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Harnden, Jr. et al.

[11] **3,781,503**
[45] **Dec. 25, 1973**

[54] **SOLID STATE INDUCTION COOKING APPLIANCES AND CIRCUITS**

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[73] Assignee: **General Electric Company,** Schenectady, N.Y.

[22] Filed: **Nov. 19, 1971**

[21] Appl. No.: **200,424**

[52] **U.S. Cl.**........ **219/10.49,** 219/10.77, 219/10.79, 321/45
[51] **Int. Cl.** **H05b 5/04**
[58] **Field of Search**...................... 219/10.49, 10.75, 219/10.77, 10.79; 321/27, 45, 4, 44

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Primary Examiner—Bruce A. Reynolds
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[57] **ABSTRACT**

An economical smooth-top cooking appliance for inductively heating cooking utensils preferably comprises a flat air-core induction heating coil driven at an ultrasonic frequency by a simplified one-thyristor, one-transistor, or two-transistor resonant inverter. The series and parallel resonant circuits in the inverters are formed by a capacitor and the induction heating coil. The one-thyristor series resonant circuit is desirable because power control to adjust the cooking temperature is obtained by the combined effect of increasing the frequency and amplitude of the sinusoidal current pulses supplied to the coil. The coil is also movable to change the gap spacing between coil and utensil to vary the coupled power. Flux beneath the coil is used for warming purposes.

23 Claims, 17 Drawing Figures

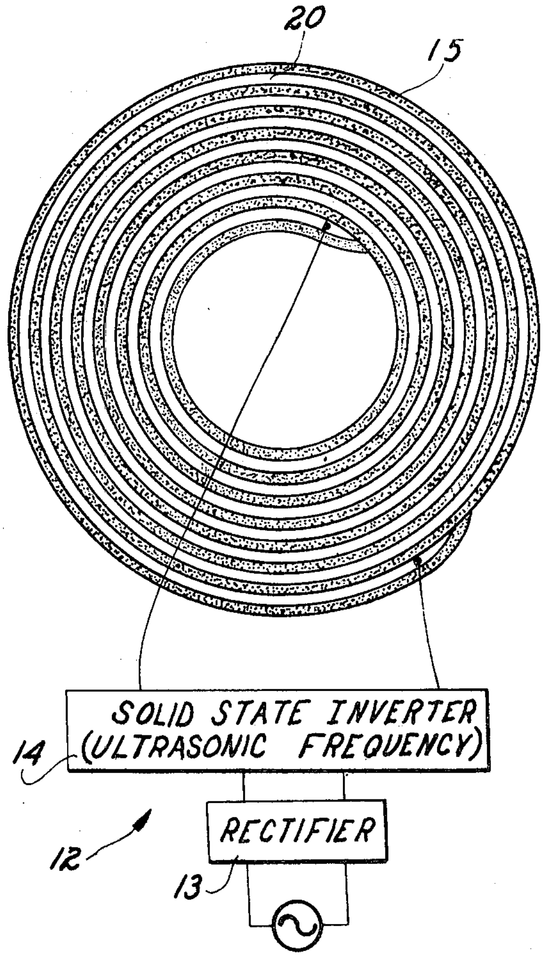


Fig. 1

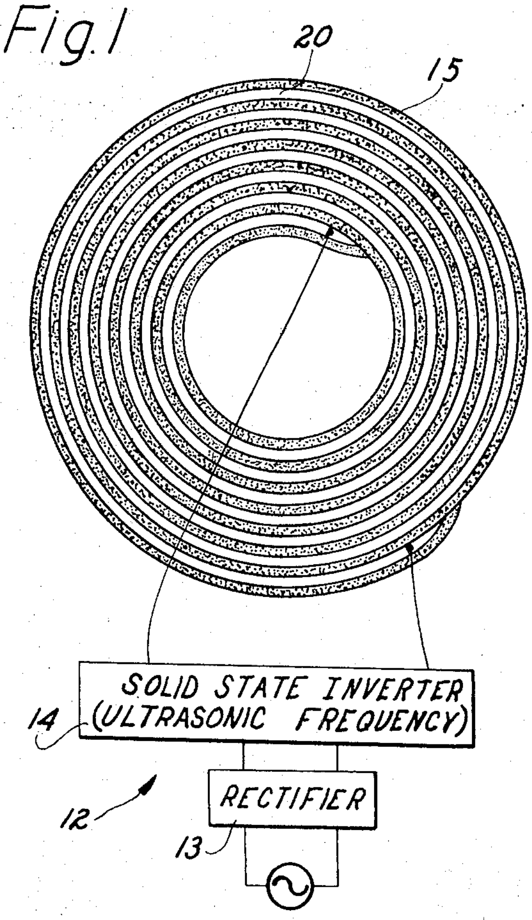
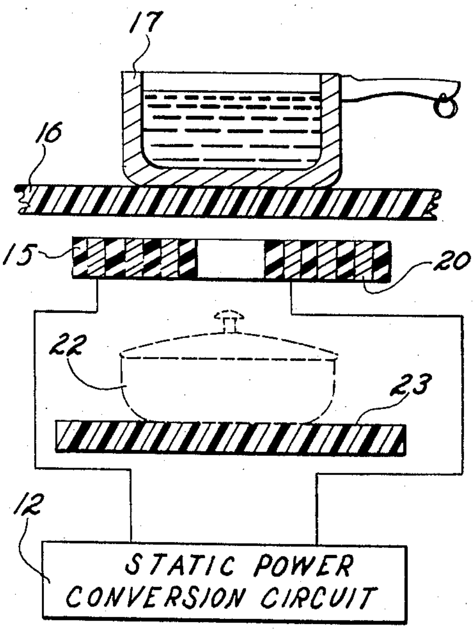


