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(54) IMPROVEMENTS RELATING TO THE STARTING OF DISCHARGE LAMPS

(71) We, THORN EMI LIMITED formerly known as THORN ELECTRICAL INDUSTRIES LIMITED, a British Company, of Thorn House, Upper Saint Martin's Lane, London, WC2H 9ED, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:-

This invention relates to the starting of discharge lamps.

The most common method of starting discharge lamps is by the use of a glow switch starter. A description of this and other starter circuits is to be found in "Lamps and Lighting" by S.T. Henderson and A.M. Marsden, Second Edition, 1972, published by Edward Arnold, London.

This type of starter is simple, cheap and generally effective, but suffers from a number of disadvantages, in particular:-

(a) It has mechanical contacts which give it a limited life.

(b) When the lamp fails the starter continues to try to start the lamp; this can not only cause the lamp to flicker annoyingly but puts great strain on the starter, which almost invariably has to be replaced along with the lamp. This problem can be overcome by adding a special thermal cut-out, but this increases expense.

(c) The starting time is long and rather variable.

(d) "Cold starting" effects may be evident near the end of the starter life, that is the arc may strike with insufficient pre-heating of the cathodes, leading to blackening of the tube walls adjacent the cathodes.

To overcome this problem the semi-resonant start circuit (see "Lamps and Lighting" *supra*) was developed as an alternative to the glow switch. This is more expensive and slightly less efficient than the glow switch starter. The fuse incorporated in the circuit must also be critically rated since a short circuit failure of the capacitor in the circuit would cause the ballast to overheat. It does however have the advantages of high reliability, a visually more acceptable start, and that it is no longer necessary to replace the starter with the lamp.

Previous proposals have been made to develop starter circuits which overcome some of the other disadvantages of the glow switch starter by using an electronic switch. One example of this is British Patent Specification No. 1,223,733 which employs a silicon controlled rectifier (SCR) as the switch, and has a triggering circuit for triggering the SCR into conduction once during each cycle of the supply voltage. The circuit operates by triggering the SCR at a point during the positive half cycle of the supply voltage waveform. Current then flows through the choke ballast, the lamp cathodes and the starter, thus heating the lamp cathodes. Due to the choke inductance, a point will arise during the subsequent negative half-cycle where the current reduces to zero, and at this point the SCR will turn non-conductive. This causes a negative inductive transient across the starter, and hence the lamp, which hopefully causes the lamp to strike. If it does not, the sequence of operations continues on subsequent cycles of the supply voltage until it does. When the lamp strikes, the voltage across the starter falls to a value which is low enough to prevent further triggering of the SCR.

The time between the previous zero-crossing of the supply voltage waveform and the instant when the SCR conducts may be termed the trigger angle. The setting of this trigger angle is critical. If the trigger angle, and hence the instantaneous supply voltage at the trigger point, is too low, then the starter may trigger when the lamp is running, and also if the lamp fails there will be a relatively high cathode current which could cause a high temperature rise in the ballast choke. Conversely, if the trigger angle is too high, the cathode heating current will be too low and the lamp may "cold start", or even fail to start, particularly if the supply voltage is at all reduced below the nominal value.

Another prior proposal is described in British Patent Specification 1,264,397, in which a thyristor switch receives a control voltage through a diac from a pair of capacitors arranged as a potential divider with a pair or resistors coupled across them. Trigger pulses are generated at a time interval after the start of the positive half cycles which depends initially on the charging rate of the smaller capacitor through the parallel combination of the larger capacitor and one of the resistors. At each triggering point the small capacitor is discharged through the diac connected to the thyristor gate, whilst the charge on the larger capacitor is increased. On subsequent positive half cycles, the charging of the smaller capacitor commences at a progressively higher instantaneous supply voltage. This causes progression of the trigger point to points or trigger angles which are progressively later in the cycle of the applied voltage, with a view to providing a high cathode heating current in the early cycles but moving later to a point where it practically coincides with the peak of the applied voltage. If the lamp does not then start, the starter will thereafter be inactivated and will not be reactivated until the current has been switched off and switched on again.

Now, with such a circuit the initial trigger point (in the first cycle) is defined by the values of all the relevant components, namely the capacitors, the resistors, and the diac. The tolerances of all these components will affect the actual initial trigger voltage, and in volume production a wide variation can result. In practice the initial trigger point is important in that it determines the cathode heating current; if the trigger point is too high the cathodes may be insufficiently heated, if too low then excessive current can flow through the thyristor and the lamp cathodes causing damage to these items.

At the end of the operation sequence, further problems can occur. The smaller of the capacitors tends to discharge slightly between each positive peak of the applied voltage, so that the thyristor can trigger on spurious voltages superimposed on the supply or, particularly under conditions of low ambient temperature, on the re-ignition spikes of the lamp. Very careful selection of the components is required if such spurious triggering is to be entirely avoided.

This invention overcomes or at least substantially reduces these problems by a simple expedient which does not require accurate tolerances of resistances and capacitors and can be achieved without a large number of additional components.

Our invention provides a discharge lamp starter circuit having two starter input terminals for connection to the cathodes of a discharge lamp for receiving a cyclically-varying voltage supplied through both the lamp cathodes and a choke ballast, the starter circuit comprising a controlled switch connected across the starter input terminals and a control circuit, including in series a capacitor and an avalanche diode having a Zener-like characteristic, coupled between a starter input terminal and the control input of the switch for rendering the switch conductive at a trigger point, during the cycle of the applied voltage, determined by the breakdown voltage of the avalanche diode and the voltage on the capacitor and means for increasing the voltage on the capacitor at each successive cycle or half cycle after switch-on of the applied voltage to progressively raise the applied voltage at which said trigger point occurs.

The use of a suitable avalanche diode in this position sets the initial trigger voltage to a well defined value, and provides a secure degree of spurious trigger immunity.

Preferably, the control circuit is arranged to charge the capacitor at a substantially linear or constant rate, thereby producing a relatively sharp and predictable cut-off, particularly in the failed-lamp condition.

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

Figure 1 is a circuit diagram of a first starter circuit embodying the invention;

Figure 2 shows a number of waveforms illustrating the operation of the illustrated embodiments, waveforms (a), (b) and (c) (on one sheet) showing respectively the lamp voltage, starter current and lamp current, and waveforms (d), (e) and (f) (on another sheet) each showing the voltage across a capacitor in the starter circuit for the embodiments of Figures 1, 3 and 4 respectively;

Figure 3 is a circuit diagram of a first improved starter circuit in which the capacitor charges only during the negative half cycles;

Figure 4 is a circuit diagram of a second improved starter circuit in which the capacitor also charges during the positive half cycles;

Figure 5 is a drawing prepared from oscillographs showing characteristics of the starter circuit of Figure 4, waveforms (a) and (b) showing the lamp voltage and starter current waveforms respectively when the lamp is successfully struck, and waveforms (c) and (d) showing the same parameters when a simulated failed lamp is used;

Figure 6 shows a modification of the starter circuit of Figure 4;

Figure 7 is a circuit diagram of a starter circuit embodying the invention which provides a substantially constant time to switch off;

Figures 8 and *9* are circuit diagrams of two other starter circuits based on that of Figure 6 which provide a substantially constant time to switch off;

Figure 10 is a circuit diagram illustrating the use of a rectifier with the starter circuit of Figure 4 or Figure 6; and

Figure 11 shows a starter circuit in which the main semiconductor switch is a triac to permit bi-directional cathode heating current.

