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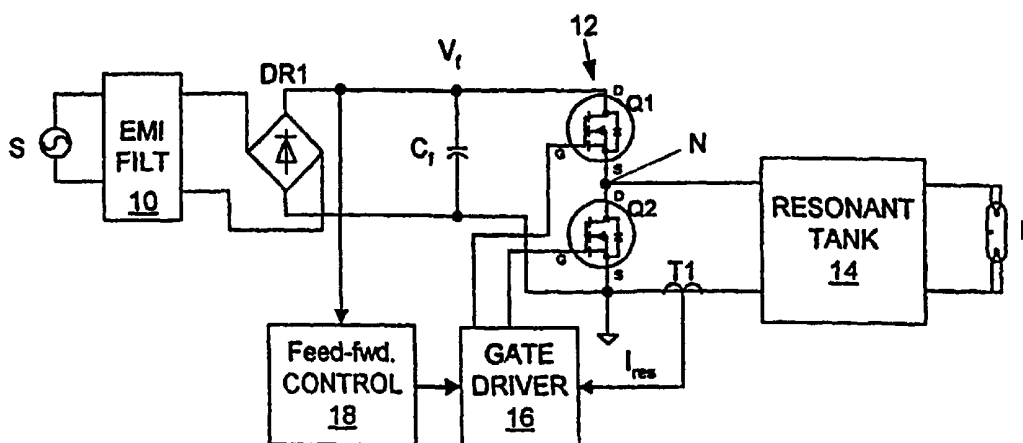
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(54) Title: ELECTRONIC BALLAST WITH FEED-FORWARD CONTROL



(57) Abstract: An electronic ballast is provided which is capable of compactly powering a discharge lamp from a source of rectified, but unregulated, power having a varying DC voltage. The ballast includes a self-oscillating converter powered by the DC voltage for producing pulses at a nominal operating frequency which is determined by a resonant tank. The resonant tank converts the pulses to a sinusoidal current for powering the discharge lamp and includes an inductive impedance in series with the lamp for providing a voltage drop which varies with the operating frequency. A feed-forward control circuit is coupled to the converter for varying the operating frequency directly with variations in the DC source voltage. The voltage drop across the inductive impedance is substantially proportional to the magnitude of the DC source voltage. This enables regulation of the voltage supplied to the discharge lamp by the ballast without sensing the lamp voltage itself.



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Electronic ballast with feed-forward control

This invention relates to electronic ballasts for discharge lamps such as fluorescent lamps and, in particular, to such ballasts which are useful in applications where compact size is desirable.

There is an ever-increasing demand for smaller electronic ballasts. In order to achieve this goal, a variety of problems must be overcome, for example:

- If the operating frequency of ballast circuitry is increased sufficiently to achieve a substantial reduction in the sizes of magnetic and filtering elements, power losses tend to increase.
- Decreasing the size of filtering components tends to have a negative impact on circuit performance.

It is an object of the invention to provide an electronic ballast for discharge lamps which can be made compact without substantially increasing cost or adversely affecting performance. In accordance with the invention, an electronic ballast includes a source of power having a varying DC voltage, a self-oscillating converter powered by the DC voltage for producing pulses at a controlled frequency, a resonant tank for converting the pulses to an alternating current for powering a discharge lamp, and a feed-forward control circuit for effecting variation of the frequency in response to variations of the DC voltage, the resonant tank having a voltage drop which varies directly with said frequency.

Such a ballast does not require a regulated DC power supply and will operate effectively with a filter capacitor that is much reduced in size from capacitors that are typically used to reduce ripple of the rectified DC power.

A self-oscillating resonant converter circuit for operating discharge lamps, which does not require a regulated DC power supply, is described U.S. Patent 6,072,710. However, that circuit utilizes a feed-back approach. In accordance with the invention, a feed-forward approach is utilized which is inherently more stable and has a greater range of correction for variations of the DC source voltage.

The invention will be explained in more detail making use of a drawing. In the drawing

Figure 1 is a combination block and schematic diagram of a system including a ballast in accordance with an embodiment of the invention.

5 Figure 2 is a detailed circuit diagram of a system including an exemplary ballast in accordance with the invention.

Figures 3A and 3B are waveform diagrams illustrating operation of the exemplary ballast of Figure 2.

