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DESIGNING LIGHT SOURCES FOR SOLAR-POWERED SYSTEMS

J.L. Duarte, J.A.A. Wijntjens, J. Rozenboom

Eindhoven University of Technology, The Netherlands

Abstract. The design of a fluorescent lamp power circuit for (portable) light sources, using a photovoltaic-supplied battery as intermediate energy buffer, is documented. The described driver circuit, which is based on a class-E resonant inverter, operates on a high frequency (125 kHz), requires low-cost components and simple design and exhibits high efficiency (over 85%). The circuit provides resonance ignition, sinusoidal lamp current and illumination intensity control. These operating conditions are optimal, and they yield a long tube life. Experimental results from a 7W-lamp are included.

Keywords. Photovoltaic lighting, resonant converters, class E.

INTRODUCTION

A solar-powered lighting system finds application in remote or difficult to access areas, especially in development countries (Bathia (1)). The system includes a photovoltaic module as DC power supply, a battery as energy storage reservoir, a gas discharge lamp as light source, and a driver circuit for their connection and matching, as shown in figure 1.

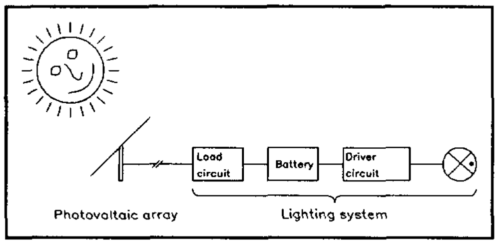

Fig. 1: A typical solar-powered lighting system

Since the surface of the photovoltaic array settles the cost of the total system, it is important to look for highly efficient power transformation devices, which allows a smaller silicon area and a smaller battery storage capacity for a desired average illuminating period.

It is well known that the low-pressure fluorescent lamps have a significant advantage over incandescent lamps because they have three to five times higher lighting efficiency (Ellenbas (2)). Therefore tubular fluorescents are very adequate for solar-powered systems. A tubular lamp is a negative-resistance device, which requires ignition voltage. In addition, it must be symmetrically driven to conduct equal currents in both directions for long life operation. A tubular lamp also demands correct electrode pre-heating before ignition, in order to avoid sputtering damage.

Fluorescent lamps have been shown to increase in efficiency as frequency of operation is increased up to some kilohertz or beyond (Hammer (3)). It is also well known that at higher frequencies the lamp behaves like a pure resistence, because the space charge density inside the lamp does not decay appreciably within one cycle. Hence, high frequency of operation allows an increase in illumination per a given solar input power.

Another desirable characteristic for a photovoltaic lighting system is the possibility of dimming the lamp. By this way the user is able to adjust the light intensity according to his needs, and therefore reducing the power consuption, which allows longer illuminating periods.

The characteristics above define the main requirements of a tubular lamp drive circuit in photovoltaic systems :

1. high efficiency;
2. high frequency of operation;
3. symmetrical driving of the lamp using alternating current;

4. electrode pre-heating;
5. high ignition voltage;
6. dimming.

The known driver circuits meet previous requirements with varying success. The classical push-pull DC-AC converter is frequently used as a low-cost and simple lamp driver (2). This topology requires two power switches and a transformer, in order to achieve voltage invertion. Since the push-pull converter operates under square-wave switching, its frequency has to be normally limited to some decades of kilohertz, for the purpose of avoiding high switching losses and low power efficiency. In the push-pull topology it is also necessary to avoid asymmetrical conducting times for the power switches, otherwise different values for the positive and negatieve voltage polarities at the transformer secondary voltage will occur. Dimming solutions increase the complexity of the circuit.

A new approach for the lamp driver circuit satisfying all the main requirements is described in this paper. The inverter topology, that is based on the class-E resonant converter, is simple, requires just one power switch and does not use magnetic transformers. On account of the zero-voltage switching characteristic of the proposed topology, the circuit becomes more efficient and minimizes the heat dissipation problem. Dimming and symmetrical current drive are provided naturally. High enough ignition voltage and electrode pre-heating are obtained by resonance, without further aditional circuitry. The operating frequency can be made high enough (beyond 100kHz) in order to obtain higher fluorescent tube luminescence and lightweight equipment.

