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PAPER

Preventing method of acoustic resonance in the high-pressure discharge lamps

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The article analyzes available methods for preventing acoustic resonance of high pressure lamps. A new method is proposed, the main idea of which is the filing of a high-voltage lamp modulated by a pseudo-random signal. An analysis of the spectral characteristics of the signal entering the lamp is made, the mathematical modeling of the set of a "discharge lamp - prototype of the device" - is implemented, which implements the proposed control method of the lamp. The results of simulation and oscillograms, taken from the prototype, which confirms the results of theoretical research, are presented.

K e y w o r d s: preventing of acoustic resonance, high-pressure discharge lamp, pseudo-random signal

1 Introduction

In order to increase the efficiency of the set, the push-regulating ballast, a gas-discharge low pressure lamp, for a long time uses electronic ballasts that operate at high frequencies [1], [2]. Their advantages are:

- high coefficient of efficiency that significantly exceeds the similar parameter of electromagnetic ballast;
- the possibility of adjusting the current of the lamp in the specified limits;
- increase of light output;

eliminating the possibility of lamp operation emergencies.

However, with the use of high-frequency electronic ballasts for work with high-discharge gas-discharge lamps (mercury and sodium vapor, metal halide lamps, etc.), there is a problem of the occurrence of acoustic resonance in the arc tubes of these lamps [3], [4]. Acoustic resonance has been studied in many scientific papers. Acoustic resonance frequencies range from 3 kHz to 150 kHz. [4], [5].

The reason for this phenomenon is that when the direction of current flow changes due to the redistribution of charge carriers, acoustic waves arise which cause the forced mechanical vibrations of the gas medium of the arc tube, its walls, and even the fittings of its suspension. For some AC current frequency, the frequency of acoustic waves in an arc may coincide with the resonant frequency of mechanical oscillations in the system. The spectrum of the above resonant frequencies of mechanical oscillations depends on the geometric dimensions of the lamp arc tube, the speed of sound in it (which, in turn, depends on the pressure), the features of the designs of the arc tube and many other parameters [4],[5].

Therefore, each of the lamps, including the same type and the same power, can have different frequencies of the major resonance due to different electrical and structural parameters, which change in the direction of decrease or increase with the increase of the lamp's life time. In addition to the major resonance, there are resonances on other frequency harmonics, which negatively affects the lamp gas discharge state. The consequences of acoustic resonance are the instability of the lamp burning, the arc extinction and, at worst, the physical destruction of the arc tube.

As a voltage supply of a high pressure lamp, in most cases, alternating voltage is used, the frequency of which does not exceed 200 Hz, thus excluding the possibility of an acoustic resonance. These operating frequencies lie in the audio range and therefore the process of lamp combustion is accompanied by significant interfering noises. In addition, the size of the reactive elements used in the lamp's switching scheme remains significant compared to the ballasts at 50-60 Hz. Therefore, the search for ways of supplying high-pressure gas discharge lamps is still relevant.

As one of the effective methods for controlling acoustic resonance is the use of modulation of the main frequency of the supply voltage of the lamp by another signal. One of these schemes (US Patent No 6,144,172) [6] (Fig. 1) contains a white noise generator, which is based on a linear feedback shift register, the output signal of which flows through a filter to a voltage-controlled variable frequency generator (VCO). The signal from the generator output

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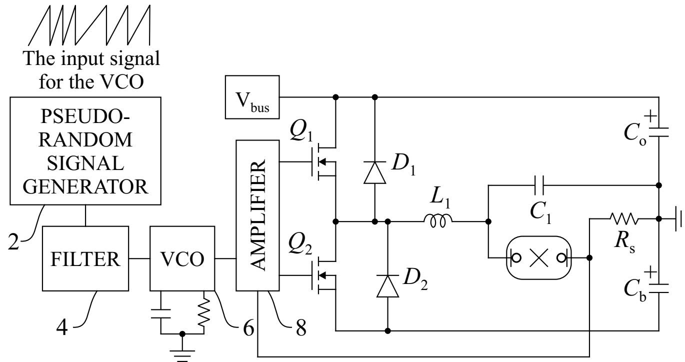

Fig. 1. Scheme of electronic ballast [4] for gas-discharge lamp: VCO(voltage controlled oscillator)

