HF OPERATION OF FLUORESCENT TUBES

A circuit is described that enables HF control of fluorescent tubes. This not only increases the already high luminous efficacy of these lamps, but also enables them to be dimmed gradually.

Although fluorescent tubes have a much higher luminous efficacy* (80-90 lm/W) than ordinary, vacuum light bulbs (about 15 lm/W), and have a much longer life expectancy, they are nowhere near as popular for use in the home. This unpopularity is caused by the 'cold' character of the light, the difficulty of controlling (dimming) the light, and the objectionable behaviour (flickering) immediately after switch-on. Although the present circuit cannot alter the character of the light (manufacturers are already producing much 'warmer' fluorescent tubes), it does obviate the other two undesirable aspects.

Economy of HF control

High-frequency control units for fluorescent lamps have been available for some time, but so far these are mainly used in factories, office blocks, and other large buildings. The principal reason for their use there is that they provide a higher luminous efficacy. This comes about because the transformation of electrical into luminous power is more efficient at higher frequencies, and also because the losses in the control units are smaller at such frequencies (the choke of a domestic 40 W fluorescent lamp dissipates about 9 W). These advantages are, of course, not of such great importance for domestic lighting, because the resulting savings on the electricity bill are small. The main reason for adopting the present circuit in the home is seen primarily in the dimming facility.

Conventional set-up

A fluorescent tube usually consists of a long glass tube T (see Fig. 1), which is internally coated with a fluorescent powder, although other shapes are now also on the market. The tube contains a small amount of argon together with a little mercury. At each end of the tube there is an electrode E that invariably consists of a coiled tungsten filament coated with a mixture of barium and strontium oxides. Each electrode has attached to it two small metal plates, one at each end of the filament. These plates act as anodes for withstanding bombardment by electrons during the half-cycles when the electrode is positive. During the other half-cycles, the adjacent hot filament acts as the cathode, emitting electrons.

Before the gas in a fluorescent tube can be ionized, certain conditions must be met by the control circuit, consisting of choke L and starter switch G. Before the gas is ionized, the resistance measured between the two electrodes is high.

Switch G, called a glow switch, is, strictly speaking, a small glow discharge lamp filled with a mixture of argon, helium, and hydrogen at low pressure. The contacts of the glow switch are normally open, but when the supply voltage is switched on, a glow discharge is started between the electrodes of the switch. The resulting heat is sufficient to bend the bimetallic strips until they make contact and close the circuit between electrodes EE of the tube. A fairly large current then flows through these electrodes, the value of which is determined by choke L. The current heats the electrodes, which, by thermal emission, results in a number of free electrons in the tube. These electrons are necessary for the onset of ionization (avalanche effect).

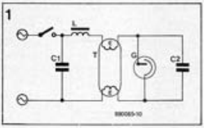

Fig. 1. Circuit of conventional low-pressure fluorescent tube.

Because the contacts of G are closed, the dissipation in this switch diminishes rapidly. This causes the bimetallic strips in G to cool and after a second or two the contact between these strips is broken. The consequent sudden reduction in current induces an e.m.f. of about 1000 V in L. The sum of this e.m.f. and the mains voltage is sufficient to ionize the argon in T. This reduces the resistance of the tube and the choke limits the current to a value specified by the manufacturer. The voltage drop across T is then of the order of 100 V, which is lower than the voltage required to ignite the glow switch.

The reason that fluorescent tubes flicker before they ignite properly is that the reduction in current caused by the bimetallic strips opening happens randomly with respect to the period of the mains voltage. If they open at the instant when the current through the choke is small, the induced e.m.f. may not be large enough to ionize the argon in T. In that case, the starting process repeats itself until ionization does take place.

The power factor of the circuit is raised from about 0.5 to 0.9 (lagging) by capacitor C_1.

Capacitor C_2 is an RF suppressor.

Most energy of this type of fluorescent lamp is radiated at a wavelength of 253.7 nm, which is in the ultra-violet region. The fluorescent coating of the tube absorbs this energy and converts it into visible radiation. Different coatings reradiate the absorbed energy at different wavelengths: zinc-beryllim silicate gives yellow to orange; cadmium borate and yttrium red; magnesium tungstate pale blue; and zinc silicate green. The use of appropriate mixtures of these powders make it possible to attain any desired colour.