Figure 1 shows a fluorescent discharge lamp 10 of the hot cathode type with two cathodes 12, 14. One side 14*a* of cathode 14 is connected directly to one 16*b* of a pair of mains input terminals 16, and one side 12*a* of cathode 12 is connected to the other mains input terminal 16*a* through an inductor or choke 18 acting as a ballast. The terminals 16 receive a normal a.c. mains supply voltage of typically 240 volts at 50 hertz. Usually a switch (not shown) will be included in the circuit in conventional manner, and a power factor correction capacitor may be connected across the terminals 16. The other side 12*b*, 14*b* of each of the two cathodes 12, 14, that is, the side not connected to the mains supply terminals 16, is connected to a respective terminal 22, 24 of a starter circuit 20, sometimes termed an igniter.

The starter circuit includes a controlled breakdown device in the form of a thyristor and shown as a silicon controlled semiconductor rectifier (SCR) 26 connected between the starter circuit terminals 22, 24. The control or trigger circuit for the thyristor 26 consists of a diode 28, an avalanche (Zener) diode 30, a capacitor 32 and a resistor 34 all connected in series between the terminals 22 and 24, with the junction between the capacitor 32 and resistor 34 being connected to the gate 36 of the thyristor 26.

A further capacitor 38 is optionally included across the terminals 22, 24, to provide radio interference suppression or to increase the negative voltage peak, and may be in series with a resistor, as described in British Patent Specification No. 1,223,733.

The operation of the circuit of Figure 1 will be described by reference to waveforms (a), (b), (c) and (d) of Figure 2. Waveform (a) shows the supply voltage in dashed lines. When the circuit is in the switched-off state the capacitor 32 is discharged. Upon switch-on, during the first positive half-cycle of the supply voltage, a small charge is impressed on the capacitor 32 through diode 28 and the reverse leakage path of Zener diode 30. When the instantaneous value of the positive voltage across the starter circuit and the lamp is approximately equal to the voltage defined by the sum of the reverse breakdown voltage V_{30-BR} of the Zener diode 30 and the voltage V_{32-1} attained by the capacitor 32, then current flows through the control circuit including diode 28, Zener diode 30 and capacitor 32 to the gate 36 of thyristor 26, to trigger the thyristor into conduction. This happens when the voltage across the starter circuit 20 has the value V_{20-1}, see waveform (a). The gate current which causes triggering further charges the capacitor 32 at a rate which depends essentially on the switching speed and gate sensitivity of the thyristor.

Thus it is seen that, neglecting the voltage drops across diode 28 and resistor 34, triggering of the thyristor 26 occurs when the lamp voltage is equal to the sum of the Zener breakdown voltage and the instantaneous voltage stored on capacitor 32. The resistor 34 is included to stabilize firing of the thyristor, and in particular to prevent spurious firing.

When thyristor 26 conducts, the voltage across the starter circuit is reduced to the forward voltage drop across the thyristor. Thus the voltage across Zener diode 30 is insufficient to sustain conduction, so that the gate current falls to zero. However, a unidirectional current flows through the choke 18 and lamp cathodes 12, 14. This provides cathode heating, the magnitude of this heating current being dependent upon the point in the cycle where the thyristor is triggered, that is, the trigger angle θ, and the saturation characteristics of the choke 18. The current waveform is shown at (b) in Figure 2.

At some point during the next following negative half-cycle of the mains supply voltage, this current reduces to zero, and at that point the thyristor 26 ceases to conduct and the voltage across the starter circuit instantaneously rises to the value of the mains supply voltage. A negative voltage transient then appears across the lamp. A damped oscillation may be superimposed on the voltage waveform at this point, due to the resonance of inductance and stray capacitance within the circuit. This effect is increased by the addition of the capacitor 38. The thyristor 26 supports the reverse voltage across the discharge lamp thereby assisting ionization between the lamp cathodes 12, 14. For the remainder of the negative half-cycle the voltage across the starter circuit and hence the lamp follows the instantaneous value of the mains supply voltage. Diode 28 prevents conduction in the forward direction through Zener diode 30, and thus prevents discharge of capacitor 32, although some charge will be lost by leakage.

In the next cycle of the mains supply the cycle of operation is repeated. Initially thyristor 26 is non-conductive until triggered and thereupon heating current flows through the cathodes 12, 14. When the current reaches zero the thyristor ceases to conduct and a voltage spike is produced.

During the initial part of this second positive half-cycle, the existing charge on capacitor 32 is reinforced by current flow through diode 28 and Zener diode 30. Again, the thyristor 26 will conduct when the instantaneous value of the voltage across the starter circuit (and hence the lamp) is equal to the Zener breakdown voltage plus the voltage across capacitor 32. In this case the voltage V_{32-2} across capacitor 32 is higher than in the first positive half-cycle, this voltage also being shown at (d) in Figure 2. Thus the inclusion of capacitor 32 causes triggering at a point which is slightly later in the cycle, at a slightly higher instantaneous mains voltage. The charge on capacitor 32 is again increased by the gate current pulse.

Provided that there has been no previous discharge through the lamp to modify the sinusoidal form of the positive voltage applied across the starter circuit prior to triggering, the peak current through the starter circuit 20 and cathodes 12, 14 will be somewhat less than that attained during the thyristor conduction period which occurred during the previous cycle. This is illustrated in waveform (b) in Figure 2.

During subsequent cycles of the mains voltage the sequence is again repeated. The trigger voltage progressively increases, see waveform (a), in line with the increasing charge on capacitor 32, waveform (d), and this increase may be accompanied by a reduction in peak cathode heating current, waveform (b).

It is assumed in Figure 2 that during the third cycle of the mains voltage a partial discharge takes place through the lamp, as shown in waveform (c). This may cause a positive spike 40 at the beginning of the next following positive half-cycle, due to the lamp voltage tending to conform to the running mode waveform of the discharge lamp. Thus, although the trigger voltage may have increased, a reduction in the trigger angle can result. Consequently, since the peak cathode current is related to the trigger angle, a reduction in the peak current may not be observed at this point in the starting cycle, and, as shown at (b) in Figure 2, an increase in cathode heating current occurs in the fourth cycle as compared with the third.

The progression of the trigger voltage in line with the increasing voltage on capacitor 32, waveform (d), continues until the lamp strikes, and in Figure 2 this is assumed to happen at the beginning of the fifth cycle, following the negative voltage spike in the second half of the fourth cycle.

Whether the lamp strikes or not the trigger voltage will go on increasing until it reaches a maximum value, determined by leakage resistances, which is too high for the thyristor to be triggered at all by the voltage across the lamp, as triggering would require a voltage across the starter which was greater than the voltage on capacitor 32 by at least the breakdown voltage of Zener diode 30. If the lamp strikes triggering ceases, as the lamp voltage falls upon striking, but even if the lamp does not strike a point is soon reached where the voltage across capacitor 32 is too high for triggering to take place. In either event no current flows through the thyristor, and hence no strain is placed upon the choke 18. The charge on capacitor 32 is maintained through the reverse leakage path of Zener diode 30 by the voltage applied to the starter circuit.