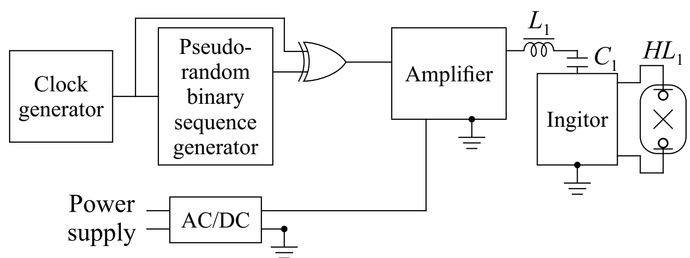

Fig. 2. Block diagram of the proposed device

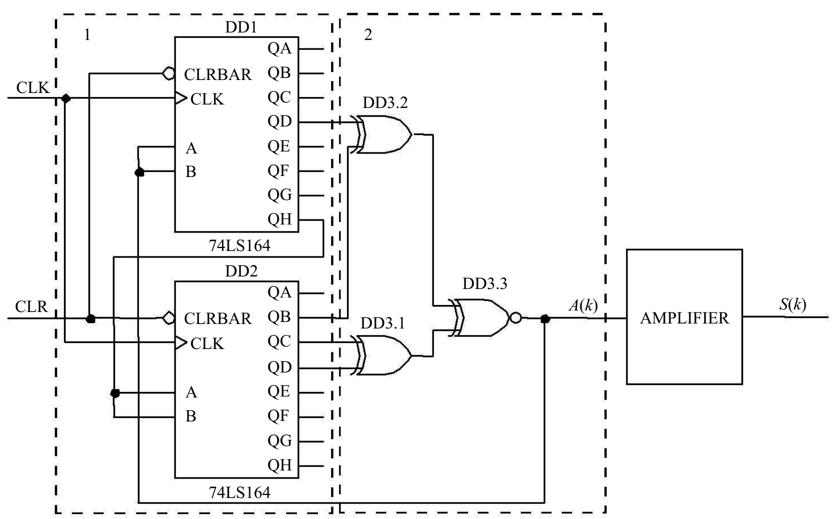

Fig. 3. Generator based on a linear feedback shift register LFSR ($N = 12$)

enters the previous output key amplifier and is fed to the circuit of the inductive ballast, constructed in the usual way. The frequency range of the frequency of the VCO generator is usually chosen small. As a result, the output frequency of the signal coming to the lamp is changed by some pseudorandom behavior. The frequency of the change of the output signal of the pseudorandom signal generator is chosen much less than the average frequency of the VCO.

When working on the circuit, the frequency of the signal on the lamp is constantly changing and the resonance of the arc tube has not time to develop due to the inertia of the processes in the lamp.

In US Pat. No 4,337,136 [7], instead of a pseudo-random signal generator, a low-frequency sawtooth generator is used. In [7], it is noted that the instability of the arc caused by acoustic resonance depends both on the shape of the bearing signal and on the form of the modulating signal, and that the rectangular shape of the bearing wave is much more acceptable for ensuring the arc stability than the sinusoidal carrier, and that the modulation signal of the sawform (from 1 ms to 10 ms per cycle with a reverse run time less than 1 ms) is better than a triangular modulating signal.

Another disadvantage ot the shem is the possibility of an acoustic resonance in the lamp at a minimum or at the maximum working frequency of the generator. This is due to the fact that the magnitude of the spectral density in the signal arriving at the lamp is the highest at the boundary of the frequency range. A significant drawback of such circuits is the complexity of their miniaturization due to the widespread use of analog signals and components in the control circuit.

The analysis of the described schemes allows us to conclude that in the case when a broadband signal is presented to a lamp, the energy distributed in a dangerous frequency interval will be small and the acoustic resonance phenomena will not occur or will have little effect. The signal must also meet these requirements:

- the average value of the signal must be zero; otherwise, the phenomenon of migration of ions to the one of the electrodes of a lamp may occur;
- the duration of the constant state at the lamp inlet does not exceed the set value T , which is connected with the current limitation by means of reactive elements.

2 The proposed device

The block diagram of the proposed device is shown in Fig. 2. It consists of a clock generator 1, which generates at its output a voltage in the form of a meandering frequency of 10-40 kHz. This signal enters the input of a pseudorandom sequence based on linear feedback shift register(LFSR), which generates a pseudo-random signal. The output signal of the generator enters the phase modulator, built on the basis of the element"Exclusive-OR " (XOR), the output of which is obtained pseudorandom phase signal.

The output signal is fed to a powerful amplifier, which feeds a gas-discharge lamp, connected through the LC circuit, and, if necessary, an ignition device. A pseudorandom signal generator uses a linear feedback shift register (LFSR). Such a generator (Fig. 3) consists of, in fact, the shift register 1, which receives pulses of clock frequency, and the feedback circuit 2, which calculates the value of the next bit, which enters the information inputs of the registers A and B of element DD1.

The register consists of two eight-bit registers that have a common CLK clock signal. The number of flip-flop circuits, which are covered by feedback circuit, considered as register length and denoted as N.

The bits of the cells will be numbered $i = 0,\ 1, \dots N-1$, the contents of the cell with the number and denoted as Q_i. The new bit value Q_0 is determined by the shift of the bits in the register by the feedback circuit.

The feedback circuit function is a linear Boolean function from the values of some case bits of register. The function executes the multiplication of the register bits by the coefficients c_i and the "Exclusive-OR" operation above the multiplication results

$$A = \overline{\bigoplus_{i=0}^{N-1} \overline{c_i} \vee Q_i}. \tag{1}$$

The number of coefficients coincides with the number of bits in the register, the coefficients c_i take the value $\{0,\ 1\}$, with the coefficient $c_{N-1} = 1$, and the remaining coefficients are selected in a special way to obtain a given sequence length. The amplifier is designed to convert the signal by the following expression

$$S(k) = 2A(k) - 1. \tag{2}$$

Note that the signal $S(k)$ takes values -1 and +1, and the signal $A(k)$ is 0 and 1.