10 The exemplary system shown in Figure 1 includes a source of AC power S, a discharge lamp L (e.g. a fluorescent lamp) and a ballast for controllably passing power to the lamp from the source S. The ballast includes an EMI filter 10, a bridge rectifier DR1, a line-filter capacitor C_f , a half-bridge converter 12, a resonant tank 14, a current transformer T1, a gate driver circuit 16 and a feed-forward control circuit 18.

15 The EMI filter 10 serves to isolate the AC power source S from interference signals generated within the ballast (e.g. high-frequency switching signals generated by the converter 12).

The bridge rectifier DR1 and the filter capacitor C_f convert the AC power from the source S to rectified, but unregulated, DC power having a varying DC voltage V_f .

20 Together, this rectifier and capacitor form a DC power source that is conventional except for its simplicity and the relatively small size of the filter capacitor that is possible because of the ripple compensation provided by the feed-forward control. Alternatively, in a ballast for powering a lamp requiring a higher DC voltage than can be provided by a simple bridge rectifier, a relatively simple voltage-step-up circuit can be substituted.

25 The half-bridge converter 12 (including serially-connected transistors Q1 and Q2) operates together with the resonant tank 14 to provide power to the lamp L. The converter switches at a nominal high frequency (e.g. 120 kHz) relative to the frequency (e.g. 60 Hz) of the AC source S and alternately connects the resonant tank 14 (via a node N) to the varying DC voltage on the capacitor C_f (through transistor Q1) and then to ground (through
30 transistor Q2).

The resonant tank 14 converts the power provided through transistor Q1 (in the form of DC pulses) to a sinusoidal AC waveform for powering the lamp L. The tank 14 operates at a resonant frequency which is determined primarily by inductance and capacitance in the tank itself and by the impedance of the lamp L.

The current transformer T1 senses the current flowing through the resonant tank and supplies a signal I_{res} representative of this current to a first input of the gate driver circuit 16. In response to this signal, the gate driver applies signals to the gates of the transistors Q1 and Q2 to effect switching of these transistors at the same frequency as that of the sinusoidal AC waveform generated within the resonant tank 14.

Collectively, the converter 12, resonant tank 14, current transformer T1 and gate driver circuit 16, operated as described thus far, form a self-oscillating resonant converter. A known converter of this type is described in greater detail in U.S. Patent 6,072,710. Contrary to the feed-back control described in that patent, however, control circuit 18 applies a feed-forward signal to a second input of the gate driver 16 to effect an offset of the driving signals applied to the gates, thereby compensating for the variations of the rectified DC supply voltage V_f on the line-filter capacitor C_f . Such feed-forward control enables compensation for substantially greater variations in the DC supply voltage, without destabilizing the self-oscillating operation of the resonant converter.

In the exemplary circuit embodiment shown in Figure 2, corresponding parts are indicated by the same reference indicia as in Figure 1. In addition to the circuit elements shown in Figure 1, a current-limiting resistor R1 is inserted in series with the AC power source S to limit inrush current through the bridge rectifier DR1 when power is initially applied.

The EMI filter is formed by a capacitor C2 for bypassing high-frequency interference signals (generated by the high-frequency switching of the half-bridge converter) to ground and by an inductor L2 for blocking passage of the high-frequency interference signals.

The line filter-capacitor C_f reduces the magnitude of the ripple of the rectified AC power supplied to the converter 12. Because of the compensation provided by the feed-forward control, the size of this capacitor can be substantially reduced. For example, a circuit having the component values specified in Figure 2 and having a 3.3 μf capacitor C_f was used to power a 28 Watt T8 fluorescent lamp at a nominal voltage of 142 Volts RMS. Without the feed-forward control, a 22 μf capacitor C_f would be required to power the same lamp or the crest factor would substantially increase.

The half-bridge converter 12 is substantially identical to that shown in Figure 1, but further includes snubber capacitors C3 and C4 connected in parallel with the respective transistors Q1 and Q2. These capacitors serve to reduce energy losses during turn off of the transistors Q1 and Q2, as is well known in the art.