The trigger voltage is thus capable of progressing from an initial low value, of typically about half the r.m.s. supply voltage and which is defined simply by Zener diode 30, up to a maximum value. This maximum value will usually be greater than the supply voltage to ensure that the starting circuit switches off. It would, however, be possible to add a Zener diode in parallel with the capacitor 32 to set the maximum trigger voltage to a desired value, though care must be taken to ensure that any resultant current through the choke, lamp cathodes and thyristor is not excessive under failed lamp conditions. The maximum trigger voltage should also be sufficiently high to prevent re-triggering of the igniter by the lamp waveform when the lamp is running normally.

In the circuit of Figure 1 the charging rate of capacitor 32 through the reverse leakage path of Zener diode 30 and gate of thyristor 26 is ill-defined due to the variation of the relevant parameters with temperature and as between individual components. In practice, the charging rate of capacitor 32 may be defined satisfactorily by a fixed value resistor (not shown) connected in parallel with the Zener diode 30, provided that low-leakage diodes and a high gate-sensitivity thyristor are employed.

Figure 3 shows an improved version 50 of the starter circuit 20 of Figure 1. Similar components are denoted by the same references where appropriate. The circuit 50 includes certain additional components, namely a diode 52 connected between the terminal 24 and the junction between Zener diode 30 and capacitor 32, a diode 54 connected between the capacitor 32 and the junction of thyristor gate 36 and resistor 34, a resistor 56 connected between the terminal 22 and the junction between capacitor 32 and diode 54, and a resistor 58 connected across the capacitor 32.

The operation of the starter circuit of Figure 3 will be described by reference to waveforms (a), (b), (c) and (e) of Figure 2. At the start of the first positive half-cycle of the supply voltage capacitor 32 is in a discharged condition and no current flows in the choke and discharge lamp cathodes. As the voltage across the starter circuit 50 increases, the thyristor 26 will be triggered into conduction when the voltage V_{20} across the starter circuit is equal to the breakdown voltage of the Zener diode 30, ignoring the voltage drop across the diodes 28 and 54 and resistor 34. Cathode heating current then flows, until at some point on the negative half-cycle of the supply voltage the cathode heating current falls to zero and the thyristor 26 switches off. The voltage across the starter circuit then rises to a value corresponding to the instantaneous negative value of the mains supply voltage at this point.

As thus-far described the operation of the circuit of Figure 3 is identical to that of Figure 1. Now, however, the capacitor 32 can be charged from the supply, current flowing from terminal 24 through diode 52, capacitor 32 and resistor 56 to terminal 22. The rate of charge depends essentially upon the time constant defined by the capacitance of capacitor 32 and the resistance of resistor 56. Charging of capacitor 32 continues until the instantaneous value of the voltage of the supply on the negative half cycle falls below the voltage attained by capacitor 32. Thus the voltage on capacitor 32 will tend to reach the peak applied voltage.

Diode 54 is included to prevent by-pass of the charging current through resistor 34, and diode 28 prevents conduction in the forward direction through Zener diode 30 during the negative half-cycle.

On the second positive half-cycle, triggering of the thyristor 26 occurs when the instantaneous voltage across the starter circuit is equal essentially to the sum of the breakdown voltage (V30-BR) of the Zener diode 30 and the voltage (V32-2) across capacitor 32 due to charging in the previous negative half-cycle.

It will be seen from waveform (e) in Figure 2 that the capacitor voltage V_{32} progressively increases from one positive half-cycle to the next, due to charging during the intervening negative half-cycles, and as with the circuit of Figure 1 this will eventually cause the thyristor to stop firing, whether or not the lamp strikes. After switch-off, spurious triggering is avoided by the Zener diode 30.

The relatively high value resistor 58 is included to permit the capacitor 32 to discharge when the supply voltage is removed (as by switching the lamp off) to reset the starter circuit to its initial conditions. There is of course some slight discharge during the positive half-cycles, as evidenced by the slope of the relevant parts of waveform (e), but this is insufficient to affect adversely the circuit operation.

One example of a circuit as shown in Figure 3 for operation on 240 volts a.c. at 50 hertz with a 4ft. 40 watt fluorescent hot cathode tubular discharge lamp complying with British Standard BS 1853 and IEC 81 had the following components:

Resistors	34	1 kΩ
	56	1 MΩ
	58	33 MΩ
Capacitors	32	0.1 μF
	38	0.0068 μF
Diode	30	avalanche voltage 110 volts
Diodes	28, 52, 54	IN4006G
Thyristor	26	TIP106M

The choke 18 can be of the same type as is presently used with glow-switch starters, such as that sold under the type No. G69321.4 by Thorn Lighting Limited. However, it may be possible to use an inductor of less iron and copper content as the inductor current in the failed-lamp condition can be guaranteed to be virtually zero.

This circuit provided a peak starting voltage of about 600 volts and an initial pre-start heating current of about 4 amps peak. In the event of failure of the lamp to strike, thyristor triggering ceased after about 2 seconds.

The circuit of Figure 3 thus improves the operation by controlling more accurately the charging of capacitor 32. This charging occurs during the negative half-cycles of the supply voltage. The alternative embodiment shown in Figure 4 provides for charging of the capacitor during the positive half-cycles also, thus enabling capacitor 32 to charge more steadily.

Those components in the starter circuit 60 of Figure 4 which are similar to corresponding components in Figure 1 are given the same references and will not be described again. The circuit of Figure 4, however, also includes a capacitor 62 which is connected between the terminal 24 and the junction between diodes 28 and 30, a resistor 64 connected across the Zener diode 30, and a resistor 66 connected across the capcacitor 32.

The operation of the starter circuit 60 of Figure 4 is illustrated in waveforms (a), (b), (c) and (f) of Figure 2. The lamp voltage, starter current and lamp current for the embodiments of Figures 1, 3 and 4 are sufficiently similar for the same waveforms (a), (b) and (c) in Figure 2 to be used in describing all the three embodiments.

In the circuit of Figure 4, initially capacitors 32 and 62 are discharged and no current flows through the lamp cathodes. As the instantaneous value of the mains supply voltage increases during the first positive half-cycle, capacitor 62 is charged through diode 28 to a voltage approaching the instantaneous value of the voltage across the starter circuit. Capacitor 32 is charged from the supply through diode 28 and resistors 64 and 34 at a rate which depends essentially upon the time constant defined by the capacitance of capacitor 32 and the resistance of resistor 64, as the value of resistor 64 is very much greater than that of resistor 34.

When the instantaneous voltage across the starter circuit becomes approximately equal to the sum of the break-down voltage of Zener diode 30 and the voltage attained by capacitor 32, thyristor 26 is triggered into conduction. Then the forward voltage across the starter circuit is reduced to the forward voltage drop across thyristor 26. Thus the voltage across the Zener diode 30 is reduced to a value which will not sustain the reverse breakdown conditions of the device and the thyristor gate current falls to zero. The short duration gate current pulse will not significantly alter the state of charge of the timing capacitor 32, provided that a thyristor with adequate gate sensitivity it utilized. Capacitor 62, however, has been charged to a peak voltage approaching the forward voltage supported by the thyristor 26 just prior to triggering, and thus continues to charge capacitor 32 through resistors 64 and 34 for the whole of the remainder of the first cycle of the supply voltage, as shown by waveform (f) in Figure 2. The value of resistor 64 is such that capacitor 32 is only partially charged during the period of one cycle of the supply voltage. Discharge of the capacitors 32 and 62 through the anode-cathode path of thyristor 26 when in its conductive state is prevented by diode 28.