During each step, the linear feedback shift register performs the following operations:

- reads the bit placed in the $N-1$-th flip-flop. This bit is the next bit of the output sequence;
- the feedback circuit function calculates a new value for a zeroth flip-flop circuit using the values of other bits by the corresponding formula;
- the content of each flip-flop moves to the next cell;
- the value of the bit calculated earlier is written to the zeroth trigger.

Obviously, the state of "all units" at register output can generate only a single value output feedback circuit, resulting in a sequence, which consists only of the units, so getting to this state should be deleted. A shifting register has 2^N initial states, which are given by the same combination of bits in the register. Consequently, the number of permissible states is $2^N - 1$, and the maximum sequence has a period not exceeding $M = 2^N - 1$. In this case, the sequence $S(k)$ with a maximum length $M = 2^N - 1$ at the output of the circuit is called the M-sequence [8].

3 Signal representation

The voltage on the amplifier output in this scheme can be represented as

$$u(t) = \sum_{n=-\infty}^{\infty} S(n) q(t/\Delta T - n) \tag{3}$$

where $S(n)$ is a pseudo-random periodic sequence consisting of a set of -1 and $+1$, and $q(t/\Delta T - n)$ is the fill pulse signal, which is defined as follows

$$q(\lambda) = \begin{cases} 0 & \text{if } \lambda < 0 \text{ or } \lambda \geq 1 \\ q_0(\lambda) & \text{if } 0 \leq \lambda < 1 \end{cases}. \tag{4}$$

To the signal imposes the following requirements: First, the signal $q(\lambda)$ must have a constant component equal to 0, otherwise the constant component of the resulting signal $u(t)$ occurs; and secondly, the signal should

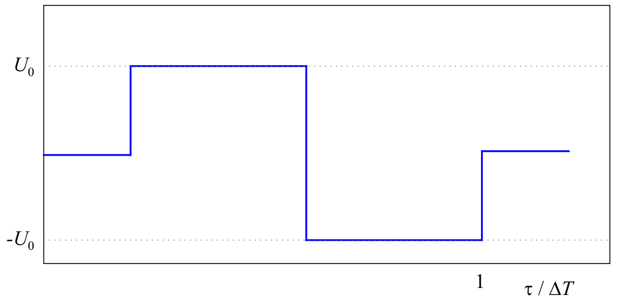

Fig. 4. Modulating signal $q(t/\Delta T)$

be simple and get only the $+1$ and -1 levels. Let us prove that the signal $u(t)$ can also be written as a convolution

$$u(t) = \lim_{L\to\infty} \int\limits_{-L\Delta T/2}^{L\Delta T/2} q(\tau/\Delta T) s(t-\tau, L) \mathrm{d}\tau, \qquad (5)$$

where $s(t, L) = \sum\limits_{n=-L}^{L-1} S(n)\delta(t-\Delta T n)$ - representation of a pulse sequence through a set of Dirac delta functions. Since outside the interval $[0,\ \Delta T]$ function $q(t/\Delta T)$ identically equals to zero, the integral can be written in the form

$$u(t) = \lim_{L\to\infty} \int\limits_{-\infty}^{\infty} q\tau/\Delta T \sum_{n=-L}^{L-1} S(n)\delta(t-\Delta T n-\tau)\mathrm{d}\tau. \quad (6)$$

Changing the order of integration and summation, and also using the filtering property of the delta functions $\delta(t)$, we come to the conclusion that the representation of the output signal can be written as

$$u(t) = \lim_{L\to\infty} \sum_{n=-L}^{L-1} \int\limits_{-\infty}^{\infty} q(\tau/\Delta T) S(n) \delta(t-\Delta T n-\tau)\mathrm{d}\tau. \qquad (7)$$

Due to the periodicity with the period $T_u = \Delta T\ M$ (where M is the period of the sequence at the output of a register with a linear feedback circuit), the voltage $u(t)$ can be expanded into a complex Fourier series at frequencies $\omega_k = \frac{2\pi\ k}{T_u} = \frac{2\pi\ k}{M\Delta T}$. Lets write down the coefficients of the expansion of the sinal $u(t)$ in the Fourier series on the interval $[-T_u/2, T_u/2,]$ As shown in [7] , the signal has an amplitude of harmonics

$$U(\omega_k) = \frac{1}{T_u}\int\limits_{-T_u/2}^{T_u/2} u(t)\exp(-j\omega_k t)\mathrm{d}t =$$
$$\frac{1}{T_u}\int\limits_{-T_u/2}^{T_u/2}\int\limits_{0}^{\Delta T} q(\tau/\Delta T)\times \sum_{n=-\infty}^{\infty} S(n)\delta(t-\tau-\Delta T n)\times$$
$$\times\ \mathrm{d}\tau \exp(-j\omega_k t)\mathrm{d}t \qquad (8)$$

$$|U(\omega_k)| = \frac{|Q(\omega_k)|}{M} \times \begin{cases} \sqrt{M+1} & \text{if } \omega_k\Delta T \neq 2\pi z \\ 1 & \text{if } \omega_k \Delta T = 2\pi z \end{cases} \qquad (9)$$

where $Q(\omega_k)$ - is the Fourier series expansion of modulation signal at interval ΔT, z - is an integer.

