PWM POWER CONVERTER FOR MECHANICAL SHOCKS GENERATING USING PIEZOELECTRIC TRANSDUCERS

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***Abstract**: This device constitutes a specific application of piezoelectric transducers, which allow the generation of mechanical shocks. The device work is based on the process of achieving of inverse piezoelectric effect. The equipment consists in a piezoelectric generator assembly and a command and supply system. The equipment was physically realized and it constituted the object of a research contract of the Optical-Electronic Institute of Bucharest. In this paper is also presented a Spice simulation of the projected equipment.*

***Keywords**: mechanical shocks, piezoelectric transducers, PWM power converter, inverse piezoelectric effects.*

1. INTRODUCTION

The device operation is based on the process of achieving inverse piezoelectric effect, meaning the deformation of the crystalline network of the piezoelectric device caused by an external electrical field. The deformation power of piezoelectric transducer is approximately 450W.

The generator is a piezoelectric transducer, which belong to the series of piezoelectric devices with elastic wave of volume. The dimensions and the composition of the piezoelectric transducers were determined depending on the working conditions and on the datum mechanical power. Many factors, included material, mechanical constructions (radiation surface area, mechanical damping, housing, connector type, etc.), electrical construction, and the external mechanical and electrical load conditions, influence the behavior of a transducer [10].

The configuration of the electro-elastic piezoelectric transducer is presented in Fig. 1.

The equipment is used for the generation of seismological shocks or as electro-acoustical press. It is a specific application of the piezoelectric crystals, which allow the obtaining mechanical shocks, based on unconventional method. The kinetic energy for the seismologic shocks generating set developed in system is approximately 45J and 100J for the electro-acoustical press. Under the action of the electrical field produced by the excitation source, the piezoelectric generator will have an axial expansion of 0.15…0.2mm in a time of 0.1s.

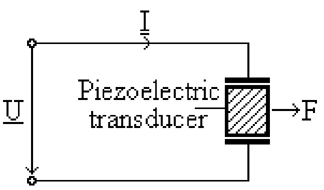

Fig. 1 Configuration of the electro-elastic piezoelectric transducer

The command and supply system of the piezoelectric device is a switch mode power supply realized using a half bridge converter - the optimally variant for capacitive loads, high voltages and output powers up to 2kW. A specific computer program is used to generate the series of datum impulses. For certain values of frequency, the equivalent electro-elastic diagram of piezoelectric transducer could be represented as a circuit with discreet elements (Fig. 2).

The elements of equivalent diagram have the following expressions and significations [5,7]:

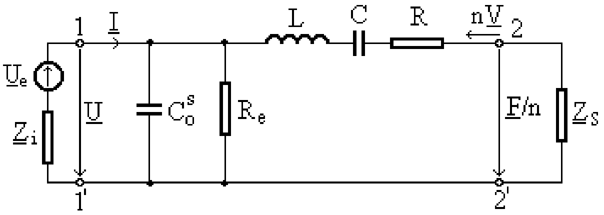

Fig. 2 Equivalent diagram of piezoelectric transducer

$$C_o^s = \frac{1}{2\pi f} \mathrm{Im}\left\{\frac{1}{\underline{Z}_{oe}}\right\} \quad (1)$$

$$R_e = \frac{Q_e}{2\pi f C_o^s} \quad (2)$$

$$L = \frac{Z_{om}}{8n^2 v_f} = Z_{om}\frac{\lambda}{16\pi f_s n^2} \quad (3)$$

$$C = \frac{4n^2}{\pi^2 f_s Z_{om}} \quad (4)$$

$$R = \frac{\pi Z_{om}}{8 Q_m n^2} \quad (5)$$

Where: $\underline{F}$ is the representative in simplified complex of elastic force at mechanical gate; $\underline{V}$ – the representative in simplified complex of vibration speed at mechanical gate; $\underline{U}$, $\underline{I}$ – the representatives in simplified complex of voltage and electrical current at electrical gate; n – the transformation ratio of ideal electro-elastic transformer; f – the oscillation frequency of electrical applied field; λ – the wave length of the gradual elastic wave; Z_{om} – the characteristic elastic impedance of the transducer; Q_m, Q_e – the qualitative mechanical and electrical factors of the transducer; f_s – the value of the frequency for which the constant phase of the transducer has the particular characteristic value at the mechanical resonance; v_f – the propagation speed of the elastic wave in the piezoelectric transducer; $\underline{U}_e$, $\underline{Z}_i$ – the complex electro-motive voltage and the internal complex impedance of the supply source for the piezoelectric transducer; $\underline{Z}_S$ – the complex load impedance.