The resonant tank is formed by an inductor L1, by a capacitor C6 in parallel with the lamp L and by the capacitance of the lamp itself. The capacitor C5 has an impedance which is very small compared to that of the lamp and functions primarily as a DC blocking impedance, as is well known in the art.

5 The current transformer includes windings T1-1, T1-2, T1-3 and T1-4. Winding T1-1 acts as a primary winding for sensing the current I_{res} flowing through the resonant tank. Windings T1-2 and T1-3, together with parallel pairs of serially-connected zener diodes Dz1-Dz2 and Dz3-Dz4, respectively, form the gate driver circuit 16. These zener diode pairs serve to convert current signals I_Z produced by the windings T1-2 and T1-3
10 to voltage signals V_Z for driving the transistors Q1 and Q2, respectively. These are composite signals of opposite polarity, each representing the sensed instantaneous tank current $I_S = [N1/N] \cdot I_{res}$, the transformer magnetizing current I_{mag} , and a control current I_C produced by the feed-forward control circuit 18.

The magnitude of the current I_Z produced by each of the windings T1-2 and
15 T1-3 (and passing through the respective zener diode pairs) is equal to one-half of the difference between the sensed tank current I_S and the sum of the magnetizing current I_{mag} plus the control current I_C , that is $I_Z = \frac{1}{2} \cdot [I_S - (I_{mag} + I_C)]$. Depending on the instantaneous polarity of I_Z in each of the windings T1-2 and T1-3, one of the transistors Q1/Q2 is ON and the other is OFF. For the polarities of I_Z shown in Figure 2, Q1 is ON and Q2 is OFF. For
20 the circuit shown in Fig. 2, $I_S(t) = [N1/N] \cdot I_{res}(t)$, $I_{mag}(t) = [V_Z/L_M] \cdot t$, and $I_C(t)$ is determined by the feed-forward control circuit, where:

- $N1, N2, N3, N4$ are number of turns of the windings T1-1, T1-2, T1-3, and T1-4, respectively
- $N = N2 = N3 = N4$; and
- 25 • L_M is the magnetizing inductance of T1.

The feed-forward control circuit 18 includes complementary first and second circuits for driving the winding T1-4. The first winding-driver circuit includes an NPN transistor Q3, a resistor R3 connected in series with the collector, a diode D3 connected in series with the emitter, and the series combination of a diode D1 and a resistor R5 connected
30 in series between the base of Q3 and a node M. The second winding driver circuit includes a PNP transistor Q4, a resistor R4 connected in series with the collector, a diode D4 connected in series with the emitter, and the series combination of a diode D2 and a resistor R6 connected in series between the base of Q3 and the node M.

Control circuit 18 further includes a bandpass filter which is formed by the serially-connected combination of a resistor R7 and a capacitor C7 (connected between nodes N and M) and by the parallel-connected combination of a capacitor C8 and resistor R8 (connected between node M and ground). This bandpass filter serves to convert a square-wave signal produced at node N (and having a voltage alternating between approximately V_f and ground) to a triangular-wave signal which is produced at node M. This triangular-wave signal has an amplitude proportional to V_f and varies substantially symmetrically above and below ground potential. The first and second winding-driver circuits operate to produce the control current I_C in the winding T1-4, which is an alternating triangular-wave current having an instantaneous polarity determined by the polarity of the voltage at the node M.

Figures 3A and 3B illustrate signals produced, during operation of the exemplary ballast shown in Figure 2, for two different values of V_f . In each of these figures:

- the square-wave signal represents the voltage at node N (which is substantially equal to the voltage V_f when the transistor Q1 is conducting);
- the triangular-wave signal represents the sum of the magnetizing current I_{mag} and the control current I_C ; and
- the sinusoidal-wave signal represents the current I_{res} passing through the winding T1-1.

