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The title of the invention has been amended (Guidelines for Examination in the EPO, A-III, 7.3).

(54) Power supply circuits for magnetrons.

(57) This invention relates to power supply circuits for example, for driving a magnetron employed in a microwave cooker. In more detail the power supply circuit of the invention comprises an inductor, a high frequency switch connected in series with the inductor the series arrangement of the inductor and switch being adapted for connection to a pulsating d.c. supply derived from a rectified a.c. supply without addition of smoothing means, and a path in which is disposed a load and which provides a unifirectional conductive path for energy in the inductor during periods when, in operation, the inductor is disconnected from the d.c. supply, the high frequency switch being adapted to connect the inductor to the d.c. supply when the current in the inductor falls to zero so that the power supply takes from the a.c. supply at any given constant frequency of switching a current ave from which is in phase with and of the same harmonic content as the corresponding part of the a.c. voltage supply wave form.

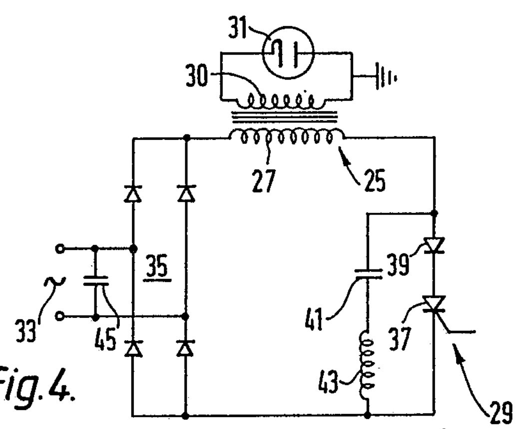

Fig.4.

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Description

Improvements in Power Supply Circuits

This invention relates to power supply circuits suitable, for example, for driving a magnetron. The conventional power supply circuit of a magnetron employed in a microwave cooker is a low frequency circuit and utilises a step-up mains transformer in the secondary circuit of which a voltage doubler circuit is provided. The output voltage of the doubler circuit is applied to the magnetron anode, the cathode filament of the magnetron being heated from a separate secondary winding of the transformer. The magnetron conducts when its anode voltage attains a predetermined value and conduction takes place over approximately 25 per cent of the period of the magnetron voltage cycle. The peak to mean current ratio, referred to as the "form factor', is accordingly poor and this factor is important since the peak radiated high frequency power of the magnetron is a function of the magnetron peak current whilst the 'cooking effect' is dependent on the mean power. Optimum operation of the magnetron accordingly calls for a power supply of relatively low form factor the achievement of which should improve safety of operation for a constant power output condition.

Although the conventional power supply circuit referred to has the merit of simplicity, it has apart from a high form factor, the further disadvantage that because of its low frequency of operation, the means transformer is both large and heavy, weighing some 6 to 7 Kg, and inefficient.

It is an object therefore of the present invention to provide an improved power supply circuit suitable, for example, for driving a magnetron.

The present invention consists in a power supply circuit comprising an inductor, a high frequency switch connected in series with the inductor the series arrangement of the inductor and switch being adapted for connection to a pulsating d.c. supply derived from a rectified a.c. supply without addition of smoothing means, and a path in which is disposed a load and which provides a unidirectional conductive path for energy in the inductor during periods when, in operation, the inductor is disconnected from the D.C. supply, the high frequency switch being adapted to connect the inductor to the d.c. supply when the current in the inductor falls to zero so that the power supply takes from the a.c. supply at any given constant frequency of switching a current wave form which is in phase with and of the same harmonic content as the corresponding part of the a.c. supply wave form.

Preferably, the series arrangement of the inductor and switch is adapted for connection to a pulsating D.C. supply derived from a full-wave rectified a.c. supply without addition of smoothing means so that the power supply takes from the a.c. supply at any given constant frequency of switching a current wave form which is in phase with and of the same harmonic content as the a.c. supply wave form.

Advantageously, the inductor comprises a high frequency transformer having a primary winding in series with the switch and secondary winding across which the path of the load is connected.

Being a high frequency operated circuit, the transformer employed is much more compact than that of the conventional low frequency circuit.