The cathode heating current applied to the lamp is again as shown in waveforms (b) and the lamp voltage as in (a), and in this respect the operation is precisely similar to that of the circuits of Figures 1 and 3.

On the second positive half-cycle, as soon as the value of the instantaneous voltage across the starter circuit exceeds the voltage remaining on the reservoir capacitor 62, charging of capacitor 62 through diode 28 is resumed. Capacitor 62 continues to charge capacitor 32 through resistors 64 and 34, and triggering of thyristor 26 occurs when the instantaneous supply voltage equals the sum of the voltage across capacitor 32 and the Zener breakdown voltage (neglecting the voltages across diode 28 and resistor 34). The operation then continues as for the previous embodiments of Figures 1 and 3. The progressively increasing voltage across capacitor 32 again ensures that, if the lamp fails to strike, the thyristor triggers later and later during the positive half-cycle and eventually fails to trigger at all. If the lamp does strike, the voltage across the starter circuit falls, and triggering ceases.

When the supply voltage is removed, the capacitor 32 discharges through resistor 66 and capacitor 62 through resistors 64, 66 and 34, thereby resetting the circuit to its initial conditions.

The provision of the reservoir capacitor 62 in the circuit of Figure 4 has the advantage of providing a more constant or linear rate of charge for capacitor 32 throughout the trigger point progression which occurs over many cycles. This ensures that capacitor 32 is adequately charged even when the voltage on the capacitor approaches the peak value of the supply voltage, thus providing a sharp and predictable cut-off point, and helping to prevent re-triggering of the thyristor on supply voltage transients and high peak lamp voltages. In the circuit of Figure 3, the rate of charge exhibits an exponential rise as the voltage on capacitor 32 approaches the peak value of the supply voltage.

One example of a circuit as shown in Figure 4 for operation on 240 volts a.c. at 50 hertz with a 4 ft. 40 watt fluorescent discharge lamp had the following components:

Resistors	34	1 k Ω
	64	3.9 M Ω
	66	30 M Ω
Capacitors	32	0.1 μF
	38	0.0068 μF
	62	0.01 μF
Diode	30	avalanche voltage 110 volts
Diode	28	IN4006G
Thyristor	26	TIP106M

The inductor 18 used was again a type G69321.4 choke made by Thorn Lighting Limited.

Figure 5 shows actual waveforms obtained with the use of the above-described example of the starter circuit of Figure 4, which did not include the capacitor 38. Waveforms (a) and (b) show respectively the lamp voltage and starter current when the circuit is used successfully to start a lamp, and waveforms (c) and (d) show the lamp voltage and starter current obtained when a failed-lamp condition is simulated by using one cathode from each of two different lamps. The detailed shape of each cycle of the waveforms cannot be seen in Figure 5 but will be clear by reference to waveforms (a) and (b) of Figure 2. It should be noted in Figure 5 that the time scales for waveforms (a) and (b) on the one hand and waveforms (c) and (d) on the other are different; in waveforms (a) and (b) a time period of one second (fifty cycles) is shown while in waveforms (c) and (d) a time period of two seconds (one hundred cycles) is shown.

Waveforms (a) and (b) in Figure 5 show the various phases illustrated in waveforms (a) and (b) of Figure 2, that is there is an initial portion I where cathode heating current flows at a gradually decreasing rate followed by several cycles II where partial discharge in the lamp takes place. The slight increase in the peak cathode current at the end of phase I is thought to be due to ionization between the individual lamp cathode supports reducing the effective cathode resistance. At point III the lamp strikes, and the waveform during normal lamp running is shown at IV. In this example the lamp strikes in rather less than one half of a second.

Waveforms (c) and (d) show what happens with a simulated failed lamp. Here the lamp voltage remains in the initial phase V as the lamp does not strike, until a point VI is reached where all triggering ceases. Thereafter in region VII the voltage waveform across the lamp is simply the sinusoidal supply waveform. At point VI it is seen that the starter, and hence cathode, current, which has been decreasing fairly steadily, now ceases altogether. Thus no further attempt is made to strike the lamp, and no damage or lamp flickering can occur. In the example shown this cut-off point is reached within $1\frac{1}{2}$ seconds. The slight increase in cathode current which occurs about twenty cycles from switch-on arises due to ionization between the cathode supports. In a real failed lamp there might also be a small amount of electron emission from the heated cathodes, in the form of a pseudo partial discharge.

Figure 6 shows a possible alternative to the starter circuit of Figure 4. In the starter circuit 70 of Figure 6, which represents a particularly preferred embodiment of the invention, the discharge resistor 66 for capacitor 32 has been removed and replaced by a resistor 72 of about one-third of its value connected directly across the reservoir capacitor 62. Upon switch-off capacitor 62 now discharges directly through resistor 72 and capacitor 32 discharges through resistor 72 *via* the forward conduction path of Zener diode 30 and resistor 34. This re-arrangement provides a reduced reset time upon switch-off, but otherwise the operaton of the circuit is identical to that of Figure 4.

A prototype of the Figure 6 circuit had the same component values as for Figure 4, except that the 30 M Ω resistor 66 was deleted, and the resistance of resistor 72 replacing it was 10 M Ω. As an alternative to the capacitor 38, a series circuit consisting of a capacitor and a resistor can be used, typical values then being 0.15 μF and 47 ohms respectively. This will tend to enhance the negative voltage peak across the starter circuit.

The circuits of Figures 4 and 6 increase the trigger voltage progressively with the cycles of the supply voltage at a rate which is broadly constant, regardless of supply voltage. This has the advantage that the cut-off state, particularly in the failed-lamp condition, is relatively sharp and predictable. However, since the starter circuit switches off when the trigger voltage exceeds the supply voltage, this means that the time to switch-off, i.e. the period of time during which the igniter tries to start the lamp, is dependent upon the supply voltage. At low supply voltages the time to switch-off can, in certain circumstances, be reduced quite considerably. If the circuit is adjusted to provide an adequate time to switch-off at such low supply voltages, then at normal supply voltages the time to switch-off could, for certain applications, be undesirably long.

In the circuit of Figure 3, the timing capacitor is charged from the negative half-cycles of the voltage across the starter circuit, the peak of which remains constant for a given supply voltage. The trigger voltage progression is therefore essentially exponential, and some measure of stabilization of the switch-off time is achieved.

Figures 7, 8 and 9 show circuits in which this effect is further ameliorated. In these circumstances the switch-off time is essentially independent of the supply voltage. In Figure 7 this is achieved by charging the capacitor 32 at a rate which is dependent upon the supply voltage, whereas in Figures 8 and 9 the charging rate is constant but the capacitor 32 is pre-charged upon switch-on of the supply to a voltage which is a fixed amount below the supply voltage.

Turning first to the starter circuit 100 of Figure 7 those components which are similar to those of the circuit of Figure 1 are given the same reference numerals and will not be described again. The circuit includes a reservoir capacitor 102 which can be charged during the negative half-cycles of the supply voltage through a diode 104 to the peak negative supply voltage. Capacitor 102 can then charge capacitor 32 during both half-cycles by way of two resistors 106 and 108, connected as shown. A diode 110 ensures the charging of capacitor 32 to the correct polarity, i.e. the junction with resistor 108 is positive with respect to the junction with resistor 106, and resistor 112 permits capacitors 32 and 102 to discharge upon switch-off of the supply.