Dimming

Dimming of fluorescent tubes operating at the mains frequency is troublesome.

* The term 'luminous efficiency' would be incorrect, since that is the ratio of output power to input power when both are expressed in the same unit.

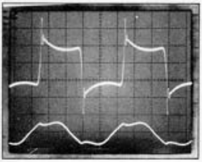

Fig. 2. Waveforms of voltage and current in a conventional fluorescent tube.

The reason for this may be seen in Fig. 2, which shows the voltage and current as functions of time. It is seen that after each and every zero crossing the voltage must rise substantially before the tube relights. Although the light output of all fluorescent tubes therefore fluctuates at twice the mains frequency, the visible effect of this is fortunately considerably reduced by the persistence of glow of the fluorescent coating.

If the tube is dimmed with the aid of a conventional triac circuit, the length of time that the current through the tube is zero becomes longer, and the risk of the tube being extinguished becomes greater. There are a number of ways of preventing this situation. The first is to maintain the high temperature of the electrodes with the aid of an external holding current. The second is to use a resistance strip along the tube as an aid to ignition. This strip is connected at one end to the electrode via a high-value resistor. At the other end it causes a kind of pre-ignition (the effective distance between the electrodes is reduced, which causes the fieldstrength to be locally much more intense). The third is to increase the frequency of the mains to a value where the period is small with respect to the recovery time of the ionized gas in the tube. The circuit described here uses this last method.

Block schematic

The circuit is, in fact, an a.c.–a.c. converter. The mains voltage is first rectified (full wave) and smoothed. The resulting direct voltage of 300 V is then converted to a square-wave voltage with a frequency of 80 kHz (at start-up) or 30 kHz (normal operation). The fluorescent tube is part of a series LC circuit that is shunted by a capacitor. As long as the tube is not lit, it has a high resistance and does not load the circuit. At the relatively high start-up frequency, the reactance of the capacitor is relatively low. When a voltage is applied across the circuit, a current will flow that causes the electrodes of the tube to be heated. Just after switch-on, the frequency will decrease gradually. As soon as it approaches the resonant frequency of the circuit, the impedance of the circuit will drop rapidly, which will result in a much larger current through the electrodes. At the same time, the voltage across both L and C is increased greatly. Since the tube is in parallel with C, it will light readily. As soon as this happens, the tube resistance drops considerably and this will damp the LC circuit. The current through the electrodes will then become much smaller. The control circuit further reduces the frequency until it reaches a value of 30 kHz. The currents through the tube and capacitor will be small, because the ignition voltage across the lamp (and thus the p.d. across the capacitor) is relatively low and also because the reactance of the capacitor at 30 kHz is relatively large.

Dimming of the tube is effected by controlling the current through it. In contrast to conventional triacs, the present circuit is a real control loop. The current is measured with a current transformer and fed back to the control circuit. The latter circuit varies the duty cycle until the measured current has the same value as the set current. This arrangement enables dimming of the tube to near-extinction. Quenching it completely is not possible, because that would necessitate a new start cycle (with the consequent frequency swing). The current regulation also ensures that at start-up, when the lamp current is zero, the duty cycle of the output signal is automatically optimized. In this manner, the tube will always start smoothly, independent of the position of the dimmer control.

Circuit description

In Fig. 6, fuse F_1 and chokes L_1 and L_3 are shunted by varistor R_{25}, which suppresses spikes on the mains supply. The mains voltage is rectified in bridge $D_3 – D_4 – D_5 – D_6$ and smoothed in C_5. The peak current through C_5 is limited by R_{26}. It should be borne in mind that switch-on may occur at any moment during the mains cycle: the peak charging currents that may occur should not be understimated. To keep the dissipation in R_{26} low, an NTC type is used here. Immediately after switch-on, this heats up, which causes its resistance to drop from 50 ohms to about 2 ohms, effectively limiting the dissipation.