In one form of circuit according to the invention the switching device has a blocking diode in series therewith.

Advantageously, the switch comprises a thyristor having connected in parallel therewith a resonant series path comprising a commutating capacitor and inductor. This thyristor may be a fast gate turn-off device having a blocking diode in series therewith.

When used with a magnetron as the load, the presence of the RFI capacitance effectively appearing in parallel with the device has to be considered. Thus, selection of a correct switching sequence produces a substantially improved form factor as compared with the conventional circuit is achieved which gives safer and more efficient operation.

The circuit of the invention can, alternatively, be employed as a battery charger in which event the magnetron in the free wheel path of the inductor, or where a transformer is used for preference, the transformer secondary sinding, is replaced with a diode in series with which is the battery to be charged. A further alternative use would be to replace the magnetron with a diode and a capacitor in series with the diode. The capacitor can then be used to supply a further circuit.

The circuit of the invention generally has application where a power supply circuit is required the voltage and current wave forms of which are in phase with the a.c. supply so that the load appears resistive to the supply voltage and the supply is not substantially distorted by current drawn therefrom.

The invention will now be described, by way of example with reference to the accompanying drawings, in which:-

FIGURE 1 is a circuit diagram of the conventional low frequency power supply circuit of the magnetron of a microwave cooker;

FIGURE 2 shows the magnetron voltage and current in relation to the supply voltage in operation of the circuit of Figure 1;

FIGURE 3 is a circuit illustrating the principle of the present invention;

FIGURE 4 ia a circuit of one embodiment of the invention, and

FIGURE 5 is a modification of the circuit of Figure 4.

Referring to Figures 1 and 2, a transformer 1 has a primary winding 3 and secondary windings 5 and 7, the primary winding 3 being connected to a sinusoidal a.c. supply and the secondary winding 5 to a capacitor 9 and diode 11 in series with the winding 5 and forming therewith a voltage doubler circuit of known form. A magnetron 13 has its anode 15 connected to the cathode of the diode which is connected to earth potential whilst its cathode 17 is supplied from the secondary winding 7 of the transformer and is connected to the anode of the diode.

The behaviour of this circuit is apparent from Figure 2. The curve A is the voltage in the secondary winding 5 and the curve B is the magnetron anode voltage. As the cathode of diode 11 and therefore the point thereof connected to winding 5 are at earth potential, the voltage at the end of winding 5 connected to the left hand plate capacitor 9 oscillates sinusoidally. At the commencement of operation that plate of the capacitor is at zero voltage and rises to V_p, the maximum voltage across the winding 5, in the first quarter of the voltage cycle. During this part of the voltage cycle, the voltage at the right hand plate of the capacitor and therefore at the anode of the magnetron, since the diode 5 is a conducting condition whilst capacitor 9 is charging, remains at zero. A the end of the first quarter of the cycle, therefore, the capacitor 9 is fully charged with the voltage V_p across it and the magnetron anode voltage is zero. In the next quarter of the voltage cycle, the voltage at the left hand plate of the capacitor 9 falls to zero and the right hand plate thereof falls below zero to maintain the voltage difference across the capacitor at V_p, the magnetron being non-conductive during this part of the voltage cycle. The magnetron anode voltage thus falls to $-V_p$ in this part of the cycle. In the next part of the voltage cycle the voltage of the left and right hand plate of the capacitor continue to fall in step, the left hand plate falling towards $-V_p$ and the right hand plate, together with the magnetron anode, towards $-2V_p$. This is the voltage doubling effect. However, before the magnetron anode reaches the voltage $-2V_p$, the magnetron anode voltage attains a voltage $-V_M$ at which the magnetron commences to conduct, curve C being the magnetron current curve, and, thereby, the diode 11 is by-passed. The capacitor 9 thus begins to discharge and the net voltage across it therefore falls sinc. the magnetron anode voltage remains constant at $-V_M$. The discharge continues until the voltage at the left hand plate of the capacitor falls to $-V_p$, when the voltage difference between the capacitor plates is V_M-V_p, this occurring at the three quarter point of the voltage cycle. The voltage at the capacitor left hand plate then commences to rise and the capacitor again charges so that the megnetron current falls to zero at which point the magnetron anode voltage starts to fall to a value less negative then $-V_M$. The charging of the capacitor continues until at the end of the cycle it is again fully charged with its left hand plate at zero volts and its right hand plate and the magnetron anode at $-V_p$. In the following quarter cycle of the voltage in the winding 5, the left hand plate of the capacitor rises to C_p and the magnetron voltage rises to zero volts and the cycle thereafter continues as before.