Concrete values of elements in equivalent diagram (Fig. 2) are determined by material parameters corresponding to transducer configuration and constructive sizes.

2. EQUIPMENT BLOCK DIAGRAM

Technical conditions for input and output were the following: the equipment supply is realized from the supply network – 220±15%V a.c., f = 50 Hz; the length of the axial expansion of the piezoelectric assembly – 0.15...02mm; the period of the axial expansion of the piezoelectric assembly – 0,1s; the operating regime – 1 pulse/10s; maximal voltage on piezoelectric device – 3500...6000±1%V, supply voltage variation determining the variation of the axial expanded of the piezoelectric assembly; the efficiency of excitation electronic source – ≥ 80%; the supply and command of the piezoelectric device were realized at maximum depth of 300m; electrical resistance of supply cable, R_C = 80Ω/km; supplementary command device which could short-circuit the piezoelectric assembly after a period of 0.2s from the receiving of the command input; protection against overload, supra-voltage, electrocution, radio-electronic interferences in/from network; the electronic source and piezoelectric assembly were introduced into a stainless steel cylinder with inside diameter – 105mm, outside diameter – 110mm and maximal height – 1m.

The block diagram of mechanical shocks generating set, which is presented in Fig. 3, has two components: a surface equipment (A) and an equipment inside a stainless steel cylinder (B), which functions at 300m depth. Considering the input and imposed output conditions there were established functional units, which compose the generating equipment. The functional units of the surface equipment (A) are the following: protective unit against radio-electronic interferences in/from network (A_1); rectify and filtering unit for supply voltage (A_2); auxiliary power supply of ±18V (A_3); auxiliary power supply for lifting motor (A_4); interface and command unit (A_5); frequency-voltage converter (A_6); circuit for amplitude discrimination of command pulses (A_7); low-pass filter (A_8). The equipment (B) has the following functional unit: steady voltage of ±29V for lifting motor supply (B_1); steady voltage of ±15V (B_2); low-pass filter (B_3); voltage-frequency converter (B_4); filter for radio-electronic interferences (B_5); power supply for triggering circuits (B_6); circuit for width discrimination of triggering pulses (B_7); circuit for amplitude and width discrimination of command pulses (B_8); reaction circuit (B_9); circuit for discharge the piezoelectric generator (B_{12}); condensers battery (B_{10}); triggering circuits (B_{11} and B_{17}); accumulation condenser (B_{13}); rectify unit for supply voltage of piezoelectric generator (B_{14}); high-voltage transformer (B_{15}); high-voltage switched circuits (B_{16} and B_{21}); command circuit of power module (B_{18}); power module (B_{19}); piezoelectric generator (B_{20}); protection overload and supra-voltage unit (B_{22}).