In operation, the feed-forward control circuit 18 cooperates with the gate-driver circuit 16 to vary the switching frequency of the converter 12 in response to variations of the DC voltage V_f . This is done by producing a contributory drive current through the winding T1-4 which varies directly with the magnitude of the triangular waveform signal at node M. Note that the converter transistors Q1 and Q2 change state whenever the sum of the magnetizing current I_{mag} and the control current I_C is equal to the sensed resonant inductor current I_s . The contributory drive current through winding T1-4 tends to increase the rate at which the magnetizing current reaches the value of the resonant inductor current. The operating frequency of the converter (and thus of the current I_{res} through the resonant tank) varies directly with the amount of the contributory drive current through the winding T1-4. As is well known in the art, the voltage drop across the resonant inductor L1 varies directly with frequency. Consequently, as the voltage V_f supplied to the tank 14 by the converter 12 varies, the resonant inductor regulates the voltage supplied to the lamp L by dropping more voltage for higher values of V_f and by dropping less voltage for lower values of V_f .

By comparison of Figures 3A and 3B, operation of the ballast of Figure 2 at exemplary higher and lower values, respectively, of the DC voltage V_f can be seen. At a higher value of V_f (Refer to Fig. 3A.) the complementary transistors Q3 and Q4 supply a

higher value of triangular drive current to the winding T1-4 resulting in a current $I_C^+ + I_{mag}^+$ which rapidly reaches the magnitude of the sensed resonant inductor current $I_S^+ = [N1/N] \cdot I_{res}^+$. This causes a higher converter frequency f^+ and a higher voltage drop across the resonant inductor L1. At a lower value of V_f^- (Refer to Fig. 3B.) the complementary
5 transistors Q3 and Q4 supply a lower value of triangular drive current to the winding T1-4 resulting in a current $I_C^- + I_{mag}^-$ which less rapidly reaches the magnitude of the sensed resonant inductor current $I_S^- = [N1/N] \cdot I_{res}^-$. This causes a lower converter frequency f^- and a lower voltage drop across the resonant inductor L1.

Note that Figure 2 represents only one exemplary embodiment of specific
10 circuitry that may be utilized to implement an electronic ballast in accordance with the invention. For example, compactness of the ballast might be further improved by forming the resonant tank with an integral device rather than discrete circuit components. One particularly interesting device is a multi-layered piezoelectric transformer, such as that described in U.S. Patent 58344882. A fluorescent lamp ballast utilizing such a piezoelectric
15 transformer is described in Ray L. Lin et al., Inductor-less Piezoelectric Transformer Ballast for Linear Fluorescent Lamps, 2000 CPES Power Electronics Seminar Proceedings, 17-19 September 2000.

CLAIMS:

1. An electronic ballast comprising a source of power having a varying DC (V_f) voltage, a self-oscillating converter (12) powered by the DC voltage for producing pulses at a controlled frequency, a resonant tank (14) for converting the pulses to an alternating current for powering a discharge lamp (L), and a feed-forward control circuit (18) for effecting
5 variation of the frequency in response to variations of the DC voltage, the resonant tank having a voltage drop which varies directly with said frequency.
2. An electronic ballast as in claim 1 in which the self-oscillating converter (12) including alternately-conducting first (Q1) and second (Q2) switching devices and in which
10 the feed-forward control circuit (18) is coupled to the switching devices for effecting variation of the switching rate of the switching devices directly with variations of the DC voltage, the resonant tank including an inductive impedance (L1) having a voltage drop which varies directly with said frequency.
- 15 3. An electronic ballast as claimed in claim 1 or 2 in which the resonant tank is coupled to the converter to control said operating frequency, said resonant tank including an inductive impedance (L1) having a voltage drop which varies directly with variations in said operating frequency.
- 20 4. A ballast as in claim 3, including driver circuitry (16) coupled to the converter for controlling the converter operating frequency in response to:
 - a. a first signal from the resonant tank representative of the alternating current;
and
 - b. a second signal from the feed-forward control representative of the varying
25 DC voltage.
5. A ballast as in claim 4 where:
 - a. the self-oscillating converter includes alternately-conducting first (Q1) and second (Q2) switching devices having respective first and second control inputs;

6. The driver circuitry includes a first transformer winding (N2) coupled to the first control input for applying a composite signal representative of the alternating current and of the varying DC voltage and a second transformer winding (N3) coupled to the second control input for applying a corresponding composite signal of opposite polarity.