It will be observed that the magnetron is conducting for only about 25 per cent of the voltage cycle and therefore has a high peak to mean current ratio or form factor which is undesirable from the standpoint of efficiency and also of safety, as it gives rise to relatively high leakage of radiated high frequency energy. This circuit does not lend itself to any form of control of output power other than on a duty cycle basis. In this form of control, the power of the system is interrupted for fractions of a fixed period generally a twelve or thirty second period. Thus to achieve half power, when operating on a twelve second period, the supply is repeatedly switched on for six seconds with intervals of six seconds between successive on periods. The power output in these circumstances is actually less than 50 per cent since approximately one second is needed to heat up the magnetron filament to the operating temperature. A major problem with this form of control is that some form of surge limitation is needed at "switch on". Thus with mechanically timed circuits, a surge limiter is introduced on "switch on" and then by-passed by a further switch when the magnetron achieves power.

As indicated earlier a further disadvantage of this known circuit arrangement is that it operates at low frequency and therefore requires a large and heavy transformer.

Turning now to Figure 3, an inductor L is connected in series with a switch S across a supply and a diode D in series with a resistor R provides a free wheel path across the inductor. The switch may be any form of switching device e.g. a semi-conductor switch or even a mechanical switch. The inductor current I, is assumed to be zero just prior to closure of the switch. With switch S closed, diode D is reverse biased and no current flows in resistor R.

From the known equation relating current flow, applied voltage, inductance and time, the magnitude of I_L, the inductor current after an "on" period of switch S is given by:-

$I_L = \frac{V}{L}$ ton

where V = the supply voltage

ton = the time the switch S has been closed,

and L = the inductance of the inductor.

The energy E_L stored in the inductor is given by:

$$E_L = \frac{1}{2} L I_L^2$$

$$= \frac{V^2 t^2{}_{on}}{2L}$$

If the switch S is opened at this instant, the energy in the inductor is circulated in the free wheel path provided by the inductor L, the diode D and resistor R. If when L_L is again zero, the switch S is again closed for a further period t_{on}, the power dissipated in the resistor is

$$P_R = \frac{V^2 t^2 on.f.}{2L}$$

where R_R is the power dissipated, and
f is the switching frequency.
It will be appreciated that if t_{on}, f and L are constant

$$P_R = \frac{V^2}{K} \quad \text{where } \frac{1}{K} = \frac{t_{on}^2 .f}{2L} \text{ is a constant}$$

The supression $PR = \frac{V^2}{K}$ is of identical form to that for defining power dissipated in a pure resistor for a given applied voltage. Accordingly, the arrangement of Figure 3 is one in which the load on the supply V appears to be purely resistive given the operating assumptions of t_{on}, f and L being constant.

Similarly, if V were a full wave rectified sine wave, the power in the load would be of the form

$$P_R = \frac{V^2 \, Sin^2 wt}{K}$$

and the current supply would be sinusoidal.

The incorporation in a practical circuit of the concept described is illustrated in Figure 4 in which the inductor is replaced by a high frequency step-up transformer 25 of which the primary winding 27 is connected in series with a high frequency switch 29 and the secondary winding 30 of which is disposed in series with a magnetron 31 to provide the free wheel path for energy transferred by way of the magnetic circuit of the transformer from the transformer primary to secondary winding during periods when the primary winding is disconnected from the source of supply which in this instance is an alternating supply 33 which is full-wave rectified by bridge rectifier 35 and unsmoothed.

The switch 29 is a thyristor switch and, suitably, comprises a fast, gate turn off device (GTO) 37 in series with a blocking diode 39 which is needed because the GTO is conductive when reverse biased. A commutating capacitor 41 in series with an inductor 43 shunts the series path of the GTO 37 and blocking diode 39.