$$Q(\omega_k) = \frac{1}{\Delta T}\int\limits_{0}^{\Delta T} q(\tau/\Delta T)\exp(-j\omega_k\tau)\mathrm{d}\tau =$$
$$= \int\limits_{0}^{,} q(\eta)\exp(-j\omega_k \eta\Delta T)\mathrm{d}\tau \qquad (10)$$

Using the bit width of the shift register N

$$|U(\omega_k)| = \frac{|Q(\omega_k)|}{2^N-1} \times \begin{cases} 2^{N/2} & \text{if } \omega_k\Delta T \neq 2\pi z \\ 1 & \text{if } \omega_k\Delta T = 2\pi z \end{cases}. \qquad (11)$$

$$Q(\omega) = jU_0 \frac{4\sin(\omega\Delta T/4)^2}{\omega \Delta T}\exp\left(-\frac{j\omega\Delta T}{2}\right) \qquad (12)$$

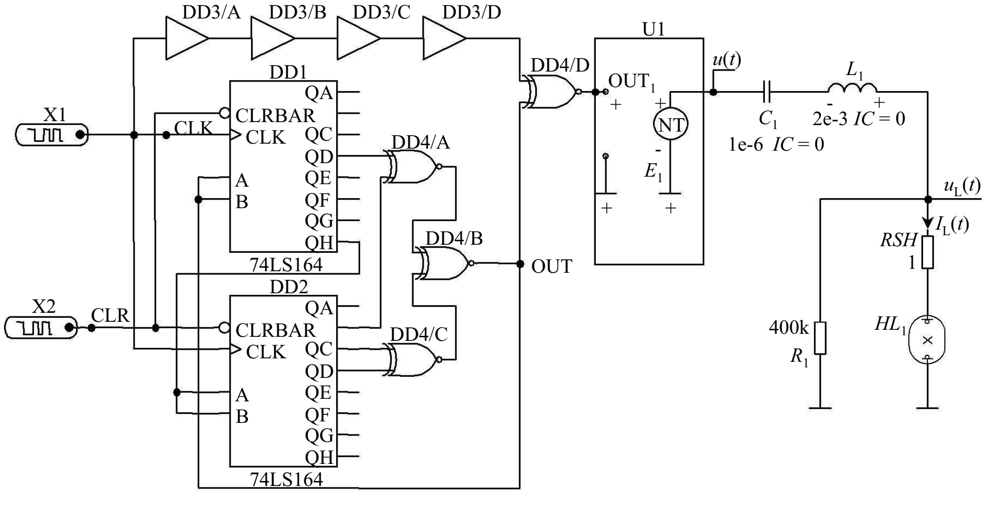

Fig. 5. Model of the proposed scheme in microcap environment

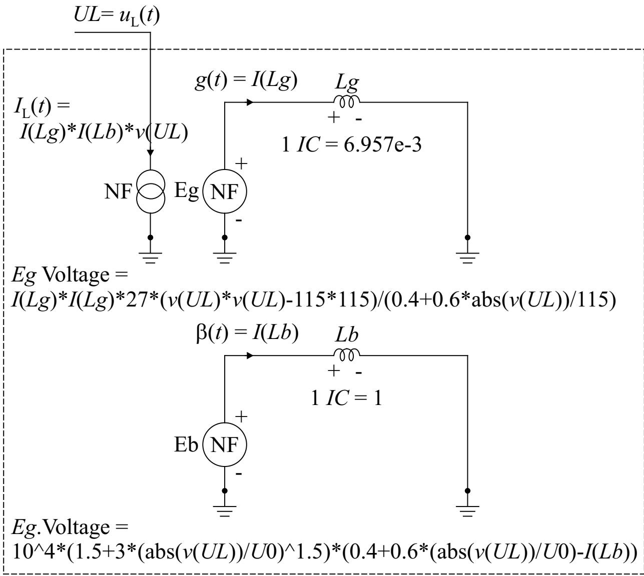

Fig. 6. Model of the discharge lamp drl-80

where j - is the imaginary unit. Module of spectral density of a signal is equal

$$Q(\omega) = U_0 \frac{4\sin(\omega\Delta T/4)^2}{\omega\Delta T} \tag{13}$$

$$|U(\omega_k)| = Q(\omega) \times \begin{cases} \sqrt{M+1} & \text{if } \omega_k\Delta T \neq 2\pi z \\ 1 & \text{if } \omega_k\Delta T = 2\pi z \end{cases} \tag{14}$$

Consequently, the received signal is broadband, so the energy density in the vicinity of a dangerous resonance frequency will be small and will not significantly affect the parameters of the arc and will not cause resonance. In addition, with an increase in the M amplitudes, the harmonics fall almost proportionally to $sqrtM$.