Positive and negative signs are given on Figure 7 to indicate the senses of charging of capacitors 32 and 102; they do not imply that these are electrolytic capacitors.

The trigger voltage now exhibits an exponential rise due to charging of capacitor 32 from capacitor 102 through resistors 106 and 108. At low supply voltages, capacitor 102 is charged to a correspondingly lower value and the rate of trigger voltage exponential rise is consequently reduced. Thus the time taken for the trigger voltage to exceed the positive voltage across the igniter is essentially the same for both high and low supply voltages, thereby stabilizing the time to switch-off of the starter circuit.

The starter circuit 120 of Figure 8 is based on that of Figure 6 but includes some additional diodes. These are: diode 122 connected between capacitor 32 and resistor 34, diode 124 connected between the terminal 22 and the junction of capacitor 32 and diode 122, diode 126 connected in series with capacitor 62, diode 128 connecting resistor 72 to the junction of capacitor 62 and diode 126, and a Zener diode 130 and diode 132 connected across the capacitor 62 and diode 126.

Upon switch-on of the supply voltage a current flows through diode 124, capacitor 32, Zener diode 30, Zener diode 130 and diode 132. The capacitor 32 will thus be charged to a value equal to the supply voltage *less* the voltage drop across these four diodes, which for practical purposes means the drop across Zener diodes 30 and 130. Thus the capacitor 32 is pre-charged to a fixed amount below the peak of the supply voltage regardless of the actual value of the supply voltage. This ensures that the trigger voltages traverse a fixed voltage range, which results in a constant time to switch-off of the starter circuit regardless of supply voltage variations.

The circuit 120A of Figure 9 is a modification of that of Figure 8 and is simpler and more reliable. The alterations made will be apparent from the figure, and involve the repositioning of diode 122, the removal of diode 126, and replacement of diode 128 by a direct connection. The operation of the circuit is similar to that of Figure 8, the capacitor 32 being pre-charged to a fixed voltage below the peak of the supply voltage through diode 132, Zener diode 130, Zener diode 30, resistor 34 and diode 124. Thus, switch-off time stabilization is achieved in a similar manner to that of the circuit of Figure 8.

It should be noted that with this circuit the charging of capacitor 32 *via* diode 132 and Zener diode 130 can only occur during the first negative half-cycle after connection of the supply, which may not be coincident with switch-on of the supply voltage.

Figure 10 illustrates how a full-wave bridge rectifier circuit 140 may be connected between the lamp 10 and the starter circuit. This is appropriate for the starter circuits 60 or 70 of Figures 4 and 6 respectively, although the circuit 70 of Figure 6 is preferred. The open circuit voltage applied across the starter circuit is thus as shown as V_s on Figure 10. If capacitor 38 is used this should be connected before the bridge rectifier. With full-wave rectification the starter circuit triggers every half-cycle of the supply voltage, providing a progressively increasing voltage on both positive and negative half-cycles of the supply voltage until triggering is cut off as described above. The cathode heating current is somewhat reduced because of the absence of saturation effects in the choke.

The starter circuits such as that of Figure 6 will also work in principle if the lamp itself is operated on a rectified a.c. supply.

Figure 11 shows an embodiment of the invention which is based broadly on the circuit of Figure 1, but in which the thyristor 26 has been replaced by a triac 84 to permit bidirectional cathode heating current. A diode 28, Zener diode 30, capacitor 32 and diode 54 are connected in series, and a resistor 86 couples the diode 54 to the gate 88 of triac 84. A discharge resistor 58 is connected across capacitor 32. A diode 91 connects the junction of Zener diode 30 and capacitor 32 to the termnal 22, and a diode 92 connects the junction of Zener diode 30 and diode 28 to the resistor 86.

During each negative half-cycle the triac 84 is triggered *via* diode 91, the reverse conduction path of Zener diode 30, diode 92 and resistor 86. The trigger point is determined essentially by the avalanche breakdown voltage of Zener diode 30, and thus does not vary. On successive positive half-cycles, however, the trigger voltage is applied to the gate 88 of the triac 84 through diode 28, Zener diode 30, capacitor 32, diode 54 and resistor 86, and thus the trigger voltage progressively increases over a number of cycles as described with reference to Figure 1.

Thus, after a predetermined period of bi-directional cathode heating current, triggering on the positive half-cycle ceases. Triggering continues on the negative half-cycles, however, and thus it is necessary for the breakdown voltage of the Zener diode 30 to be such that the current through the choke, lamp cathodes and starter circuit is limited to an acceptable level. Nevertheless the circuit does provide the advantage that the cathode and choke current in the failed lamp condition will be substantially less than the initial cathode heating current. Furthermore, as the heating current flows on both positive and negative half-cycles any effects of choke saturation may be minimised.

It will be appreciated that the various features of the separate embodiments described may be used in combinations other than those illustrated.

It will be seen from the above that the circuits described and illustrated avoid the disadvantages of the known glow switch and semi-resonant starters, and provide in particular with the embodiments of Figures 1 to 9 higher initial pre-start cathode heating currents, a suppressed initial positive lamp voltage which minimises the likelihood of cold starting effects, and low or even zero cathode current in the failed-lamp condition which means that constraints on the ballast design are much reduced.

WHAT WE CLAIM IS:

1. A discharge lamp starter circuit having two starter input terminals for connection to the cathodes of a discharge lamp for receiving a cyclically-varying voltage supplied through both the lamp cathodes and a choke ballast, the starter circuit comprising a controlled switch connected across the starter input terminals and a control circuit, including in series a capacitor and an avalanche diode having a Zener-like characteristic, coupled between a starter input terminal and the control input of the switch for rendering the switch conductive at a trigger point, during the cycle of the applied voltage, determined by the breakdown voltage of the avalanche diode and the voltage on the capacitor and means for increasing the voltage on the capacitor at each successive cycle or half cycle after switch-on of the applied voltage to raise progressively the applied voltage at which said trigger point occurs.

2. A starter circuit according to claim 1, wherein the controlled switch comprises a controlled breakdown device.

3. A starter circuit according to claim 1, wherein the controlled switch comprises a thyristor.

4. A starter circuit according to claim 1, wherein the controlled switch comprises a silicon controlled semi-conductor rectifier.

5. A starter circuit according to claim 1, wherein the controlled switch comprises a triac.

6. A starter circuit according to any preceding claim, wherein the control circuit tends to increase the instantaneous applied voltage which is required for conduction of the switch to occur, with successive cycles or half-cycles of the applied voltage after switch-on of the circuit, to a point at which, with a substantially constant cyclically-varying voltage, conduction of the switch will cease.

7. A starter circuit according to any preceding claim, including a resistor connected across the avalanche diode.

8. A starter circuit according to any preceding claim, including a resistor coupled

between the capacitor and the other starter input terminal, the junction of the capacitor and the resistor being connected to the control input of the switch.

9. A starter circuit according to claim 8, including a further diode connected between the capacitor on the one hand, and the resistor and the control input of the switch on the other.

10. A starter circuit according to any preceding claim, wherein the control circuit includes a further diode.

11. A starter circuit according to claim 10, wherein the further diode is connected to the starter input teminal, and the avalanche diode is connected to the further diode.

12. A starter circuit according to claim 11, including a second capacitor coupled between the said other starter input terminal and the junction of the avalanche diode and the further diode.

