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Operating Circuit for an Electrodeless Low-pressure Discharge Lamp

ABSTRACT

The invention relates to an operating circuit for an electrodeless low-pressure gas discharge lamp having a switching system comprising a load circuit (CK, CR, L1, L2), a frequency generator (C0, TO, TU) and a drive circuit (Ci, CP, CS, LP, LS, TR),and which operates in a freewheeling fashion close to resonance.

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FOR A STANDARD PATENT

ORIGINAL

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Invention Title:	Operating Circuit for an Electrodeless Low-pressure Discharge Lamp

The following statement is a full description of this invention, including the best method of performing it known to me/us:-

OPERATING CIRCUIT FOR AN ELECTRODELESS LOW-PRESSURE DISCHARGE LAMP

The present invention relates to an operating circuit for a low-pressure gas discharge lamp.

Low-pressure gas discharge lamps have been widespread for decades, and there is a correspondingly large number of known operating circuits for such lamps. The invention proceeds in this case from a known operating circuit for operating a low-pressure gas discharge lamp, having a load circuit which applies radio-frequency power to the lamp, a frequency generator for operating the load circuit, and a drive circuit for driving the frequency generator.

Electrodeless low-pressure gas discharge lamps are an important and novel technical development. Here, the voltage or power required to ignite and maintain the discharge plasma is coupled into the discharge gas without electrodes fitted in the lamp bulb. This can be performed, in particular, by a closed coil core which encloses part of the lamp bulb and thus couples an induced voltage into the discharge gas. Further technical details relating to the electrodeless low-pressure gas discharge lamp follow from the Patent Application PCT/EP96/03180 of the same applicant, the disclosed content of which is expressly included in the present application.

The invention proceeds from the technical problem that the novel electrodeless low-pressure gas discharge lamps cannot be operated using known operating circuits.

In accordance with one aspect of the present invention, there is provided an operating circuit for operating a low-pressure, electrodeless, gas discharge lamp, the operating circuit comprising:

a load circuit for applying radio-frequency power to the lamp,

a frequency generator for operating the load circuit, and

a drive circuit for driving the frequency generator, the drive circuit including a transformer with a ferrite core, and being designed to operate in the linear B-H drive field or non-saturation region;

wherein switching in the frequency generator is provided in a freewheeling fashion close to resonance and contains the load circuit with the lamp and the drive circuit.

The circuit which operates in a freewheeling fashion close to a resonant frequency permits a substantially "softer" operating mode by comparison with conventional circuits, in particular ones with IC driving of a frequency generator. This means that the voltage and current-time characteristics, in particular of the drive circuit, are substantially closer to the sinusoidal shape of the fundamental mode at the operating frequency.

This "softer" mode of operation leads to substantially lower losses in the circuit. This relates, in particular, to the switching losses of the switching element or elements of the frequency generator, but also to magnetization losses in the coil cores etc. A further benefit is the low harmonic content for the electromagnetic compatibility, specifically with respect to the parasitics in a grid supply, on the one hand, and, if no screening housing is used, also with respect to the non-conductive radiation, on the other hand.

The described advantages of operating close to resonance gain in importance in view of the fact that the circuit is designed, in particular, for substantially higher frequencies concerning the ignition and continuous operation of the lamps than is known from conventional circuits (conventionally approximately 20 to 50 kHz). In the case of the inductive coupling of the radio-frequency power into the discharge, the higher frequencies produce induced voltages proportional to the respective frequencies. This is particularly important, because the omission of the electrodes also eliminates the conventional possibilities of accomplishing adequate preionization by electron emission by means of a coating of the electrodes which lowers the electron work function, or of preheating the electrodes. The preionization leads to a substantial reduction in the critical field strength for igniting a plasma.

The increased operating frequency is preferably above 70 kHz, over 200 kHz being better. A plurality of operating frequencies are involved here, because in general in the case of changes in the outer or inner parameters of the discharge in conjunction with a variable temperature, variations in the operating frequency can occur owing to differences between ignition operation and normal operation, on the one hand, and owing to frequency changes described further below, on the other hand.

