Vladimir DIAGILEV[1], Valery KOKOVIN[1], Saygid UVAYSOV[2], Andrzej SMOLARZ, Saule RAKHMETULLINA, Yedilkhan AMIRGALIYEV

State University “Dubna”, Branch “Protvino” (1), Moscow Technological University (2), Lublin University of Technology (3), East Kazakhstan State Technical University named after D.Serikbayev (4), Institute Information and Computational Technologies CS MES RK (5)

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Generator modes for technological installations with variable parameters of the oscillating circuit

***Abstract**. This paper presents new approach to the construction of harmonic signal generators based on two-circuit resonant circuits. The purpose of this project is to make essential contribution to the development of generators with stable characteristics when the parameters of the technological process change.*

***Streszczenie.** W artykule przedstawiono nowe podejście do konstrukcji generatorów sygnałów harmonicznych opartych na komplementarnych obwodach rezonansowych. Celem tego projektu jest wniesienie istotnego wkładu w rozwój generatorów o stabilnej charakterystyce przy zmianie parametrów procesu technologicznego. (**Tryby generatora dla instalacji technologicznych ze zmiennymi parametrami obwodu oscylacyjnego**).*

Keywords: generator, filter, interconnected resonant circuits.
Słowa kluczowe: generator, filtr, obwody rezonansowe.

Introduction

In technological installations for ultrasonic machining (USM), piezoelectric and magnetostrictive transducers (PET and SME) of electric oscillations are used in mechanical deformation of the medium with processed products as executive bodies in various technological processes. To generate electric oscillations, specialized generators (inverters) are used. Technical characteristics and operating modes of this generator are subject to special requirements.

Generally, the PET is a package of piezoceramic washers with a diameter of 20 to 120 mm and a thickness of 3 to 10 mm, reinforced with metal straps. When the piezo packet is generated by electric oscillations due to the secondary piezoelectric effect, its bends occur and mechanical oscillations arise [1].

For example, in engineering technologies where ultrasonic treatment is applied, a variety of operations can be performed. Such as:

- Cleaning and washing products,
- Cutting, microwelding, brazing,
- Shaping of parts from hard or brittle materials,
- Hardening of the cutting tool,
- Actuation of a percussion instrument.

In technological installations, especially where percussion impacts on the tool are used, there is a sharp change of the load PET. This affects the generator operating modes. It is known [2,3] that piezoceramics possess a very high electromechanical Q-factor and its resonance characteristic is very sharp, so if the frequencies of the feeding generator and the instrument do not coincide, emergency regimes may arise. In this case, the generator will operate in modes from idle to short circuit, which is accompanied by the occurrence of either over voltages or over currents in the circuit.

Formulation of the problem

On the assumption of the foregoing, it is possible to determine a number of requirements for supplying PET generators capable of operating both on a regular basis and in emergency conditions:

- Sinusoidal shape of the load current,
- High-speed overcurrent and overvoltage protection at the generator output,
- Generator operation with sudden changes in the magnitude of the load.

Schemes of generators for supplying PET and SME are known. As a rule, these are bridge and half-bridge circuits on semiconductor devices, at the output of which a bipolar signal of rectangular shape is formed. To obtain a sinusoidal signal, inductive capacitive filters are used. The use of powerful power transistors (MOSFET and IGBT) with reverse diodes simplifies the problem of creating highly reliable voltage generators of almost any frequency (up to 500–700 kHz). The protection requirements and the operation of the generator under sudden changes in the load value are ensured by using a filter with two interconnected resonant circuits.

The replacement circuit of a transistor generator is shown in Fig.1. This scheme includes the following items:

- stabilized power supply E;
- bridge from transistors M1–M4;
- Control signal drivers *V1–V4* of control unit (CU) of these transistors;
- series-parallel oscillatory circuit, consisting of two contours K1 and K2, which includes a common throttle L_1, a series load of the capacitor C_1 and a parallel capacitor C_2;
- load R_L.

Transistor bridge and filter based on two oscillatory circuits is a serial-parallel inverter.