In the following sections, the proposed driver circuit and its model are described. Next, experimental results are commented.

DRIVER CIRCUIT ANALYSIS

The class-E inverter (figure 2) is a load resonant network suitable for use in lightweight, low power, high frequency power converters. The circuit is reliable and can be easily built (Kazimierczuk and Bui (4)). As long as the value of R_o in figure 2 remains bounded by an upper value (that is, if $0<R_o<R_{o\,max}$), the circuit will operate under zero-voltage switching (zvs) conditions.

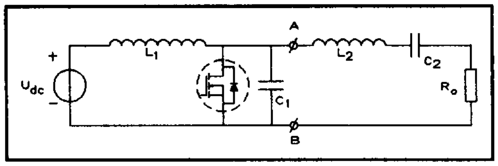

Fig. 2: A class-E inverter

If one tryes to use a class-E inverter in lighting applications, some kind of impedance matching will be unavoidable. This is due to the fact that the fluorescent lamp operating at high frequencies can be viewed as a resistance varying from infinity (before ignition) to a minimum value (at nominal power). Hence, the zvs boundary would be overshoot if the lamp would replaced R_o in the circuit of figure 2.

An impedance matching network which satisfies the zvs boundary can be achieved in a simple way by substituting the circuit components to the right of points A and B in figure 2 by the network in figure 3, with the following relationships:

$$\frac{X_p R_{la}(\omega L_3 + X_p) - \omega L_3 X_p R_{la}}{R_{la}^2 + (\omega L_3 + X_p)^2} = R_o \qquad (1)$$

$$X_s = \omega L_2 - \frac{1}{\omega C_2} - \frac{R_{la}^2 X_p + \omega L_3 X_p (\omega L_3 + X_p)}{R_{la}^2 + (\omega L_3 + X_p)^2} \qquad (2)$$

where

$$X_p = \omega L'_2 \qquad X_s = \frac{1}{\omega C'_2} \qquad \omega = 2\pi f_s$$

with

f_s : switching frequency of the transistor in figure 2;
R_{la} : equivalent resistance of the discharge lamp.

It is straightforward from equation (1) that if

$$R_{la\,min} < R_{la} < \infty,$$

then R_o will stay within the boundary conditions

$$R_{o\,max} > R_o > 0.$$

Another intrinsic advantage of the circuit with impedance matching is that if R_{la} tends to infinity in figure 3 (which corresponds to a tubular lamp before ignition) the voltage over inductor L'_2 tends to grow up due to undamped resonance. Therefore, high ignition voltage can be reached in a natural way, without transformers.

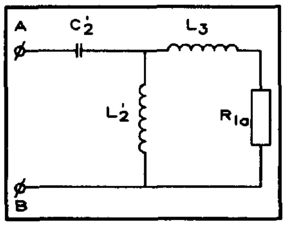

Fig. 3: Matching network

The tube ignition voltage depends on the electrode heating current. When the heating current is lower than a threshold value, the electrode will be warmed insufficiently for electron emission, and the required ignition voltage will be high. For electrode current values larger than the threshold value, the electrode emission temperature is reached, and the ignition voltage is close to the lamp operating voltage. The ignition circuit in figure 4 contains only capacitor C_v connected in series with both electrodes.

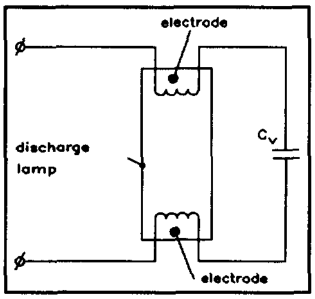

Fig. 4: Pre-heating network

When the tube is not ignited, the impedance of C_v provides a path for current circulation. By adjusting the switching frequency above the nominal operating frequency, it is possible to reach the electrode threshold current with low voltage at the lamp terminals. Then, if the switching frequency is brought smootly to its nominal value, a sufficiently high ignition voltage will be induced by resonance, which will start ignition. This method provides both electrode warm up and ignition voltage in an expensive and simple fashion.