Fig. 2



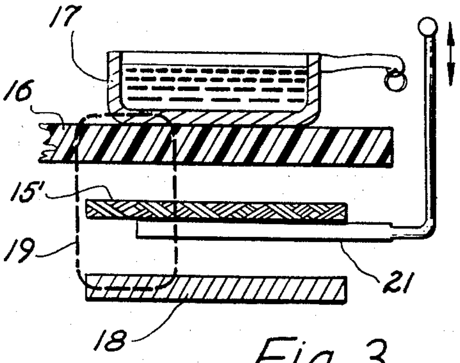


Fig. 3

Fig. 4

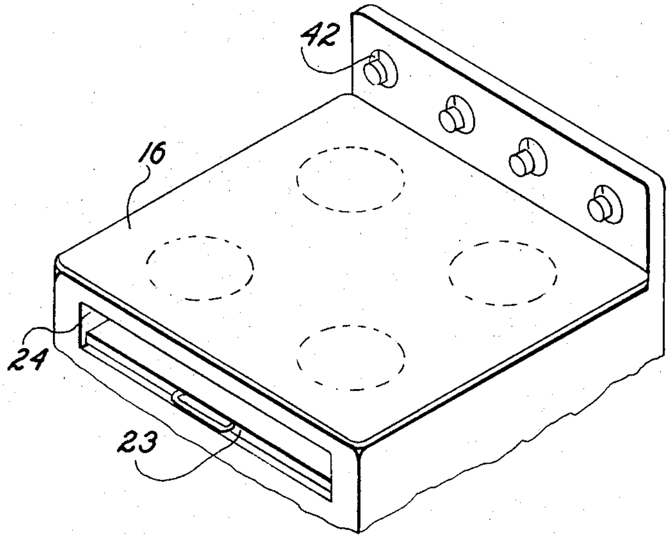


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Fig. 5

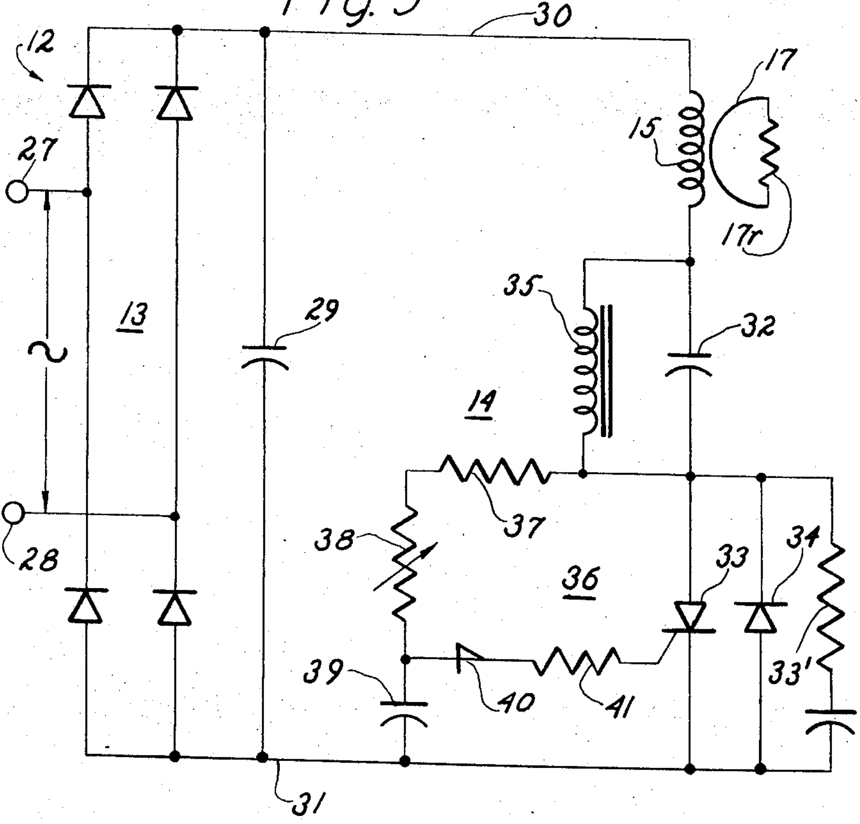


Fig.6

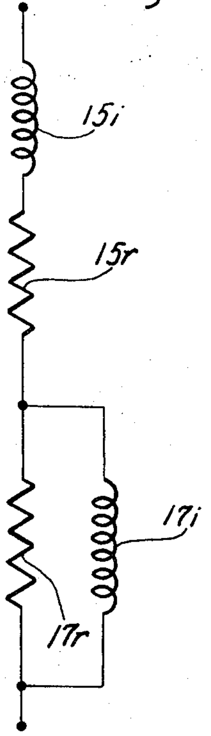


Fig.7a

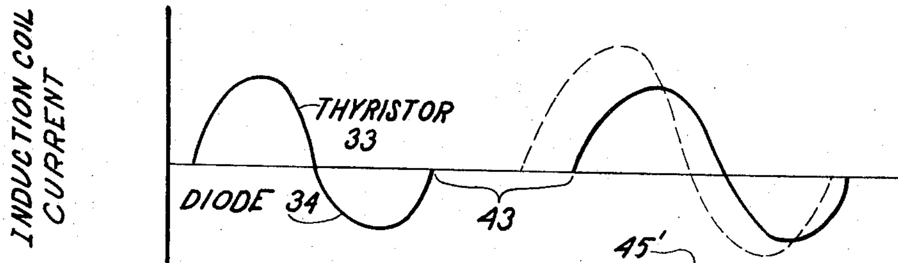
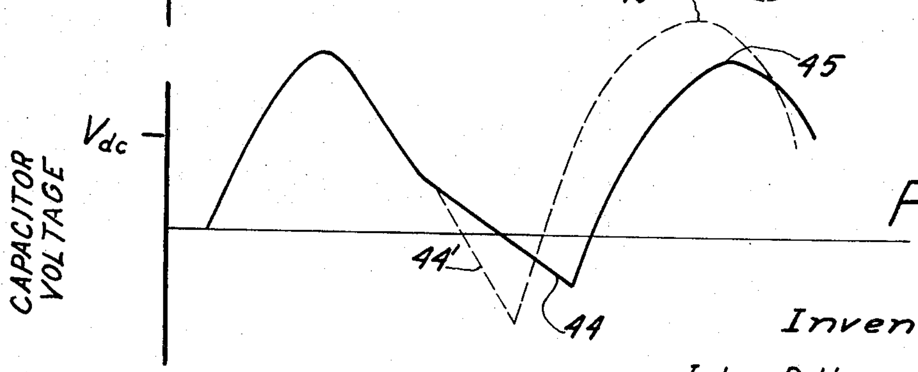


Fig.7b



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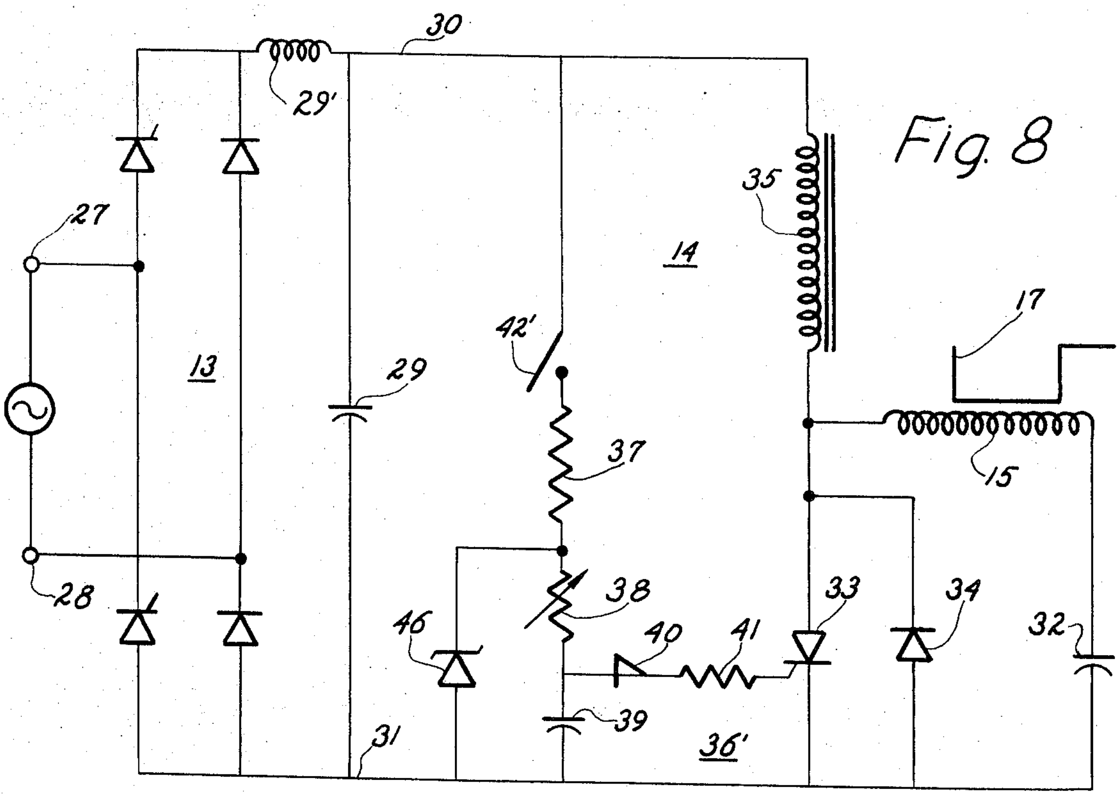