4 Simulation result

A schematic diagram that corresponds to the above structural scheme and generates the signal described, was modeled in the MicroCAP environment (Fig. 5). The clock source X1 generates a signal with a period of 60 μs and a frequency of 16.6 kHz, which is used for general synchronization of the circuit.

The functional generator X2 generates a reset signal that enters the corresponding inputs of the shift registers 74LS164 (DD1, DD2). The sequence of buffers DD3/A DD3/D is designed to delay the clock signal and avoid race signals. In the case of using more high-speed shift registers, there is no need for these buffers. The shift registers, together with the logical elements DD4/A DD4/C, form a linear feedback shift register. The DD4/D element is used to form a modulated pseudorandom signal that enters the output amplifier U1. To the output of the amplifier is connected sequentially LC ballast and discharge lamp HL1.

Results of simulation of the digital part of the scheme are shown in Fig. 7-9, from which it follows that the phase of the output signal becomes 0 or 180° depending on the pseudorandom signal. As the timing diagram in Figure 7 shows, the signal on the amplifier's input (D(OUT1)) has a complex structure and does not appear to have a period comparable to the period of the clock signal D(CLK).An 80 W discharge lamp was used as a test discharge lamp, the model of which was built in accordance with the description in [10, 11,12].

In this model, the components of lamp conductivity are described by two differential equations

$$\frac{dg_L}{dt} = {g_L}^2 M_1(u_L(t)). \tag{15}$$

$$\frac{d\beta}{dt} = M_2(u_L(t))(\beta_0 - \beta). \tag{16}$$

where g_L is the component of the conductivity of the lamp, which depends on the concentration of electrons in the discharge gap, β is a component of the conductivity, which takes into account the additional effects. The voltage and current of lamp are related by the algebraic equation

$$i_L(t) = \beta\ g_L\ u_L(t). \tag{17}$$

The functions $M_1(u_L(t))$ and $M_2(u_L(t))$ are depended on the ratio of the instantaneous value of the voltage on the lamp $u_L(t)$ to the nominal voltage at the lamp at DC U_0 and are described by the folowing dependencies

$$M_1(u_L(t)) = \frac{A_L U_0^2\left((u_L(t)/U_0)^2 - 1\right.}{)} 0.4 + 0.6\ \|u_L(t)/U_0\|. \tag{18}$$

$$M_2(u_L(t)) = 10^4\left(1.5 + 3|u_L(t)/U_0|^{1.5}\right). \tag{19}$$

The parameter A_L depends on the design parameters of the lamp arc and for the discharge lamp DRL-80 becomes . Value of β_0 is determined from the equation

$$\beta_0 = 0.4 + 0.6\ |u_L(t)/U_0|. \tag{20}$$

Using equations (15) - (20), a model of discharge lamp was constructed, which was used in the simulation of the analog part of the scheme. The schematic diagram of the corresponding model is shown in Fig. 6.

The current flowing through the inductance L_g models the component of the conductivity of the lamp, which depends on the electron concentration in the discharge gap. The voltage source E_g of the NFV type controls the change in current through an inductance of L_g equal to 1 H. The voltage at the terminals of the source $E_g(t)$ is determined by the dependence of

$$E_g(t) = \frac{27 I(L_g)^2 U_0^2\left((u_L(t)/U_0)^2 - 1\right)}{0.4 + 0.6\,|u_L(t)/U_0|} \tag{21}$$

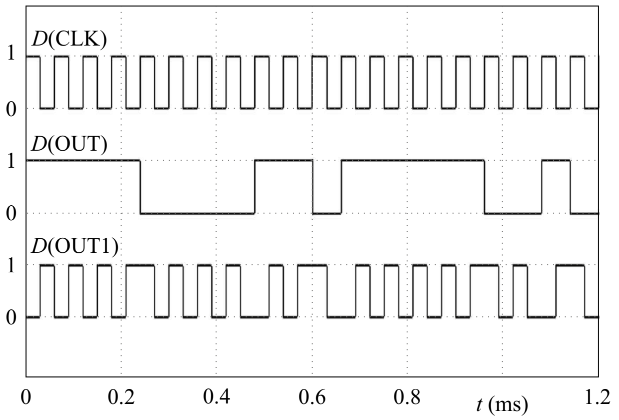

Fig. 7. Timing diagram of the main binary signals in the circuit: D(?lk)-signal at the output of the clock generator, D(out)-the signal at the output of the pseudorandom binary sequence, D(out1)-the signal at the input of the amplifier