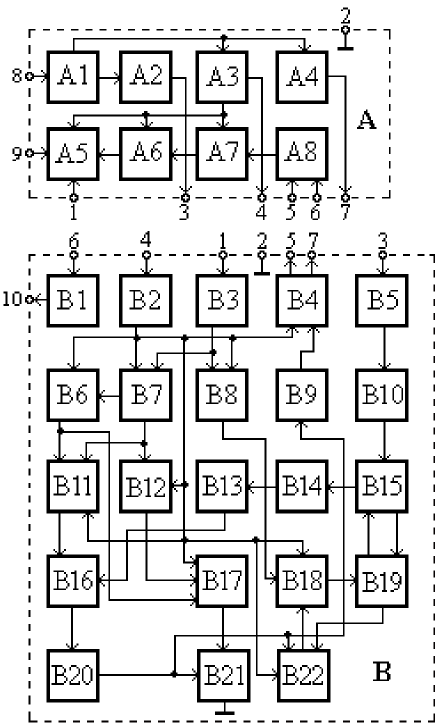

Fig. 3 Block diagram of the mechanical shocks generating set

The interface and command unit realizes the interface between PC and functional unit (B), processes input and output data, and establishes working conditions. Because the command pulses are conducted through a 300 m long cable, it was necessary to utilize some receiving circuits for command pulses, like: low-pass filter, pulse height discriminator realized with a Smith trigger, circuit for time discrimination, circuit for reject the spikes and unlike interferences.

The block diagram of designing power module is presented in Fig. 4.

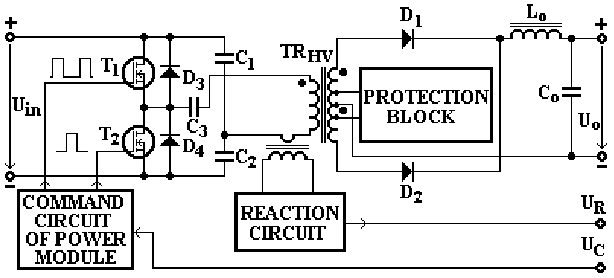

Fig. 4 Block diagram of power module

The half bridge converter is a converter with input-output galvanic isolation. The energy transfer of primary winding – load is realized during the conduction period of the switching elements. As switching elements there were used Power MOS transistors, because they allow obtain efficiency with at least 5 percentages higher than the switch mode power supplies using bipolar transducers.

The commutation frequency chosen is approximately 100kHz and duty cycle is adjusted at any point from 0 to 98%. From that results a diminution of volume for the ferromagnetic core oh the high-voltage transformer. Input and output parameters are presented on display, and working conditions are established with the computer keyboard.

The command circuit (B_{18}) realizes charge and discharge the gate-drain capacitance of Power MOS transistors, in a very short period, determining saturation or blocking them [3].

The switching elements command using the coupling transformers assures a controlled increase of the drain currents of the power transistors by applying a linear variable voltage on the gate. A way of controlling piezoelectric assembly supply current it is to control the switching sequences to the main Power MOS devices. The devices can be switched a constant frequency using a PWM method current control [1,3,8]. Controlling the PWM duty cycle and piezoelectric assembly supply current can tightly control the device piezoelectric axial expansion.

One main advantage of the PWM converter is the feasibility to drive different transducers with varying resonance frequencies without complete redesign of the output filter. High-voltage transformer delivers necessary voltage to supply piezoelectric generator; also, it realized the load matching. The transfer of energy is made sin-phase. The output transformer is needed to ensure an electrical isolation and adjustment to the required level of output voltage.

Protection circuitry includes cycle-by-cycle current limiting, over current protection, soft start capability, voltage protection and feedback loop protection circuits.

3. DESIGNING ELEMENTS

The dimensions of the piezoelectric transducers used for the construction of the piezoelectric assembly are: external diameter, ϕ_{ext} = 38mm; internal diameter, ϕ_{int} = 16mm; height, h = 6mm. The results of the experimental researches accomplished [9] (Table 1) indicate that by supplying such a piece with a voltage of 6kV, it will be axially expanded with approximately 4μm. For an axial expansion of 0.2mm, the piezoelectric device must be realized using 50 piezoelectric pieces, parallel connected.

For the mechanical shocks generator, the developed kinetic energy is equivalent with a weight of 3kg which is falling from a height of 1.5m, resulting E_c = 45J. Considering that the period of the axial expansion of the piezoelectric assembly is 0.1s, the mechanical power developed by the piezoelectric device is 450J/s. The equivalent capacitance of the piezoelectric device is determined using the relation:

$$C_e = \frac{2E_c}{U_o^2} \tag{6}$$

Where: U_o is the supply voltage of the piezoelectric device.

As a consequence of the experiments achieved (Table 1), it results that for a 0.15mm axial expansion of the piezoelectric device, the supply voltage necessary is 4.5kV, and for an expansion of 0.2mm, $U_o = 6\text{ kV}$.