A capacitor 45 is connected across the mains to filter radio frequency harmonics.

In operation, commutating capacitor 41 is initially charged to the supply voltage peak and the GTO 37 is then switched into conduction by a voltage pulse applied to its gate. The capacitor 41 discharges through the diode 39 and GTO 37 and because of the resonant circuit provided by the inductor 43 and capacitor 41, the latter is reverse charged, subsequent attempt thereof again to reverse charge effecting commutation of the GTO and reverse biassing thereof and of the blocking diode 39. The conduction time of the GTO is constant and given by the reversal time of capacitor 41 which is:-
$t_{on} = L_{43}C_{41}$ where L_{43} is the inductance of inductor 43 and C_{41} is the capacitance of capacitor 41.

In the periods between conduction of the GTO 37, energy in the primary winding by transformer action is dissipated in the free wheel path of the winding 30 and the magnetron 31, the step-up form of the transformer providing the necessary voltage to effect conduction of the magnetron.

If the switching frequency is constant the power supplied to the magnetron load is proportional to the square of the supply voltage and therefore appears purely resistive to the mains supply. Power variation is accomplished by changing the frequency of switching which is suitably of the order of 25 Hz. This is done progressively or, to avoid audio noise, by suppressing firing of the GTO during parts of the mains output voltage cycle, i.e. a type of phase firing.

The circuit provides magnetron current which is in phase with the supply voltage and all energy supplied from the mains supply goes to the magnetron which is therefore continuously fed. As the magnetron current and the supply voltage are in phase, fall of the supply voltage is accompanied by fall of the magnetron current.

It will be noted that no high voltage diodes or capacitors are needed and the material cost is therefore less than that of the conventional circuit described. Also, the transformer having its secondary winding earthed is of simple and inexpensive construction.

Figure 5 illustrates an alternative to the embodiment of Figure 4 where the switch utilised may be another form of semi-conductor device such as a IGBT (Insulated gate bi-polar transistor) not requiring the commutation circuit referred to in Figure 4.

In Figure 5, the reflector capacitance of the magnetron 31 is indicated at 38. The presence of this capacitance forms a resonant circuit with the effective transformer inductance causing the voltage at point 25A of the transformer 25 to swing towards the negative rail at the termination of the energy transfer sequence and reduced the voltage across the switch 51 to zero prior to "switch-on". In fact, the voltage across the switch 51/diode 39 combination may be reversed depending upon the circuit constants and the relation values of the reflected magnetron voltage and the instantaneous supply potential. By interlocking the "switch-on" state of the switch 51 with the resonant voltage excursions at the point 25A, "loss-free" switching can be achieved in conjunction with an appropriate input characteristic.

Claims

1. A power supply circuit comprising an inductor, a high frequency switch connected in series with the inductor the series arrangement of the inductor and switch being adapted for connection to a pulsating d.c. supply derived from a rectified a.c. supply without addition of smoothing means, and a path in which is disposed a load and which provides a unifirectional conductive path for energy in the inductor during periods when, in operation, the inductor is disconnected from the d.c. supply, the high frequency switch being adapted to connect the inductor to the d.c. supply when the current in the inductor falls to zero so that the power supply takes from the a.c. supply at any given constant frequency of switching a current ave form which is in phase with and of the same harmonic content as the corresponding part of the a.c. supply wave form.

2. A power supply as claimed in Claim 1, characterised in that the series arrangement of the inductor and switch is adapted for connection to a pulsating d.c. supply derived from a full-wave rectified a.c. supply without addition of smoothing means so that the power supply takes from the a.c. supply at any given constant frequency of switching a current wave form which is in phase with and of the same harmonic content as the a.c. supply wave form.

3. A power supply as claimed in Claim 1 or Claim 2, characterised in that the inductor comprises a high frequency transformer having a primary winding in series with the switch and a secondary winding across which the path of the load is connected.

4. A power supply as claimed in any one of Claims 1 to 3 characterised in that the switch has a blocking diode in series therewith and the switching intervals are determined by the reflective capacitance of the load.