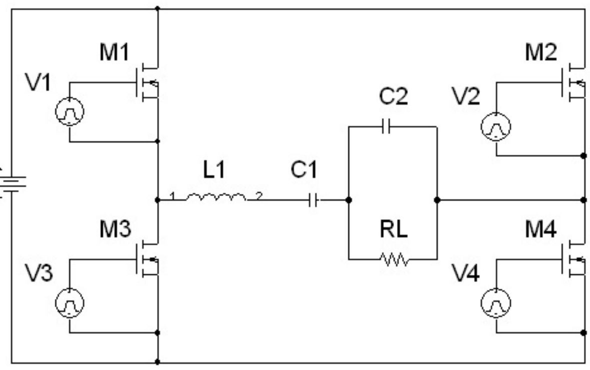

Fig.1. The generator equivalent circuit

The device works as follows. Constant stable voltage is applied to one bridge diagonal of four transistors M1-M4.

The gate of these transistors is fed with control signals from the CU. In pairwise cross switching of transistors M1, M4 and M2, M3 on the other bridge diagonal, an alternating voltage of rectangular shape arises. The voltage amplitude is equal to the voltage of the power supply E, which arrives at the input of the filter L_1, C_1, C_2. This filter is formed by two interconnected resonant circuits, so that the rectangular voltage is converted into a harmonic signal. The process is described in detail in [4]. Before proceeding to the analysis of such a filter, consider single-circuit circuits based on Fig.1, which are obtained by shorting the capacitor C1 (parallel inverter) or by eliminating the capacitor C2 (serial inverter). To analyze such schemes, we use the differential equation [4,5].

$$\frac{U_K}{LC} = \frac{d^2 U_L}{dt^2} + \frac{1}{R_L C}\frac{dU_L}{dt} + \frac{U_L}{LC} \tag{1}$$

U_K – voltage across the diagonal of the transistor bridge, in which a single-loop filter is included, and instead of C we substitute the value of the corresponding capacitor. After solving equation (1), we obtain the expression for the voltage on the R_L.

$$U_L = \frac{U_K}{\omega^2 LC\sqrt{\left(1+\left(\frac{1}{\omega LC}\right)^2 - \left(\frac{2}{LC\omega^2}\right) + \left(\frac{1}{\omega^2 LC}\right)^2\right)}} \tag{2}$$

where $\omega = \frac{f_R}{2\pi}$, f_R – resonant circuit frequency.

To obtain an expression, describing the voltage on the R_L of a series-parallel circuit (Fig.1), it is necessary to solve a third-order differential equation [6].

$$\frac{dU_K}{dtLC_2} = \frac{d^3 U_L}{dt^3} + \frac{1}{R_L C_2}\frac{d^2 U_L}{dt^2} + \frac{C_1 + C_2}{LC_1 C_2}\frac{dU_L}{dt} + \frac{U_L}{LC_1 C_2 R_L} \tag{3}$$

The solution of equation (3) is quite complicated, therefore, in our opinion, it is convenient to use computer simulation of the generator (Fig.1). The advantage of this method of analysis is that the results are obtained in the form of temporal and parametric dependencies. This allows us to evaluate the quantitative and qualitative simulation results, which can serve as initial data for the design of generators with given parameters.

To study the operation modes of the generator replacement circuit, mathematical modeling on a computer was carried out. Herewith the features of the filter construction were considered, namely, a series resonance circuit L_1, C_1, R_L (K_1) and parallel L_1, C_2, R_L (K_2). Initially, these circuits are tuned to the resonance frequency necessary to execute the technological process. In generator design this resonance frequency is specified along with other generator parameters presented below.

- f_R – resonant circuit frequency;
- U_{Lm} – output harmonic voltage amplitude on the load;
- P_{Lm} – maximum power in load.