Fig. 8

Fig. 10

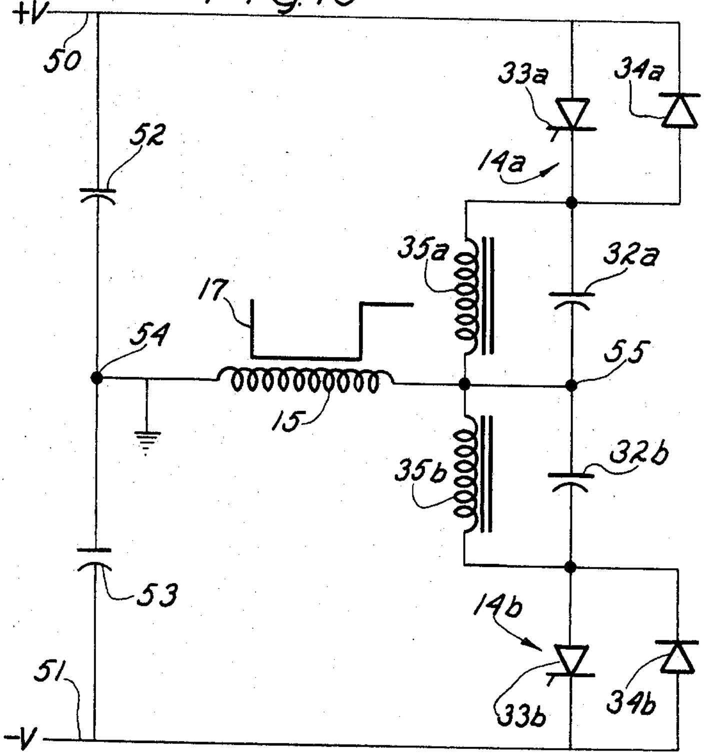

Fig. 9

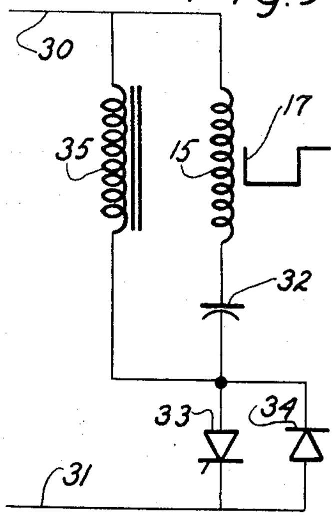

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Fig.11

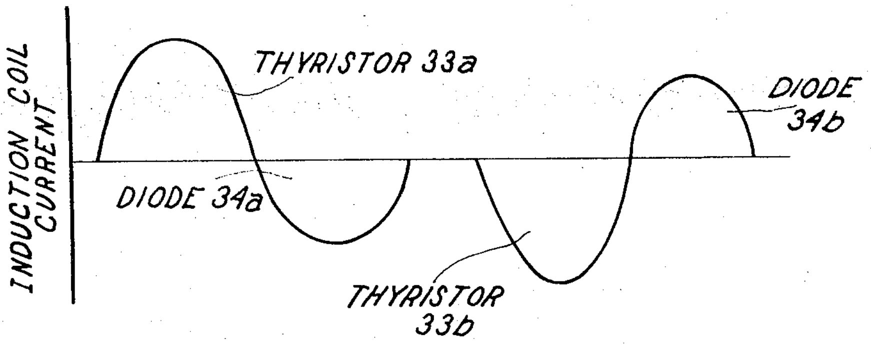


Fig.12

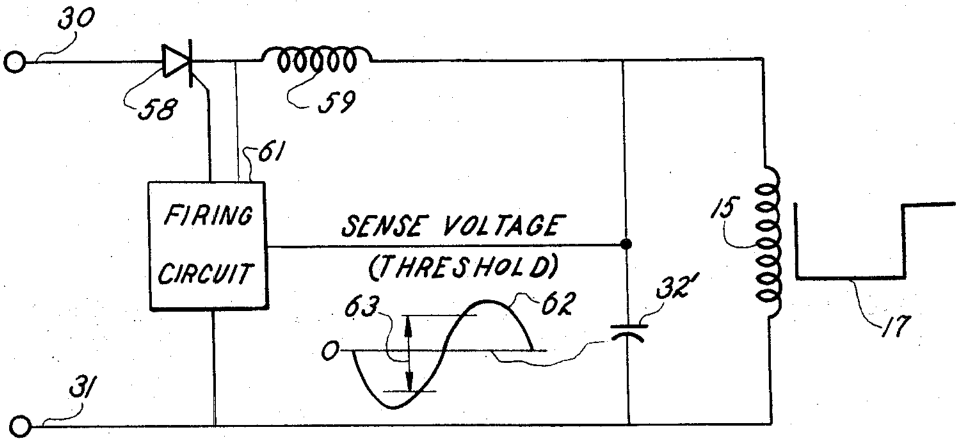
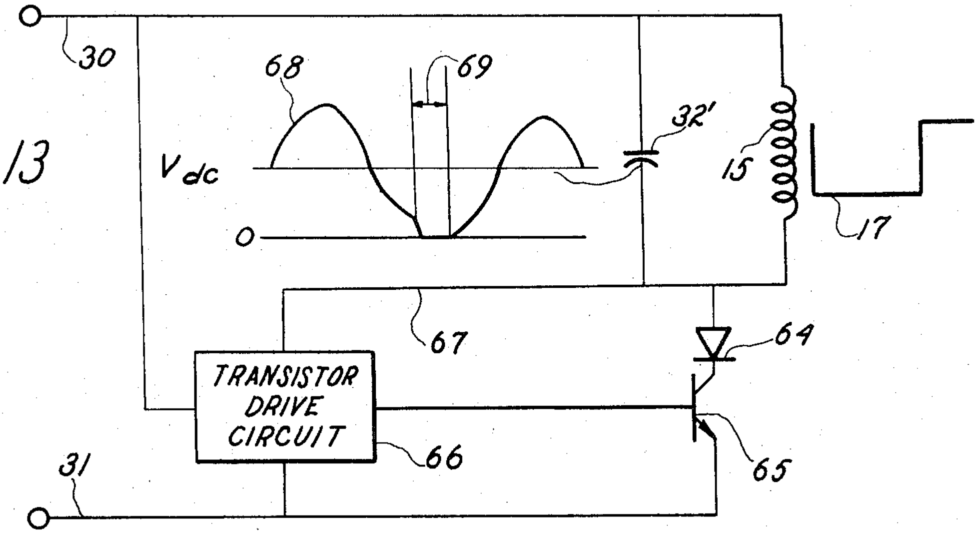


Fig.13



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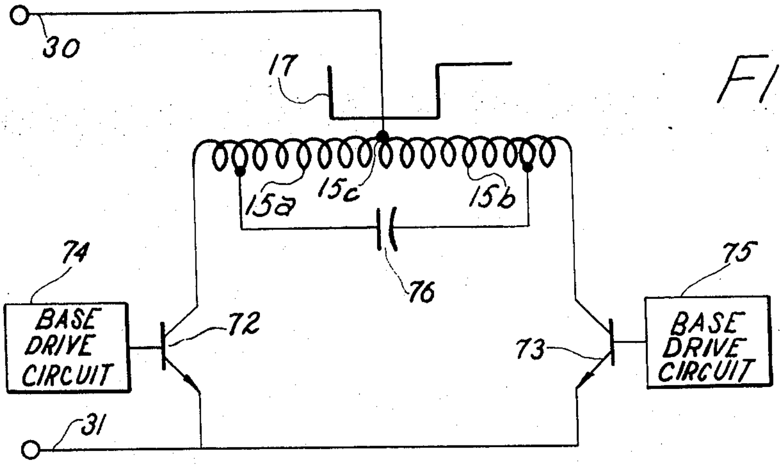


Fig.14a

Fig.15

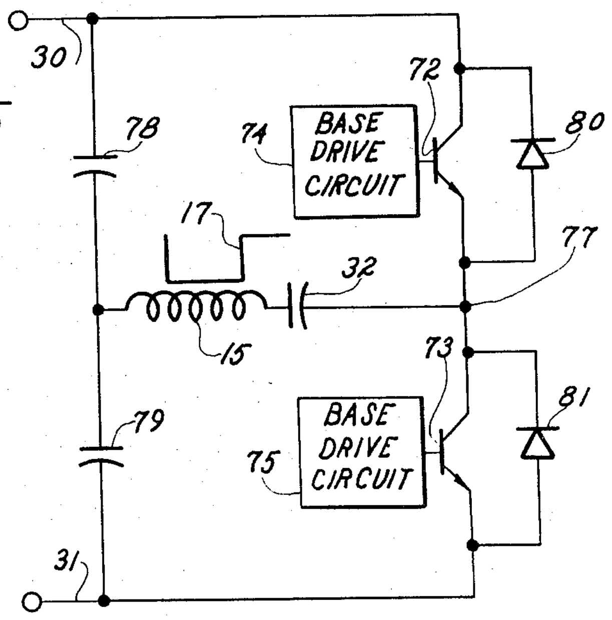
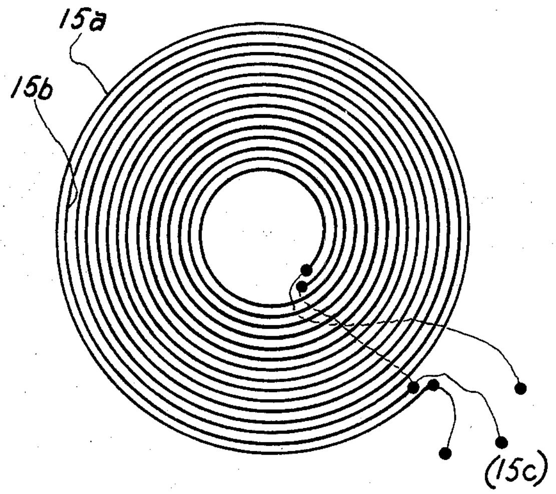


Fig.14b



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SOLID STATE INDUCTION COOKING APPLIANCES AND CIRCUITS

CROSS-REFERENCE TO RELATED APPLICATIONS

Induction cooking appliances with other inverter power circuits and multicylinder power circuits are respectively disclosed and claimed more broadly in the following concurrently filed applications assigned to the same assignee as this invention: U.S. Pat. Ser. No. (200,526) by David L. Bowers, Donald S. Heidtmann, and John D. Harnden, Jr.; and U.S. Pat. Ser. No. (200,528) by William P. Kornrumpf and John D. Harnden, Jr.