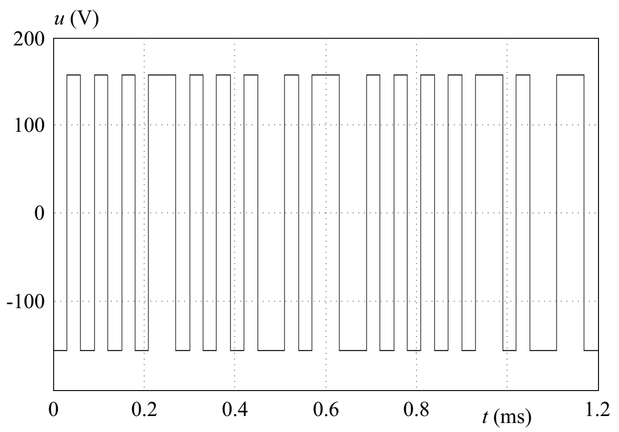

Fig. 8. Fragment of the oscillogram of the signal at the amplifier(v(out2)output

The differential equation describing the current through the inductance L_g, which corresponds to the first component of the conductivity of the lamp, is as follows

$$L_g \frac{\mathrm{d}I_g(t)}{\mathrm{d}t} = E_g(t) = \frac{27I(L_g)^2U_0^2\big((u_L(t)/U_0)^2 - 1\big)}{0.4 + 0.6|u_L(t)/U_0|} \tag{22}$$

where $u_L(t)$ is the voltage on the lamp, $I(L_g)$ is the current through the model inductance L_g Since the inductance L_g is virtual, for simplicity, take its inductance equal to 1 H. In this case, the virtual current through the inductance will be numerically equal to the lamp conductivity.

The current flowing through the inductance of the model Lb is numerically equal to the component of the conductivity of the lamp, which takes into account additional effects. For simplify the value of the inductance Lb is selected to be 1 H. Similar to the previous model circle, the inductance Lb is controlled by the voltage source E_b, the value of which is determined by the right-hand side of equation (16) and (19), (20). The voltage E_b is equal to

$$\begin{aligned} E_b(t) = 10^4\big(1.5 + 3|u_L(t)/U_0|^{1.5}\big)\times \\ \times\big(0.4 + 0.6|u_L(t)/U_0| - I(L_b)\big) \end{aligned} \tag{23}$$

The differential equation describing the model current due to the inductance Lb is as follows

$$\begin{aligned} L_b\frac{\mathrm{d}I_b(t)}{dt} = E_b(t) = 10^4\big(1.5 + 3|u_L(t)/U_0|^{1.5}\big)\times \\ \times(0.4 + 0.6|u_L(t)/U_0| - I(L_b)\big), \end{aligned} \tag{24}$$

where $I(Lb)$ is the current through the virtual model inductance Lb. Since $Lb = 1$ H, the equations essentially coincide with equation (16). The lamp current is defined as the product of the model quantities $I(Lb)$, $I(L_g)$ and the voltage on the lamp ($u_L(t)$), which is described in the model using a dependent current source of the NFI type. The output current is

$$i_L(t) = I(Lb)\ I(L_g)\ u_L(t) \tag{25}$$

The adequacy of the adopted model is confirmed by the qualitative coincidence of the waveforms of voltages and currents through the lamp obtained experimentally and using simulation (Fig. 9 and Fig. 10).

A fragment of the oscillogram of the signal at the amplifier V (OUT2) output is shown in Fig. 8. In Fig. 9 a the oscillogram of the voltage on the gas-discharge lamp is shown, and in Fig. 9 b - oscillogram of current through it.

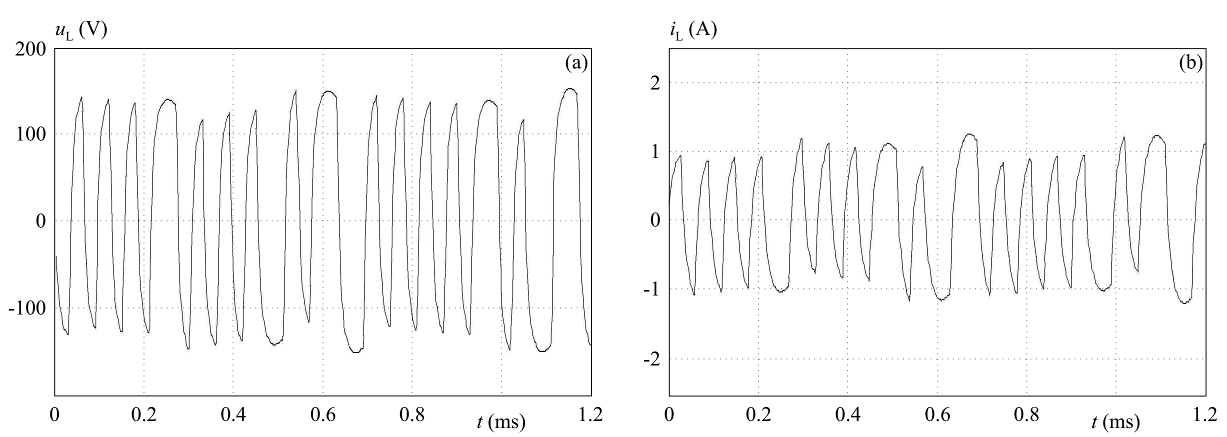

Fig. 9. Fragment of voltage oscillogram on lamp(a)and current through it(b)