Higher operating frequencies can render it necessary to use faster transistors, such as field-effect transistors, in particular MOS-FETs, instead of the conventionally used bipolar power transistors, for the switching element or elements in the frequency generator. In order to keep the transistor losses within acceptable bounds, the bipolar transistors are operated in the saturation region, the result being the charge carrier storage with a relatively long recombination phase which is characteristic of bipolar components. The recombination phase or storage time can contrast with an increase in frequency.

This disadvantage is avoided by field-effect transistors, but the latter requires a substantially higher voltage level for driving (approximately 4 V for MOS-FETs by contrast with 0.7 V for silicon bipolar transistors). Moreover, in default of detectable charge carrier storage of the unipolar transistors, this voltage level must be maintained over the entire desired turn-on time. In accordance with this development, the required gate voltage is generated by using a voltage overshoot, generated by exciting a resonant circuit close to resonance in order to drive a field-effect transistor gate. The required temporal length of the voltage, which must exceed the gate voltage, can be set by the amplitude of the resonance voltage, because at a higher amplitude the voltage oscillation, which is nearly sinusoidal, is situated for a correspondingly longer period between two zero crossings above the threshold value of the gate voltage.

A further refinement relates to the use of the transformer with the ferrite core, in the drive circuit, which, for example, can excite the resonant circuit supplying the described gate drive voltage. It has turned out to be essential in this case to operate the transformer core in the non-saturation region, in order to avoid distortions in the gate sinusoidal voltage and undesired losses. The distortions counteract the "soft", that is to say nearly sinusoidal, mode of operation of the switching system. Moreover, they can lead to disadvantageous distortions in the gate drive voltage, and this can influence the duration of the turn-on pulse. In particular, the reduction in inductance associated with the saturation can cause an undesirable "pointed" voltage waveform between the zero crossings, and this is transferred to the gate drive voltage.

Another advantage of the gate sinusoidal drive consists in that a very small gate charge, that is to say a little energy is stored in the transistor immediately before the latter is turned off, and this leads to a very fast drop in drain current and thus to very small turn-off losses.

In order to obtain a switching system which is freewheeling and close to resonance overall, the energy for the drive circuit is advantageously drawn from the load circuit. Since, by contrast with the bipolar transistors, the field-effect transistors require, rather, a voltage drive at a lower power, it is envisaged in a further development, tapping a voltage from the load circuit, for example by means of a capacitor which taps the lamp voltage. This also has the advantage of eliminating the loss problems, more critical because of the higher operating frequencies of heavily loaded transformer cores and the larger core dimensioning, necessary as a result, as in the case of conventional, saturated current transformers in the primary coil of which the entire load current flows.

With regard to the wiring up of the load circuit itself, it is provided, in particular, to select a series-parallel configuration. In accordance therewith, a series resonant circuit is combined with a branch, connected in parallel with a part of the resonant circuit, in which branch a coil is situated which applies radio-frequency power to the lamp.

Before the ignition, this parallel part is slightly damped, and the series circuit can supply the resonance voltage overshoot, which is typically pronounced for slightly damped series resonant circuits, in order to generate the required ignition voltage. This ignition voltage is tapped via the parallel part and coupled inductively into the discharge. After ignition, the series resonant circuit is strongly damped by the transformed resistance of the plasma discharge and advantageously serves to limit the current in the lamp (important because of the negative differential resistance of the low-pressure gas discharge lamps).

The current-limiting coil in the series resonant circuit, normally termed a lamp inductor, is essentially connected in parallel in terms of radio frequency with the parallel lamp coil in the operating state. Above all, when, in addition, the inductance of the current-limiting coil is smaller than that of the lamp coil, the result is a substantial reduction in the influence of fluctuations in the lamp coil inductance on the equivalent inductance of the said series-parallel circuit, and thus on the resonant frequency of the series-parallel arrangement.