Dimming is easily provided if the switching frequency is brought below the nominal frequency of operation. Frequency generators can be implemented by means of simple digital ic's and potentiometers, as shown in figure 5.

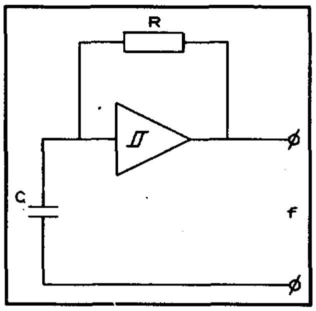

Fig. 5: A simple frequency generator

DESIGN GUIDELINES

The initial design parameters, which can be freely choosen, are :

(a) the input voltage U_{dc};
(b) the nominal rms lamp current I_{lamp};
(c) the nominal output power P_o;
(d) the desired switching frequency f_s;

From these parameters on, the values for the circuit components shown in figures 2 and 3 can be assigned as follows:

$$R_o = \frac{b \times U^2_{dc}}{P_o} \tag{3}$$

$$C_1 = \frac{c}{\omega \times R_o} \tag{4}$$

$$C_2 = \frac{d}{\omega \times R_o} \tag{5}$$

$$L_2 = \frac{e \times R_o}{\omega} \tag{6}$$

$$L_1 = \frac{10}{\omega^2 \times C_1} \tag{7}$$

The coefficients b, c, d and e in the equations above are given in table 1 (reproduced from ref.(4)), for the case where the transistor is switched at 50% duty cycle.

Tabel 1: Design coefficients of a class E invertor at 50% duty cycle.

Q	b	c	d	e	$\hat{I}_s/I_{dc}$	$\hat{U}_s/U_{dc}$
0	0.3587	0.2177	∞	1.788	3.128	3.732
1	0.4008	0.2204	2.1040	2.104	2.886	3.703
2	0.4570	0.2190	0.7124	2.850	2.761	3.662
3	0.4916	0.2150	0.4166	3.750	2.759	3.636
5	0.5249	0.2067	0.2269	5.673	2.783	3.610
7	0.5401	0.2017	0.1560	7.624	2.800	3.597
10	0.5514	0.1971	0.1062	10.62	2.816	3.587
20	0.5644	0.1909	0.0515	20.60	2.837	3.574
100	0.5744	0.1851	0.0101	100.58	2.857	3.565
∞	0.5768	0.1836	0	∞	2.862	3.560

U_{dc} : input voltage; I_{dc} : input current;
$\hat{I}_s$: top value of the current through the switch;
$\hat{U}_s$: top value of the voltage at the switch.

In table 1 the parameter Q represents the quality factor of the resonant tank in figure 2. The higher Q, the closer to sinusoidal in shape will be the resonant current. On the other hand, the efficiency of the resonant circuit is higher as Q is lower. Also the dimming sensitivity of the lamp circuit to the switching frequency depends on Q. The higher Q, the sharper will be the frequency range for dimming the lamp. Therefore a lower value of Q makes it easier to implement the dimming circuitry.

From the ideas above it is clear that the choice of the value of Q for nominal circuit operation involves a trade-off. In practice, it is not necessary to make Q bigger than 3, which results in a good harmonic content for the lamp current and yields to a not to sharp dimming range, while maintaining high efficiency.

It is possible to estimate the voltage and current stress of the transistor, normalised to the input dc voltage and input dc current, which are also given in table 1.

The values for the components in the matching network (figure 3) can be calculate from the outcomes of equations (3) to (7), after substituting

$$R_{la} = P_o/I_{lamp}^2$$

in equations (1) and (2).

EXPERIMENTAL RESULTS

An experimental setup for a 7W lamp (I_{lamp}=175mA rms, P_o=6.5W), operating at 125kHz from a 12Vdc input voltage, has been built for the purpose of testing the ideas above. The final circuit is shown in figure 6, where Q=2. Some typical waveforms are given in figures 7 and 8. Practical results confirm that it is possible to dim the lamp from 6.5W down to 2.5W. The measured global circuit efficiency was above 85%.

CONCLUSIONS

Simplicity, low cost, high efficiency, as well as the ability to adjust the lamp power level, are the main characteristics of the proposed driver circuit, that make it advantageous for application in solar-powered systems.

