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RESEARCH ARTICLE

Research and development of pulse electronic control devices with UV lamps

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Abstract
Objectives. When used in lighting installations with tubular low-pressure ultraviolet (UV) lamps, electronic ballasts should meet the following basic requirements: low cost, reliable ignition at low temperatures, as well as combining high energy efficiency with reliable lamp operation. As compared with electromagnetic ballasts, electronic ballasts allow the luminous efficiency and power factor of discharge lamps to be increased, reducing the consumption of scarce materials along with the weight of devices. In order to improve their energy efficiency, complete UV lamps are based on low-pressure discharge lamps with pulsed electronic ballasts supplying power at the frequency of 22–50 kHz. Various circuit designs include such basic units as mains filter, rectifier, power factor corrector, smoothing filter, high-frequency converter, ballast, and ignition device. The present study aimed to develop an electronic semiconductor circuit for switching on and powering a discharge lamp of increased energy efficiency using a pulsed electronic ballast.
Methods. Classical methods of mathematical research were applied for determining the flux of the 254-nm mercury resonance line using a structural electronic ballast diagram along with a mathematical description and adaptive model.
Results. Equations for determining the parameters of pulses formed by an envelope having the form of input voltage and current supplied at industrial frequency were formulated for different instants of time. A mathematical description is given for determining pulse duration and lamp current depending on the values of nominal and operating voltage, as well as nominal current. Diagrams for instantaneous voltage values at the high-frequency switch input and generated pulsed current are presented. The parameters of the ‘UV lamp–electronic ballast’ set were calculated using an adaptive model for determining the flux of the 254-nm mercury resonance line according to the condition of lamp power constancy.
Conclusions. Relative values for radiant efficiency of the 254-nm mercury line for UV lamps under study were determined. Theoretical research of electronic ballasts led to the development of a semiconductor switching and power supply circuit for the discharge lamp based on high-frequency rectangular pulses. The parameters of the element base were calculated along with selected basic initial characteristics of the blocking generator.

Keywords: electronic ballast, power, mathematical description, filter, converter, pulse, mercury resonance line, blocking generator

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НАУЧНАЯ СТАТЬЯ

Исследование и разработка импульсных электронных пускорегулирующих аппаратов в комплекте с ультрафиолетовыми лампами

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Резюме
Цели. В облучательных приборах, работающих в светотехнических установках с трубчатыми ультрафиолетовыми (УФ) лампами низкого давления, к электронным пускорегулирующим аппаратам (ЭПРА) предъявляются следующие требования: невысокая стоимость, обеспечение надежного зажигания разрядных ламп низкого давления в условиях пониженных температур и надежная работа ламп при повышенной энергетической эффективности. По сравнению с электромагнитными пускорегулирующими аппаратами, ЭПРА обеспечивают повышение светоотдачи разрядных ламп и коэффициента мощности, снижение расхода дефицитных материалов, уменьшение массы. Для повышения энергетической эффективности УФ ламп в комплекте с ними целесообразно использовать импульсные ЭПРА, обеспечивающие питание на частоте 22–50 кГц. Различные схемные решения ЭПРА включают в себя такие основные узлы как сетевой фильтр, выпрямитель, корректор коэффициента мощности, сглаживающий фильтр, высокочастотный (ВЧ) преобразователь, балласт и зажигающее устройство. Целью работы является разработка электронной полупроводниковой схемы включения и питания разрядной лампы повышенной энергетической эффективности с импульсным ЭПРА.
Методы. Использованы классические методы математического исследования с применением структурной схемой ЭПРА, его математическим описанием и адаптивной модели для определения потока резонансной линии ртути с длиной волны 254 нм.
Результаты. Для разных моментов времени представлены уравнения определения параметров импульсов, образованных огибающей в форме входного напряжения и тока промышленной частоты. Дано математическое описание для определения длительности импульсов и тока лампы в зависимости от значений номинального и рабочего напряжения и номинального тока. Представлены диаграмма мгновенных значений напряжения на входе ВЧ ключа и диаграмма формируемого импульсного тока. В работе проведен расчет параметров комплекта «УФ лампа – импульсный ЭПРА» при условии постоянства мощности лампы и использовании адаптивной модели для определения потока резонансной линии ртути длиной волны 254 нм.
Выводы. В результате расчетов были определены относительные значения лучистой отдачи резонансной линии ртути исследуемых УФ ламп. Теоретические исследования ЭПРА позволили разработать электронную полупроводниковую схему включения и питания разрядной лампы прямоугольными импульсами высокой частоты. В ходе работы для предложенного схемного решения импульсного ЭПРА проведен расчет параметров элементной базы с выбранными основными исходными характеристиками блокинг-генератора.