According to relation (6), the value of the equivalent capacitance of the piezoelectric device will be: Ce = 2.5…4.4μF. Because of the low loading efficiency of the piezoelectric device through a resistor device, it results in a primary approximation that the value of the capacitance of the accumulation condenser is: Ca = 5.5…9μF. In Table 1 there are presented a series of experimental results (axial expansion) obtained when a piezoelectric crystal and respectively an entire piezoelectric generator (stack) are supplied with different supply voltages. For a supply of a piezoelectric crystal, the experiments were realized for a great number of crystals and there were calculated the average values of the axial expansion which were obtained.

Table 1 Experimental results

U_o [V]	Measured axial expansion (d)		Calculated axial expansion d[mm]
	Piezoelectric transducer d[μm]	“Stack” d[mm]	
3000	1.98	0.096	0.099
3500	2.31	0.109	0.116
4000	2.66	0.128	0.133
4500	3.00	0.147	0.150
5000	3.34	0.163	0.167
5500	3.67	0.178	0.184
6000	4.01	0.197	0.201
6500	4.32	0.211	0.216

From the presented table it results that the measured axial expansion of the piezoelectric device is smaller than the calculated one, because of the copper electrodes, situated between the piezoelectric crystals, which retard the expansion.

Piezoelectric generator assembly (stack) is show in Fig. 5. The piezoelectric generator assembly is composed by the following elements: metallic inertial mass (1); insulated pieces (2); non-conductive metallic axle (3); copper electrodes (4); piezoelectric transducers (5); metallic piece (6); sealing piece (7); anvil (8); cylindrical stainless steel tube (9); connections between electrodes (10).

The piezoelectric generator consists in fifty piezoelectric radial polarized transducers, which are parallel connected. The piezoelectric transducers are made of ceramic materials as PZT and the research was realized using a material as $Pb(Zr_{0,53}Ti_{0,47})O_3$ doped with Nb_2O_5, BiO_3 and MnO. The piezoelectric generator represents a preponderant capacitive load with a capacitance around 2.5μF.

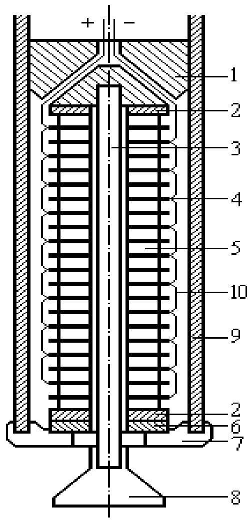

Fig. 5 Piezoelectric generator assembly

4. SPICE SIMULATION

By Spice simulation [2] was tested in time and frequency domains the power supply of piezoelectric device. In order to simplify the analysis and to reduce simulation time, from designed power supply was considered only the power module. The power supply is in essence a closed loop regulating system [4] (Fig. 6), and it must be analyzed its stability.

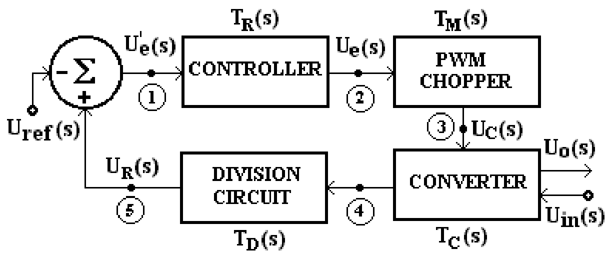

Fig. 6 Power supply as a closed loop regulating system

The converter output-control transfer function is determinate by mediation method [3]. It is given by the following equation:

$$T_C(s) = \frac{U_O(s)}{U_{C(s)}} = K \cdot \frac{1 + \frac{s}{s_1}}{\frac{s^2}{\omega_o^2} + \frac{s}{\omega_o \cdot Q} + 1} \qquad (7)$$

Where: r_C – series equivalent resistance of transducer capacitance, C_o; $K = \frac{n \cdot D}{2} U_{in}$;

$\omega_o = \frac{1}{\sqrt{L_o \cdot C_o}}$; $\omega_o \cdot Q = \frac{R_S}{L_o}$; $s_1 = \frac{1}{r_C \cdot C_o}$.