Capacitors C_4 and C_6 and diodes D_1, D_2, and D_7 form a pre-control for the supply voltage to the drive circuit. This voltage is stabilized at 12 V by IC_4. The maximum current that can be drawn from this supply is 30 mA (determined by C_4). The drive circuit draws about 20 mA.

The power stage consists of T_1 and T_2, which are connected as a half-bridge. The voltage at the junction of T_1 source and T_2 drain swings between 0 V and 300 V (= the rectified mains voltage). The d.c. component of this voltage is blocked by capacitors C_2 and C_3. One capacitor would have been sufficient, but two in series give some extra decoup-

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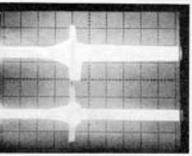

Fig. 4. Electronic starting: the frequency swings from 80 kHz to 30 kHz. When it is about 50 kHz, the tube lights.

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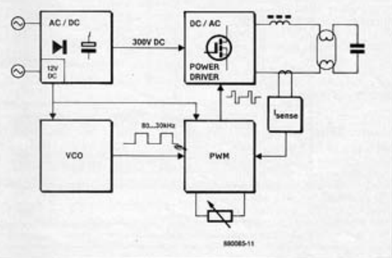

Fig. 3. Block schematic of HF controller.

ling of the high-voltage supply. As far as the a.c. through the lamp is concerned, the two capacitors are in parallel.

The power FETs contain parasitic free-wheeling diodes that are active during the dimming of the lamp. During dimming, both FETs are switched off for part of the period of the applied voltage. The voltage at the junction of T_1 source and T_2 drain, because of series circuit L_1-C_1, will swing several times between 0 V and 300 V during that time, which causes the free-wheeling diodes to conduct alternately (see Fig. 5b). A new period starts with T_1 being switched on. Now assume that D_{17} is shunted, D_{16} is not there, and that the free-wheeling diode in T_2 conducts just at the instant T_1 is switched on. During the recovery time of the free-wheeling diode in T_2 a short peak current will flow through both T_1 and T_2, which will affect the dissipation adversely. Since this problem is caused by the relatively long reverse-recovery-time of the internal free-wheeling diode in T_2 (typically of the order of 1.8 μs), it is obviated by connecting diode D_{17} in series with T_2, because this prevents the parasitic diode from conducting. The series-connected diodes can then be shunted by a much faster free-wheeling diode, D_{16} (T_{rr} = 25 ns typically).

The series LC circuit is formed by L_1 and C_1. The circuit is damped by R_{23} and R_{24}. Without these resistors, the damping of the circuit would be dependent solely on the resistance of the tube electrodes. Because this is very low, very large values of current and voltage might ensue before the tube lights. Resistor R_{23} guarantees a given minimum series resistance in the circuit. The resistance of varistor R_{24} will drop as soon as the voltage across C_1 exceeds a maximum value of about 1 kV. The clamping of the potential across C_1 will prevent too high an upswing of voltage and current in the circuit. As soon as the tube lights, its resistance will further damp the circuit. Since the final potential drop across the lamp is relatively low, additional dissipation in R_{24} is prevented because the varistor has a high resistance at that voltage.

Since the operating frequency of 30 kHz is much higher than the conventional 50 Hz, the self-inductance and dimensions of choke L_1 can be accordingly smaller. Although it would be possible to limit the lamp current to a given value with the aid of the current regulating circuit, it is better done by the choke. The self-inductance is chosen so that at maximum duty cycle the lamp current does not exceed the value specified by the manufacturer of the tube.

5a

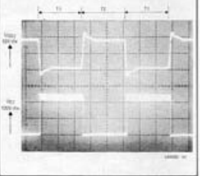

Fig. 5a. Gate signal (upper trace) and the voltage at the junction of T_1 source and T_2 drain at maximum duty cycle. The 'broad band' in the lower trace is caused by the 50 Hz ripple.

5b

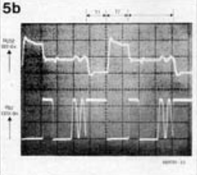

Fig. 5b. The same signals as in 5a, but with the tube dimmed. During the freewheeling period neither of the MOSFETs conducts, and the drain – source junction swings several times between 0 V and 300 V.