To obtain the greatest oscillation amplitude of an ultrasonic instrument, it is necessary to observe the equality of the frequencies of mechanical and electrical oscillations. Based on the given parameters, it is possible to determine the active resistance of the load R_L, the wave resistance of the contours Z_{w1}, Z_{w2} and the frequency of their resonance f_R :

$$R_L = \frac{U^2{}_{Lm}}{P_{Lm}} \tag{4}$$

$$Z_{w1} = \sqrt{\frac{L_1}{C_1}},\ Z_{w2} = \sqrt{\frac{L_1}{C_2}} \tag{5}$$

$$f_R = \sqrt{\left(\frac{1}{L_1 C_1} - \frac{R^2}{4L^2{}_1}\right)} \tag{6}$$

It should be noted that to use high Q-factor loads (piezoceramic transducer), in expression (5), the subtrahend $R^2/4L^2{}_1$ can be neglected. In expression (5), R is the loss resistance in the circuit.

To study the generator replacement circuit, we set: the voltage of the power supply E = 100 V, the output frequency of the sinusoidal signal f_R = 25 kHz, the wave resistance of the oscillating circuit Z_w = 50 Ohm. Thus, using the procedure for calculating the generators given in [2] and expressions (3) – (5), we can determine the parameters of the oscillatory circuits. The Table 1 shows the values of the contour element values, contour type, the formulas and the filter operating conditions, in which the generator output voltage is sinusoidal. The scheme was studied for four variants of combining the elements of these circuit.

The study of the replacement circuit (Fig. 1) makes it possible to obtain the results in the form of time dependences of the currents, voltages and powers in its elements. It is also possible to present these results in a parametric dependences form: U_{Lm} (C_2), I_K (C_2), U_{Lm} (R_L), on the change in load resistance R_L or capacity of capacitor C_2.

Table 1. Parameters of resonant circuits

Exp. No	C_1, nF	C_2, nF	L_1, uH	R_L, Ohm	Contour type	Sinusoid Generation conditions
1	128	no	320	10–100	serial	$R_L < Z_{w1}$
2	no	128	320	10–100	parallel	$R_L > Z_{w2}$
3	128	128	320	10–100	sequential-parallel	$Z_{w1} = Z_{w2}$
4	128	128–1000	320	10–500	sequential-parallel	$Z_{w2} \leq Z_{w1}$

In the experiment No 1 (Table 1), studies were of a serial inverter [6] were carried out, considering the sinusoidal condition of the output signal, when $R_L < Z_{w1}$. In this figure (Fig. 2), the input voltage of the circuit U_K is rectangular, bipolar.

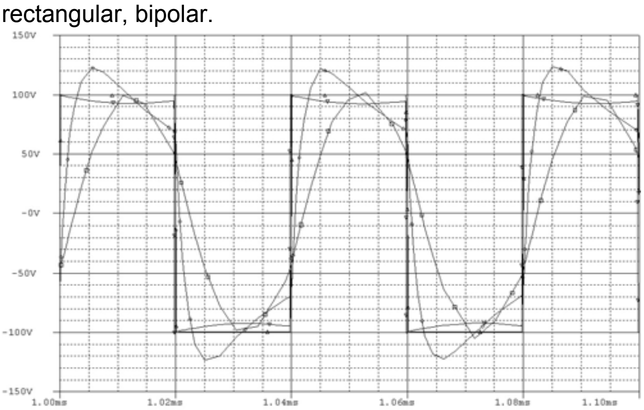

Fig.2. Voltage at the input of the circuit and on the load. Serial circuit. U_K = 100 V, R_{L1} = 10 Ohm, R_{L2} = 100 Ohm

U_K – voltage on the diagonal of the transistor bridge, in which a single-loop filter is included, i.e., L_1, C_1 and R_L.

Obviously, if $R_L < Z_{w1}$ (in the experiment R_{L1} = 10 Ohm) the shape of the curve is harmonic. With the increase of the load resistance (to an infinitely large value) if $R_L > Z_{w1}$ (Fig. 2. R_{L2} = 100 Ohm), the waveform distorts and becomes non-sinusoidal. This property of a serial inverter – to generate a sinusoid in a rather narrow range of load resistance variation (R_L = 0...Z_{w1}) is a significant drawback of transistor circuits. For thyristor circuits, this drawback leads to disruption of inverting and failure [6]. But for any changes in R_L, the amplitude of the output signal remains stable.The magnitude of the amplitude $U_{Lm} = 1,41U_K$, as follows from the expansion of the rectangular voltage U_K in the Fourier series [4].