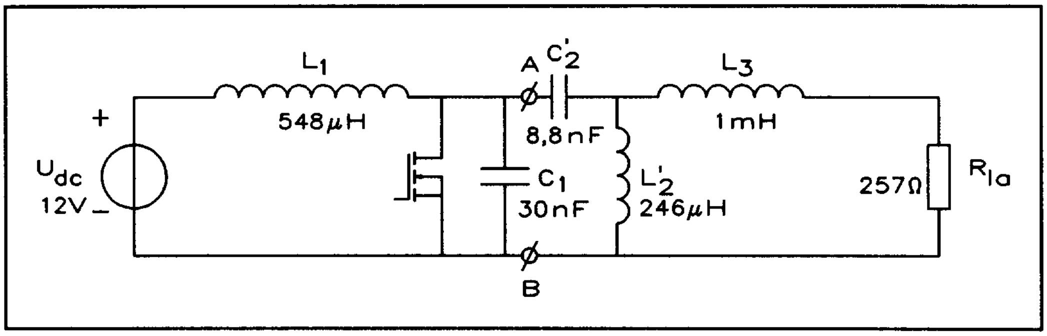

Fig. 6: Final driver circuit for a 7W tubular lamp

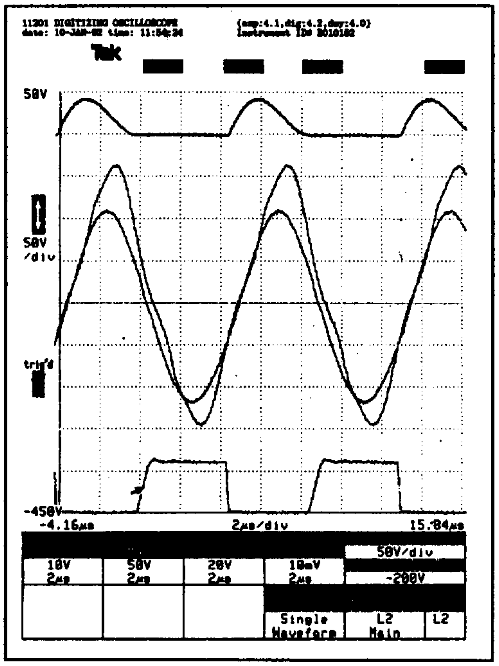

Figure 7: Typical waveforms (u_s, u_{la}, i_{la} en u_{gs}) if P_{la} = 6.5W

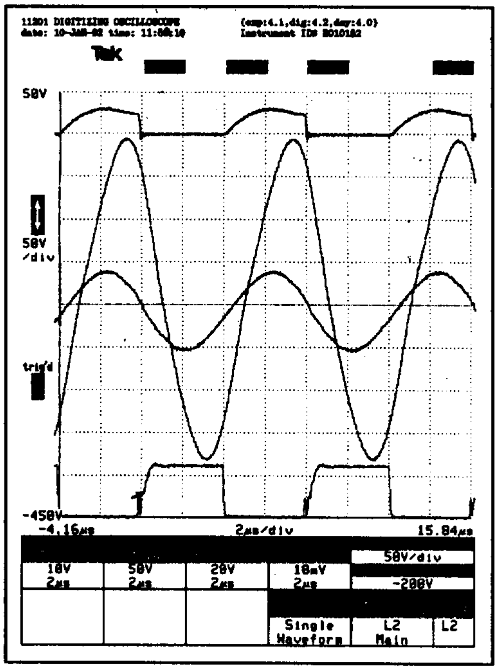

Figure 8: Typical waveforms (u_s, u_{la}, i_{la} en u_{gs}) if P_{la} = 2.5W

References

1. Bhatia,R., 1991, Int.J. of Global Energy Issues, 3, 103-108.

2. Ellenbas,W., 1971, "Fluorescent lamps", MacMillan, London, UK.

3. Hammer,E.E., 1987, J. of the Illuminating Soc., 3, 52-63.

4. Kazimierczuk,M.K. and Bui,X.T., 1990, IEEE Trans. on Ind. Elec., 37, 160-166.