Control circuit

The control circuit has two tasks:

- the generation of a frequency that within about 2 seconds from switch-on swings from 70-80 kHz via the resonance frequency of 50 kHz to the normal operating frequency of 30 kHz.
- the controlling of the lamp current in accordance with a variable desired value to enable dimming of the lamp. The current is controlled by varying the pulse width of the drive signal.

Frequency synthesis is provided by the VCO in IC_1, a Type 4046 CMOS PLL. The supply voltage is kept steady by zener D_{15}. Should the supply drop below 11 V, both T_7 and T_8 are switched off. The 4046 is then inhibited. When the input voltage is not lower than 11 V, C_7 is connected to the positive line via T_7. Since the capacitor at first has no charge, the VCO input will also tend to rise to 12 V, but is prevented by D_{12} from exceeding 4.5 V. From this voltage, a signal at a frequency of about 70 to 80 kHz is generated. Capacitor C_7 is then charged via R_{16}, which causes a drop in the potential at the junction of C_7 and R_{16}. When this voltage drops below 4 V (the earlier mentioned 4.5 V less the drop across D_{13}), the VCO input is pulled down and the frequency of the output signal drops. The operating VCO input, and thus the operating frequency, is determined by potential divider $R_{17}-R_{18}$.

Multivibrators MMV_1 and MMV_2 provide the pulse width modulation. The VCO signal has a duty factor of 50% (square wave). MMV_1 is triggered at the leading edge of this signal. Immediately on termination of the mono period of MMV_1, the other multivibrator, which has an identical mono period, is triggered. The mono period of the multivibrators is variable because C_{15} and C_{16} are not charged via a fixed resistance, as is usual, but by a variable current source (strictly, current mirror): T_4 and R_6 and T_3 and R_7 respectively.

The magnitude of the current, and thus the mono period and duty cycle, is constantly adjusted, as required, by the current regulating circuit. The mono periods can not become longer than the half-periods of the VCO signal. Were one of the multivibrators likely to generate a longer period, this would be terminated prematurely by the reset input. In this manner, it is ensured that the maximum duty cycle of the circuit is exactly 50% as determined by the 50% duty factor of the VCO signal. This is, of course, essential to guarantee symmetrical control of the output stage.

The output stage is driven by a pulse transformer, Tr_1, which is contained in bridge $T_5-T_6-T_9-T_{10}$. Any d.c. components caused by small deviations of the mono periods are blocked by C_{12}. Such d.c. components would cause an unnecessarily large current in the low-ohmic primary of the pulse transformer, which might lead to saturation of the core of the transformer.

The MOSFETs are driven direct by the secondaries of Tr_1. It is, of course, imperative that these windings are connected in anti-phase to make sure that the MOSFETs cannot be switched on simultaneously. Resistors R_2 and R_3 serve to damp any oscillations caused by parasitic self-inductances. The zener diodes in the gate circuits limit the amplitude of the gate voltage.

To make current regulation possible, the lamp current is measured by a current transformer, Tr_2. A complication here is C_1, which is in parallel with the tube. This means that not only the current through the lamp, but also that through the capacitor, is measured. When the lamp is dimmed, and the current through it is, therefore, small, the current through the capacitor is relatively large and would put paid to any current regulation. Direct measurement of the lamp current alone is not possible, and it is, therefore, measured indirectly. This is done by first measuring the total current (winding 1) and deducting from this the current through the capacitor (winding 2 — wound in anti-phase to winding 1).

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Readers should note the difference between 'duty cycle' and 'duty factor', a source of confusion for many! Duty cycle refers to variations of the load with time. Duty factor is used in pulse techniques and is the ratio of the average pulse width to the average pulse spacing of pulses in a pulse train.