BACKGROUND OF THE INVENTION

This invention relates to cooking appliances based on induction heating and to solid state circuits therefor, and more particularly to improved, economical power circuits for induction cooking appliances operating in the ultrasonic frequency range.

The use of induction heating to heat a food containing cooking utensil is a theoretically efficient process since heat is generated only in the metallic utensil where it is wanted. The ordinary gas range and electric range by comparison have greater losses due to poor coupling of heat to the utensil and heating the surrounding atmosphere. Although known in principle for a number of years, prior food cooking appliances based on induction heating have been unsatisfactory. Equipment using available line frequencies of 50 Hz or 60 Hz was inadequate and cumbersome, and eddy current cookers employing a circular arrangement of alternately poled permanent magnets rotated by an electric motor were bulky, expensive, and for other reasons not suitable for wide usage.

Induction cooking appliances employing solid state power conversion circuits to drive the induction heating coil at the higher frequencies that are desirable have made possible a significant reduction in cost and size of the equipment. By operating at ultrasonic frequencies of 18 kHz and above, the appliance is inaudible to most humans, and solid state power conditioning at these frequencies is presently reliable. The above-identified application of Bowers et al discloses a power converter including a rectifier and a two-thyristor series sine wave inverter that drives a pancake ferromagnetic-core induction heating coil. To be truly competitive for commercial introduction, however, improved and more economical appliances and circuitry are needed.

SUMMARY OF THE INVENTION

The solid state induction cooking appliance to which the invention applies comprises a substantially nonmetallic, plate-like support having a substantially unbroken utensil supporting surface. A flat or nominally flat induction heating coil is mounted adjacent the support and generates an alternating magnetic field that couples with metallic portions of a utensil placed on the support. A static power conversion circuit typically comprising a rectifier and an inverter generates an ultrasonic output frequency wave for driving the induction heating coil. To obtain an economical appliance, such as a cooktop unit or a portable counter-top warming or cooking appliance, the improvement is made of using a relatively simple inverter comprising a capacitor and the induction heating coil connected as a series or parallel resonant circuit that is controlled by a single solid state switching device and control circuit therefor. While it is desirable to use an inexpensive air-coil core, the simplified inverters are usable with the ferrite ferromagnetic-core coils also.

In the preferred embodiments, the inverter is a series resonant sine wave inverter in which a thyristor (SCR) and an inverse-parallel connected diode are connected in series with the capacitor and coil, and reset inductor means is provided to reset the capacitor during nonconducting intervals of the thyristor-diode combination. Power control to adjust the cooking temperature or utensil heating level is obtained by the combined effect of both increasing the frequency and amplitude of the sinusoidal current pulses supplied to the coil. Other embodiments are one-thyristor and one-transistor parallel resonant circuits comprising a capacitor and the coil connected in parallel. The inverter power output and thus the power coupled to the utensil is adjusted by respectively changing the amplitude or frequency of the sinusoidal current pulses.

Other low cost power conversion circuits disclosed are a multi-cylinder inverter based on the one-thyristor series resonant inverter and, two-transistor inverters using parallel and series resonant circuits. Output power control in any of these power conversion circuits is also achieved by using a phase controlled rectifier to vary the d-c supply to the inverter. Another technique is to mount the coil adjustably relative to the utensil support to change the gap spacing between coil and utensil. These power control techniques can be used in any selected combination to obtain the range of cooking temperatures and settings desired. An additional feature of an appliance with a flat air-core induction heating coil is a non-metallic warming tray beneath the coil for supporting covered utensils heated by magnetic flux emanating from the bottom of the coil.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a solid state converter for supplying ultrasonic frequency power to a flat spiral induction heating coil, shown in plan view, in an induction cooking appliance constructed according to the invention;

FIG. 2 is a diagrammatic cross-sectional view illustrating the relation of the induction heating coil, support plate, cooking utensil, and optional warming tray in a cooking appliance;

FIG. 3 shows several modifications of FIG. 2 including a coil made with braided ribbon, an improved ferromagnetic core for the coil, and adjustment of the cooking temperature by changing the coil position;

FIG. 4 is a perspective view of the upper portion only of an electric range with a food warming facility;

FIG. 5 is a detailed schematic circuit diagram of one embodiment of a static power conversion circuit comprising an economical series resonant inverter using only one thyristor and the induction heating coil in a dual function as the commutating inductance;

FIG. 6 is the equivalent circuit diagram of the induction heating coil and cooking utensil load;

FIGS. 7*a* and 7*b* are waveform diagrams of the induction coil current and commutating capacitor voltage for the circuit of FIG. 5, showing in each diagram the waveforms at two different inverter output frequencies;

FIG. **8** is a modification of the FIG. **5** converter employing a phase controlled rectifier and a modified gating and power circuit;

FIG. **9** shows another modification of the inverter of FIG. **5**;

FIG. **10** is a schematic circuit diagram of a low cost multi-cylinder power converter (less the rectifier) based on the inverter configuration of FIG. 5;

FIG. **11** is an induction coil current waveform diagram useful in explaining the operation of FIG. **10**;

FIGS. **12** and **13** are schematic circuit diagrams of parallel resonant inverters respectively using a single thyristor and a transistor;

FIG. **14***a* shows a two-transistor inverter circuit;

FIG. **14***b* is a plan view in schematic form of the series aiding, equal-turn induction heating coil used in the FIG. **14***a* circuit; and

FIG. **15** is a detailed circuit diagram of another two-transistor resonant inverter.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The induction cooking appliance shown in FIGS. **1–4** will be described with regard to an induction surface unit in an electric range, but essentially the same mechanical structure and circuitry in a lower power version is also suitable for a portable counter-top food cooking or warming appliance. The static power conversion circuit indicated generally at **12** is preferably energized by a single phase commercially available 60 Hz, 120 volt or 240 volt source of alternating current potential, however in appropriate cases this equipment can be designed for use with other low frequency, low voltage or d-c sources. Static power converter **12** comprises generally a rectifier **13** and a solid state inverter **14** for converting the unidirectional rectifier output to an ultrasonic frequency wave for driving an induction heating coil **15**. Induction heating coil **15** is a single layer, annular, flat spiral, air-core coil wound with solid flat strip conductors or braided ribbon with a rectangular cross section. To generate sufficient magnetic flux to heat the utensil to the desired cooking temperature, coil **15** is tightly wound with the short cross sectional dimension facing upwards and adjacent turns separated by a flat insulating strip **20**. While coil **15** is usually perfectly flat, it is within the scope of the invention to use a nominally flat coil such as one that is slightly dished to improve the magnetic field distribution.

In the cooking appliance (FIG. 2), induction heating coil **15** is appropriately mounted in a horizontal position immediately below a non-metallic support **16** typically made of a thin sheet of glas, ceramic, or plastic. Support plate **16** is commonly referred to as the cooking surface and supports the metallic cooking utensil **17** to be heated. If required, support **16** can have some metallic content for electrostatic shielding or decorative purposes, but this is necessarily limited to a small amount to permit nearly full power to be coupled to the utensil. 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; 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. Because of their relatively thin skin depth at ultrasonic frequencies which results in a high equivalent impedance and also because of the high magnetic losses, magnetic steel utensils couple well to coil **15** and are heated most efficiently. Some copper-clad utensils and thick aluminum utensils do not couple well to the coil due to their low equivalent impedance, while the laminated and cast iron utensils are inbetween. Any of these may be used, however, in an induction cooking appliance when the coil **15**, static power conversion circuit **12**, and the gap between the 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** to allow space for non-metallic support **16**, and the gap is no greater than about one-half inch at full power rating in order to couple sufficient power into the utensil bottom to produce adequate heating for cooking purposes. It is also important to impedance match the utensil to the power circuit for best overall efficiency.