5. A power supply as claimed in any preceding claim, characterised in that the switch comprises a thyristor having connected in parallel therewith a resonant series path comprising a commutating capacitor and inductor.

6. A power supply as claimed in Claim 5, characterised in that the thyristor is a fast gate turn off device having a blocking diode in series therewith.

7. A power supply as claimed in any preceding claim, characterised in that the load comprises a magnetron.

8. A power supply as claimed in any one of Claims 1 to 6, characterised in that the load comprises a battery with a diode in series therewith.

9. A power supply as claimed in any one of Claims 1 to 6, characterised in that the load comprises a capacitor having a free wheel diode in series therewith.

10. A microwave oven including a power supply circuit as claimed in anyone of Claims 1 to 9.

11. A battery charger having a power supply circuit as claimed in anyone of Claims 1 to 3 and 5 to 9.

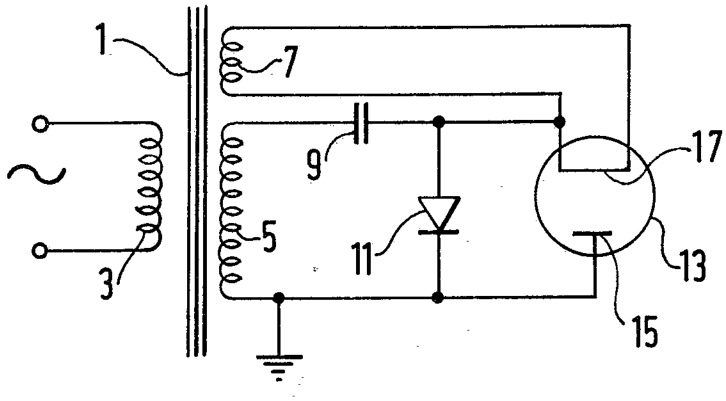

Fig.1.

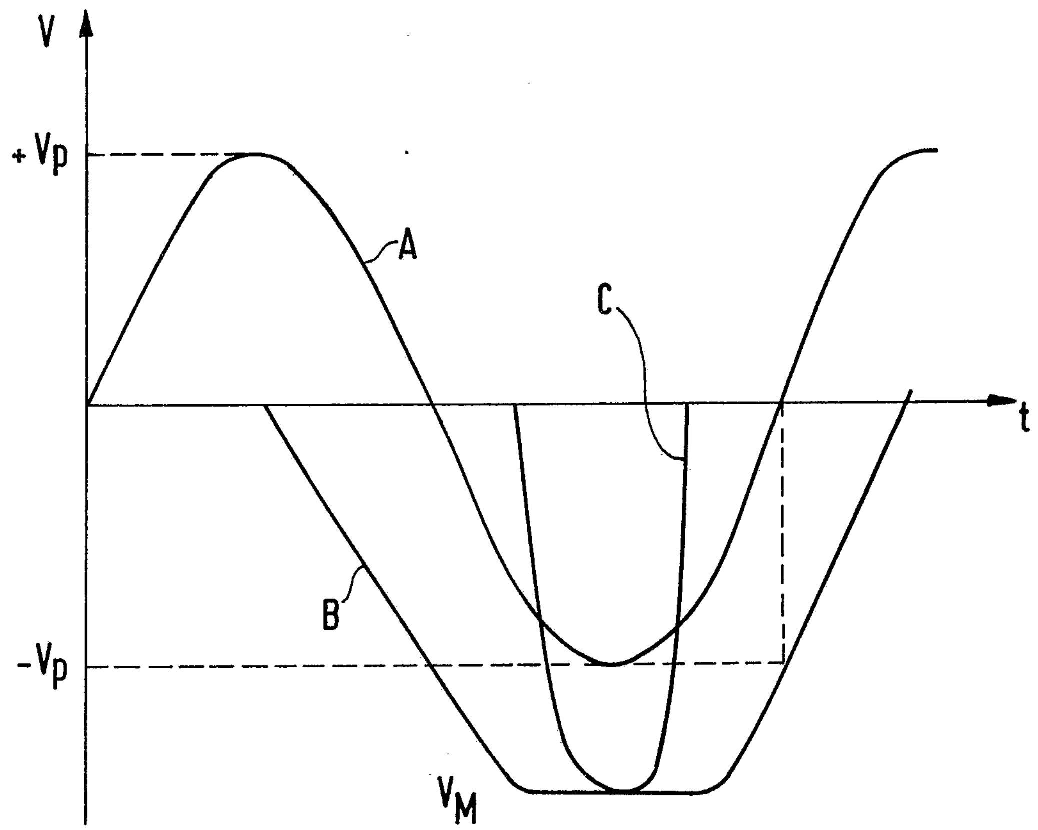

Fig.2.