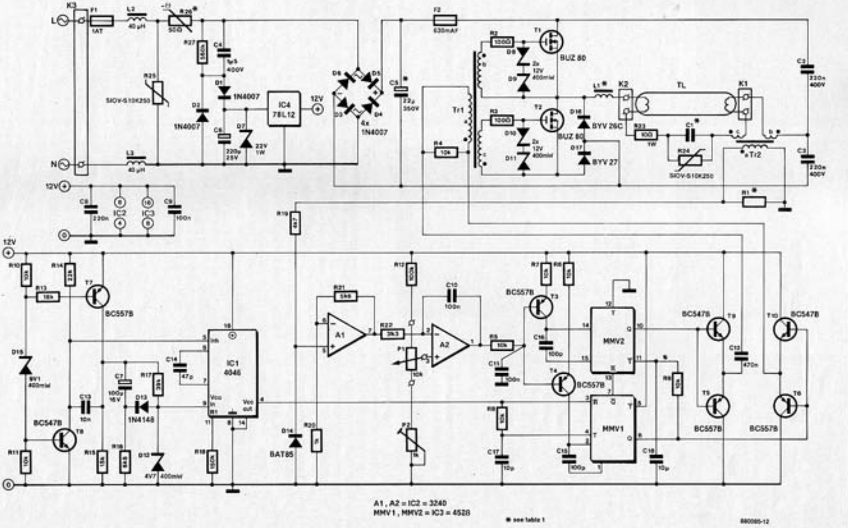

Fig. 6. Circuit diagram of the HF controller.

The secondary current of Tr_2 is converted into a voltage by R_1. Of this voltage, the positive half is amplified by A_1 and its average value is then compared with a voltage whose level is preset with P_1. If any differences are measured, A_2 increases the drive to the bases of T_3 and T_4, which varies the duty cycle until the two voltages are equal. The minimum lamp current (when the lamp just does not get extinguished) is preset by P_2.

Construction

Since the circuit is connected direct to the mains, it cannot be stressed too much to BE CAREFUL.

The circuit is best constructed and tested in stages. It is strongly recommended to use an isolating transformer during tests on the circuit.

Start with the control section at the centre of the PCB. That is, mount all ICs, except IC_4, and all associated components, including the transistors. Resistors R_1 and R_4 may also be fitted, but the two transformers must wait a little. Potentiometer P_1 may also be connected with the aid of three (temporary) short wires.

Apply a stabilized voltage of 15 V in place of the wire links near C_4 (earth closer to the edge of the board). Check the output signal of the VCO (IC_1 pin 4) with an oscilloscope or frequency meter. This square-wave signal must remain stable at 70 – 80 kHz for about a second and then drop to 30 kHz ± 5 kHz within a few seconds. Any deviations from the stated values of frequency are caused by tolerances in IC_1 and must be compensated by small changes in the values of R_{18} and C_{14}.

The same square-wave signal should be present across R_4, but here it is not a pulse train, but an alternating signal with a peak-to-peak value of about 12 V. Since at this stage there can be no lamp current, the current regulator will automatically optimize the duty cycle.

When the supply input is decreased to less than 11 V, the oscillator should stop functioning. When the voltage is then raised again to 12 V, a new start cycle should commence.

Check the current drawn by the control circuit: this should be 10 – 15 mA.

Choke and transformers

Choke L_1 and two transformers, Fig. 8 and Fig. 9, are not available commercially.

The choke, L_1, is wound on a readily available pot core with an air gap, measuring 30×19 mm, with A_L=1,000. The number of turns depends on the tube with which it is intended to be used — see Table 1. Since high voltages occur across the choke, particularly during start-up, it is essential to separate each

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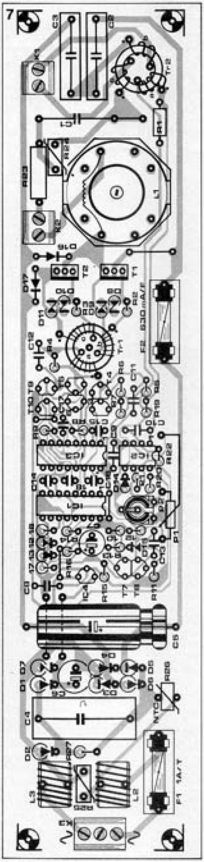

Fig.7. The printed circuit of the HF controller.