This is advantageous because, for example, temperature fluctuations in the lamp coil core owing to fluctuations in outside temperature and to heating up caused by the lamp, and the like have a very strong effect on the magnetic properties (initial and amplitude permeability) and thus on the inductance of the lamp coil. The resulting frequency detuning can lead to operating problems, chiefly in the case of fixed-frequency driving. For example, it can happen that the lamp can no longer be ignited in the case of particularly low or particularly high temperatures, because the resonant frequency of the arrangement is too far removed from the control frequency of the generator. This is counteracted by the effect described of parallel connection with the current-limiting coil with a smaller inductance in the series resonant circuit. The influence of temperature fluctuations in the lamp coil core is also so decisive because, by contrast with the lamp inductor, a gapless ferrite core, that is to say a core having the smallest possible air gap (in the micrometer range), should be applied here, because of the coupling efficiency.

Moreover, or as an alternative, the total arrangement of load circuit, drive circuit and frequency generator can be designed so that a frequency shift in the load circuit into this "feedback loop" is automatically counteracted. For example, an unusually low temperature of the lamp coil core, and thus a very low inductance can lead to an increased resonant frequency of the load circuit, and thus to an increased total operating frequency of the freewheeling circuit system. The higher induced voltage associated therewith in the low-pressure gas discharge lamp leads to a power reduction characteristic of such lamps and to a correspondingly higher discharge voltage. A linear rise in the gate control voltage amplitude of the switching transistors of the power generator corresponds to a higher discharge voltage and leads to a longer turn-on time of the switching transistors. This longer turn-on time lowers the operating frequency of the power generator, and thus correspondingly increases the lamp power. The result overall is that the entire system acts in a self-stabilizing fashion which is characteristic of the freewheeling resonance drive.

The advantages reside not only in the greater reliability and the lower sensitivity of the circuit to parameter fluctuations. In addition, it is also possible to permit larger component tolerances, and this leads to advantages in cost, in particular for the core of the lamp coil.

The invention is explained below with the aid of an exemplary embodiment.

In the drawings:

Figure 1 shows a circuit diagram of the exemplary embodiment, and

Figure 2 shows a diagrammatic timing diagram for a better understanding of the mode of operation of the exemplary embodiment.

Figure 1 shows an operating circuit as part of an electronic ballast for an electrodeless low-pressure gas discharge lamp. Connected on the left at the input to the circuit is a rectified supply voltage U_0, which charges a storage electrolyte capacitor C0. The latter feeds a "Class D" half-bridge frequency generator having two MOS-FET switching elements TO and TU and the centre tap MP. The latter drives a series-parallel load circuit having a DC disconnecting or RF coupling capacitor CK connected between the centre tap and the negative supply branch (earth), a current-limiting and series resonant circuit coil (lamp inductor) L2, a series circuit resonance capacitor CR and, connected in parallel therewith, a lamp coil L1 with a coupling core and, as power output of the circuit, an electrodeless low-pressure gas discharge lamp E connected to the coupling core, specifically in the sequence enumerated and shown.

The lamp coil or resonance capacitor voltage U_1 (negative supply branch to earth) is tapped by a tapping capacitor Ci of a drive circuit for the "Class D" half-bridge frequency generator, and fed to a transformer, operating in the linear B-H field, that is to say far from the saturation region, having a ferrite core TR, primary winding LP and two secondary windings LS. The black points in the circuit diagram correspond to the respective start of the windings of the transformer TR. It can be seen that the secondary windings are connected in opposition. The transformer excites two resonant circuits which in each case comprise the winding LS and the total gate capacitance CG of the MOS-FET TO or TU. The gate capacitance is transistor-specific, comes from technical and physical effects, and essentially contains the static input capacitance Ciss, as well as the dynamically variable Miller capacitance between gate and drain.

A tuning capacitor CP is provided in parallel with the winding LP in order to tune the tapping branch of the drive circuit with the capacitor Ci and the winding LP; the resonant circuits likewise contain tuning capacitors CS in parallel with the windings LS for the purpose of MOS-FET gate drive. These tuning capacitors are smaller than the gate capacitance, and merely serve the purpose of fine tuning of the gate resonant frequency, these capacitors being definitively prescribed by the other capacitances and inductances described.