Ключевые слова: электронный пускорегулирующий аппарат, мощность, математическое описание, фильтр, преобразователь, импульс, резонансная линия ртути, блокинг-генератор

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INTRODUCTION

Recent advances in electrotechnical development involve the effective low-pressure ultraviolet (UV) lamps using electronic ballasts (EBs) [1, 2], which are used in disinfection systems and the control of unwanted odors in the air. Studies of UV radiation and the effectiveness of low-pressure UV lamps are presented in[1, 2, 3] [3–5]. When used in radiation sources for lighting installations based on tubular low-pressure UV lamps, EBs should meet the following basic requirements: low cost, reliable ignition of low-pressure discharge lamps at low temperatures, and ensuring the high energy efficiency of lamps without sacrificing reliability.

Compared with electromagnetic ballasts, EBs allow the luminous efficiency and power factor of discharge lamps to be increased, reducing the weight of units by 2–4 times along with the consumption of scarce materials. Currently available high-frequency (HF) EBs support additional functions, such as pre-heating of lamp electrodes, the ability to regulate radiation flux, etc.

In the present paper, a circuit design for EB with the lamp powered by HF rectangular pulses was proposed. The review of the published literature has revealed HF pulse power modes to be more effective than the sinusoidal ones [6, 7].

To improve the energy efficiency of UV lamps related to low-pressure discharge lamps, they should be completed with pulsed EB supplying power at the frequency of 22–50 kHz. Various EB circuit designs may include such basic units as a line filter, rectifier, power factor corrector, smoothing filter, HF converter, ballast, and ignition device [8–12].

RESEARCH AND MATHEMATICAL DESCRIPTION OF PULSED EB

The structural diagram shown in Fig. 1 has been used for implementing the pulsed EB practically.

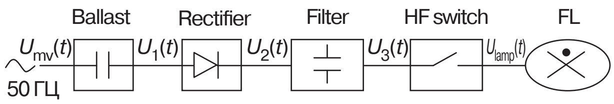

Fig. 1. Structural diagram of the pulsed EB. $U_{mv}(t)$ is mains voltage (voltage at the pulsed EB input), $U_{lamp}(t)$ is a lamp operating voltage, and FL is a fluorescent lamp

Along with the instantaneous voltage values given in Fig. 2, the structural diagram shows that the amplitude of HF pulses may be limited by the mains voltage curve $U_1(t)$ transformed by the rectifier. At the HF switch input, a smoothing filter is located. The voltage begins to drop exponentially $U_3(t)$ at the point in the diagram (Fig. 2) at which the sinusoidal voltage $U_2(t)$ becomes lower than the filter capacitor voltage. Here, the dashed line indicates the smoothing filter input voltage while the solid line shows its output voltage.

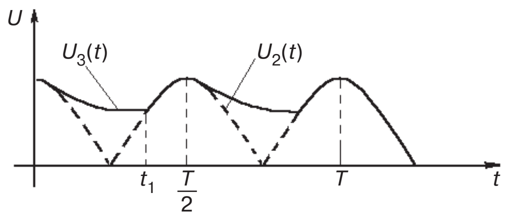

Fig. 2. Diagram for instantaneous values of the voltage at the HF switch input

Two equations describing the parameters of the pulses formed by the envelope in the form of the input voltage $U_{input}(t)$ and the industrial frequency current can be written for different instants of time. The HF switch output voltage has an amplitude corresponding to the amplitude of voltage $U_3(t)$, while the duration of pulses $t_{pulse}(t)$ (or pause $t_{pause}(t)$) depends on their amplitude. The value $t_{pulse}(t)$ is determined according to the lamp operating voltage $U_{lamp}(t)$ and empirical constant coefficients a, b.