Parts list

Resistors (±5%):

R_1 = see text
R_2;R_3 = 100R
R_4 . . . R_{11} incl. = 10K
R_{12} = 100K
R_{13} = 18K
R_{14} = 22K
R_{15} = 15K
R_{16} = 6K8
R_{17} = 39K
R_{18} = 150K
R_{19} = 4K7
R_{20} = 1K0
R_{21} = 5K6
R_{22} = 3K3
R_{23} = 10R; 1 W
R_{24};R_{25} = varistor 510K250 (ElectroValue*).
R_{26} = NTC 50 Ω; 1 W e.g. Mullard no. 2322 610 11509.
R_{27} = 560K
P_1 = 1K0 preset
P_2 = 10K linear potentiometer with plastic shaft.

Capacitors:

C_1 = see text.
C_2;C_3 = 220n; 400 V
C_4 = 1µ5; 400 V
C_5 = 22µ; 350 V
C_6 = 220µ; 25 V; radial
C_7 = 100µ; 16 V; radial
C_8 = 220n
C_9;C_{10};C_{11} = 100n
C_{12} = 470n
C_{13} = 10n
C_{14} = 47p
C_{15};C_{16} = 100p
C_{17};C_{18} = 10p

Semiconductors:

D_1 . . . D_6 incl. = 1N4007
D_7 = zener diode 22 V; 1 W
D_8 . . . D_{11} incl. = zener diode 12 V; 400 mW
D_{12} = zener diode 4V7; 400 mW
D_{13} = 1N4148
D_{14} = BAT85 (Cricklewood)
D_{15} = zenerdiode 9V1; 400 mW
D_{16} = BYV28C (Mullard)
D_{17} = BYV27 (Universal Semiconductor Devices)
T_1;T_2 = BUZ80 (ElectroValue*)
T_3 . . . T_7 incl. = BC557B
T_8;T_9;T_{10} = BC547B
IC_1 = 4046
IC_2 = 3240
IC_3 = 4528
IC_4 = 78L12

Miscellaneous:

F_1 = fuse 1 A; delayed action
F_2 = fuse 630 mA; fast
2 off PCB-mount fuseholders.
K_1;K_2 = 2-way terminal block for PCB mounting.
K_3 = 3-way terminal block for PCB mounting.
L_1 = the following parts from Siemens are required for making this inductor:
1 off pot core B65701-L1000-A48;
1 off coil former B65702-B-T2;
2 off washers B65705-A5000;
1 off mounting assembly B65705-B3;
1 off white screw core B65679-E1-X22;
1 off threaded flange B65679-L3;

These parts are listed in the Siemens Preferred Products Catalogue, and are available from ElectroValue*.
L_2;L_3 = suppessor choke 40 μH; 2 A.
TR_1 and TR_2 are wound on 2 ferrite cores Type RK60 (Mullard no. 4322 020 97060).
PCB Type 880085

* ElectroValue Limited • 28 St Judes Road • Englefield Green • Egham • Surrey TW20 0HB. Telephone: (0784) 33603. Telex: 264475. Northern branch: 680 Burnage Lane • Manchester M19 1NA. Telephone: (061 432) 4945.

layer from the next with good-quality insulating tape. Use enamelled copper wire 24–26 SWG (0.5 mm dia.).
Both transformers are wound on the same type of ferrite toroid. The primary winding of the pulse transformer, Tr_1, consists of 40 turns enamelled copper wire, SWG 35 (0.2 mm dia.). Both secondary windings consist of 30 turns enamelled copper wire, SWG 14. It is important that the secondaries are wound in opposite directions from one another to ensure anti-phase drive of the power MOSFETs. Furthermore, the potential difference between the primary and the secondary windings is some 300 V: it is therefore important to keep the secondaries well away from the primary.
The current transformer is fairly easy to make. Both primary windings consist of 2 turns enamelled copper wire, SWG 25 (0.5 mm dia.), wound in opposite directions from one another. The secondary consists of 4 turns of the same wire as the primaries.