The resistors RG, the depletion-mode transistors T1 and the diodes D3 in the drawing serve to improve the switching performance, particularly the switching-off losses. The protective Zehner [sic] diodes Z connected in an anti-series fashion limit the gate voltage of the MOS-FETs during ignition of the lamp. The diagram also contains a conventional start circuit for a frequency generator in the form of the saw-tooth voltage generator which is formed from the components R1, C1, D2 and D1 (DIAC) and is turned off at the operating frequency by the diode D2 after the start-up. The resistor RS serves to prescribe a defined potential of the centre tap MP (at positive supply potential) before the saw-tooth voltage generator described starts the power oscillator.

The capacitors CT are known as "trapezium capacitors" and limit the steepness of the sudden change in potential of the centre tap MP in the event of a change in the switching states of the MOS-FETs TO and TU.

The correct tuning of the resonant frequencies, and thus of the operating frequency, is important for designing the circuit. In the load circuit, the capacitors CK and CR and the inductors L2 and L1 determine an undamped resonant frequency f_R, whereas the capacitors CP, Ci and CS and the dynamic gate capacitors CG (not shown) and the inductors LP and LS in the drive circuit fix the total resonant frequency f_D. The operating frequency f_0 (with damping by the lamp discharge, and equally without such discharge) is formed during operation as an intermediate value of the frequencies f_D and f_R by the coupling of the oscillatory systems, in a fashion shifted by damping. Since the operation of the circuit and the lamp requires the lamp to be operated as an inductive load, that is to say in a fashion tracking the current, the frequency f_D is selected to be higher than the frequency f_R so that the operating frequencies f_0 are in any case above the resonant frequency of the load circuit. This applies both when the load circuit is unloaded (before ignition) and equally when it is loaded.

In order to achieve a total oscillation of the switching system which is as near as possible to sinusoidal ("soft") and permits an optimum efficiency far above 95%, the frequencies f_D, f_0 and f_R are in each case to differ by a few per cent. Too small a difference, however, entails the risk of capacitive operation of the half-bridge, in particular during the start-up of the power oscillator, and this is not in fact desired.

Depending on the target operating frequency, the annular core (toroidal core) of the transformer TR has to be designed with regard to the cross-sectional area so that it can operate in the non-saturation region, and a core loss limit of approximately 0.3 W/cm^3 is as far as possible not exceeded.

The series-parallel configuration (arrangement) of the load circuit essentially has the following properties: before ignition, the series-parallel configuration is essentially damped only by the core losses of the lamp coil L1, with the result that the resonant circuit, subjected to a low load, supplies a high voltage which is close to resonance and excessive for ignition. In this case, the magnetic core losses in the lamp coil L1, which increase approximately at the power of 2.5 of the voltage, have a fundamentally limiting effect. The generator behaves as a controlled voltage source. After exceeding the ignition voltage of the lamp, the parallel part of the load circuit (with L1) is loaded with the effective resistance of the plasma discharge, transformed by the windings of L1 ($R1 = N^2 \cdot RE$), the operating frequency is increased, and the inductor L2 acts as a current-limiting lamp inductor, so that the generator, in turn, behaves as a controlled current source. In this case, stable operation presupposes that the total AC resistance of the generator current source (determined by

L2) is always larger than the negative differential resistance of the lamp characteristic.

Figure 2 shows diagrammatic curves of the time characteristics of the voltage U_{MP} at the centre tap of the frequency generator, of the load circuit current I_{L2} and of the gate voltage U_{Gate} of the lower (n-channel) MOS-FET TU. The potential of the centre tap MP is alternately at that of the positive and that of the negative supply branch. In this case, the trapezium capacitors CT connected in parallel with the two MOS-FETs are decisive in producing specific transition times t_T. As is known, these are provided, on the one hand, to improve the electromagnetic compatibility and, on the other hand, to minimize the switching losses: a drain-source voltage which rises too quickly would overlap too strongly with the drain current, which does not drops arbitrarily quickly ("crossover"), resulting in a turn-off power loss. Both functions of the trapezium capacitors, which can also be replaced by other circuit variants which operate analogously, are very important in the case of the increased operating frequencies of the circuit according to the invention.