Operation of solid state inverter **14** to impress an ultrasonic frequency wave on induction heating coil **15** results in the generation of an alternating magnetic field. The magnetic flux, in particular flux emanating from the top of coil **15**, is coupled across the air gap through nonmetallic support **16** to utensil **17**. An ultrasonic frequency above 18 kHz or so is normally considered to be the upper range of human hearing and is selected to make the cooking appliance inaudible to most people. The induction heating coil **15** shown in FIG. **2** is constructed with solid copper flat strip with a rectangular cross section. Conveniently, the coil is wound using alternating flat strips of copper conductor and a suitable insulating material. To reduce the high frequency losses due to the skin effect, it is preferable to use a coil **15'** made with braided ribbon as is illustrated schematically in FIG. **3**. A still further reduction in losses is obtained by using ribbon litz wire. Because of the usual physical constraints, only a limited number of ampere-turns can be included in a practical induction heating coil. Since the power coupled to the utensil is theoretically proportional to the square of the ampere-turns, the reduction of losses is of consequence in increasing the efficiency.

Some of the other options that are possible as to the mechanical and electrical arrangement of induction heating coils **15** and **15'** are also illustrated in FIG. **3**. One of these is to use a ferromagnetic-core coil rather than air-core coil. To this end, a ferromagnetic core **18** for coil **15'** is mounted horizontally beneath the coil spaced from it by a predetermined air gap. The core serves as a high permeability path for the return magnetic flux, one such path being illustrated at **19**, and is preferably a thin plate of ferrite dispersed for instance in an extruded rubber matrix. The ferrite plate runs cool and has superior high frequency performance as compared to a laminated steel plate, and for a given induction heating coil the power output requirements of static power conversion circuit **12** are lower as compared to the air-core coil situation. Usually, coils **15** and **15'** are mounted stationary beneath utensil support **16** with a fixed air gap spacing by means of an appropriate mechanical support structure not here shown. Increasing or decreasing the gap between the coil and utensil **17**, however, changes the amount of power coupled to the utensil and therefore the temperature to which the utensil is heated. Other ways of adjusting the cooking temperature by control of the power output of static power conversion circuit **12** will be discussed later. Rather than moving utensil support **16** relative to coil **15'** (FIG. 3), a preferred arrangement in view of the fact that coil **15** is relatively light is to change the gap spacing by mounting coil **15'** for vertical movement. As illustrated here schematically, coil support **21** underlies coil **15'** and has a vertical extension that extends above the surface of support **16** so as to be available to the person doing the cooking to make a manual adjustment. Another suitable arrangement employs a wire wound on the shaft of a control knob on the range control panel.

FIG. 4 shows an induction cooking appliance in the form of an electric range with four induction surface unit positions indicated in dotted lines on the surface of utensil support **16.** An important feature of the invention is that support **16** is made of a non-metallic material such as plastic or glass, and preferably has a smooth and unbroken utensil supporting surface. This is not to preclude the inclusion of sensors or indicators in support **16.** At ultrasonic frequencies there are insignificant reaction forces which at lower frequencies would cause utensil **17** to move horizontally when placed on the support plate approximately centered with respect to one of the induction surface unit positions. The transfer of energy to the utensil 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 coil and utensil. Although induction heating coil **15** may require some cooling, the surface of support **16** is relatively cool since the highest temperatures involved are about 450° F, the approximate maximum temperature to which the bottom of utensil **17** is heated to cook food as for example in frying operations. Because of the cool cooking surface, spilled foods do not burn and char and both support **16** and utensil **17** are easy to clean. The cool, smooth support **16** also makes it possible to use this surface before cooking, or even immediately after cooking, for other functions related to food preparation such as opening cans, trimming and cutting vegetables, transferring cooked food from the cooking utensil to a serving dish, etc. Another advantage of induction cooking is that induction heating results in a low thermal mass system. Since there is a relatively low storage of heat in utensil **17** itself, the temperature to which the utensil is heated can be changed rapidly, as from boiling to simmering to warming temperatures.

A new feature in an electric range or a portable counter-top warming or cooking appliance made possible by the induction cooking principle is the inclusion in the appliance of a food warming opening and tray beneath the induction heating coil. Referring to FIG. 2, an alternating magnetic field is also produced at the bottom of air-core induction heating coil **15** as well as the top, and a portion of this magnetic flux is available for warming or heating food in a closed metallic container **22** (shown in dotted lines) supported on a non-metallic tray **23.** Frozen foods in a closed aluminum foil container can also be defrosted in this manner. To provide the food warming facility in an electric range, the upper portion of the range (FIG. 4) has a food warming cavity **24** that extends beneath all four coils of the four induction surface units. Tray **23** is preferably made of plastic and is slidable in and out of the food warming cavity. A variety of thermoplastic and thermosetting plastics, with decorative surface designs if desired, can be used to make tray **23** and utensil support **16.** As previously mentioned, this is because no point in the system needs to be in excess of a maximum temperature of about 450° F. Suitable plastics that can be used are Textolite (trademark of the General Electric Company), epoxy, silicone, polyimides, and others. These plastic materials can also be used in the fabrication of induction heating coils **15** and **15'**.

The embodiment of power converter circuit **12** illustrated in FIG. 5 is characterized by a relatively simple and inexpensive inverter that uses only one thyristor and gating circuit, and employs induction heating coil **15** in a dual function to couple power to the utensil (load) and to provide commutating inductance in the thyristor commutation circuit. To gain commercial acceptance, the ultrasonic frequency converter must be relatively low cost and reliable under both load and no-load conditions. The power converter input terminals **27** and **28** are adapted to be connected across a 120 volt, 60 Hz source of a-c supply voltage. The power supply section of the converter circuit includes a full wave diode bridge rectifier **13** and a filter capacitor **29** connected between the rectifier output terminals, thereby providing a pair of direct current supply terminals **30** and **31** for inverter **14.** Inverter **14** is a one-thyristor series capacitor commutated or series resonant inverter that generates damped sinusoidal pulses. The power circuit comprises essentially induction heating coil **15** connected in series circuit relationship with a commutating capacitor **32** and a unidirectional conducting thyristor **33** between the d-c power supply terminals **30** and **31.** A diode **34** to conduct power current in the reverse direction is connected across the load terminals of thyristor **33.** A series RC circuit **33'** is usually connected across the load terminals of thyristor **33** for dv/dt protection to limit the rate of reapplication of forward voltage to the device. The power circuit also includes a reset inductor **35** connected directly across commutating capacitor **32.** As is explained in detail later, the function of reset inductor **35** is to recharge commutating capacitor **32** between complete cycles of operation when both thyristor **33** and diode **34** are nonconductive.

Thyristor **33** is more particularly a silicon controlled rectifier, but other solid state switching devices including a pair of transistors connected to operate in thyristor fashion can also be used. Power diode **34** can also be replaced by a thyristor controlled to be conductive for a complete half cycle. In this low cost circuit, however, the combination of the inverse-parallel connected silicon controlled rectifier and diode are clearly preferred. Only one gating circuit is required since diode **34** becomes forward biased and conducts when the current in the series resonant circuit reverses in the negative polarity half of the cycle. Gating circuit **36** for thyristor **33** includes a series RC timing circuit comprising a fixed resistor **37,** an adjustable resistor **38,** and a timing capacitor **39** connected between the anode of the power device and negative d-c supply terminal **31.** A voltage sensitive signal level semiconductor such as Shockley diode **40** and a series resistor **41** are connected between the junction of resistor **38** and timing capacitor **39** and the gate of thyristor **33.** Timing begins when both power devices **33** and **34** have ceased conducting, and the next gating pulse is generated by the charging of timing capacitor **39** to a predetermined voltage which casues Shockley diode **40** to break over and conduct.