To obtain a sinusoidal voltage on the load with resistances $R_L > Z_{w1}$, it is necessary to connect capacitor C_2 in parallel with the load (experiment No 2). The curves in Fig. 3 illustrates the fact that R_{L1} = 10 Ohm ($R_{L1} < Z_{w2}$) the voltage is not sinusoidal, and at R_{L1} = *100* Ohm – sinusoidal.. Studies have shown that the sinusoidal voltage on the R_L increases if the shunting effect of the load on the capacitor C_2 decreases, i.e., the resonant L_1, C_2 circuit becomes less damped.

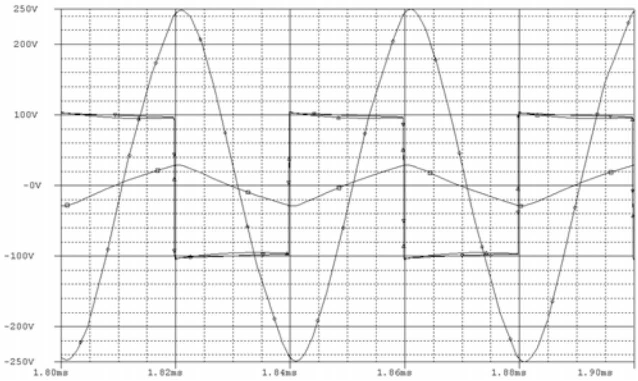

Fig.3. Voltage at the input of the circuit and on the load. Parallel circuit. U_k = 100 V, R_{L1} = 10 Ohm, R_{L2} = 100 Ohm

In the experiment No 3 serial and parallel capacitors interact via throttle L_1 that in the entire range of load resistance (R_L = 0 – ∞) is sinusoidal voltage [8]. In the range $R_L > Z_{w2}$ the amplitude is stable and equal to $U_L = 1,41U_K$. Fig. 4 illustrates this fact.

Experiment No 4 consists of two parts. In the first case, the load resistance is fixed (R_L = 100 Ohm) and the capacitance value of capacitor C_2 changes [8]. In the second case, on the contrary, the capacitance value of the capacitor C_2 is fixed (C_2 = 600 nF), and the load resistance varies (Table 1).

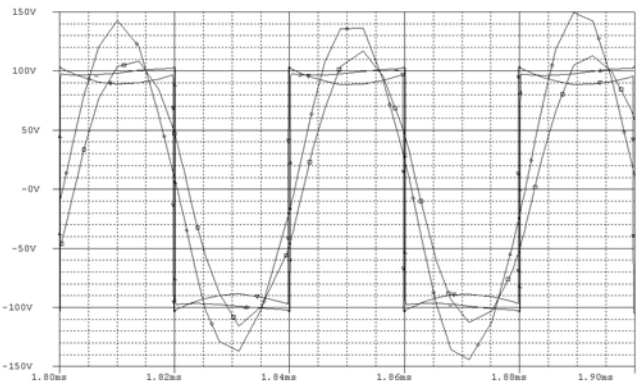

Fig.4. Voltage at the input of the circuit and on the load. Sequential-parallel circuit. U_k = 100 V, R_{L1} = 10 Ohm, R_{L2} = 100 Ohm

Analyzing the results of the first part of the experiment No 4 (Fig. 5), we see that as the capacity of capacitor C_2 increases, the voltage on it, and hence the voltage on the load also increase. The reason is an increase in the contour current *(I_K)* L_1, C_1, C_2 if the resistance of the capacitor C2 decreases.

In Fig. 4, the $U_K(t)$ curve of a rectangular voltage contains dips. They can be explained by the voltage drop on the internal resistance (Fig. 1 does not indicate) the power supply of the generator E, when large sinusoidal currents flow. This reduces the efficiency of the generator.