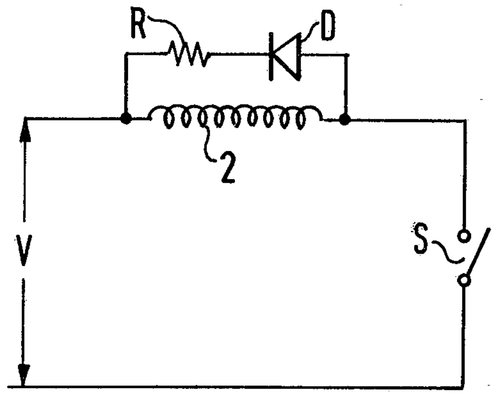

Fig. 3.

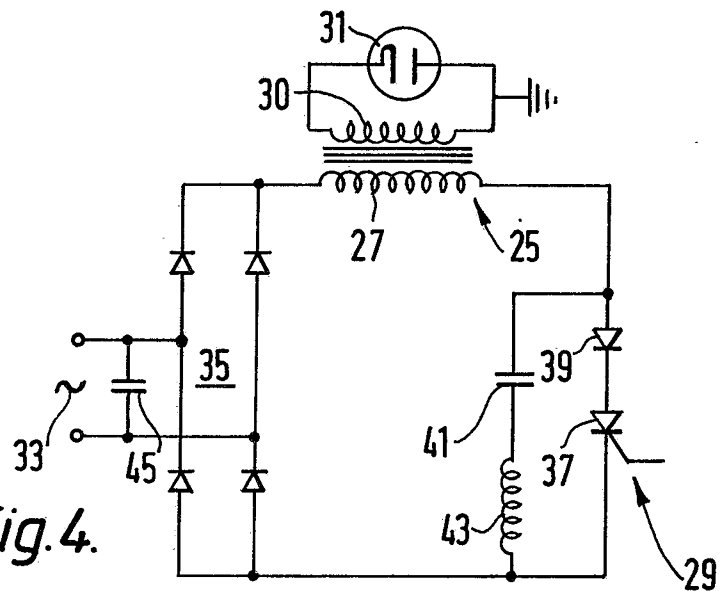

Fig. 4.

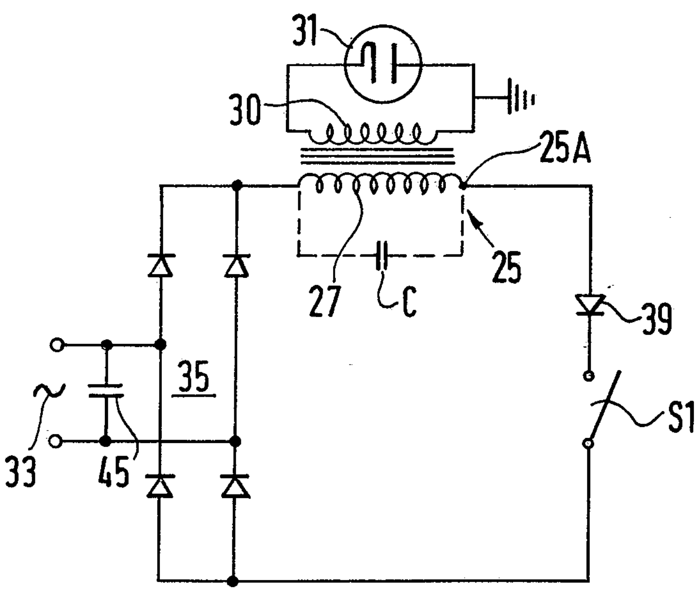

Fig. 5.