Although utensil **17** is referred to loosely as the inverter load, it is more accurate to say that the inverter load is the electrical loss in the utensil. With respect to the utensil load, induction heating coil **15** functions as the primary winding of an air-core transformer. Utensil **17** functions as a single-turn secondary winding with a series resistance **17r** representing the resistive part of the I^2R or eddy current losses, and hysteresis losses where applicable. The currents and voltage induced in utensil **17** when the induction surface unit is in operation are determined essentially by the transformer laws. The physical equivalent for utensil **17** in the form of a single turn winding and resistive losses **17*r*** is given in FIG. **5**. FIG. **6** shows the equivalent electricl circuit for coil **15** and utensil **17**. Coil **15** is represented by a series connected inductance **15*i*** and resistance **15*r***, and these are in turn in series with the parallel combination of an inductance **17*i*** and resistance **17*r*** representing the utensil. This electrical equivalent circuit is based on conventional transformer equivalent circuit analysis and has been found to reasonably agree with experimental results.

With the utensil load in place, the commutating inductance for the series resonant circuit comprising coil **15** and commutating capacitor **32** is composed of both the coil inductance **15*i*** and the reflected utensil inductance **17*i***. Under no-load conditions, with the utensil 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, so that there is a slight decrease in the inverter output frequency. With an average or selected utensil load in place, the series resonant circuit is tuned to resonance at a resonant frequency higher than the highest desired output frequency. The ultrasonic output frequency range of interest is between approximately 18 kHz and 40 kHz. The upper limit of this frequency range is determined largely by economic considerations, in conjunction with the high frequency limitations of available thyristor devices.

The operation of an induction cooking appliance employing the static power conversion circuit illustrated in FIG. **5** is as follows. The appliance is turned on by means of an on-off switch **42** shown only in FIG. **4** on the rear control panel, at the back of the electric range. Switch **42** is preferably combined with adjustable resistor **38** in gating circuit **36** to control the gating signal repetition rate and therefore the cooking temperature. When the circuit is initially energized thyristor **33** is nonconducting and diode **34** is reverse-biased, but a circuit is completed through coil **15**, commutating capacitor **32**, and reset inductor **35** to the series RC timing circuit in gating circuit **36**. Adjusting resistor **38** changes the time constant of this timing circuit. After the selected time delay, timing capacitor **39** charges to the predetermined voltage at which Shockley diode **40** breaks over and conducts. A gating pulse is supplied to the gate-cathode circuit of power thyristor **33**, turning it on, and at the same time timing capacitor **39** is reset. A positive polarity half-sinusoidal current pulse flows through induction heating coil **15** and theoretically charges commutating capacitor **32** to a value approaching twice the supply voltage V_{dc}. Because of the resistive coil and utensil losses, the circuit energized is more exactly a damped series R-L-C oscillatory circuit. At the end of the half cycle, the current drops below the holding current of thyristor **33**, so that it begins to turn off, and upon the current reversal diode **34** conducts and aids the turn-off of thyristor **33** by applying reverse voltage to the device. At the end of the negative polarity half cycle (see FIG. **7*a***) the current through induction heating coil **15** remains at zero since the next gating pulse is not applied to thyristor **33** at this time. While power devices **33** and **34** were conducting, the current in reset inductor **35** on a steady state basis was increasing due to the net positive d-c voltage on commutating capacitor **32** during the conduction cycle. During the circuit off-time reset inductor **35** discharges, thereby leaving commutating capacitor **32** negatively charged at the end of the circuit off-time. Voltage is supplied to gating circuit **36** during the circuit off-time, and at the end of the predetermined time delay determined by the setting of adjustable resistor **38**, a gating pulse is produced to render conductive thyristor **33** and begin the next cycle of operation.

FIG. **7a** shows in full lines the sinusoidal induction coil current for two complete cycles of operation separated by a time delay **43**. The corresponding commutating capacitor voltage is shown in full lines in FIG. **7*b***. At the end of the first conduction cycle, capacitor **32** has a net positive d-c voltage. The action of reset inductor **35** during the time delay period **43** is to change the capacitor voltage almost linearly as indicated at **44**, leaving the capacitor negatively charged at the end of time delay interval **43**. Due to this extra charge on commutating capacitor **32**, the peak capacitor voltage **45** during the next cycle of operation is higher than in the dampened oscillatory case since the system energy is replenished. The effect of shortening time delay **43** by adjusting resistor **38** is to increasc 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. This is illustrated in FIG. **7a** 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 **35**. The result is that, referring to the dashed line capacitor voltage characteristic in FIG. **7*b***, commutating capacitor **32** is charged negatively to a higher negative voltage during the circuit off-time as indicated by **44′** so that the peak capacitor voltage **45′** during the next conduction cycle is higher than the peak voltage **45** for the lower inverter frequency case. A limit on inverter frequency is reached when the value of the current in reset inductor **35** becomes significant in comparison to the high frequency reverse current pulse in coil **15** and commutating capacitor **32**, since this in effect reduces the commutation time available to the thyristor. In summary, there are two effects that increase the power in watts supplied to utensil **17** when the inverter frequency is increased. There are larger, more frequently applied current pulses in induction heating coil **15**.

The static power conversion circuit illustrated in FIG. **8** shows several modifications of the FIG. **5** converter. The full wave diode rectifier **13** is replaced by a phase controlled rectifier simply by substituting thyristors for two of the diodes in FIG. **5** to thereby provide a variable source of d-c voltage for inverter **14**. The filter additionally includes filter inductor **29'**. Suitable phase controlled gating circuits for the thyristors are described in the General Electric SCR Manual, 4th edition, copyright 1967, available from Electronics Park, Syracuse, New York. Adjustable components in these phase controlled gating circuits can be connected to be adjustable by rotation of on-off switch **42** (FIG. **4**). The four mechanisms that have been described for achieving variable power control of the static conversion circuit can be used in any desired combination. These are, briefly, the mechanical method of raising and lowering the induction heating coil (FIG. **3**) to change the gap spacing, the power circuit technique of varying the inverter output frequency to change the frequency and magnitude of the current pulses supplied to the coil, and the control circuit technique of using a phase controlled rectifier to adjust the d-c supply voltage. Still another mechanism disclosed in the first cross-reference application is to step change the commutating circuit capacitance and inductance parameters. To obtain a large range of power output, such as a 30:1 ratio, combinations of these techniques undoubtedly are required.

Gating circuit **36'** in FIG. **8** is a modified form of the gating circuit disclosed in FIG. **5**, which times the delay interval **43** between the end of one cycle and the beginning of the next. The disadvantage of this arrangement is that it is load dependent. The preferred timing arrange-ment obtained by gating circuit **36'** is to time from the beginning of one cycle to the beginning of the next cycle. To this end, resistor **37** in the timing circuit is connected through an on-off switch **42'**, which can be identical to the switch **42** in FIG. **4** or operated concurrently with it, to the positive d-c supply terminal **30**. Also, a constant source of voltage for adjustable resistor **38** and timing capacitor **39** is provided by connecting a Zener diode **46** in parallel with both these components. Once gating circuit **36'** is energized by closing switch **42'**, gating pulses for thyristor **33** are produced at an approximately constant repetition rate depending on the setting of adjustable resistor **38**. One possible shortcoming of the FIG. **5** power circuit is that the return path for high frequency current pulses is through filter capacitor **29**, which is ordinarily an electrolytic capacitor normally having a high impedance at ultrasonic frequencies. The power circuit modification of FIG. **8** eliminates this problem and has improved performance. In this power circuit, the resonant circuit comprising coil **15** and commutating capacitor **32** is connected between the anode of thyristor **33** and negative d-c supply terminal **31**. Reset inductor **35** is now connected in series with thyristor **33** between d-c terminals **30** and **31**, the latter normally at ground potential. The impedance of reset inductor **35** is sufficiently large to supply relatively constant current to the resonant circuit.

With thyristor **33** or diode **34** conducting, the ultrasonic frequency return path is to ground rather than through filter capacitor **29**. The operation of this modified power circuit is believed to be obvious from the previous discussion of FIG. **5**. Reset inductor **35** discharges during the circuit off-time through coil **15** to charge commutating capacitor **32** positively. As the inverter output frequency increases, the average current in reset inductor **35** also increases, thereby resetting capacitor **32** to a more positive level in each cycle.