The dependence of the lamp current on voltage is determined by its current voltage characteristic at known values of nominal voltage $U_{nom}(t)$ and current $I_{nom}(t)$, as well as the operating voltage $U_{lamp}(t)$.

The mathematical description may be represented by a system of equations, as follows:

$$\begin{cases} U_{lamp}(t) = U_m \exp\left(-\frac{1}{RC}t\right) \text{ at } 0 < t < t_1, \\ U_{lamp}(t) = U_m \cos 314t \text{ at } t_1 < t < \frac{T}{2}, \\ t_{pulse}(t) = \frac{a}{U_{lamp}(t) + b}, \\ i(t) = I_{nom} \exp\left(\frac{\ln U_{lamp}(t) - \ln U_{nom}(t)}{\rho}\right). \end{cases} \quad (1)$$

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Here, U_m is mains voltage amplitude, V; C is the smoothing filter capacity, F; R is an active component of the lamp resistance, Ohm; $i(t)$ is the current at the HF switch input, A; the angular frequency ω at signal frequency f = 50 Hz is equal to $\omega = 2\pi f = 314\ s^{-1}$; ρ is the constant factor equal to 0.20–0.26; a and b are constant factors equal to 0.0025 s · V and 30 V, respectively.

The parameters of the 'UV lamp–EB' set on condition of the lamp power constancy were calculated for the UV lamps under study by equations (1) and using an adaptive model for determining the flux of the 254-nm mercury resonance line presented in the work of Kovalenko [4].

The main calculation results are shown in Table.

Table. Relative values for radiant efficiency of the 254-nm line for UV lamps complete with pulsed EB (ratio of radiant efficiency in pulsed (H_{pulse}) and stationary (H_{st}) modes). P_{av} is an average power of the lamp complete with pulsed EB

P_{av}, W	f, kHz	t_{pulse}, µs	Duty cycle	C, µF	H_{pulse}/H_{st}
30.1	23.1	25	2.35	30	0.687
30.0	23.7	25	2.42	50	0.822
30.0	41.0	6	1.32	50	0.927
29.9	43.8	10	1.77	50	0.975
40.0	23.6	25	2.41	50	0.746
39.9	43.6	10	1.77	50	0.880

The relative values for radiant efficiency of the 254-nm mercury line for the considered UV lamps (LE 30 and LER 40) complete with pulsed EB (ratio of radiant efficiency in pulsed and stationary modes) were determined on the basis of the calculation results. The lamp operating mode with a constant-voltage power supply was taken for stationary mode. However, despite its efficiency, stationary mode cannot be used for discharge lamps due to the cataphoresis phenomenon resulting in the decreased radiation flux of the lamp for a short period of time.

Table shows that the modes at a frequency of 41–44 kHz at a duty cycle of 1.77 may be considered the most effective ones for UV lamps complete with pulsed EB under study.

CIRCUIT DESIGN FOR PULSED EB

An electronic semiconductor switching and power supply circuit for the discharge lamp with selected original elements developed on the basis of theoretical EB research provides high stability of the radiant flux at unstable input voltages as a result of using feedback to determine the dependence of current pulse frequency $t_{pulse}(t)$ on the input voltage (Fig. 3).

The switching and power supply circuit for the discharge lamp shown in Fig. 3 is self-excited. The HF switch operating frequencies are above 25 kHz. A midfrequency transistor may be used as the power semiconductor element. Upon voltage being applied to the input, a voltage jump may occur at the collector of VT transistor; this is transmitted through the C5 capacitor to the primary winding of Tr transformer with a ferrite core having a hysteresis loop of rectangular shape.

When calculating the element parameters for the selected version of the pulsed EB, the lamp power values and HF power supply modes were selected.

Computational formulas and results of calculating main parameters for the circuit (Fig. 3) are presented taking the parameters of pulses—amplitudes of current and voltage, their duration, and frequency—into account.

The following basic initial parameters for calculating the blocking generator (HF switch) could be taken as an example:

$E_{C} = 150$ V, $t_{pulse} = 6–10$ µs, $f = 40–50$ kHz, $R_s = 239$ Ohm,

$I_{av} = 0.43$ A, $T^0 = 20–25$ °C, $R_d = 20$ Ohm, $R_b = 100$ Ohm.

