction surface cooking unit comprising

an induction heating coil for inductively heating a cooking utensil,

a solid state power conversion circuit for converting a unidirectional voltage to variable ultrasonic output power that is applied to said induction heating coil and produces a range of utensil heating levels, a gating circuit for controlling said solid state power conversion circuit to produce a heating level in dependence upon the algebraic sum of a plurality of input signals,

a plurality of control logic circuits each generating one of said input signals and including start circuit means, stop circuit means, watts control means, user safety means, and circuit protection means, summing means for deriving the sum of the control logic circuit input signals and applying the sum to said gating circuit, and

user control means for energizing and de-energizing said solid state power conversion circuit and setting said watts control means to obtain a selected heating level.

17. A cooking unit according to claim 16 in which said solid state power conversion circuit includes input voltage control means for reducing the magnitude of said unidirectional voltage for wide range control of the ultrasonic output voltage and therefore the range of utensil heating levels.

18. A cooking unit according to claim 16 in which said user safety means comprises a utensil presence detection circuit that is operative when metallic objects significantly smaller than a cooking utensil are coupled with said induction heating coil as well as when a cooking utensil is not coupled therewith.

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