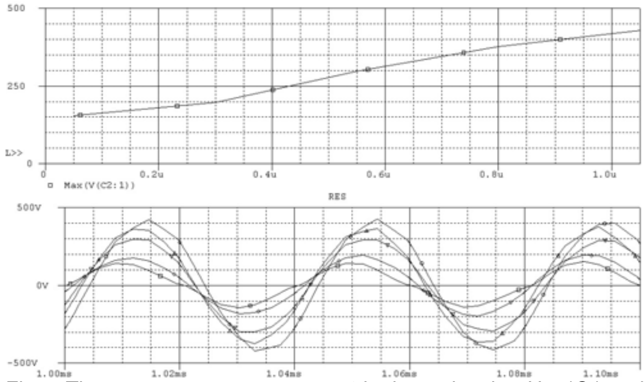

Fig.5. The upper curves are parametric dependencies U_{Lm} (C_2) and I_K (C_2), lower curves are time voltage diagrams $U_L(t)$

The second part of the experiment No 4 (Fig. 6) shows that if increase $R_L > Zw_2$, so the output voltage changes little (almost stably). It should be noted that the less the load circuit C_2, R_L is damped, the higher U_{Lm}.

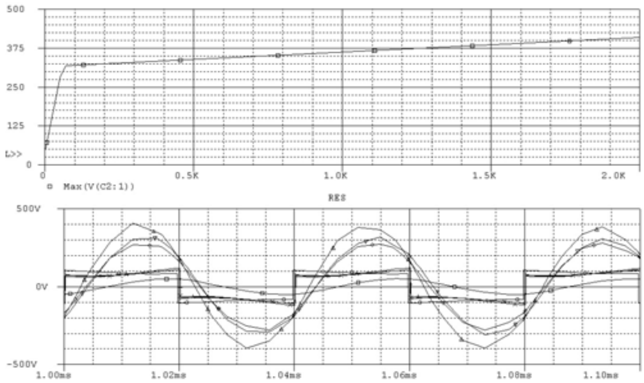

Fig.6. The upper curves are parametric dependencies U_{Lm} (R_L), lower curves are time voltage diagrams $U_L(t)$ and $U_K(t)$

In addition to the experiments carried out, studies were conducted in critical or emergency generator operation modes. For example, the short circuit of the load and its breakage. Under these modes, the circuit remains functional. When the load is breaken (R_L = ∞), the voltage U_L is sinusoidal and corresponds to the specified parameters of the circuits *K1* and *K2*, i.e. does not exceed the nominal value. In the case of a short circuit (R_L = 0), the voltage U_L = 0 and the current I_K is limited by the resistance of the capacitor C_1.

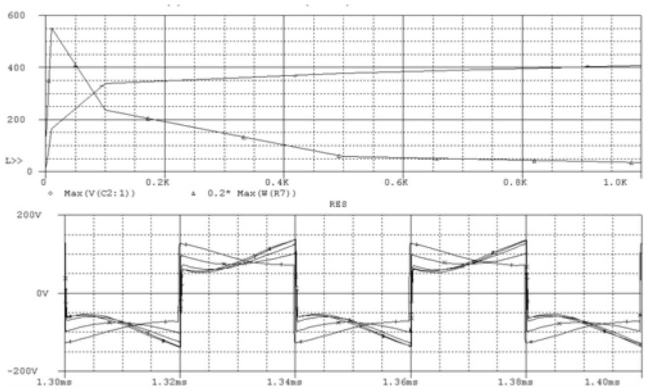

Fig.7. The upper curves are parametric dependencies $P_L(R_L)$ and $U_{Lm}(R_L)$, lower curves are time voltage diagrams $U_K(t)$

Fig.7 shows the power diagrams $P_L(R_L)$ and the voltage U_{Lm} (R_L) in the load as a function of its resistance, as well as the time diagram of the input voltage of the circuit $U_K(t)$. The reasons for the dips on the rectangular form of the supply voltage are explained above. It should be noted that due to dips, the average value of the supply voltage is less than the value E = 100 V. Analysis of the curve $P_L(R_L)$ shows that the peak power value exactly corresponds to the equality $R_G = R_L$, where R_G is the internal resistance of all elements of the generator.