13. A starter circuit according to any preceding claim including a discharge resistor connected across the capacitor.

14. A starter circuit according to any preceding claim, wherein the means for increasing the voltage on the capacitor includes means for charging the capacitor from the supply during half-cycles of the supply when the switch is non-conductive.

15. A starter circuit according to any preceding claim, wherein the means for increasing the voltage on the capacitor includes means for charging the capacitor during half-cycles of the supply when the switch is conductive.

16. A starter circuit according to claim 15, wherein the means for charging the capacitor comprises a further capacitor which is charged through a diode to substantially the voltage across the starter input terminals.

17. A starter circuit according to claim 16, including a discharge resistor connected across the further capacitor.

18. A starter circuit according to any preceding claim wherein the means for increasing the voltage includes means for charging the capacitor at a substantially linear rate.

19. A starter circuit according to any one of claims 1 to 17, wherein the means for increasing the voltage includes means for charging the capacitor at a rate which is dependent upon the supply voltage.

20. A starter circuit according to any one of claims 1 to 17, wherein the control circuit includes means for pre-charging the capacitor to a voltage which is a predetermined amount below the supply voltage.

21. A starter circuit according to any preceding claim, including a suppression capacitor connected across the starter input terminals.

22. A starter circuit according to any preceding claim, wherein the starter input terminals are connected to the output of a rectifier.

23. A starter circuit according to any preceding claim, wherein the switch is triggered on both half-cycles of the supply voltage.

24. A starter circuit according to claim 23, wherein the increase in the applied voltage required for triggering occurs only during alternate half-cycles.

25. A starter circuit constructed substantially in accordance with any of the embodiments herein described with reference to the accompanying drawings.

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Agent for the Applicants.

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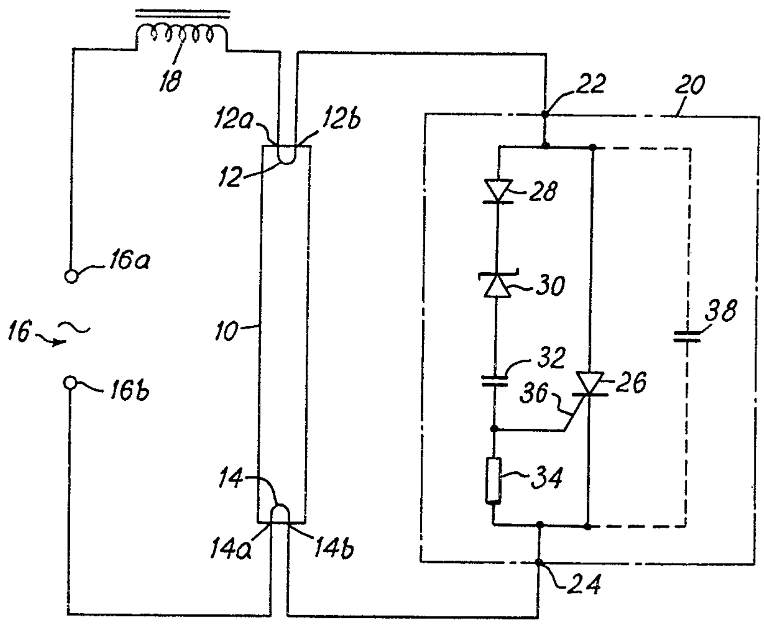
FIG. 1



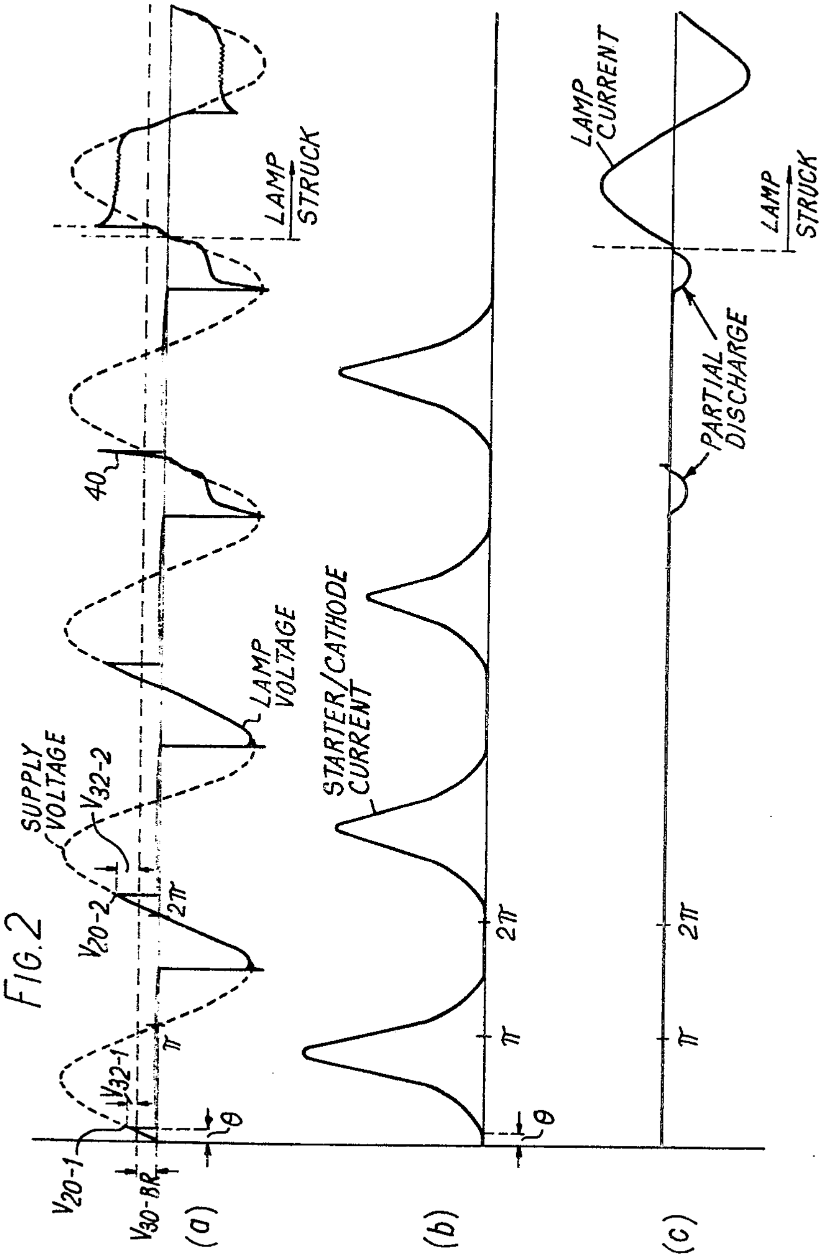

(a)
(b)
(c)
V20-1
V30-BR
V32-1
V20-2
V32-2
SUPPLY VOLTAGE
LAMP VOLTAGE
40
LAMP STRUCK
STARTER/CATHODE CURRENT
PARTIAL DISCHARGE
LAMP CURRENT
θ
π
2π