The conduction state of a MOS-FET, which contains an inherent body diode, comprises, on the one hand, the phase which can be recognized in the lowest curve, in which the gate voltage is below the threshold voltage U_{THR} of the MOS-FET and, on the other hand, the phase above the threshold voltage U_{THR}, in which the transistor is turned on. In this time domain, the load circuit current I_{L2} flows in a fashion rising monotonically (with a time constant given by the load circuit impedances). The resonant filter effect of the arrangement, however, produces so strong a relative damping of the harmonics contained therein that the sinusoidal current fundamental wave illustrated in Figure 2 essentially prevails.

The current flow through the MOS-FETs is produced before the phase just described, that is to say before the threshold voltage U_{thr} [sic] is reached by counterflowing current through the so-called "body diode" of the MOS-FET. This produces the current illustrated in the middle curve, which is advanced in time and counterflowing and which is denoted by I_{DU} and I_{DO}, respectively, for the lower and upper transistors. The actual transistor current with the channel opened is denoted by I_{TU} and I_{TO}, respectively.

During the changeover phases t_T, the "missing piece" of the current, which is nearly sinusoidal overall, flows in the trapezium capacitors and the output capacitances Coss of the transistors.

It is essential in this case for the ability of the circuit to function that the channel of the transistors is conducting, that is to say the threshold voltage U_{thr} [sic] is reached, before the load current I_{L2} changes sign, because the body diode would block the current of reverse sign after the zero crossing.

When well designed, the circuit is suitable for outside temperatures of -35°C to +50°C and component temperatures of between -35°C and +125°C, can be operated with rectified supply voltages of between 50 and 450 V, and can be designed for powers of between 20 and 1000 W. The operating frequencies can be between 100 kHz and 3 MHz. The values specified correspond to the preliminary experimental results and are not to be understood as in any way restrictive.

In the example illustrated, only a ferrite coupler (coil toroidal core) is indicated between a lamp coil L_1 and a lamp E. Ignition problems can occur at very high lamp powers (500 - 1000 W), and uniformity problems can arise in the case of discharge geometries which are large or otherwise problematic. In such cases, a plurality of ferrite couplers, that is to say a plurality of lamp coils, can be sensible. Of course, it is also possible to conceive of a plurality of lamps which are fed from one power oscillator.

In the case of a plurality of lamp coils and ferrite couplers, it is possible in principle to have a series circuit or a parallel circuit. However, the parallel circuit is preferred, particularly in the case of high powers. The known rules of calculation for inductances, currents and voltages apply. The coupler inductances should be as equal as possible.

It is also important to have as high as possible an inductance of the lamp coil L1, specifically in order to reduce the magnetizing current. It is necessary for this purpose to use a ferrite material with a high permeability and slight variations both in the initial permeability and in the amplitude permeability, and to apply it with a minimum air gap and a high permeance factor. (It is chiefly the temperature dependencies of the permeability which can cause the load current detuning described at the beginning.)

The reduction in the magnetizing current of the ferrite coupler L1 has a very advantageous effect on the phase angle ϕ between the coupler voltage U_1 and the coupler current I_1, as illustrated in Figure 1. In the case of a small phase angle ϕ, cos ϕ is large and the effective power $P_1 = U_1 I_1 \cos \phi$, which is coupled into the discharge, is high. It is to be seen in this case that the current I_1 can be reduced for a specific power P_1 if ϕ is from 10 to 15°, and consequently cos ϕ is greater than 0.95. The smaller current I_1 produces a smaller load current I_{L2}; smaller currents produced thereby in the entire power oscillator produce smaller losses and a higher efficiency of the entire system.

The magnetic material of the coupler should be selected such that no specific losses of more than 60 mW/cm³ occur in the target frequency range at the core temperatures to be expected (approximately 100 - 120°C). A closed magnetic circuit of high inductance but low leakage inductance benefits the radio interference suppression and the reduction in the apparent power of the system.

The result of the said specific ferrite losses, a suitable selection of the coupler coil and the output values U_1, I_1, and cos ϕ is a very high energy transfer efficiency of 98 to 99%, that is to say the losses in the ferrite coupler amount to only 1 to 2% of the total transmitted power.