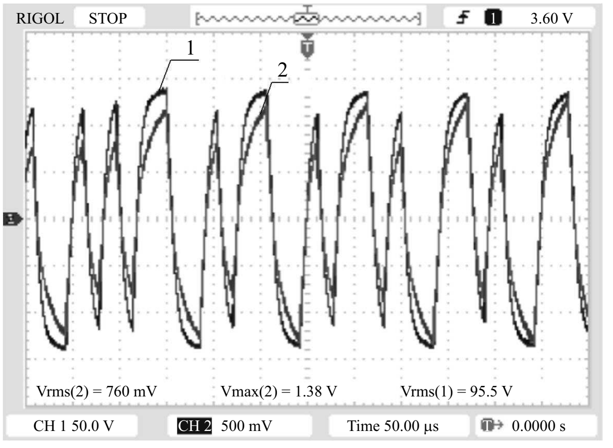

Fig. 10. Fragment of the oscillogram of the voltage on the lamp(1)and the current through it(2), removed from the layout of the system

The proposed driving principle was tested on the layout of the system. The oscillograms obtained on the layout are shown in Fig. 10. Matching the shape of the voltage and current through the lamp in each of the individual fragments of oscillograms, obtained from the real oscillograms of the model system, confirm the adequacy of the adopted model of the discharge lamp. As well as the robustness of the corresponding design.

Figure 11 shows the spectrum amplitude harmonics of lamp voltage obtained as a result of mathematical simulation in MicroCap. As can be seen from Fig. 11, each harmonic of the output signal does not exceed the amplitude of 5 V in the frequency range from 0 to 100 kHz, while the voltage at the output of the amplifier varies from $-220\sqrt{2}/2 = -156$ to $220\sqrt{2}/2 = 156$V.

5 Experimental research

An experimental setup was developed to confirm the theoretical concepts, witch schematic diagram is shown in the following figure 12. The circuit is designed to powering the discharge lamp HL1 type DRL-80. The following components are used in the layout of the system layout:

- pseudo random sequence generator card with output signal converter(# 1),
- digital output signal amplifier board based on IR2103 (# 2)
- power supply unit (#3).

The pseudo-random sequence generator contains a clock generator (25 kHz) on the elements DD1/1DD1/3. For the formation of a pseudorandom sequence, a registers is used (DD2 and DD3). The next bit of the sequence is generated using the logical element DD4/1 and DD1/6. The output signal is formed by the logical element DD4/3. The card # 2 is intended to amplify the signal from the card # 1 and is based on the half-bridge driver (IR2103) and the IRF820 transistors Q1 and Q2. The power supply unit (# 3) with an output voltage of 310 V, designed to power the power section of the circuit.

Stabilization of current through a lamp is carried out with the help of LC ballast. Which is based on components L_b and C_b.

For the determination of shape the current through lamp and lamp voltage, a digital storage oscilloscope Rigol DS-1022C was used, while for the determination of the voltage on the lamp and the current through, a voltmeter / milliammeter PB7-22A was used. (The devices Rigol DS-1022C and PB7-22A not shown in Fig. 12.)

The measured values of instantaneous current and voltage on the lamp are shown in the oscillogram (Fig. 10). No visual manifestations of acoustic resonance: changes in brightness or flashing of the lamp, the appearance of sounds, changes in the mean square voltage value were not observed, which indicates the absence of acoustic resonance in the proposed scheme. The current oscillogram shows the permissible ratio of the maximum current value to the rms value, so the circuit has a practical application.

6 Conclusions

The proposed principle of controlling high-pressure discharge lamps allows avoiding the phenomenon of acoustic resonance or reducing its effect. The main point of the scheme is to distribute energy over the largest possible frequency spectrum, which is being successfully implemented. As can be seen from Fig. 8, 9, 11, each harmonic of the output signal does not exceed the amplitude of 5 V in the frequency range from 0 to 100 kHz, while the voltage at the output of the amplifier varies from $-220\sqrt{2}/2 = -156$ V to $220\sqrt{2}/2 = 156$ V.

The circuit implementation of the principle is quite simple and does not require the presence of a microcontroller. Although, of course, the scheme for generating the necessary pseudo-random signal can be transformed into an algorithm and executed by some microcontroller.

The reasonableness using of the circuit is verified using mathematical modeling and experimentally. During of the mathematical modeling, the model of a gas discharge lamp described in the book [11] has been used.

An experimental verification of the proposed principle was carried out using the circuit diagram of Fig. 12. During experimental verification of the circuit during continuous operation, a constant brightness of the discharge lamp was observed, which proves the absence of visual manifestations of acoustic resonance. Oscillograms of voltage and current, Fig. 9(b) taken during modeling and during experimental verification (Fig. 10) coincide in shape with each other, which indicates the adequacy of the selected mathematical model of the lamp. They also show the permissible ratio of the maximum current to the rms value.