The transfer function of the closed loop regulating system may be expressed by the equation:

$$F(s) = \frac{U_o(s)}{U_{ref}(s)} = \frac{T_R(s) \cdot T_M(s) \cdot T_C(s)}{1 + T_D(s) \cdot T_R(s) \cdot T_M(s) \cdot T_C(s)} \Rightarrow$$

$$F(s) = \frac{S(s)}{1 + T_D(s) \cdot S(s)} \qquad (8)$$

Where: $T_M(s)$ represents the PWM chopper transfer function, $T_R(s)$ is the PI controller transfer function; $T_D(s)$ is the division circuit transfer function; $S(s) = T_R(s) \cdot T_M(s) \cdot T_C(s)$ represents the open loop gain; $T_D(s) \cdot S(s)$ is the open loop transfer function.

By resolving $1 + T_D(s) \cdot S(s) = 0$ equation, are determined the closed loop transfer function poles. The waveforms for: drain currents, primary winding current of high-voltage transformer, filtering inductance (L_o) current, and supply voltage of piezoelectric device are presented in Fig. 7 and Fig. 8.

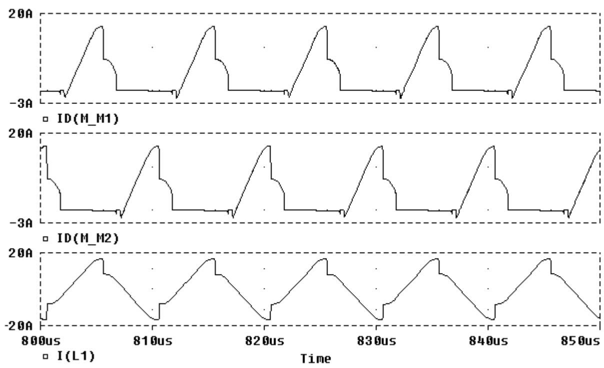

Fig. 7 Waveforms for drain currents and primary winding current of high-voltage transformer

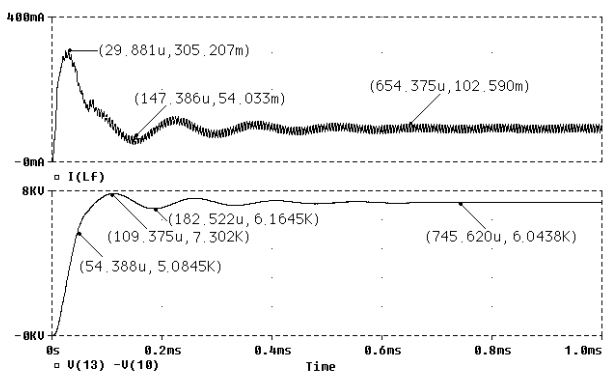

Fig. 8 Waveforms for filtering inductance (L_o) current and supply voltage of piezoelectric device

The waveform for piezoelectric assembly supply current is presented in Fig. 9. The value of the intensity output current supplied by the power converter is 91,733mA, and its maximal variation is about 9mA.

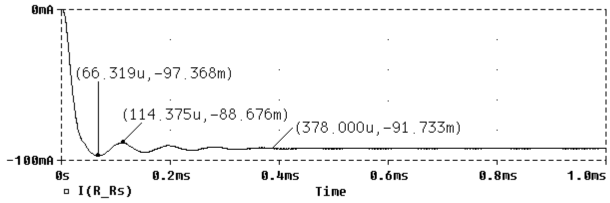

Fig. 9 Waveform for piezoelectric assembly supply current

In order to determinate the project supply response to input voltage perturbation it was considered a linear variation of the input voltage.

It was obtained by Spice simulation the waveforms for output voltage and filtering current (Fig. 10).

The current variation through high-voltage transformer primary winding is presented in Fig. 11, for a time period that lasts form 0 to 200ms.