The claims defining the invention are as follows:

1. An operating circuit for operating a low-pressure, electrodeless, gas discharge lamp, the operating circuit comprising:

a load circuit for applying radio-frequency power to the lamp,

a frequency generator for operating the load circuit, and

a drive circuit for driving the frequency generator, the drive circuit including a transformer with a ferrite core, and being designed to operate in the linear B-H drive field or non-saturation region;

wherein switching in the frequency generator is provided in a freewheeling fashion close to a resonance formed in the load circuit and the drive circuit.

2. An operating circuit as claimed in Claim 1, further incorporating an operating frequency above 70 kHz.

3. An operating circuit as claimed in Claim 1 or 2, wherein the drive circuit is designed to generate a voltage required to drive at least one gate of a field-effect transistor of the frequency generator using resonance voltage overshoot.

4. An operating circuit as claimed in Claim 3, wherein the drive circuit further includes a resonant circuit connected to the transformer, to effect the resonance voltage overshoot.

5. An operating circuit as claimed in any one of the preceding claims, wherein the drive circuit further includes a device which taps a voltage associated with the load circuit and which provides for the drive circuit to be driven by voltage.

6. An operating circuit as claimed in any one of the preceding claims, wherein the load circuit includes:

a series resonant circuit including a resonance capacitor,

a coil for application to the lamp, the coil being connected in parallel with the resonance capacitor of the series resonant circuit to form a parallel resonant circuit,

wherein the coil belongs to each of the series and parallel resonant circuits.

7. An operating circuit as claimed in Claim 6, wherein the series resonant circuit includes a current-limiting coil which in the operating state essentially has the effect of being connected in parallel in terms of radio frequency with the coil for application to the lamp, the current limiting coil having an inductance smaller than the inductance of the coil for application to the lamp.

8. An operating circuit as claimed in Claim 1, wherein the frequency generator is designed as a half-bridge, full-bridge or single-transistor frequency generator.

9. An operating circuit for operating a low pressure gas discharge lamp, said circuit being substantially as herein described with reference to the accompanying drawings.