A second modification of the one-thyristor series resonant power circuit is given in FIG. **9**. This is similar to FIG. **5** with the exception that reset inductor **35** is connected in parallel with both coil **15** and commutating capacitor **32**. This allows the discharge reset current of reset inductor **35** to circulate through induction heating coil **15** (as in FIG. **8**), thereby increasing the power for a given set of circuit parameters. For a given ultrasonic output frequency, the FIG. **8** configuration gives the highest output power and accordingly is preferred.

By way of example of a specific induction cooking appliance suitable for use as an induction surface heating unit in an electric range, the required maximum power output is 1,500 watts and the ultrasonic frequency operating range is about 18 kHz to 25 kHz. Using a 120 volt, 60 Hz a-c source, the peak input d-c voltage is 150 volts. Induction heating coil **15** has an outside diameter of seven and one-half inches and an inside diameter of one and one-half inches. Coil **15** more specifically has 43 turns of No. 11 braided ribbon conductor having a cross section of about five-sixteenths inches by less than one-sixteenth inch with a turn-to-turn spacing of at least 10 mils. The combined equivalent coil inductance **15*i*** and utensil conductance **17**i (see FIG. **6**) is typically **150** microhenries, and the combined equivalent series coil resistance **15*r*** and utensil resistance **17*r*** is 15 ohms. For a counter-top warming or cooking appliance a lower maximum output power is satisfactory, such as 200–400 watts.

The outstanding advantage of the cooking appliance power conversion circuits shown in FIGS. **5** and **8**, and of the modification of FIG. **9**, is that these circuits are relatively simple and economical though yet being satisfactory for a full range of cooking tasks. A minimum of power circuit components are employed, due particularly to the use of the thyristor-diode combination, and to the dual function of induction heating coil **15** as a substantial part of the commutating inductance and as a transformer to couple power to the utensil load. Furthermore, only one relatively simple gating circuit for thyristor **33** is required. This one-thyristor series resonant power circuit operates in a full satisfactory manner under both load and no-load conditions. Although not optimized for every conceivable type of available pot and pan, a variety of ordinary utensils that couple well or reasonably well to the coil can be used. This inverter is appropriate for operation by non-technical persons since a minimum number of user controls are needed. There is no failure due to shoot-through when adjustable resistor **38** is slewed.

The low cost multi-cylinder cooking appliance power converter shown in FIG. **10** is based on the simple one-thyristor inverter of FIG. **5**. This is a two-cylinder converter using two such inverters **14a** and **14b** assembled in mirror-image fashion between d-c power supply terminals **50** and **51** and common point **54**. A center-tapped type power supply is used providing +V (such as +150 volts) at positive d-c terminal **50** and −V (−150 volts) at negative terminal **51**. Between these terminals are a pair of voltage dividing capacitors **52** and **53**, with their junction **54** connected to ground. Induction heating coil **15** is common to both inverters and is connected in the bidirectional conducting branch of the converter between point **54** and the junction **55** between the remaining components of the two FIG. **5** type inverfers.

Referring also to FIG. **11**, the two converters **14a** and **14b** can be operated alternately with or without a time delay between conduction cycles, or can be operated alternately in overlapping fashion. In the first mentioned mode, thyristor **33*a*** and diode **34*a*** conduct consecutively, and then thyristor **33*b*** and diode **34*b*** are rendered conductive as in the usual half bridge inverter configuration. The induction coil currents are shown in FIG. **11.** Variable output power in watts is obtained with this circuit in the same manner as previously discussed, by control of the frequency of the current pulses through coil **15** by varying the repetition rate of supplying gating pulses alternately to thyristors **33*a*** and **33*b*.** The advantage of this circuit is that the high frequency requirements of thyristors **33*a*** and **33*b*** are not as stringent, since in the usual mode of operation each has more turn-off time than in the FIG. **5** inverter. In the same manner the other components have a lower duty cycle and are lower cost components.

FIGS. **12** and **13** show low cost inverters suitable for induction cooking appliances characterized as one-thyristor and one-transistor parallel resonant circuits. In these circuits induction coil **15** and capacitor **32′** are connected parallel to one another in a tank circuit rather than in series as in the previous inverters. In FIG. **12,** thyristor **58** is connected in series with a commutating inductor **59** and parallel-connected coil **15** and resonating capacitor **32′**, this entire circuit being connected between d-c supply terminals **30** and **31.** A solid state firing circuit **61** is connected between the gate of thyristor **58** and negative terminal **31**, and is controlled by a sense voltage derived from the voltage across capacitor **32′**, thus closing the oscillatory loop. Waveform **62** represents the capacitor voltage. Power control is achieved by varying the voltage at which thyristor **58** fires within the thresh-old limits indicated by arrow **63.** The theory of operation is similar to that for conventional Class C tube oscillators. The interval of conduction of thyristor **58** is limited to a small part of the oscillatory cycle. When the threshold capacitor voltage at which thyristor **58** is fired is between zero volts and the upper positive limit (the voltage on terminal **30**), the amplitude of the sinusoidal oscillations decreases, and thus the power output decreases as the threshold voltage becomes larger. With increasing negative threshold voltages, the power output increases. The parallel resonant circuit comprising coil **15** and capacitor **32′** is, of course, tuned to resonate at a selected ultrasonic frequency. Commutating inductor **59** provides a means for turning off thyristor **58** by reverse biasing it during a part of each cycle when the capacitor voltage resonates above the supply voltage. Suitable firing circuits that can be used are described in the General Electric SCR Manual.

The advantage of both the FIG. **12** and FIG. **13** parallel resonant circuits is that the high frequency circulating currents do not pass through the solid state power device. If the circuit has had appreciable operating Q, the power device losses can be considerable compared to the useful power delivered to the load. A circuit which removes the thyristor or transistor from the oscillating tank circuit theoretically exhibits a higher efficiency and less of a heat disposal problem. FIG. **13** is the transistor version of the one-thyristor parallel resonant circuit. In this power circuit the capacitor **32′**-coil **15** tank circuit is in series with a blocking diode **64** and a power transistor **65.** A commutating inductor is not required since the transistor is turned off by base drive circuit **66.** Suitable solid state base drive circuits that can be employed are described in the General Electric Transistor Manual, seventh edition, copyright 1964. A feedback connection **67** senses the transistor collector voltage and is operative to turn on transistor drive circuit **66** to supply base current to power transistor **65** when the collector voltage is at its minimum. Referring to capacitor voltage waveform **68,** during the conduction time of transistor **65** the capacitor voltage falls to zero, after which coil **15** is charged with current until a timing circuit shuts off the transistor. The resulting transistor dissipation is the minimum possible with this circuit. Control of the conducting interval of transistor **65,** indicated by arrow **69,** accomplishes power output control of the circuit. Increasing the conduction interval of transistor **65** increases the current in coil **15.** Decreasing the interval conversely decreases the current and therefore the power delivered to the utensil. An alternative technique for controlling power output is by varying the peak transistor current.

FIGS. **14*a*** and **15** show low cost two-transistor ultrasonic frequency inverters for solid state cooking appliances. The induction heating coil for the FIG. **14*a*** parallel resonant circuit comprises two coil sections **15*a*** and **15*b*** with the center-tap **15*c*** connected to the positive d-c supply terminal **30.** Coils **15*a*** and **15*b*** are series aiding, equal-turn coils wound two-in-hand as shown in FIG. **14*b*.** The free terminals of the two coils are connected to negative d-c supply terminal **31** through the respective power transistors **72** and **73** controlled by base drive circuits **74** and **75.** A tuning capacitor **76** is connected across a selected number of turns of coils **15*a*** and **15*b*.** In operation, power transistors **72** and **73** are rendered conductive alternately for desired intervals of conduction. When transistor **72** conducts current flow through coil **15**a produces a pulse of one polarity, and a pulse of the other polarity is generated when transistor **73** conducts. Variable power control is achieved by input voltage control, or by varying the conduction interval of the two transistors to change the amplitude of the ultrasonic wave.

In the low cost two-transistor series resonant sine wave inverter shown in FIG. **15**, the two power transistors **72** and **73** are connected in series between d-c supply terminals **30** and **31**, and diodes **80** and **81** are connected across the emitter-collector terminals of the respective devices. The series resonant circuit comprising commutating capacitor **32** and coil **15** is connected to the junction **77** between the two power transistors and to the junction between a pair of voltage divider capacitors **78** and **79.** In operation, transistor **72** is rendered conductive during generation of the positive polarity half sinusoidal current pulse, and diode **80** conducts when the current reverses and the series resonant circuit generates a negative polarity half sinusoidal pulse. Transistor **73** and diode **81** conduct during the next conduction cycle. The output power is again controlled by modulating the inverter output frequency, or by input voltage control.