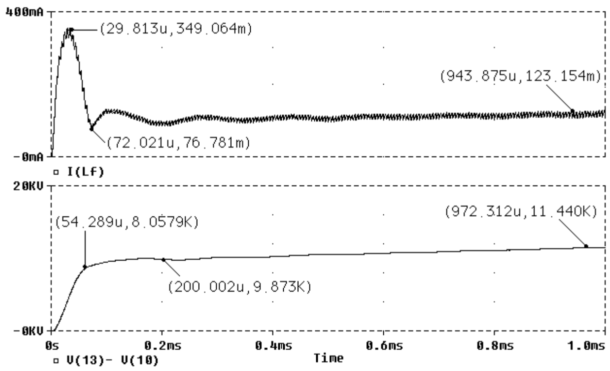

Fig. 10 Waveforms for filtering current and supply output voltage for a linear variation of the input voltage

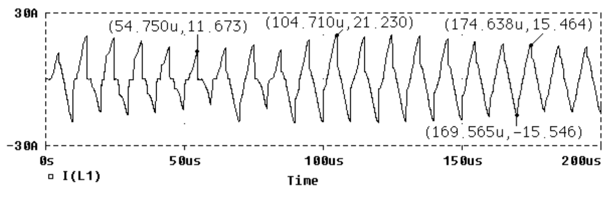

Fig. 11 Current variation through high-voltage transformer primary winding

The frequency attenuation characteristic and envelope-delay characteristic (phase response), for supply source, are presented in Fig. 12.

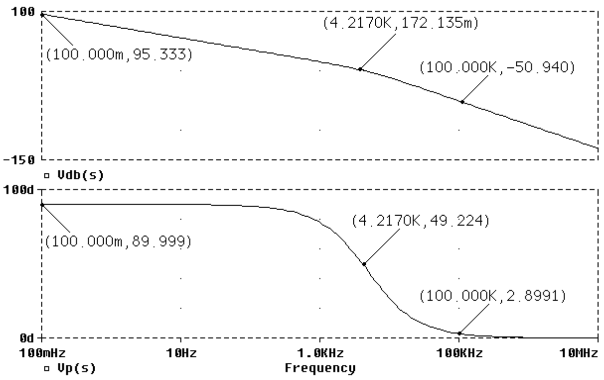

Fig. 12 Waveforms in frequency domain

The open loop transfer function of the system has a pole in fixed point, which is introduced by the controller, a double pole introduced by the converter, and two zero, one introduced by the controller and the other one introduced by the converter. The presence of pole in fixed point ensures a high gain at low frequencies.

The zero introduced by the controller is placed near the double pole introduced by the converter, so that the passing through f_{cross} is realized with value: 20dB/dec.

It results f_{cross} = 4.2kHz. The phase edge is positive and has the value equal to 49,3^{o}.

5. CONCLUSIONS

The presented equipment is a complex system, purposed for generating seismological shocks or as an electro-acoustical press, by an unconventional method, using piezoelectric transducers.

It is constituted of a piezoelectric assembly composed of fifty piezoelectric transducers axial polarized, a switch mode power supply which supply the piezoelectric generator and a command block which allows to obtain the supply voltages of the electronically circuits and also to realize the operation mode.

The basis of the power supplies is a converter stage in half bridge topology. The PWM converter is able to drive the piezoelectric generator assembly, which develops a mechanical power of 450 J/s. Power MOS devices are ideally suited for this type of converter.

The advantages of power MOS devices include their simple gate drive requirements, rugged performance, easy of use in parallel configurations, switching performances.

The numbers of piezoelectric transducers also as their geometry were established considering the mechanic energy that the stack must develop.

Considering the results of performed analyze it is allowed to affirm that the open loop transfer function of the system ensures its stability.

As a consequence of the performed Spice analysis, it results that the evolution in time of the electrical quantities and also the obtained signal levels has a good concordance with calculated values.

It was used an accumulation condenser which is discharging mediate through an high-voltage switched circuit on the piezoelectric assembly, at an external command, for transferring the electric energy from the power supply into the piezoelectric assembly.

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