Since the circuit is in no way tied to the properties of a particular type of lamp, there are no fundamental problems with the applicability of the proposed principle

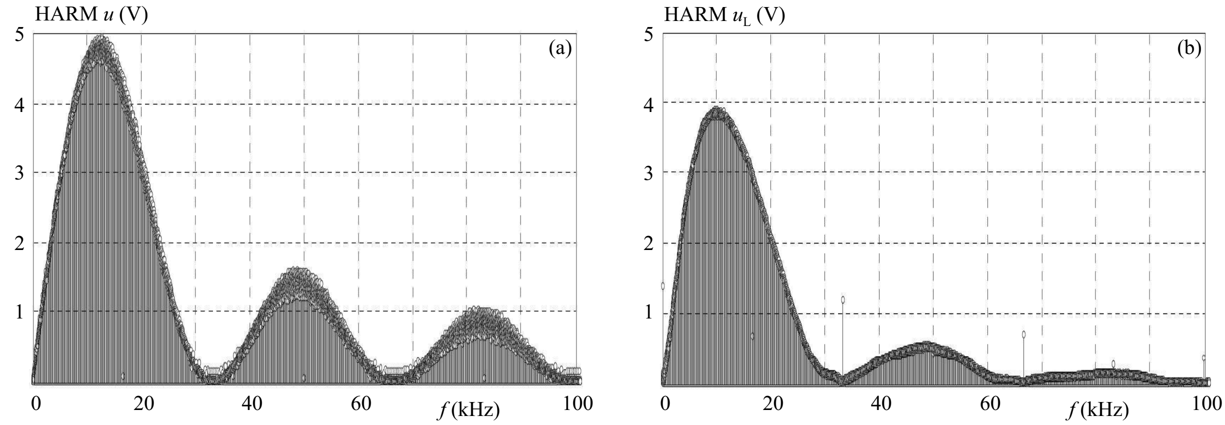

Fig. 11. Amplitude of harmonics of the output signal at the output of the corresponding amplifier $HARM(u(t))$ and at he entrance of the gas discharge lamp $HARM(u_L(t))$

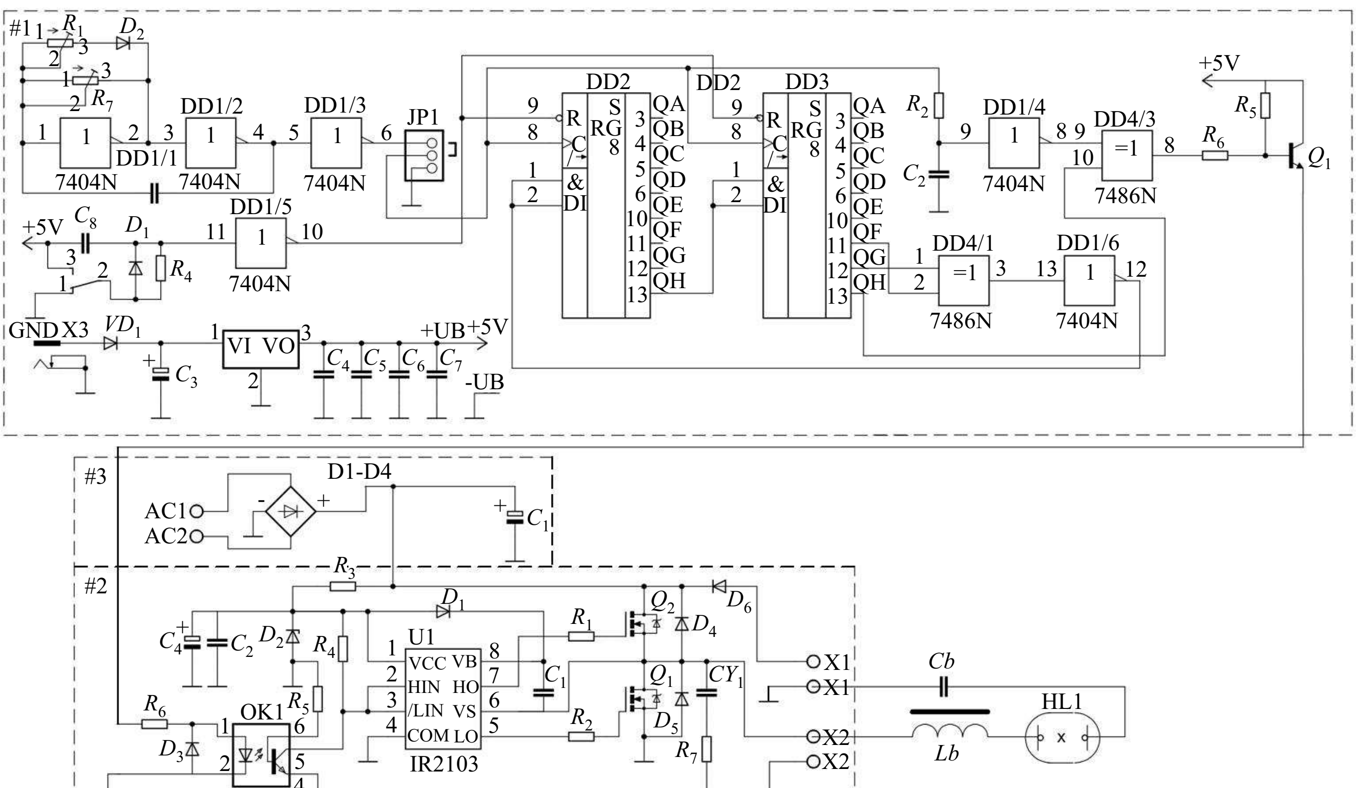

Fig. 12. The schematic diagram of the proposed system

of power supply to discharge lamps of other types, for example, sodium.

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