FIG. 2

1602456 COMPLETE SPECIFICATION

9 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 3

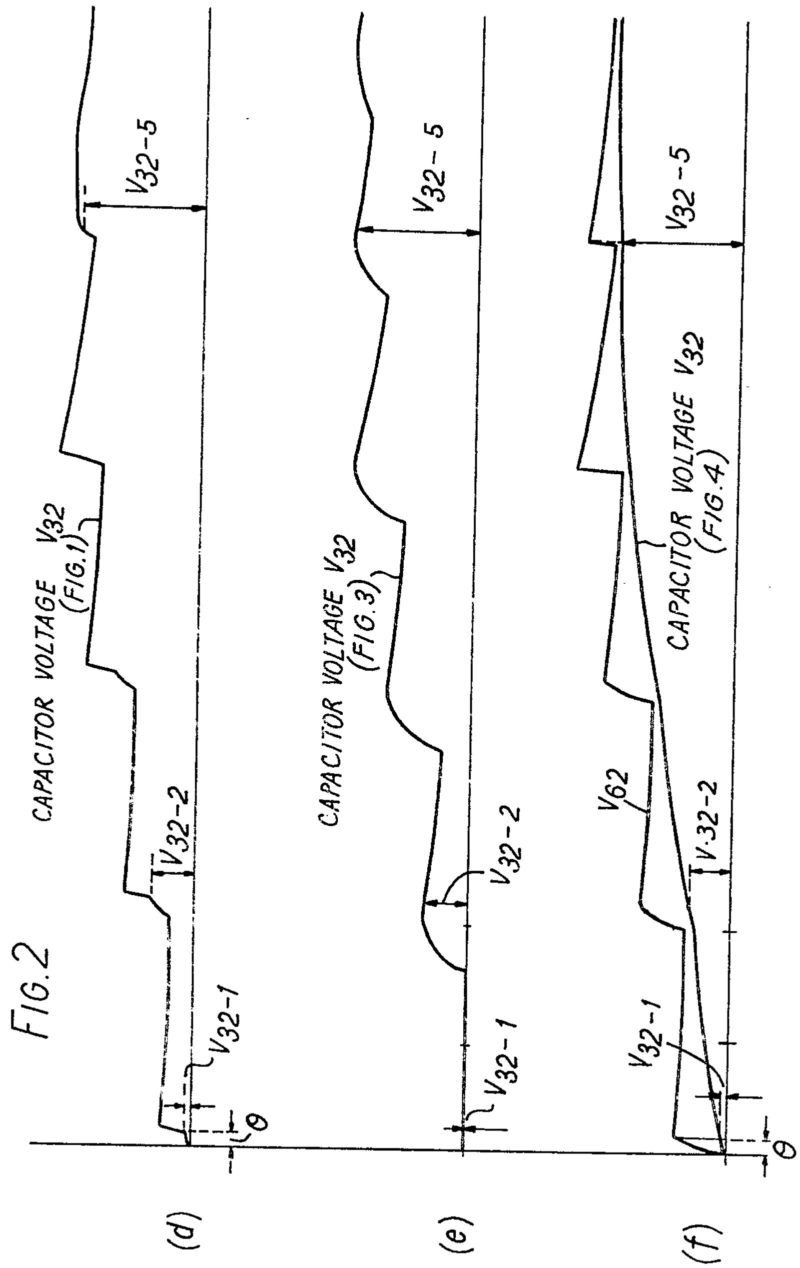
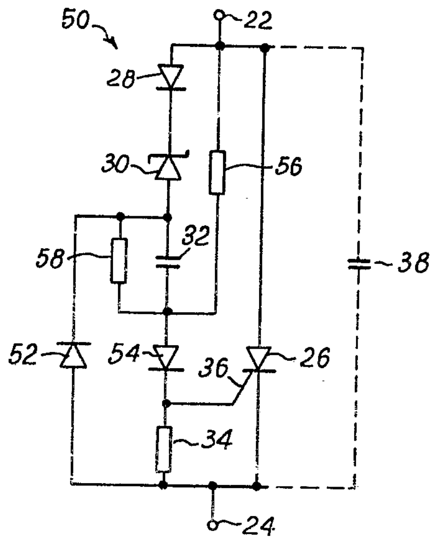


FIG.3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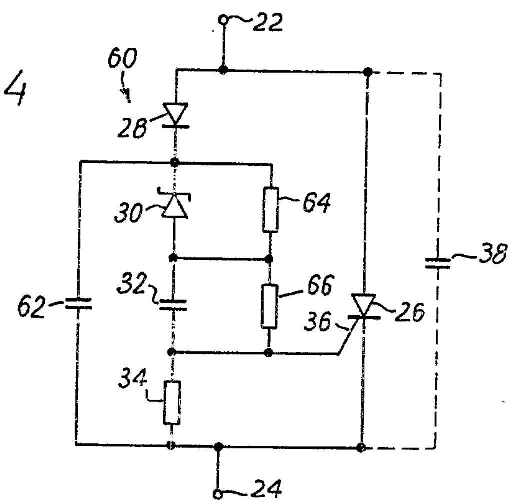
24

FIG.4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30
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62
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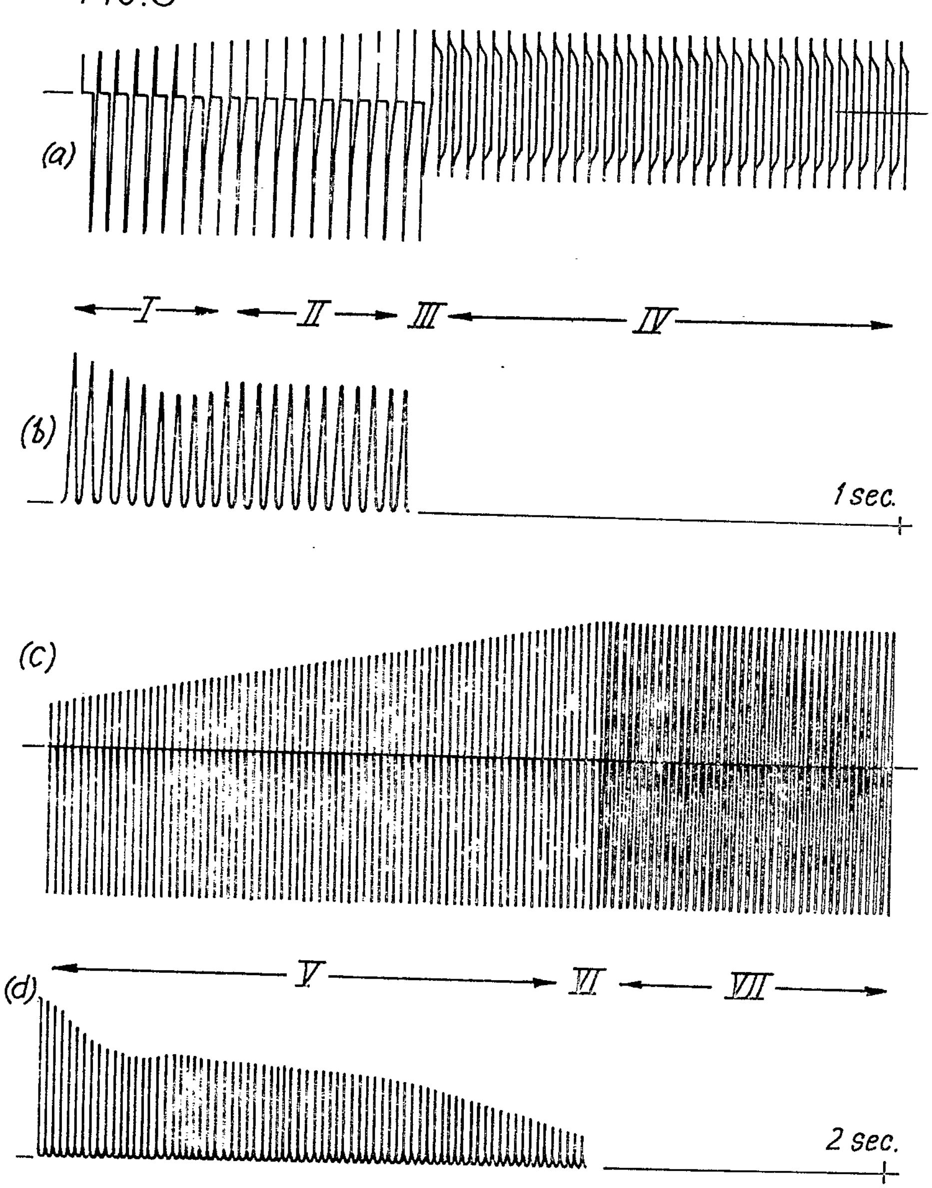
24