Here, E_C is an electromotive force in the transistor output circuit, R_s is the signal source resistance or output resistance of the previous stage, I_{av} is an average value of the lamp pulse current, T^0 is the transistor case temperature in operating mode, R_d is the damping circuit resistance, and R_b is the base volume resistance.

A KT809A transistor was selected considering such parameters as the collector power dissipation, collector voltage, and pulse duration.

The inductance L of the primary winding may be calculated from the following ratio:

$$L = \frac{\left(E_C - U_{CR}\right) t_{pulse}}{I_{CA} - \left(I_{IC} - 0.8 E_C / r_{in}\right)}. \quad (2)$$

Here, U_{CR} is the collector residual voltage of saturated transistor (U_{CR} = 3 V); I_{CA} is the allowable collector current of transistor (I_{CA} = 5 A); I_{IC} is the initial current in collector circuit; and r_{in} is the input resistance of the transistor in the circuit with common radiator (r_{in} = 34 Ohm).

The maximum collector voltage may be determined by the following formula:

$$U_{Cm} = E_C\left(1 + \frac{t_{pulse}}{L} R_e\right), \quad (3)$$

[4] Kovalenko O.Yu. *Lighting installations for increasing the productivity of farm animals*. Dr. Sci. Thesis (Eng.). Saransk: Ogarev MSU; 2009 (in Russ.).

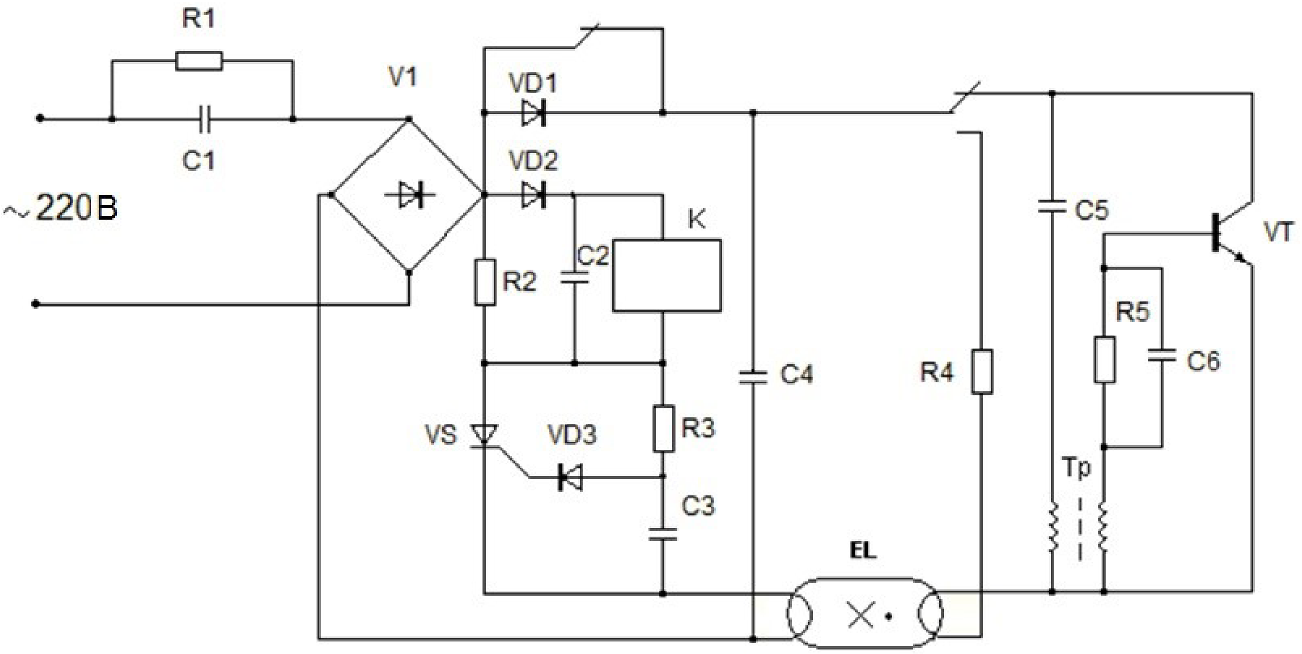

Fig. 3. Switching and power supply circuit for a discharge lamp with rated voltage 220 V

where R_e is the equivalent resistance of collector circuit written as follows:

$$R_e = \frac{R_s\left(R_d + r_d\right)}{R_s + R_d + r_d}. \qquad (4)$$

Here, R_d is assumed to be equal to 20 Ohm; r_d is the forward resistance of diode (r_d = 5 Ohm).