Analyzing the results of the study, several important factors can be noted:

- U_L voltage is sinusoidal over the entire load resistance range.
- The voltage on the load increases almost linearly with the capacitance of the parallel capacitor C_2.
- If the capacitance C_2 is increased (experiment No 4, part 1), the (wave resistance) of circuit *K2* changes, but the frequency of the output voltage does not change, since it is set in this case by the leading circuit *K1* (master tank). The slave contour *K2* (slave tank) determines only the value of the output voltage.

Selecting parameters of Control Unit

For efficient operation of USM, as noted earlier in introduction, it is necessary to control the acceptable oscillation amplitude of the piezoelectric transducer and adjust the frequency of the generator output harmonic signal to the PETs resonance frequency. In this regard, there is a need to measure the oscillation amplitude of the radiating surface of the oscillating system and measure the current through the PETs, defining its maximum value (resonant mode) [4].

Modern development of microelectronics provides a large selection of tools for measuring the PETs oscillation amplitude. Optical measurement methods and a variety of microelectronic mechanical devices based on MEMS – Technology (Micro-Electro-Mechanical Systems) [7]. are widely used. For the following task it is convenient to use MEMS-accelerometer, which permits to convert oscillation amplitude value to digital output signal.

To maximize the efficiency of using PETs as a part of process unit, current is generally controlled, which measurement can be performed, for example with the use of a transformer current sensor. Another method of controlling a resonant mode associated with the phase detector that allows to select the phase relation of PETs voltage and current passing there through. This method is useful for low power radiation or as an additional control to main (for example, current control). To control the PETs current resonant value it is necessary to have a transducer amplitude-frequency response characteristic (AFC). Determining methodology given in [8,9]. AFC allows to specify the source data for the control unit.

Define problems for the control unit:

- Maintenance of a given output voltage amplitude through generator's power level adjustment (PWM – control). At the same control characteristics can be selected depending on the mode of use of USM.
- Allowable PETs oscillation amplitude control through tuning the voltage generator power.
- PETs resonant mode control through adjustment of the oscillator frequency.
- Digital processing of the control system is based on the digital matrix – programmable logic integrated circuits (FPGA – Field Programmable Gate Array). Advantages of using this technique are the high matrix performance, convenient implementation of the control algorithm in the form of stream processing, a large number of library functions presented in the form of IP-cores. The big advantage is the ability to use PLIC reconfiguration hardware implementation unlimited number of times. In addition, the development can be done on hardware description languages (Verilog, VHDL), that increases development productivity and allows you to perform functional and timing simulation project.

Authors: *dr. Vladimir I. Diagilev, State University "Dubna", Branch "Protvino", Protvino, Moscow region, Severny pas. 9, Protvino 142281 Russia, E-mail: dvi-39@mail.ru; dr. Valery A. Kokovin, State University "Dubna", Branch "Protvino", Protvino, Moscow region, Severny pas. 9, Protvino 142281 Russia, E-mail: kokovin@uni-protvino.ru; prof. dr hab.,Saygid U. Uvaysov, Moscow Technological University (MIREA), Moscow, 78 Vernadsky Avenue, 119454 Russia, E-mail: uvaysov@yandex.ru; PhD., Prof. Andrzej Smolarz, Lublin University of Technology, Institute of Electronics and Information Technology, Nadbystrzycka 38A, 20-618 Lublin, Poland, e-mail: a.smolarz@pollub.pl; M.Sc. Saule Rakhmetullina, East Kazakhstan State Technical University named after D.Serikbayev, email: rakhmetulinas@mail.ru; M.Sc. Yedilkhan Amirgaliyev, Institute Information and Computational Technologies CS MES RK, email: amir_ed@mail.ru;*

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