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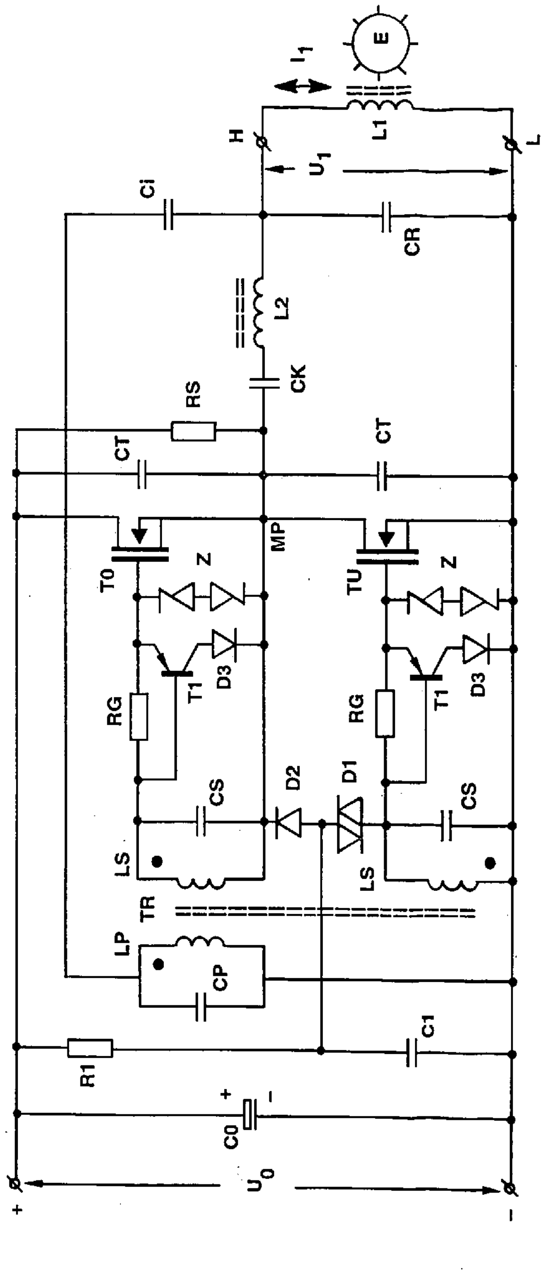
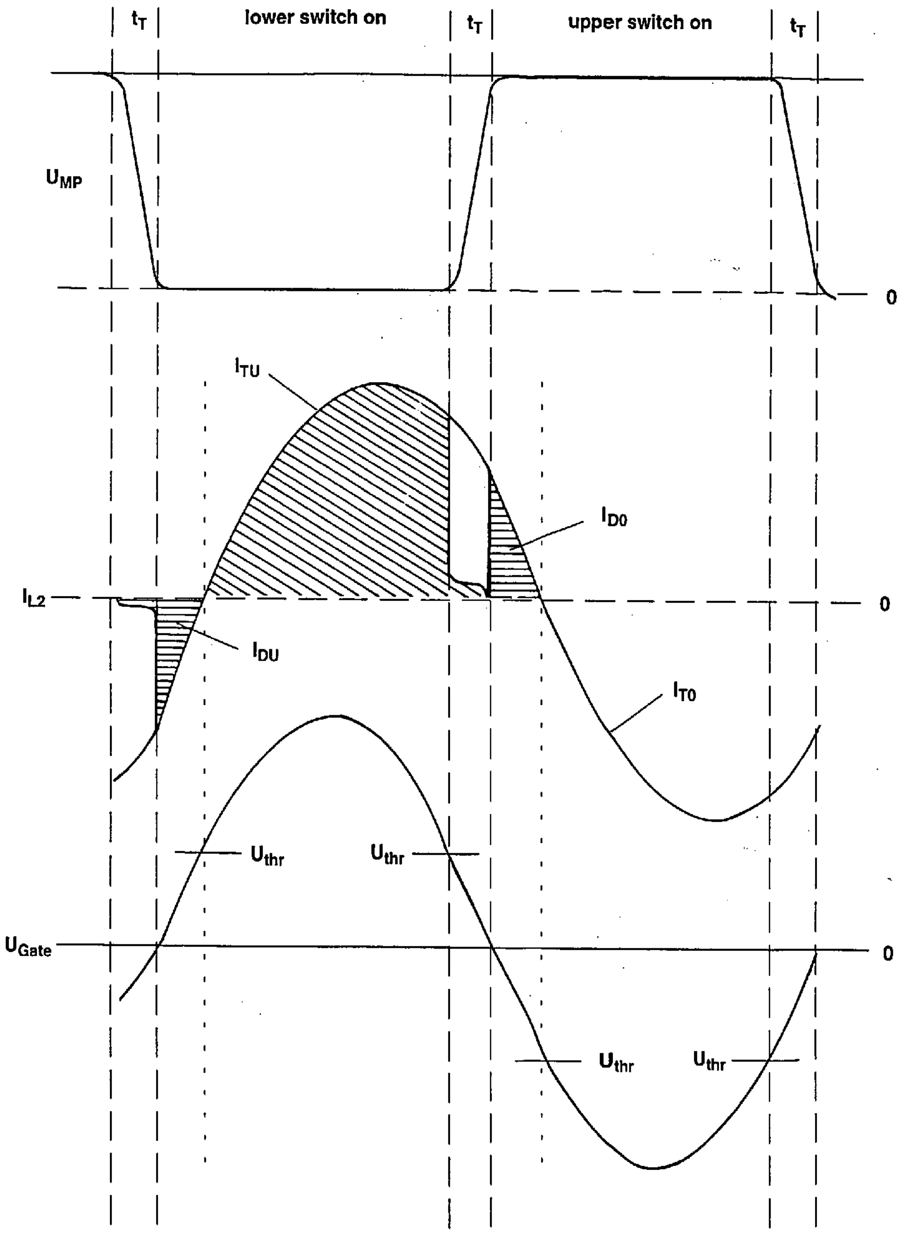


FIG. 1



t_T
lower switch on
t_T
upper switch on
t_T
U_{MP}
0
I_{TU}
I_{D0}
I_{L2}
0
I_{DU}
I_{T0}
U_{thr}
U_{thr}
U_{Gate}
0
U_{thr}
U_{thr}

FIG. 2