5

7. A ballast as in claim 1 in which the resonant tank comprises a piezoelectric transformer.

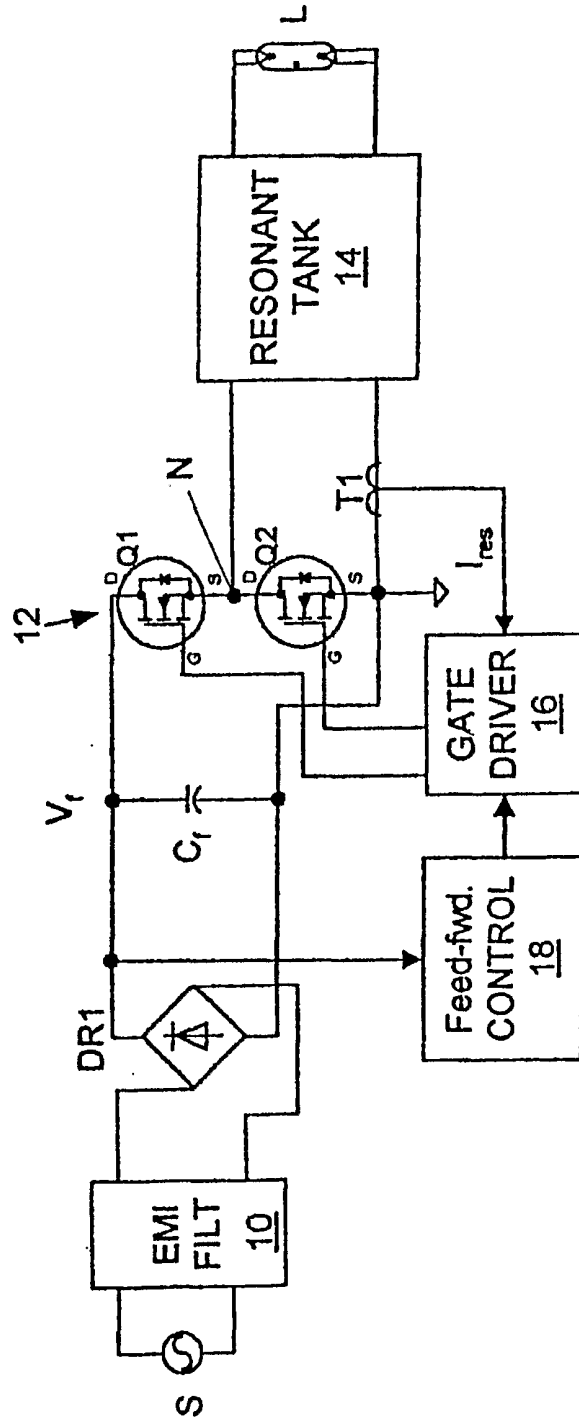


FIG. 1

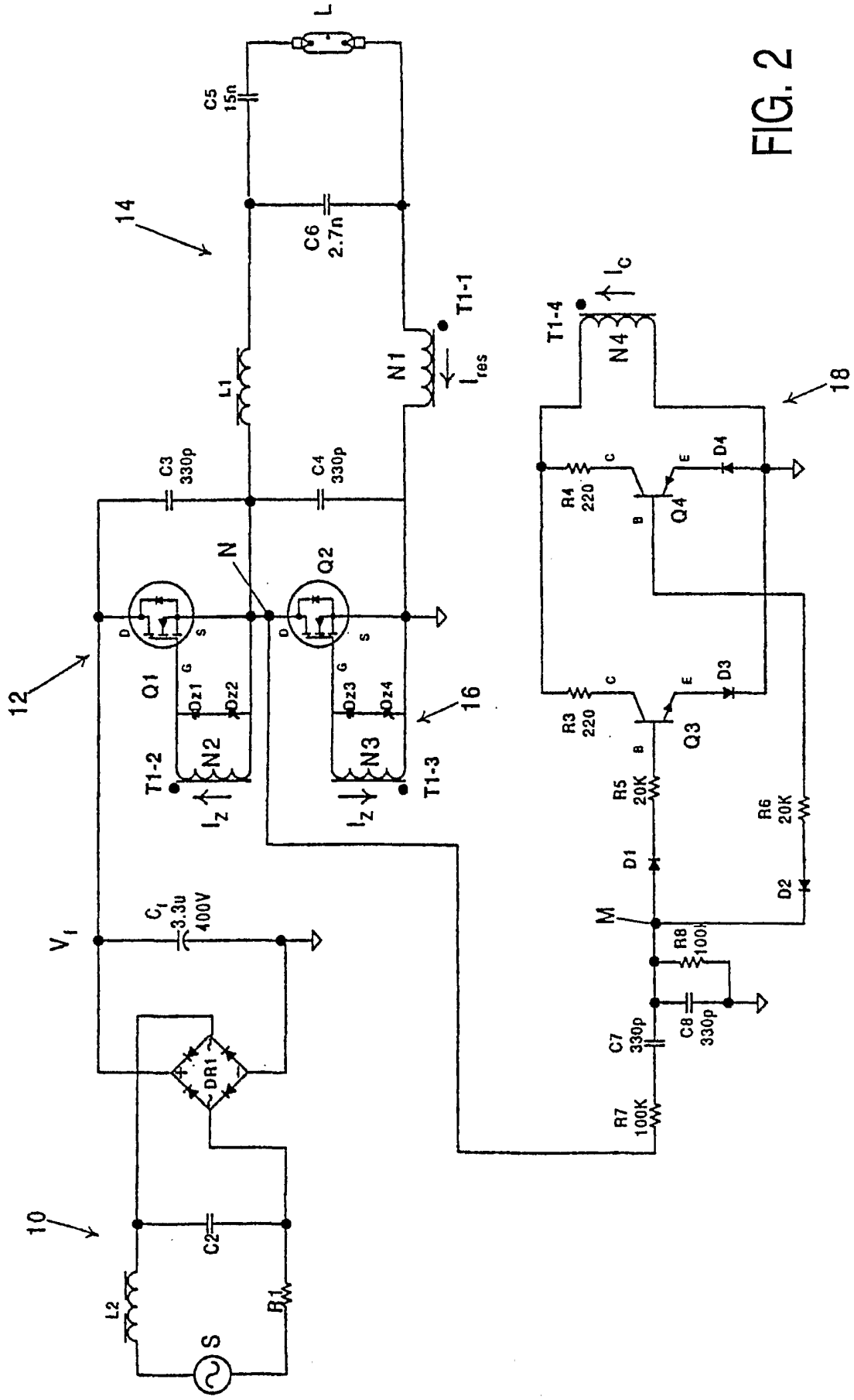


FIG. 2

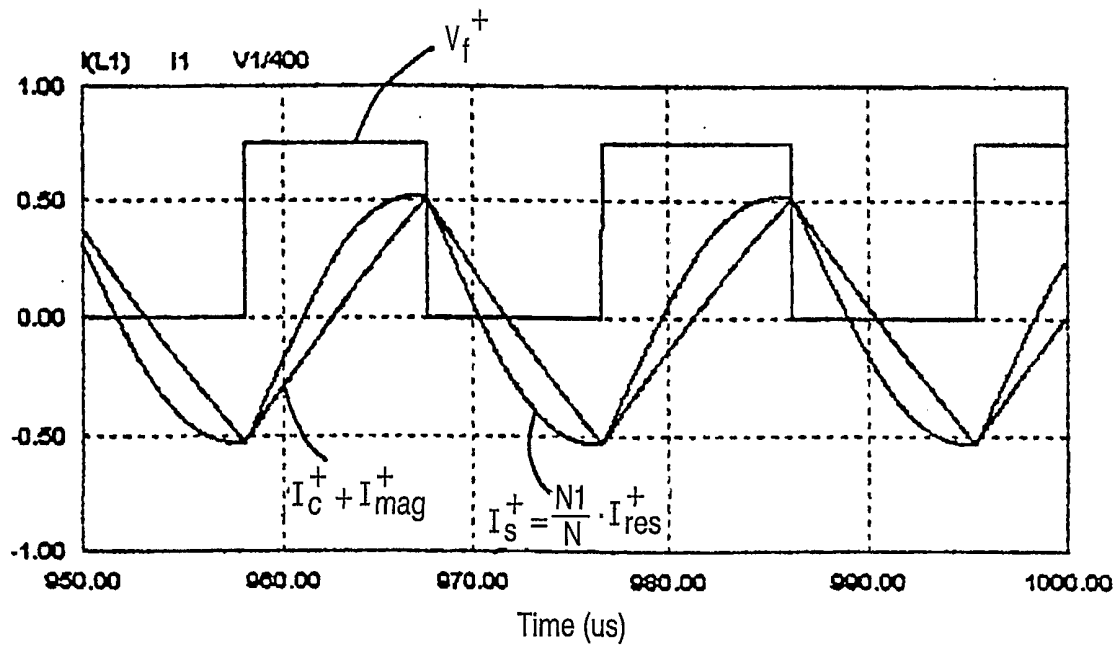


FIG. 3A

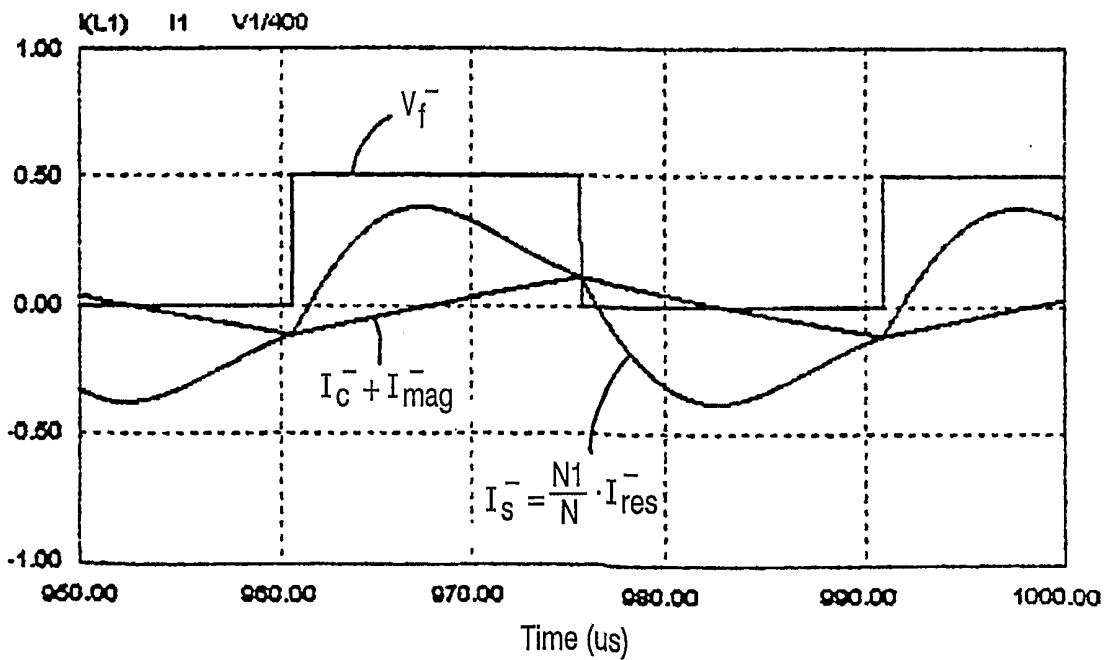


FIG. 3B

INTERNATIONAL SEARCH REPORT

International Application No
PCT/IB 01/02312

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H05B41/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H05B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 560 908 A (FELLOWS MARK W ET AL) 24 December 1985 (1985-12-24) column 5, line 4 -column 8, line 53; figure 1	1-5
X	US 4 701 671 A (FELLOWS MARK W ET AL) 20 October 1987 (1987-10-20) abstract	1
A	US 6 072 710 A (CHANG CHIN) 6 June 2000 (2000-06-06) cited in the application column 3, line 34 -column 4, line 63; figure 3	1-7

Further documents are listed in the continuation of box C.

Patent family members are listed in annex.

° Special categories of cited documents :

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- *O* document referring to an oral disclosure, use, exhibition or other means
- *P* document published prior to the international filing date but later than the priority date claimed

- *T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- *X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- *Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- * & * document member of the same patent family

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INTERNATIONAL SEARCH REPORT

Information on patent family members

In: International Application No

PCT/IB 01/02312

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