Final construction

Fit Tr_1 and Tr_2 in position on the PCB, followed by R_2, R_3, D_8, D_9, D_{16}, D_{11}, T_1, and T_2. Apply a voltage of 12 V from an external source and ascertain the current drawn: this should be 20–25 mA after about 5 seconds (i.e., at the normal operating frequency).
Next, check that the secondary windings are in anti-phase by temporarily interconnecting the source connections on the PCB and verifying that there is NO signal between the two gate connections. Then, mount K_3, F_1, L_2, L_3, R_{25}, R_{26}, R_{27}, C_4, C_6, D_2 and D_7. With a suitable mains cable, connect K_1 to the mains and switch on. Measure the voltage across D_7, which should be 18 V. REMEMBER YOU ARE NOW WORKING WITH MAINS VOLTAGES!
Disconnect the mains from K_1, discharge C_6 through a resistor, and mount IC_4. Then, fit the two wire links near C_5 (but not yet this capacitor). Again, connect the mains to K_1 and check the output of IC_4 as 12 V. Afterwards, measure

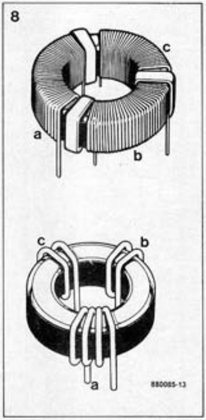

Fig. 8. Showing how the pulse transformer (a) and the current transformer (b) should be wound.

the gate signal with an oscilloscope (compare with Fig. 5a upper trace.).
Finally, mount all other components, and do not forget the wire link near T_1.
The values of C_1, L_1, and R_1 are given in Table 1. Take care not to confuse D_{16} with D_{17}: these components look very much alike!
When tubes with a power rating >30 W are used, it is advisable to mount T_1 and T_2 on a simple heat sink: an L-shaped piece of aluminium as shown in Fig. 10 is sufficient. Note, however, that the MOSFETs must be insulated from the heat sink. In view of the relatively high potentials involved, use ceramic, not mica, insulating washers.

Assembly and connecting-up

Connect the tube to the circuit, turn P_2 completely anti-clockwise, set P_1 to the centre of its travel, take a deep breath, and connect the mains. The tube should light after 1–2 seconds and it should be possible to dim it with P_1. It is possible that you experience odd running-light effects in the tube: these may be eliminated by turning the adjustment screw in the core of L_1.
Set P_2 to a position where the tube just remains lit. It will be noticed that a

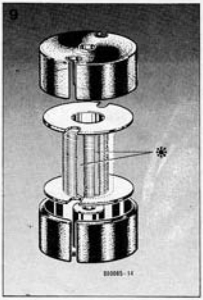

Fig. 9. Showing how choke L_1 should be wound. The number of turns for a variety of tubes is given in Table 1.

Table 1

Tube rating	L_1	C_1	R_1
20 W	2.0 mH 45.5 turns	4n7 1500 V	2R2
30 W	1.8 mH 43.5 turns	5n6 1500 V	1R8
40 W	1.6 mH 42.5 turns	6n8 1500 V	1R8
60 W	1.1 mH 32.5 turns	10 n 1500 V	1R0

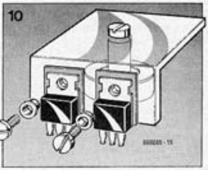

Fig. 10. When fluorescent tubes of rating >30 W are used, the MOSFETs should be cooled, for example, with the aid of a simple L-shaped piece of aluminium as shown here.

warm tube can be dimmed to a larger degree than a cold one. It is, therefore, best to set P_2 when the tube is cold.
In view of the operating frequency and the waveform of the output signal of the circuit, the connections between the cir-

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cuit and the tube must be kept short. In practice, that means that the circuit will have to be built into the armature. This has been taken into account during the design of the PCB. Make sure that there will be at least 6 mm (¼ in) space between live parts of the board and metal parts of the armature. The existing starter and choke may, of course, be removed.

Potentiometer P_1 is connected to the PCB by a 3-core cable: remember that it is connected to the mains (neutral) via P_2 and L_3! It is, therefore, advisable to use a potentiometer with a man-made fibre spindle.

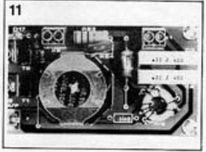

Fig. 11. The current transformer and choke L_1.

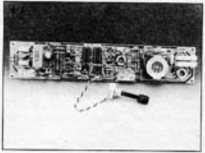

Fig. 12. Completed HF controller ready for fitting into the tube armature.