FIG. 5



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Sheet 6

FIG. 6

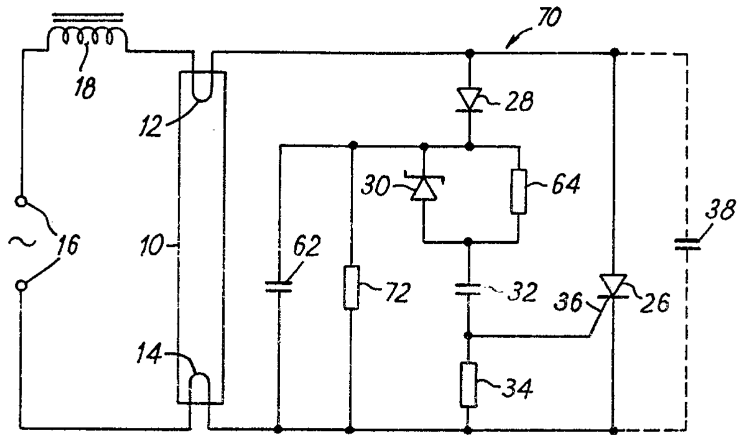
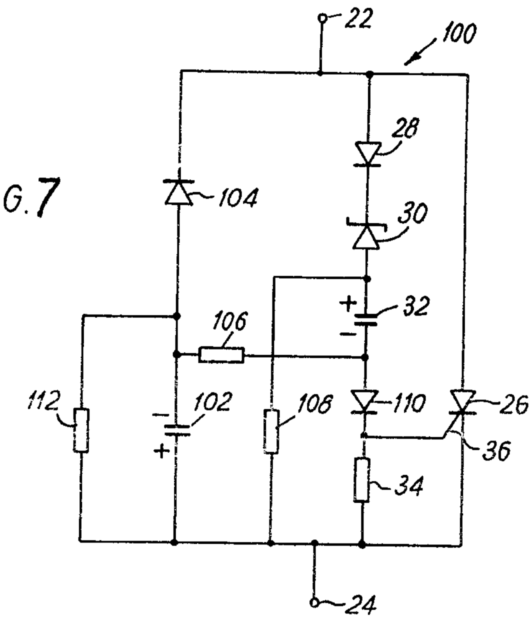


FIG. 7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−
106
112
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26
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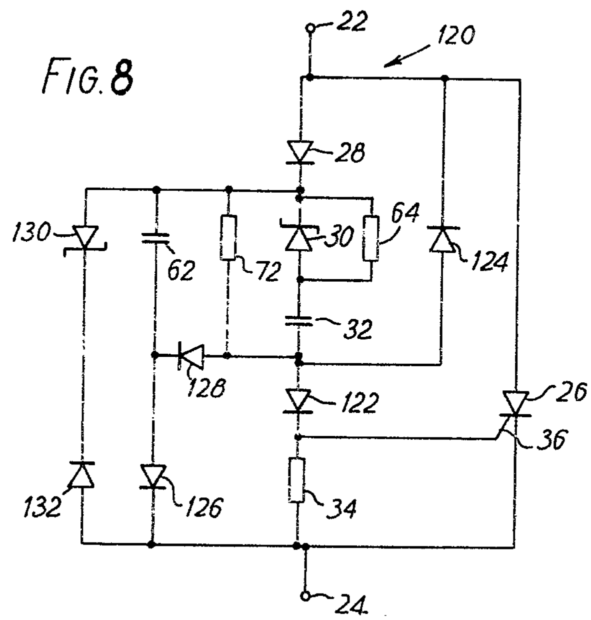
34
24

FIG. 8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72
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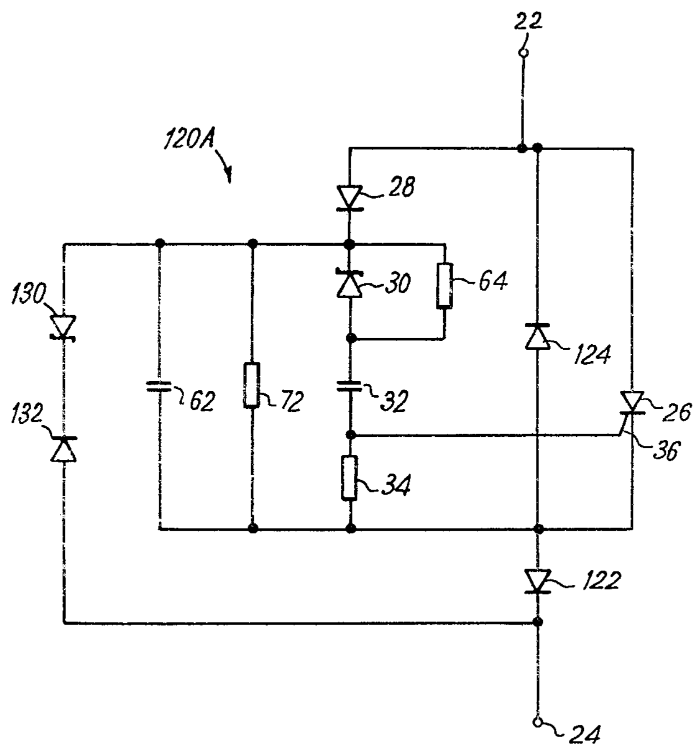
122
26
36
132
126
34
24

FIG. 9



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Sheet 9

FIG.10

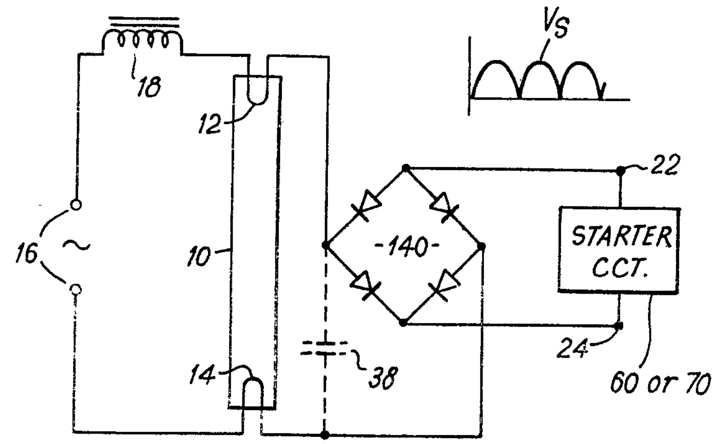

FIG.11