When the temperature rises $(T^0 > T_1^e)$, the value of thermal current generated by the collector residual voltage of a saturated transistor may be determined, as follows:

$$I_{CT} = I_{CT}\left(T_1^e\right)e^{0.08\left(T^0 - T_1^e\right)}. \qquad (5)$$

Here, T_1^e is the environment temperature. The current I_{CT} (transition thermal current) may approximately double with the temperature increased by 10°C. Assuming the base potential (constant voltage source) E_b = E_C, capacitance C5 at resistance R_b = 100 Ohm may be determined in the following way:

$$C5 = \frac{\tau_{acc}}{\left(1 - \theta\frac{\tau_{acc}}{\tau_{pulse}}\right)\left(r_b + R_b\right)}. \qquad (6)$$

Here, τ_{acc} is the accumulation time constant (for KT809A transistor, τ_{acc} = 28.9 μs); τ_{pulse} is the pulse duration, μs; r_b is the transistor base input resistance; and θ is the coefficient defined by the following formula:

$$\theta = \frac{t_{pulse}\left(\tau_{in} - \tau_{acc}\right)}{\tau_{in}\tau_{acc}}. \qquad (7)$$

Here, τ_{in} is the capacity charging time constant characterized by the pulse leading edge time; τ_{in} = 40 μs.

The capacitor C6 required for compensating the inductive resistance of the transformer secondary winding and resistance R1, R_d is selected on the basis of calculations. The load resistance is taken as R_s = 349 Ohm. Diodes should be selected to account for the value of current through the load equal to the average value of the lamp pulse current I_{av} = 0.43 A.

The pulsation ratio K of the rectifying voltage is taken as equal to 0.3.

The smoothing filter capacity may be determined by the following formula:

$$C4 = \frac{1}{\omega R_s}\sqrt{\frac{1.68}{\operatorname{arth}^2 K} - 4}. \qquad (8)$$

The alternating current circuit capacitance at constant empirical coefficient m, depending on the rectifier type (for a double half-period rectifier, m = 0.34), is determined by the following formula:

$$C1 = \frac{(0.455K + 1.15)}{\omega R_s\sqrt{\frac{1}{m^2} - (1+K)^2\frac{K}{0.57}\left(2 - \frac{K}{0.57}\right) - (1+K)\left(1 - \frac{K}{0.57}\right)}}. \qquad (9)$$

Thus, the following element base is defined on the basis of calculation results with selected main parameters for the blocking generator:

- Capacitors: C1, 5 μF × 250 V (KBG-MP); C4, 50.0 μF × 350 V (K-50-7), C5, 470 μF; C6, 5 μF;
- Resistors: R1 = 10 Ohm; R2 = 20 Ohm; R3 = 200 Ohm; R4 = 2 Ohm; R5 = 5.1 Ohm;
- Diodes: VD1–VD4, D 229 L; VD5, D 226 B;
- Transistor: VT, KT 809 A.

CONCLUSIONS

In the study, the relative values for radiant efficiency of the 254-nm mercury line have been calculated for the considered UV lamps complete with pulsed EB (ratio of radiant efficiency in pulsed and stationary modes). The most efficient modes were defined along with the circuit design for the pulsed EB allowing the HF switch operation to be controlled. The high stability of the radiant flux was ensured using feedback to control the duration of current and voltage pulses.

Authors' contributions

O.Yu. Kovalenko—overall supervision, planning and conducting research.

S.A. Mikaeva—conducting research, data collection and processing, and literature review.

Yu.A. Zhuravleva—conducting research, analysis of results, and writing the text of the article.

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