In summary, improved economical solid state induction cooking appliances are characterized by relatively simple power conversion circuits for use with inexpensive flat air-core induction heating coils as well as improved ferromagnetic-core coils. The ultrasonic frequency inverters preferably employ a single controlled switching device, and therefore only one control circuit, and use the induction heating coil in a dual function to couple power to the utensil and as a commutating inductor or resonating inductor. One-thyristor series resonant circuits, one-thyristor and one-transistor parallel resonant circuits, two-transistor circuits, and multicylinder series resonant circuits have been discussed. The first is advantageous because power control to adjust the temperature to which the utensil is heated is by the combined effect of increasing both the amplitude and frequency of the sinusoidal current pulses supplied to the coil. Other power control techniques usable in different combinations are to employ a phase controlled rectifier and to move the coil relative to the utensil support to change the gap spacing. An additional feature of the air-core coil is the provision of a warming cavity and tray beneath the coil.

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 various changes in form and details 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 solid state cooking appliance for inductively heating cooking utensils comprising

a substantially non-metallic, plate-like support having a substantially unbroken utensil supporting surface,

a nominally flat induction heating coil mounted adjacent said support for generating an alternating magnetic field that extends across a gap including said support and beyond said utensil supporting surface, and

a static power conversion circuit including a unidirectional voltage supply and a solid state inverter for generating an ultrasonic frequency wave that drives said induction heating coil,

said inverter comprising a capacitor and said induction heating coil connected as the only resonating components of a single resonant circuit that is operated by a single controlled solid state switching device and control circuit therefor.

2. A cooking appliance according to claim **1** wherein said induction heating coil is an air-core coil, and the appliance further includes

a non-metallic warming tray mounted beneath said air-core coil for supporting a utensil to be warmed.

3. A cooking appliance according to claim **1** wherein said induction heating coil is adjustably mounted relative to said support to change said gap and therefore the power coupled to the utensil.

4. A cooking appliance according to claim **1** wherein said induction heating coil is a ferromagnetic-core coil and further includes a ferrite plate mounted approximately parallel to said coil to serve as a high permeability path for return magnetic flux.

5. A cooking appliance according to claim **1** wherein said induction heating coil is a single layer coil made with braided ribbon conductor.

6. A cooking appliance according to claim **1** wherein said induction heating coil is a single-layer coil made with ribbon litz wire.

7. A cooking appliance according to claim **1** wherein said source of unidirectional voltage supply is a source of variable input unidirectional voltage to thereby modulate the power output of said inverter and thus the power coupled to the utensil.

8. A cooking appliance according to claim **1** wherein said inverter resonant circuit is a series resonant circuit in which said capacitor and induction heating coil are effectively connected in series circuit relationship with one another and said controlled solid state switching device,

a diode connected in inverse-parallel with said controlled switching device, and

reset inductor means operative during nonconducting intervals of said controlled switching device and diode for resetting said capacitor.

9. A solid state cooking appliance for inductively heating a cooking utensil comprising

a substantially non-metallic, plate-like support having a substantially unbroken utensil supporting surface,

a nominally flat air-core induction heating coil mounted adjacent said support for generating an alternating magnetic field that extends across a gap including said support and beyond said utensil supporting surface, and

a static power conversion circuit including full wave rectifying means and a solid state inverter for generating an ultrasonic output frequency wave that drives said induction heating coil,

said inverter comprising a capacitor and said induction heating coil connected as the only resonating components of a single resonant circuit that is operated by a single controlled solid state switching device and control circuit therefor.

10. A cooking appliance according to claim **9** wherein said inverter resonant circuit is a series resonant circuit in which said capacitor and induction heating coil are effectively connected in series circuit relationship with one another and said controlled solid state switching device, said controlled switching device being a thyristor,

a diode connected directly in inverse-parallel with said thyristor to form a thyristor-diode combination, and

reset inductive means for resetting said capacitor during nonconducting intervals of said thyristor and diode.

11. A cooking appliance according to claim **10** wherein said series connected capacitor, induction heating coil and thyristor-diode combination are effectively coupled between the output terminals of said rectifying means, and

said reset inductive means is connected across said capacitor.

12. A cooking appliance according to claim **10** wherein said reset inductive means and thyristor-diode combination are effectively coupled in series circuit relationship between the output terminals of said rectifying means, and

said series connected capacitor and induction heating coil are connected across said thyristor-diode combination.

13. A cooking appliance according to claim **10** wherein said series connected capacitor, induction heating coil, and thyristor-diode combination are effectively coupled between the output terminals of said rectifying means, and said reset inductive means is connected across said series connected capacitor and induction heating coil.

14. A cooking appliance according to claim **10** wherein said control circuit for said thyristor controlled switching device operates at a variable repetition rate to change both the amplitude and frequency of said output frequency wave and therefore the power coupled to the utensil.

15. A cooking appliance according to claim **10** wherein said rectifying means comprises a phase controlled rectifier which supplies a variable input voltage to thereby change the amplitude of said output frequency wave and thus the power coupled to the utensil.

16. A cooking appliance according to claim **9** wherein said induction heating coil is adjustably mounted relative to said support to change said gap and therefore the power coupled to the utensil.

17. A solid state induction cooking appliance comprising

a substantially non-metallic, plate-like support having a planar, substantially unbroken utensil supporting surface,

a nominally flat air-core induction heating coil mounted beneath said support for generating an alternating magnetic field that extends across a gap including said support and is coupled with metallic portions of a cooking utensil placed thereon, and

a static power conversion circuit including unidirectional voltage supply and a solid state inverter for generating an ultrasonic frequency output wave that drives said induction heating coil,

said inverter comprising a capacitor and said coupled induction heating coil and utensil connected as a resonant circuit that is operated by a single controlled solid state switching device and control circuit.

18. A cooking appliance according to claim **17** further including a non-metallic warming tray movably mounted beneath said induction heating coil for supporting a utensil to be warmed.

19. A cooking appliance according to claim **17** wherein said induction heating coil is adjustably mounted relative to said support to change said gap and therefore the power coupled to said utensil.

20. A solid state cooking appliance for inductively heating a cooking utensil comprising

a substantially non-metallic, plate-like support having a substantially unbroken utensil supporting surface,

a nominally flat air-core induction heating coil mounted adjustably beneath said support for generating an alternating magnetic field that extends across a gap including said support and beyond said utensil supporting surface,

a static power conversion circuit including a unidirectional voltage supply and a solid state inverter for generating an ultrasonic frequency wave that drives said induction heating coil,

means for modulating the power output of said inverter to thereby control the power coupled to the utensil, and

means for moving said induction heating coil relative to said support to independently control the power coupled to the utensil by changing the gap between said coil and support.

21. A solid state cooking appliance for inductively heating a cooking utensil comprising

an induction heating coil mounted adjacent a substantially non-metallic unbroken utensil support and generating an alternating magnetic field,

a static power conversion circuit having a pair of unidirectional voltage terminals and including a solid state inverter for converting the unidirectional voltage to an ultrasonic output frequency wave that drives said induction heating coil,

said inverter being a one-thyristor series resonant inverter comprising reset inductive means connected in series circuit relationship with said thyristor and an inverse-parallel connected diode between said unidirectional voltage terminals, and only a commutating capacitor and said induction heating coil connected in series circuit relationship directly across said thyristor and inverse-parallel diode, and

a single control circuit for turning on said thyristor at a variable repetition rate to adjust both the amplitude and frequency of said output frequency wave and therefore the power coupled to the cooking utensil.

22. A cooking appliance according to claim **21** wherein said reset inductive means is a reset inductor that operates to recharge said commutating capacitor during nonconducting intervals of said thyristor and inverse-parallel diode.

23. A cooking appliance according to claim **21** wherein said static power conversion circuit further includes unidirectional voltage power supply connected to said pair of unidirectional voltage terminals that converts an alternating supply voltage to a variable unidirectional voltage to further control the power coupled to the cooking utensil.

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